Active Passive Monolithic Platforms in Si_3N_4 Technology

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ACTIVE PASSIVE MONOLITHIC PLATFORMS IN Si_3N_4 TECHNOLOGY

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Table of Contents

1	Introduction	1
1.1	PICs: challenges and integration methods.....	1
1.2	Silicon nitride photonics.....	2
1.3	Active-passive integration on silicon nitride	4
1.3.1	Hybrid integration of Si_3N_4 with III-V materials	4
1.3.2	Monolithic integration of Si_3N_4 with RE^{3+} doped materials.....	4
1.3.3	Integration of modulators onto the Si_3N_4 platform.....	6
1.4	Outline of the thesis.....	7
	Bibliography.....	8
2	Design, fabrication, and characterization of passive components in Si_3N_4.....	15
2.1	Part I: Optimized MMI-based multi/demultiplexers with low loss and broadband performance	16
2.1.1	Introduction of Part I	16
2.1.2	The MMI structure and working principle	18
2.1.3	Simulation results	20
2.1.4	Fabrication of the MMIs on the Si_3N_4 platform	24
2.1.5	Characterization results	25
2.1.6	Optimal design for an MMI on a 200 nm Si_3N_4 layer	28
2.1.7	Conclusion of Part I.....	29
2.2	Part II: Add-drop ring resonators and propagation loss characterization	30
2.2.1	Loss of a Si_3N_4 waveguide bend.....	30
2.2.2	The principle of an add-drop ring resonator.....	31
2.2.3	Experimental results and discussions	34
2.3	Part III: Sagnac loop mirrors	36

2.4	Conclusion.....	39
	Bibliography.....	40
3	High-performance optical coupling for polymer-on-Si₃N₄ integration	45
3.1	Introduction	46
3.2	Part I: Hybrid integration by flip-chip bonding.....	48
3.2.1	Device design	48
3.2.2	Fabrication process	52
3.2.3	Experimental results and discussion.....	54
3.2.4	Conclusion of Part I.....	56
3.3	Part II: Monolithic integration using vertical Si ₃ N ₄ taper	57
3.3.1	Device design	57
3.3.2	Fabrication results	61
3.3.3	Experimental results and discussion.....	62
3.3.4	Conclusion of Part II	65
3.4	Conclusion.....	65
	Bibliography.....	66
4	Double-layer active-passive platforms for Al₂O₃-on-Si₃N₄ integration..	69
4.1	Introduction	70
4.2	Part I: Double-layer platform development.....	72
4.2.1	Device design	72
4.2.2	Simulation results	75
4.2.3	Fabrication results	81
4.2.4	Characterization.....	87
4.2.5	Alternative integration scheme without SiO ₂ buffer layer	93
4.2.6	Conclusion of Part I.....	96
4.3	Part II: Active-passive integration.....	97

4.3.1	Fabrication results	97
4.3.2	Characterization results	98
4.3.3	Conclusion of Part II	99
4.4	Part III: Investigation of resonant coupling effect.....	99
4.4.1	Resonant coupling effects.....	100
4.4.2	Experimental results and discussions	104
4.4.3	Conclusion of Part III	105
4.5	Conclusion.....	105
	Bibliography.....	106
5	Al₂O₃:Er³⁺-Si₃N₄ amplifiers based on the double-layer active-passive platform.....	111
5.1	Introduction	111
5.2	Simulation	114
5.2.1	Waveguide design	114
5.2.2	Gain simulation	118
5.3	Fabrication results	123
5.4	Measurement principle and setups	126
5.4.1	Gain measurement principles	126
5.4.2	Gain measurement setups.....	128
5.4.3	Approaches for measuring absorption and propagation losses.....	129
5.4.4	Estimation of ion concentration.....	130
5.5	Results I: The Amp-I type integrated amplifiers	131
5.5.1	Absorption and propagation losses.....	131
5.5.2	Transmission spectra and the amplifier losses	134
5.5.3	Net gain	137
5.6	Results II: The Amp-II type integrated amplifiers	139
5.6.1	Absorption and propagation losses.....	139
5.6.2	Signal enhancement and net gain	142

5.7 Conclusion.....	145
Bibliography.....	147
6 Summary	151
Bibliography.....	153
Appendix	155
A. CMP polishing rates	155
B. Etching rates	158
Bibliography.....	159
Samenvatting	161
List of publications	165
Peer-reviewed journal articles	165
Contributions to conferences.....	165
Other contributions.....	166
Acknowledgements.....	167

1 Introduction

1.1 PICs: challenges and integration methods

Photonic integrated circuits (PIC) were first proposed by Miller in 1969 [1]. It was then when the term “integrated optics” was created. Since that moment, numerous research activities in the field of integrated optics have been carried out in industrial, governmental and university laboratories. Especially over the past two decades, integrated photonics has attracted increasing interest [2-8]. However, since its conception, the growth of the integration density of PICs has not experienced the exponential scaling of integrated electronic circuits (EIC), which has led to electronic chips containing billions of transistors [9-11]. In photonics, the integration density is defined by the refractive index contrast and the wavelength of light. The index contrast is limited by the available materials. The optical wavelength cannot be freely adapted due to the material properties, and it is much larger than electron sizes. These fundamentally slower the growth of the photonic integration density. As described by Kamninow [12], some more challenges include:

1. A more diverse set of building blocks are required in PICs than electronic ICs including multi/demultiplexers, lasers, amplifiers, modulators, polarization controllers, phase adjusters, and attenuators.
2. Active devices in PICs require a much more diverse set of materials that are harder to control and manufacture than EICs.
3. Lack of an application leading to volume manufacturing, although applications in mobile communications and automotive, which might drive high volume manufacturing, are emerging [13].

Many materials have been employed for the realization of PICs, including silicon-on-insulator (SOI) [14, 15], III-V semiconductors [16, 17], silicon nitride (Si_3N_4) [18-20], lithium niobate (LiNbO_3) [21, 22], polymers [23-25] and rare-earth-ion (RE^{3+}) doped materials [26-28]. In the last decade, great efforts have been directed towards the development of “generic” photonic platforms that will enable the “foundry” concept and the scaling of the manufacturing of PICs [15, 16, 29-31] such as industrial implementation of a silicon photonics platform using 300-mm SOI wafers [31]. In this moment, three material platforms offering generic processes are commercially available and accessible via multi-project

wafer (MPW) runs. These technologies are the SOI platform [14, 15], the InP platform [16] and the Si_3N_4 platform [18-20]. An important advantage of these platforms is that they have an entire supply chain including foundries with good compatibility with the electronic IC industry, software suppliers that support both custom and process design kits (PDK) driven designs, testing services and packaging foundries.

Each of these photonic platforms have their own advantages and limitations. To achieve more diverse functionalities on a photonic chip, the combination of different material platforms is extremely important. This is generally carried out by either hybrid integration, heterogeneous integration or monolithic integration [2, 32]. Hybrid integration combines processed photonic chips or chiplets in a package or an interposer. For example, using flip-chip bonding, high performance optical couplers between the polymer and SOI waveguides can be achieved for Datacom applications and high-performance computers [24, 25, 33]. Using photonic wire bonding, flexible chip-scale optical interconnection can be realized between the processed chips [34, 35]. Short reach optical connectivity between SOI chips has been demonstrated using femtosecond laser-inscribed waveguides in a glass interposer [36]. Heterogeneous integration, alternatively, combines different materials on a single substrate by wafer-scale fabrication during the process flow. It is commonly used, for example, to integrate indium phosphide active layers on silicon photonic wafers using wafer bonding [37, 38]. Monolithic integration provides a straightforward path towards cost-effective co-integration of different materials with the potential for large scalability. Examples include the direct growth of InP lasers on silicon [39], and the deposition of rare-earth-ion ion doped Al_2O_3 lasers on Si_3N_4 [28]. Monolithic integration takes place at the front-end, while heterogeneous and hybrid integration are back-end processes. General challenges in the different integration approaches are achieving high-performance optical coupling between different waveguides, exhibiting low-loss and broadband behavior, and being highly tolerant to fabrication error to allow for the realization of very high-density integration with low propagation losses.

1.2 Silicon nitride photonics

The Si_3N_4 platform has been chosen in this thesis due to its promising optical properties. As shown in Fig. 1.1, Si_3N_4 has a wider transparency window (i.e., from the visible to the near-infrared, ~ 400 nm to $4\text{ }\mu\text{m}$) than the III-V

semiconductors and the SOI platforms, which can be mainly employed in near infrared (NIR). Compared to the devices based on the SOI platform, which usually have propagation losses of 0.1–0.5 dB/cm for a ridge waveguide configuration and 1–3 dB/cm for fully etched waveguides [15], the devices in the Si_3N_4 platform exhibit lower propagation losses (~ 0.1 dB/cm) from the visible till the near infrared [18–20], while it becomes dominated by SiO_2 absorption at the longer wavelengths (~ 4 μm). For a high-aspect-ratio core geometry, 0.1 dB/m ultra-low-loss has been achieved in the Si_3N_4 platform [40]. The refractive index contrast between the Si_3N_4 core (1.98) and the SiO_2 cladding (1.45) can be obtained. In addition, the Si_3N_4 platform is nowadays commercially provided by companies such as Lionix [41], Ligentec [42], IMECs BioPIX [43] and IMB-CNM [44]. More details concerning the specifications of the Si_3N_4 waveguides from these providers can be found in [19].

Fig. 1.1. Wavelength ranges of different materials commonly employed in generic processes with multi-project wafer (MPW) run accessibility [45].

Benefiting from these outstanding optical properties, tremendous progress was made on applications based on passive Si_3N_4 photonics. For example, in microwave photonics, the Si_3N_4 waveguides are used for beamforming systems [46] and programmable signal processing chips [47]. In non-linear optics, optical combs [48, 49] and supercontinuum generation [50, 51] are demonstrated using thick Si_3N_4 waveguides with high mode confinement. In the bio-sensing field, interferometric sensors [52], fluorescence imaging [53] and Raman spectroscopy [54, 55] on the Si_3N_4 platform have been demonstrated. More recently, the Si_3N_4 platform are presented in range and position sensors for autonomous drive technologies such as Lidar [56, 57] and optical gyroscopes [58, 59].

A big challenge in Si_3N_4 PICs is the integration of active sources such as lasers, amplifiers, and modulators. *The goal of this thesis is to develop generic integrated platforms and building blocks that enable various active-passive photonic applications based on the Si_3N_4 platform.* A great effort has been devoted in the last decade to investigate the integration, both monolithic and

hybrid, of active devices on the Si_3N_4 platform. The rest of this chapter gives an overview of active devices such as lasers, amplifiers and modulators on the Si_3N_4 platform. The advantages and drawbacks of these devices, and especially of the integration methods, are discussed. Finally, the layout of this thesis is presented.

1.3 Active-passive integration on silicon nitride

1.3.1 Hybrid integration of Si_3N_4 with III-V materials

By using hybrid integration, lasers with emission from the visible to the near-infrared have been realized. Some laser effects in the visible spectrum were demonstrated both by bonding an organic dye-doped Poly(methyl methacrylate) (PMMA) cladding onto a Si_3N_4 spiral resonator [60] and by embedding colloidal quantum dots on Si_3N_4 discs [61]. The commonly used scheme in hybrid integration, is combining commercially standard III-V semiconductor optical amplifiers (SOA) with external Si_3N_4 cavities [62-67] by facet bonding, i.e., through butt-coupling. World-record-performance for a narrow linewidth hybrid laser (290 Hz) [64] was realized by butt-coupling an InP SOA to a high Q external cavity on the Si_3N_4 platform.

The main advantage of this type of hybrid integration is that the SOA is commercially available, and high-performance devices can be independently fabricated on the Si_3N_4 platform. Good performance of the hybrid lasers requires careful optimization of the interface between the III-V and Si_3N_4 waveguides for butt-coupling [18]. Such assembly and packaging requires precise alignment accuracy, leading to difficulties in realizing large-scale, cost-effective and efficient processes, especially when scaling to PICs with complex functionalities and high integration density.

1.3.2 Monolithic integration of Si_3N_4 with RE^{3+} doped materials

Besides the above mentioned lasers by hybrid integration, monolithic integration of rare-earth-ion doped materials and Si_3N_4 provides a promising alternative for high-performance and mass-manufacturable active devices.

Compared to the carrier lifetimes of III-V materials, i.e., tens to a few hundred picoseconds [68], rare-earth-ion doped materials commonly have high intrinsic lifetime, which ranges from 0.1–10 ms among different types of RE^{3+} and host materials [27], and much weaker refractive index change caused by the excitation of the RE^{3+} is low $\sim 10^{-6}$ [26, 69, 70], making RE^{3+} amplifiers a better

candidate for applications requiring high data rate amplification. For example, the first high-speed optical amplifiers using $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ achieved 170 Gbit/s amplification [71]. Additionally, RE^{3+} materials generally have lower noise figure and larger gain bandwidth [26], which are advantageous for amplification of more signal channels and narrow-linewidth laser. For instance, the first distributed feedback (DFB) waveguide lasers in $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ obtained 1.7 kHz instantaneous linewidth [72]. RE^{3+} materials also enable to provide high gain (~ 935 dB/cm) performance, which is comparable to the III-V material, e.g., RE^{3+} doped monoclinic potassium double tungstates [73].

Many distributed Bragg reflectors (DBR) or DFB lasers have been developed by depositing the $\text{Al}_2\text{O}_3:\text{RE}^{3+}$ layers directly onto the Si_3N_4 platform [74-79]. These DBR and DFB lasers have in common that the optical mode is guided in a ridge waveguide formed by several Si_3N_4 segments and a deposited $\text{Al}_2\text{O}_3:\text{RE}^{3+}$ layer, as shown in Fig. 1.2(a) [77]. With this integration scheme, more complex cascaded DFB cavities and ring filters can be well-determined in the Si_3N_4 layer, e.g., to realize wavelength division multiplexed light sources [80-82].

Fig. 1.2. Schematics of $\text{Al}_2\text{O}_3:\text{RE}^{3+}$ - Si_3N_4 lasers by directly depositing the $\text{Al}_2\text{O}_3:\text{RE}^{3+}$ layer (a) onto the Si_3N_4 platform [77] or (b) into a trench into the SiO_2 cladding on top of the Si_3N_4 platform [83].

Furthermore, the $\text{Al}_2\text{O}_3:\text{RE}^{3+}$ layers can also be deposited into trenches fabricated in the SiO_2 cladding of the Si_3N_4 platform [83-86] to form a more confined mode for ring lasers, as shown in Fig. 1.2(b). Still, the optical modes guided in the trenches are assisted by the Si_3N_4 waveguides/elements. Both schemes, i.e., by directly depositing $\text{Al}_2\text{O}_3:\text{RE}^{3+}$ onto the Si_3N_4 components and into the SiO_2 trenches, can minimize the process to only a single backend deposition. In the ridge waveguide configuration, the less confined mode in the lateral direction limits the minimum radii of the waveguide bends. The lower

intensity of such large mode can probably result in higher lasing threshold. Moreover, high resolution lithography is necessary to precisely determine the DBR and DFB parameters. Ultra-precise alignment between the trench cavity and Si_3N_4 structures underneath is needed.

Recently, a compact integrated $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ - Si_3N_4 amplifier shows that high gain per unit length amplification (20 dB/cm) is possible [87]. In this amplifier, an $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ was deposited in a slotted- Si_3N_4 waveguide 250 μm long by an atomic-layer deposition (ALD) process with a high Er^{3+} doping concentration of $\sim 4.9 \times 10^{21} \text{ cm}^{-3}$. Although high gain per unit length is achieved, the net gain is generally very low, with narrow bandwidth, and the fabrication processes is time-consuming. It is challenging for these devices to achieve higher gains due to quenching processes of the Er^{3+} ions originating from energy-transfer up-conversion (ETU), and insufficient inversion because of high pump absorption, limiting the overall gain. On the other hand, the highest net gain of ~ 20 dB has been reported in $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ spirals on thermally oxidized silicon [88] based on the co-sputtering technology that is used in the above lasers. This shows a great potential to realize high net gain amplifiers in the Si_3N_4 platform with low-loss optical solutions for interconnecting the Si_3N_4 and $\text{Al}_2\text{O}_3:\text{RE}^{3+}$ waveguides.

1.3.3 Integration of modulators onto the Si_3N_4 platform

Toward system-on-chip applications, there are also many integration schemes that are applied to achieve light modulation in Si_3N_4 photonics. Especially for high-speed modulators, the Si_3N_4 platform has additional advantages, such as much lower nonlinear losses and a thermo-optic coefficient compared to the SOI platform [89]. Modulators with a frequency of $\sim \text{kHz}$ up to hundred MHz have been demonstrated on the Si_3N_4 platform by depositing electrically drivable materials to obtain surface acoustic wave induced strain-optic effect [90, 91]. High modulation frequency (tens of GHz) is more achievable by integrating the Si_3N_4 with electro-optic (EO) materials such as BaTiO_3 (15 GHz) [92], graphene [93] and ferroelectric lead zirconate titanate (PZT) (33 GHz) [94]. High-speed modulation from tens of GHz up to 100 GHz have been realized in EO polymers [95-97] and lithium niobate (LiNbO_3) [98, 99]. Phase shifters have been studied by directly spinning an EO polymer onto Si_3N_4 waveguides [100], showing lower loss (0.8 dB/cm) than an all-polymer phase shifter but weaker electro-optic efficiency (27%). Wafer-scale heterogeneous integration is also applied to integrate thin film modulators onto the Si_3N_4 platform [101]. A common drawback of these devices is the increased propagation loss in the Si_3N_4

waveguides because the mode in the Si_3N_4 waveguide core overlaps with the EO materials. Optical coupling between the Si_3N_4 waveguide and the one integrated in the EO material is challenging. Vertical mode transition by etching a terrace structure shows optical coupling of ~ 0.8 dB between the Si_3N_4 and $\text{LN-Si}_3\text{N}_4$ waveguides [102], implying great potential to realize high-speed modulators on the Si_3N_4 platform with low propagation loss.

1.4 Outline of the thesis

In this thesis, Chapter 2 describes the design, fabrication and characterization of different passive building blocks in the Si_3N_4 platform including MMI-based multi/demultiplexers, ring resonators, and Sagnac loop mirrors. The multi/demultiplexers are specifically optimized to achieve low-loss and broadband performance, which will later be applied to the integrated $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ - Si_3N_4 amplifiers. The add-drop ring resonators are studied to characterize the propagation losses of the Si_3N_4 waveguides. The Sagnac loop mirrors are studied for future lasers applications. In Chapter 3, optical coupling with low-loss, broadband, and highly tolerant to fabrication errors is studied for the integration of the Si_3N_4 and polymer waveguides. Both hybrid and monolithic polymer- Si_3N_4 -polymer integrated platforms are developed and demonstrated using SU-8. In Chapter 4 a double-layer monolithically integrated platform for the integration of Si_3N_4 and Al_2O_3 is investigated. With the developed fabrication processes, such platform enables scalable and tolerant active-passive integrations with promising optical coupling solutions. Chapter 5 presents integrated $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ - Si_3N_4 amplifiers based on our double-layer active-passive platform. A novel gain characterization is discussed benefiting from the active-passive integration. High net gain of the integrated amplifiers is demonstrated. Appendix A describes the results during the process development of the chemical mechanical polishing (CMP) for the thin isolation film in the double-layer platform. Appendix B shows the characterization of etching speed for the Al_2O_3 and photoresist.

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2 Design, fabrication, and characterization of passive components in Si₃N₄

In this chapter, passive components that constitute basic building blocks for devices integrating active/passive functionalities in the Si₃N₄ platform are presented. Part I of this chapter introduces a low-loss and broadband MMI-based multi/demultiplexer. The multi/demultiplexer serves as a basic building block to combine/split the pump and signal lights. This component is especially important for the integration of rare-earth-ion doped materials onto the Si₃N₄ photonic platform for the realization of on-chip amplifiers and lasers. We employed a fast and reliable optimization process to design the MMI-based multi/demultiplexers. The method combines the field mode matching (FMM) method, a modified effective index method (EIM), and a fully vectorial 2D beam propagation method (BPM). The optimized devices exhibit calculated total insertion losses of 0.19 dB and 0.23 dB at the 980 nm pump and 1550 nm signal wavelengths, respectively. To experimentally verify the results, the MMIs are fabricated on both 110 nm and 200 nm thick Si₃N₄ layers on oxidized silicon wafers. In the 110 nm thick case, as multiplexers, the MMIs show average losses of 0.4 ± 0.3 dB for both pump and signal wavelengths. Less than 1 dB loss has been achieved in the whole C-band. As demultiplexers, extinction ratio (ER) of the optimal MMIs are 21.4 ± 1.2 dB for the pump and 26.3 ± 0.8 dB for the signal. The results show good agreement with the simulations. The fabricated devices on 200 nm thick Si₃N₄ also achieve low-loss and broadband performance. The results of Part I have been published on Journal of Lightwave Technology [J. Mu, S. A. Vázquez-Córdova, M. A. Sefunc, Y.-S. Yong, and S. M. García-Blanco, "A Low-Loss and Broadband MMI-Based Multi/Demultiplexer in Si₃N₄/SiO₂ Technology," *J. Lightwave Technol.*, vol. 34, pp. 3603-3609, 2016/08/01].

Ring resonators play an important role in wavelength filters for tunable lasers [1-6]. They are thus essential building blocks in the design of active cavities in the Al₂O₃/Si₃N₄ platform. In Part II of this chapter, ring resonators are designed, fabricated and characterized on 200 nm thick Si₃N₄ layers on oxidized silicon wafers. Here, the parameters of the ring resonators such as free spectral range (FSR), full width half maximum (FWHM) of the resonances, group index, Q-factors, coupling coefficients, and propagation losses, are described in the

spectral window of 1460–1635 nm. The propagation losses of Si_3N_4 waveguides with different widths (i.e., 0.8 μm , 1 μm , and 1.4 μm) are characterized from the analysis of the performance of series of ring resonators. Similar waveguides are employed in the integration work in the following chapters.

Sagnac loop mirrors exhibit a broadband performance and are widely employed as reflectors in waveguide lasers [7, 8]. Part III introduces Sagnac loop mirrors designed, fabricated and characterized on 200 nm thick Si_3N_4 layers on thermally oxidized wafers. The measurements show that high reflectivity can be achieved by adjusting the coupling lengths on the micrometer scale. The reflectivity has good tolerance to the gap distance variation.

2.1 Part I: Optimized MMI-based multi/demultiplexers with low loss and broadband performance

2.1.1 Introduction of Part I

As described in Chapter 1, Si_3N_4 has promising optical properties [9-11] such as a large transparency window from the visible to the near infrared (~ 400 nm to 4 μm), low propagation loss (< 0.1 dB/cm) and high refractive index of ~ 1.98 at the C-band wavelengths (1530–1565 nm). These attributes make the Si_3N_4 platform a promising candidate, not only for passive applications in fields such as microwave photonics [12, 13], non-linear optics [14, 15] and bio-sensing [16-18], but also for integration with other materials for different applications, such as with silicon-on-insulator (SOI) for polarization rotators [19], polymers for modulators [20, 21], and with III-V [1, 2] and rare-earth-ion (RE^{3+}) doped materials for lasers and amplifiers [22-25]. Amongst them, the integration of Si_3N_4 and RE^{3+} doped materials will enable the realization of lasers and amplifiers exhibiting properties such as narrow linewidth [26], high power [27], tunability [28, 29] and high gain [30]. Additionally, this integration makes high bit rate amplification [31] more readily achievable due to the much longer intrinsic lifetime of RE^{3+} ions (0.1–10 ms) [32] compared to the III-V materials.

The pump and signal lights employed in RE^{3+} doped materials are widely spectrally separated such as 808 nm/1064 nm for Nd^{3+} , 980 nm/1030 nm for Yb^{3+} , 980 nm/1550 nm or 1480 nm/1550 nm for Er^{3+} , 790 nm/2000 nm for Tm^{3+} . These spectral separations demand on-chip multi/demultiplexers to combine and split different wavelengths.

The most common device structures that have been proposed for combining and splitting different wavelengths include directional couplers (DC) [19, 33], asymmetric Y-junctions [34-36], Mach-Zehnder interferometers (MZI) [37], and multimode interference (MMI) devices [38-40]. Directional couplers are very sensitive to fabrication errors, especially the gap distance variation between two coupled waveguides. The devices based on asymmetric Y-branches and MZIs are typically long and exhibit relatively high insertion losses (i.e., >1 dB). MMI-based devices can produce compact and low-loss wavelength multi/demultiplexers with better tolerance to fabrication errors than directional couplers. Many MMI devices have been implemented in the SOI platform to achieve tunable splitting ratios [41, 42], low-loss performance (0.2 dB) [43] and compactness [44, 45]. A dual-channel MMI multiplexer with a silicon oxynitride (SiON) core [46] was simulated to have losses of 0.28 dB and 0.63 dB for the signal at 1550 nm and the pump at 980 nm, respectively. However, it had a large footprint with device lengths of 2.5 mm.

The typical numerical methods to design MMI couplers are the vectorial beam propagation method (BPM), the finite-difference time-domain (FDTD) method, the eigenmode expansion (EME) method and the finite-element mode propagation analysis (FE-MPA) [47-49]. The implementation of these methods in three-dimensions (3D) usually provides better accuracy compared to the 2D counterpart, especially when the structures have wide propagation angles and large refractive index contrast. The optimization of an MMI multi/demultiplexer involves multiple design parameters leading, at this moment, to an excessive computational cost by directly simulating the 3D structures. The Effective Index Method (EIM) is typically used to convert 3D structures [50] to 2D planar structures with calculated effective indices. However, the effective refractive indices of the regions where no mode exists are not accurate enough for precise device calculations [51].

In this section, we introduce a combined simulation approach that combines the field mode matching (FMM) method, a modified EIM, and a fully vectorial 2D beam propagation method (BPM), to achieve a fast and reliable optimization of an MMI device. The design goal is a low-loss and broadband MMI-based multi/demultiplexer for combining/splitting the 980 nm pump (λ_p) and the 1550 nm signal (λ_s) wavelengths. These wavelengths are used in the $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ - Si_3N_4 integrated amplifiers in Chapter 5. The optimized MMIs are fabricated and characterized in the C-band as both multiplexer and demultiplexers. The

experimental results show good agreement with the simulations, with low-loss and high fabrication tolerance.

2.1.2 The MMI structure and working principle

The structure of the proposed 2×1 MMI coupler is shown in Fig. 2.1(a). The cross-section of the waveguide structure is shown in Fig. 2.1(b). A dual-port, asymmetric, non-center fed design was selected as it allows for reversible operation (i.e., combiner in the left-right direction of Fig. 2.1(a) and divider in the right-left direction) with low insertion losses.

Fig. 2.1. (a) Schematic top view of the proposed MMI coupler. Input and output ports are tapered with $W_{\text{end},i} = 1 \mu\text{m}$ ($i = 1, 2, 3$). (b) Cross-section of the buried MMI coupler cladded by a LPCVD SiO_2 ($\sim 600 \text{ nm}$ thick) cladding.

Tapered cosine S-bends are used to separate the input ports (P_1 and P_2) to match an input fiber array (i.e., $127 \mu\text{m}$ pitch), and a linear taper is employed for the output port (P_3). The ends of the tapers are connected to $1 \mu\text{m}$ wide straight waveguides to ensure single-mode propagation at the input/output of the device for both pump (980 nm) and signal (1550 nm) wavelengths. To maintain the adiabatic condition, both the length of the tapered cosine bends (L_{bend}) at the inputs of the MMI and the length of the linear taper ($L_{\text{taper},3}$) at its output are set to $800 \mu\text{m}$, based on the result of simulations. The lateral distance between the center of the MMI and the center of each of its ports is denoted as L_i ($i = 1, 2, 3$).

According to the self-imaging principle [52], multiple confined modes in the multimode region of the MMI device interfere at the end of the structure to produce single or multiple images of the launched field in the MMI. The field profile at position L along the propagation direction, z , can be expressed as a superposition of the field distributions of the different guided modes supported by the multimode region [52]

$$\psi(y, L) = \sum_{v=0}^{m-1} c_v \psi_v(y) \exp\left[-\frac{iv(v+2)\pi L}{3L_\pi}\right] \quad \text{Eq. 2-1}$$

where v is the mode order, m is the number of modes supported by the multimode region, c_v is the mode excitation coefficient, L is the propagation distance of the field inside the MMI section, and L_π is the beat length between the two lowest order modes, which can be calculated as

$$L_\pi = \frac{\pi}{\beta_0 - \beta_1} \quad \text{Eq. 2-2}$$

where β_0 and β_1 are the propagation constants of the two lowest order modes of the multimode region. The field profile, $\psi(y, L)$, is therefore determined by c_v and the phase factor. The mode excitation coefficient, c_v can be numerically calculated as the overlap integral between the fundamental mode of the input port and the v -th order mode of the MMI section. Self-imaging of the input field will take place at propagation distances $L = N(3L_\pi)$, where $N = 0, 1, 2, \dots$, with direct images occurring for even N numbers and mirrored images for odd N numbers. If the remainder of $(v(v+2)/3)$ is equal to zero, paired interference is obtained. In this case, self-imaging can be realized at three times shorter propagation distances, i.e., $L = NL_\pi$. Such excitation condition can be achieved if the lateral offset of the input and output waveguides (L_i , $i = 1, 2, 3$) is equal to one-sixth of the effective width of the MMI, which considers the penetration depth of the electromagnetic field into the cladding. For the MMI device to work in both directions as a coupler (forward direction) and a splitter (backward propagation direction), the same values of L_i (i.e., $L_1 = L_2 = L_3$) should be selected in the design due to the reciprocal property.

For the MMI coupler depicted in Fig. 2.1(a) to work as a wavelength combiner, the length of the MMI section, L_{MMI} should be selected so that a mirrored image is obtained from port 1 (i.e., 1550 nm signal, λ_s) to port 3 and a direct image is achieved from port 2 (i.e., 980 nm pump, λ_p) to port 3. As discussed above,

paired interference requires that the length of the MMI is selected as $L_{MMI} = pL_{\pi}^{\lambda_p}$ with p an *even* integer ($p = 2, 4, 6 \dots$) to achieve a direct image for the pump, and $L_{MMI} = qL_{\pi}^{\lambda_s}$ with q an *odd* integer ($q = 1, 3, 5 \dots$) to obtain a mirrored image for the signal. Therefore, the length of the MMI should satisfy $L_{MMI} = pL_{\pi}^{\lambda_p} = qL_{\pi}^{\lambda_s}$ to work as a wavelength combiner/splitter for λ_p and λ_s .

2.1.3 Simulation results

In this work, a hybrid design method including the FMM algorithm, followed by a modified EIM and 2D BPM is utilized to optimize a multi/demultiplexer in the $\text{Si}_3\text{N}_4/\text{SiO}_2$ waveguide technology working for transverse-electric (TE) polarization. A 2D-BPM algorithm was chosen over the eigenmode expansion method (EME) because it considers all the modes of the multimode MMI region while presenting a small advantage in simulation time.

Fig. 2.2. Beat length ratio as a function of the MMI width at different thicknesses of the Si_3N_4 layer including 70 nm, 90 nm and 110 nm.

As a first step, a 2D-FMM algorithm (PhoeniX Optodesigner) is utilized to select the width and length of the MMI region. The propagation constants of the different modes supported by MMI cross-sections of different widths (W_{MMI}) are calculated for both $\lambda_p = 980$ nm and $\lambda_s = 1550$ nm. The beat lengths (L_{π}) for both signal and pump wavelengths are calculated using Eq. 2-2. The ratio of the beat lengths of pump and signal is then computed to determine the width of the MMI section. As discussed above, $L_{\pi}^{\lambda_p} / L_{\pi}^{\lambda_s} = q/p$ is required to achieve the correct direct (for the pump) and mirrored (for the signal) image at the output of 20

2.1 Part I: Optimized MMI-based multi/demultiplexers with low loss and broadband performance

the MMI to combine the wavelengths. Fig. 2.2 shows that a q/p ratio of 1.5 (i.e., $p = 2$, $q = 3$) can be achieved for an MMI width of $\sim 12 \mu\text{m}$ on a Si_3N_4 thickness of 110 nm, which supports 10 and 6 confined TE modes for 980 nm and 1550 nm respectively. The 1.5 ratio means that the input signal field is eventually mirrored, and the pump input field forms a direct image at a propagation distance of $647 \mu\text{m}$ ($L = 2L_\pi^{\lambda_p} = 3L_\pi^{\lambda_s}$).

Table 2-I lists the refractive indices of the materials used in the simulations. The effective refractive indices for the two lowest order modes of the MMI region as well as the resulting beat lengths are also shown. Once the width and length of the multimode region of the MMI device have been chosen, the next step uses the 2D-BPM algorithm (PhoeniX Optodesigner) to optimize the dimensions of the input and output ports as well as their exact locations. The effective indices (n_{eff}) used in this 2D BPM is obtained through a modified effective index method (EIM) as described below.

Table 2-I. Refractive indices of the materials used in the simulations for MMI dimensions $12 \mu\text{m}$ (width) $\times$ $647 \mu\text{m}$ (length) $\times$ 110 nm (thickness).

Wavelength	Material	n under TE	n_{eff} of two lowest TE modes	L_π (μm) at W_{MMI} of $12 \mu\text{m}$
980 nm	SiO_2	1.4492	1.5604	323.8
	Si_3N_4	1.9936	1.5589	
1550 nm	SiO_2	1.4456	1.4957	215.7
	Si_3N_4	1.9835	1.4921	

Table 2-II. Comparison of beat lengths calculated using the 2D FMM and modified-EIM methods for various W_{MMI} . Device parameters: $t_{\text{Si}_3\text{N}_4} = 110 \text{ nm}$. TE Polarization.

Wavelength (nm)	980	1550
n_{core}	1.5609	1.4969
n_{clad}	1.3918	1.420
L_π (μm) ($W_{MMI} = 4 \mu\text{m}$)	40.26 (2D FMM) 40.19 (EIM)	33.46 (2D FMM) 32.80 (EIM)
L_π (μm) ($W_{MMI} = 8 \mu\text{m}$)	147.99 (2D FMM) 147.97 (EIM)	103.44 (2D FMM) 103.3 (EIM)
L_π (μm) ($W_{MMI} = 12 \mu\text{m}$)	323.8 (2D FMM) 323.8 (EIM)	215.68 (2D FMM) 215.68 (EIM)
L_π (μm) ($W_{MMI} = 20 \mu\text{m}$)	879.32 (2D FMM) 879.33 (EIM)	564.25 (2D FMM) 564.41 (EIM)

In this work, the effective refractive index of the cladding, n_{clad} , is modified. The refractive index for the core, n_{core} , is the 1D effective index of the $n_{\text{SiO}_2}/n_{\text{Si}_3\text{N}_4}/n_{\text{SiO}_2}$ stack. Our algorithm modifies n_{clad} until the beat lengths

calculated by the EIM and 2D FMM method match. A convergence test is implemented in parallel for Si_3N_4 core widths ranging from 4 μm to 20 μm . Table 2-II shows a comparison of beat lengths calculated by the modified EIM and by FMM. The finally optimized refractive indices for the cladding region are 1.3918 at 980 nm and 1.420 at 1550 nm, which are used in the 2D BPM model for the optimization of the input and output ports as described in the following sections.

Fig. 2.3. (a) MMI loss (in dB) of 980 nm pump from port 2 to port 3, as a function of the width of port 2 (W_2) and offset (ΔL) with respect to the nominal location at $W_{MMI}/6$. (b) MMI loss of 1550 nm signal from port 1 to port 3 as a function of the width of port 1 (W_1) and offset (ΔL) with respect to the nominal location at $W_{MMI}/6$.

Both the dimension and location of the input/output port can affect the MMI performance since the port parameters determine the mode fields at the input/output ports, and they are correlated with the fields launched into the MM region. To investigate this influence, only one input port is considered in each simulation. As described in Fig. 2.1(a), the input field is launched at the end of the tapered input port [i.e., port 1 for λ_s , and port 2 for λ_p]. The loss of the MMI coupler is defined as the loss between the output and input ports, i.e., $-10 \log_{10} P_3/P_{1,2}$. Fig. 2.3(a) and (b) show the simulated MMI losses (in dB) for different widths of the relevant port (i.e., $W_{1,2}$) and offsets (ΔL) of the location of each port with respect to the “nominal” $W_{MMI}/6$ for the 980 nm pump and the 1550 nm signal wavelengths, respectively. The effective width (i.e., considering the penetration depth of the electromagnetic field into the cladding) is larger than the waveguide width W_{MMI} . Thus, only positive ΔL is considered in the optimization. As shown in both figures, the wider the input port, the lower the MMI losses for both wavelengths. Furthermore, as the width of the input port becomes larger, the range of offset values (ΔL) for low losses

increases. Multiple values of W_3 have been considered, from which $W_3 = 4 \mu\text{m}$ is found to have the best performance.

Fig. 2.4. (a) Field profile inside the MMI coupler for the 980 nm pump wavelength. (b) Field profile for the 1550 nm signal wavelength. Device parameters: $W_{MMI} = 12 \mu\text{m}$, $L_{MMI} = 647 \mu\text{m}$, $W_1 = 3.6 \mu\text{m}$, $W_2 = 3.0 \mu\text{m}$, $W_3 = 4 \mu\text{m}$ and $\Delta L = 0.1 \mu\text{m}$. TE Polarization is used.

Cross-talk between the two input ports occurs as the distance between them decreases. The maximum values of W_1 and W_2 that avoid cross-talk were calculated using the 2D FMM method to be $W_1 < 3.8 \mu\text{m}$ and $W_2 < 3.2 \mu\text{m}$. $W_1 = 3.6 \mu\text{m}$, $W_2 = 3.0 \mu\text{m}$, $W_3 = 4 \mu\text{m}$ and $\Delta L = 0.1 \mu\text{m}$ were adopted in the optimal design. The propagating fields in the optimal MMI coupler are displayed in Fig. 2.4(a) and (b), for pump and signal wavelengths respectively.

Prior to fabrication, the robustness of the design to fabrication errors was studied by varying the different fabrication parameters such as the width of the MMI sections, the length of the MMI section, and the thickness of the Si_3N_4 layer. Fig. 2.5(a) and (b) demonstrate the total MMI loss as the functions of both W_{MMI} and L_{MMI} at the wavelengths of 980 nm and 1550 nm, respectively. The MMI coupler is more tolerant to changes of the length ($\pm 6 \mu\text{m}$) than to changes of the width ($\pm 0.1 \mu\text{m}$) for both pump and signal wavelengths to remain the loss less than 1 dB. The effect of the Si_3N_4 layer thickness variation on the total MMI loss is shown in Fig. 2.5(c). For a Si_3N_4 thickness variation range of $\pm 10 \text{ nm}$, the total losses of the device are below 0.34 dB for both wavelengths. For the selected dimensions (i.e., $12 \mu\text{m}$ width, $647 \mu\text{m}$ length and 110 nm thickness), the optimized MMI losses are $\sim 0.19 \text{ dB}$ at 980 nm and $\sim 0.23 \text{ dB}$ at 1550 nm.

Fig. 2.5. Total MMI loss as functions of the optimal device length and width at the wavelength of (a) 980 nm and (b) 1550 nm. (c) Total MMI loss for ± 10 nm variations of Si_3N_4 thickness for both wavelengths.

2.1.4 Fabrication of the MMIs on the Si_3N_4 platform

The waveguides are fabricated using standard microfabrication process technology [53] as employed in the Si_3N_4 waveguides in Chapter 2 to 5. Due to the high sensitivity of the performance of the device to the width changes, the designed MMI width is varied from 11.5 μm to 12.5 μm in steps of 0.1 μm for the tolerance study.

First, a 110 nm thick Si_3N_4 layer is deposited by LPCVD deposition on a thermally oxidized silicon substrate with 15 μm of thermal oxide, which avoids leaking of the propagating fundamental TE mode into the silicon substrate. The thickness of the LPCVD Si_3N_4 layers can be controlled to ± 5 nm. The measured thickness (Woollam M-20000UI ellipsometer) of the deposited Si_3N_4 layer is 112.4 ± 0.4 nm. The MMI structures are then patterned using UV lithography in vacuum contact mode, after which a reflow of the photoresist is carried out to

smoothen the waveguide sidewalls. Reactive ion etching (RIE) is employed to fabricate the waveguides. The critical dimension variation of the devices can be typically controlled within 0.2 μm . However, the measured fabricated widths are about 0.3 μm smaller than the design values after etching. A layer of LPCVD SiO_2 (~200 nm thick) is deposited on the top of the waveguide as the lower part of the upper cladding. The protrusion of SiO_2 on the top is removed by chemical-mechanical polishing (CMP). A micrometer scale SiO_2 layer is further deposited by plasma enhanced chemical vapor deposition (PECVD) followed by the same annealing process. Eventually, the devices are diced perpendicularly to the input and output waveguides using a Loadpoint Micro Ace 3 dicing saw with an NBC-Z dicing blade from Disco. No antireflection coating is applied to the end-facets.

Fig. 2.6. Schematic of the waveguide fabrication process. (a) A 110 nm Si_3N_4 layer is deposited using LPCVD. (b) Waveguide structures are fabricated by conventional photolithography followed by RIE etching. (c) LPCVD SiO_2 is deposited on the top of the structure. (d) The surface is polished using CMP. (e) A thick SiO_2 cladding is deposited using the PECVD technique.

2.1.5 Characterization results

The MMI couplers are characterized in the C-band (1530-1565 nm) with a tunable laser (Agilent 8164B), and at 976 nm with a diode laser. A single mode polarization maintaining fiber (PM980-XP) is used to couple TE polarized light into the waveguides. The MMIs are polarization sensitive and are designed to work for TE polarization. The waveguide output is coupled into a single-mode fiber (UHNA3) connected to a power meter. The width of the input/output Si_3N_4 waveguide is 1 μm , which supports single mode operation at both the pump and the C-band wavelengths.

2.1.5.1 MMI losses

Fig. 2.7(a) shows the transmitted power after a reference straight-waveguide and the MMI coupler. The typical propagation loss of a single mode Si_3N_4 waveguide is <0.1 dB/cm at the thickness of 112 nm of the fabricated devices. The reference

waveguide (length of 0.5 cm) has a propagation loss, therefore, of less than 0.05 dB. The insertion loss of the straight reference waveguide (1 μm width, 112 nm thick) located next to the MMI structures on the chip is mainly caused by fiber-to-chip coupling loss. At 1550 nm, the mode field diameter (MFD) of the input fiber is calculated to be $10 \pm 0.5 \mu\text{m}$ and the MFD of the output fiber is $4.1 \pm 0.3 \mu\text{m}$. The total theoretical coupling losses caused by the mode mismatch between the input and output fibers and waveguides are calculated to be ~ 15.5 dB at 1550 nm, since the input/output Si_3N_4 waveguides are not specifically optimized for fiber-to-chip coupling in MMI dies. The measured reference waveguide insertion losses closely match the calculated losses. The MMI coupler can be assumed to have the same input/output coupling loss as the neighboring reference waveguide. Therefore, the total loss of the MMI coupler is obtained by subtracting the insertion loss of the reference waveguide from the insertion loss of the MMI coupler, as plotted in Fig. 2.7(b). Some resonances are visible in the transmission measurements of Fig. 2.7(a), but they are almost identical for both the transmission measurements of the reference waveguide and MMI device. By performing the Fourier analysis, the same frequency component is found for the reference and MMI waveguides, as well as between the input and output fiber coupling without the device under test. The amplitude of the oscillations dramatically increases when introducing the device under test, but it reduces when introducing a circulator prior to the chip. The origin of the oscillations is, therefore expected to be back-reflections into the tunable laser cavity rather than caused by the fabricated chips.

Fig. 2.7. (a) Measured power after MMI coupler (width 12 μm) and after reference straight waveguide (width 1 μm) besides the MMI coupler. (b) The total loss of an MMI coupler across all the C-band wavelengths for the optimal design dimensions of $W_{\text{MMI}} = 12 \mu\text{m}$, $L_{\text{MMI}} = 647 \mu\text{m}$, $t_{\text{Si}_3\text{N}_4} = 112 \text{ nm}$. The shadow indicates standard deviation of the measurement.

The total losses across the C-band of the MMI coupler with 12 μm width are shown in Fig. 2.7(b). The simulated losses are also plotted (dotted line) in Fig. 2.7(b). The total losses are 0.4 ± 0.3 dB at 1550 nm, and less than 1 dB for all wavelengths of the C-band. Fig. 2.8(a) and (b) show the total losses for pump and signal as a function of MMI width. The measured results have good agreement with the simulations. The MMI coupler is sensitive to variations of the width of the multimode region. To keep the device losses below 1 dB, the width of the multimode region should be controlled within ± 0.14 μm .

Fig. 2.8. Total MMI losses as a function of W_{MMI} at the wavelength of (a) 980 nm and (b) 1550 nm.

2.1.5.2 Extinction ratio (ER)

To measure the performance of the MMI couplers working reversely as splitters, both λ_p and λ_s are launched into port 3 and the output fibers for pump and signal are aligned to the corresponding ports 2 and 1 respectively. When launching the pump into port 3, the transmitted power to both ports 2 ($P_{2,p}$) and 1 ($P_{1,p}$) are measured. In the same way, the signal power transmitted to both output ports, $P_{1,s}$ and $P_{2,s}$ is measured. The ER values are expressed as $10 \log_{10} P_{2,p}/P_{1,p}$ and $10 \log_{10} P_{1,s}/P_{2,s}$, representing the splitting capability of the MMI as a demultiplexer for the pump and signal lights.

A comparison between the experimental and simulated ERs is shown in Fig. 2.9(a). The maximum average ER value for the 1550 nm signal is 26.3 dB for the MMI with a fabricated width of 12.1 μm while the maximum ER for the pump is 21.4 dB for the MMI with fabricated width 12.0 μm . The measured ER values for both wavelengths are lower than the simulated ones, which is

attributed to low levels of stray light arriving at ports 1 and 2 respectively. Furthermore, scattering due to imperfection in the propagation region of the MMI could affect the pump more strongly than the signal due to the wavelength. The variation of calibrated polarization from the diode pump could also contribute to the ER. The measured and calculated ER values for the wavelengths within the C-band (1530–1565 nm) are also plotted in Fig. 2.9(b). The shorter the wavelength, the bigger ER can be obtained.

Fig. 2.9. (a) A comparison of the measured and calculated ER (in dB) of the MMI couplers as a function of MMI width. (b) The calculated and measured ER in the C-band, at W_{MMI} of 12 μm .

Since the proposed device is intended to be integrated with active devices, reflections from the MMI structure back to the active material could affect the performance of the active devices. Thus the power reflected from the MMI is calculated using the Eigenmode expansion simulations (commercial tool Lumerical MODE). The reflection coefficient is extracted from the s11 component of the scattering matrix. A power reflection coefficient of $\sim 10^{-31}$ was calculated, which can be considered negligible.

2.1.6 Optimal design for an MMI on a 200 nm Si_3N_4 layer

Since the multi/demultiplexers are required in the integrated $\text{Al}_2\text{O}_3:\text{Er}^{3+}\text{-Si}_3\text{N}_4$ amplifiers (Chapter 5), the complete design process is performed to obtain a more compact MMI for the Si_3N_4 thickness of 200 nm. The beat length ratio $L_{\pi}^{\lambda_p}/L_{\pi}^{\lambda_s} \cong 1.5$ is chosen for this Si_3N_4 thickness. The MMI width is determined to be 4.5 μm . The beat lengths $L_{\pi}^{\lambda_p}$ and $L_{\pi}^{\lambda_s}$ are 50.6 μm and 33.7 μm , respectively. The same MMI structure is employed, as shown in Fig. 2.1(a). The

2.1 Part I: Optimized MMI-based multi/demultiplexers with low loss and broadband performance

designed parameters are listed in Table 2-III. The port locations are optimized using the same procedure as for the MMIs on 110 nm thick Si_3N_4 layer. The calculated losses are 0.63 dB at 980 nm and 0.24 dB at 1550 nm.

Table 2-III. Parameters of the MMIs on a 200 nm thick Si_3N_4 .

W_1 (μm)	W_2 (μm)	W_3 (μm)	L_1 (μm)	L_2 (μm)	L_3 (μm)	W_{MMI} (μm)	L_{MMI} (μm)
1.4	1.2	2.2	1.3	0.85	0.95	4.5	101

Here the fabrication process is the same as that shown in Fig. 2.6. MMIs with designed widths of 4.4–4.7 μm are characterized. Their total losses are shown in Fig. 2.10(a). The MMI with designed width of 4.6 μm gives the lowest losses of 0.42 ± 0.13 dB at 980 nm and 0.35 ± 0.2 dB at 1550 nm. The measured MMI losses shift about 0.1 μm in the width direction compared to the calculated values in Fig. 2.10(a). The width variation can be caused by fabrication errors. The fabricated widths are 0.1 μm narrower. In addition, the losses in the C-band are measured. Less than 0.8 dB losses are obtained by the MMIs at the designed widths of 4.6 μm and 4.7 μm .

Fig. 2.10. MMI losses with a Si_3N_4 thickness of 200 nm. (a) Measured and calculated MMI losses as a function of W_{MMI} at 980 nm and 1550 nm. (b) Measured MMI losses in the C-band.

2.1.7 Conclusion of Part I

In this part, a low-loss and broadband multi/demultiplexer for erbium-doped amplifying and laser applications is presented. A 110 nm thick Si_3N_4 multi/demultiplexer is designed by combining the modified EIM, 2D-FMM and 2D-BPM, which avoids time-consuming 3D simulations. Thus, it enables the optimization via variation of multiple design parameters of the MMI. The

fabricated couplers are characterized at 976 nm and in the C-band as both combiners and splitters. In case of the Si_3N_4 thickness of 110 nm, the total losses of the MMIs are as low as 0.4 ± 0.3 dB for both pump and signal wavelengths, and less than 1 dB within the C-band. The extinction ratios are measured to be 21.4 dB and 26.3 dB for pump and signal respectively. In case of the Si_3N_4 thickness of 200 nm, the lowest losses of the MMIs are 0.42 ± 0.13 dB at 976 nm and 0.35 ± 0.2 dB at 1550 nm. In both the 110 nm and 200 nm thick MMI devices, the losses are low (< 0.8 dB) across the entire C-band.

2.2 Part II: Add-drop ring resonators and propagation loss characterization

Ring resonator serves as basic building block in Vernier-effect based wavelength filters that can be used as wavelength selective elements in tunable laser cavities [1-6]. In this work, we focus on the performance of add-drop ring resonators and on their utilization to characterize the propagation losses of the fabricated optical waveguides.

2.2.1 Loss of a Si_3N_4 waveguide bend

The smaller waveguide bend radius is, the more compact ring resonator can be achieved. The minimum radius is limited by the radiation loss of a bent waveguide, which is the same in Si_3N_4 ring resonators. By calculating the bend losses, optimal bend radii can be chosen for the Si_3N_4 ring resonators.

A Finite Difference (FD) method in the Phoenix software is used to calculate the effective refractive index, $n_{eff} = n_{eff}^0 + in_i$, of the fundamental TE mode. A calculation window of $16 \mu\text{m} \times 12 \mu\text{m}$ is selected for the 2D cross-section shown in Fig. 2.1(b). The bend loss, α_{bend} (dB/cm), is computed from the imaginary part, n_i , of n_{eff} . The amplitude of the field E_0 after propagating a distance z in the bent waveguide can be expressed as

$$E(z) = E_0 \exp\left(\frac{i2\pi n_{eff} z}{\lambda}\right) = E_0 \exp\left(\frac{i2\pi n_{eff}^0 z}{\lambda}\right) \exp\left(-\frac{2\pi n_i z}{\lambda}\right) \quad \text{Eq. 2-3}$$

where the factor $\exp\left(-\frac{4\pi n_i z}{\lambda}\right)$ determines the attenuation of the intensity. Thus the bend loss can be extracted from the attenuation as

$$\begin{aligned}\alpha_{bend} &= -10 \log_{10} E(z)E^*(z) \cdot \frac{1}{z} \\ &= -10 \log_{10} \exp\left(-\frac{4\pi n_i z}{\lambda}\right) \cdot \frac{1}{z} = 10 \log_{10} e \cdot \frac{4\pi n_i}{\lambda}\end{aligned}\quad \text{Eq. 2-4}$$

Fig. 2.11 plots the bend loss as a function of bend radius (R) for a Si_3N_4 thickness of 200 nm. In the design, the waveguide width and related radii are chosen to satisfy negligible bend losses ($<10^{-3}$ dB/cm) after dividing the bend length according to Eq. 2-4. Thus, the propagation loss in a ring resonator is approximately equal to the propagation loss (α_0) of a straight waveguide with the same width. Si_3N_4 widths of 0.8 μm , 1 μm and 1.4 μm are considered. The corresponding minimal bend radii are 350 μm , 240 μm and 150 μm , which are utilized for the design of the Si_3N_4 ring resonators.

Fig. 2.11. Bend loss for different bend radii at the wavelength of 1550 nm. Three widths of Si_3N_4 waveguide are considered namely 0.8 μm , 1 μm , and 1.4 μm . The Si_3N_4 thickness is 200 nm.

2.2.2 The principle of an add-drop ring resonator

A schematic of the simplest form of add-drop ring resonator is shown in Fig. 2.12. It consists of two bus waveguides and a ring. A common coupling scheme is based on a directional coupler. Evanescent fields between the bus waveguide and the ring are coupled over a certain gap distance (g). The coupling efficiency is described by the coefficient $k_{1,2}^2$ and the transmittance in the bus waveguide is $t_{1,2}^2 = 1 - k_{1,2}^2$, with the assumption that the directional coupler is lossless. Resonances occur when the optical path is an integer multiple of the wavelength of incoming field [54-56]. The spectral characteristics of a ring resonator enables the extraction of parameters including the coupling coefficients and the

propagation losses with good precision [57-59]. For instance, losses as low as 0.1 dB/cm can be determined, where other characterization methods such as cut-back and Fabry -Pérot resonator break down. It is a very beneficial method to study the low propagation loss in Si_3N_4 waveguides [53].

Fig. 2.12. Schematic of an add-drop ring resonator (RR).

The distance between two resonances is defined as the free spectral range (FSR), which depends on the optical length and the dispersion of the waveguide. The FSR can be calculated as

$$\Delta\lambda_{FSR} = \frac{\lambda^2}{n_g L} \quad \text{Eq. 2-5}$$

$$L = 2\pi R$$

where $n_g(\lambda) = n_{eff}(\lambda) - \lambda_0 \left(\frac{dn_{eff}(\lambda)}{d\lambda} \right)$ is the group index, which takes into account the waveguide dispersion. The spectral profile for the thru (T_p) and drop ports (T_d) are determined by the coupling coefficients, the propagation losses and the detuning phase ϕ related to the central resonant wavelength, as shown in Eq. 2-6 and Eq. 2-8 [56].

$$T_p = \frac{a^2 t_2^2 - 2t_1 t_2 a \cos \phi + t_1^2}{1 - 2t_1 t_2 a \cos \phi + (t_1 t_2 a)^2} \quad \text{Eq. 2-6}$$

$$a^2 = \exp\left(-\frac{\alpha_0}{10 \log_{10} e} L\right) \quad \text{Eq. 2-7}$$

$$T_d = \frac{(1 - t_1^2)(1 - t_2^2)a}{1 - 2t_1 t_2 a \cos \phi + (t_1 t_2 a)^2} \quad \text{Eq. 2-8}$$

Here a factor a computed from the propagation loss α_0 (in dB/cm) (Eq. 2-7) is used to describe the amplitude attenuation. For an add-drop ring, the critical coupling can be achieved at $t_2 a = t_1$. This implies that a symmetric coupling scheme can easily realize critical coupling when the propagation loss is very low, i.e., $a \cong 1$.

The full width at half maximum (FWHM) that describes the linewidth of resonance can be derived from the above transmission equations [56] as

$$\Delta\lambda_{FWHM} = \frac{\lambda^2}{n_g \pi L} \frac{1 - t_1 t_2 a}{\sqrt{t_1 t_2 a}} \quad \text{Eq. 2-9}$$

For most ring resonators, there are two terms commonly employed to describe the sharpness of the resonances. One is the finesse, which shows the sharpness of the resonance related to the FSR, and the other is the Q-factor, which exhibits the sharpness related to the central resonant wavelength/frequency.

$$F = \frac{\Delta\lambda_{FSR}}{\Delta\lambda_{FWHM}} = \frac{\pi\sqrt{t_1 t_2 a}}{(1 - t_1 t_2 a)} \quad \text{Eq. 2-10}$$

$$Q = \frac{\lambda}{\Delta\lambda_{FWHM}} = \frac{\pi n_g L}{\lambda} \frac{\sqrt{t_1 t_2 a}}{1 - t_1 t_2 a} = \frac{n_g L}{\lambda} F \quad \text{Eq. 2-11}$$

High F or high Q ring resonators require low coupling coefficients (i.e., $t_{1,2} \cong 1$) and low propagation loss.

In practice, the FSR and FWHM can be directly extracted from the measured spectra. To obtain the coupling coefficient and propagation loss, the model from [57] is employed. For low propagation loss and weak coupling between the bus waveguides and the ring, $\cos(\pi/F)$ can be approximated by a Taylor series as follows [57]:

$$\cos \pi/F = \cos \frac{(1 - t_1 t_2 a)}{\sqrt{t_1 t_2 a}} \cong 1 - \frac{1}{2} \left[\frac{(1 - t_1 t_2 a)}{\sqrt{t_1 t_2 a}} \right]^2 = -\frac{1 + A^2 - 4A}{2A} \quad \text{Eq. 2-12}$$

where $A = t_1 t_2 a$. However, the coupling coefficient and propagation loss still cannot be individually extracted from A . Fortunately, the ratio between the maximum and minimum of T_p provides a way to obtain the coupling coefficient using Eq. 2-13. Using Eq. 1-12 and 1-13, both the coupling coefficient and loss coefficient can be determined.

$$\frac{\max(T_p)}{\min(T_p)} = \left[\frac{(t_{1,2}^2 + A)(1 - A)}{(t_{1,2}^2 - A)(1 + A)} \right]^2 \quad \text{Eq. 2-13}$$

2.2.3 Experimental results and discussions

Ring resonators with waveguide widths of 0.8 μm , 1 μm and 1.4 μm were fabricated using a 200 nm thick Si_3N_4 layer. To demonstrate the reverse characterization of the parameters, several ring resonators with the above waveguide widths and different bend radius are employed.

The ring resonator with a waveguide width of 1.4 μm , a bend radius of 150 μm , and a gap distance of 1.1 μm , is used as an example to explain the aforementioned characterization procedures. First, transmission spectra from the thru-port are measured in the 1460–1635 nm spectral window by scanning the wavelength with a resolution of 0.5 pm (Agilent 8164B). PM fibers (PM1550-XP) are employed for input and output coupling. Fig. 2.13(a) shows part of the spectrum. The distance between two neighboring resonances (the FSR) is measured [Fig. 2.13(b)]. From the FSR, the group index is calculated [Fig. 2.13(c)] according to Eq. 2-5. For each resonance [Fig. 2.13(d)], the FWHM can be directly calculated from the measured spectrum (labeled as “Data”) or from the fitted Lorentzian distribution (labeled as “Fit”). The FWHM of the resonances for the whole spectral window is shown in Fig. 2.13(e).

With the obtained FSR and the FWHM, more parameters can be determined, such as the Q-factor using Eq. 2-11 [Fig. 2.13(f)], the finesse using Eq. 2-10, and the factor A using Eq. 2-12. Here, the coupling coefficients for both bus waveguides are designed to be identical, having the same gap distance, i.e., 1.1 μm . The transmittance coefficient, $t_{1,2}$, is plotted in Fig. 2.13(g), from which the coupling coefficient and the propagation loss can be estimated. Fig. 2.13(h) shows the propagation loss of the bent waveguide. Due to scattering, the shorter wavelengths have higher losses. Less than 0.2 dB loss can be achieved in the whole C-band.

Fig. 2.13. The parameters of the ring resonator: (a) Part of the measured spectra, (b) FSR, (c) Group index. (d) Example of ring resonator spectrum with Lorentzian fitted shape. (e) FWHM, (f) Q-factor, (g) coupling coefficient ($t_{1,2}$), (h) Obtained roundtrip loss. The Si_3N_4 waveguide dimension is $1.4 \mu\text{m} \times 200 \text{ nm}$. The bend radius is $150 \mu\text{m}$. The gap distance between the bus waveguide and the ring is $1.1 \mu\text{m}$. The ‘Fit’ in figure (e-h) means the results from the Lorentzian fit in figure (d).

The propagation losses of ring resonators with a width of $0.8\ \mu\text{m}$ and $1\ \mu\text{m}$ are also characterized, which is shown in Fig. 2.14(a) and (b). Low propagation losses ($<0.2\ \text{dB/cm}$) can still be realized in the C-band. However, for a width of $0.8\ \mu\text{m}$, the loss naturally rises when the wavelength increases beyond $1565\ \text{nm}$. This is caused by the increase of the bend loss at longer wavelengths. Due to fabrication errors (as expected from the MMIs), here, the fabricated width is about $0.1\ \mu\text{m}$ smaller than $0.8\ \mu\text{m}$. This further increases the bend losses, especially at the long wavelengths, due to decreased mode confinement. Nevertheless, the propagation loss from the ring resonators indicates that the losses of the Si_3N_4 waveguides for widths of $1\ \mu\text{m}$ and $1.4\ \mu\text{m}$ are tolerable.

Fig. 2.14. The propagation loss of the ring resonators for waveguide widths of (a) $0.8\ \mu\text{m}$ ($R = 340\ \mu\text{m}$, $g = 1.9\ \mu\text{m}$) and (b) $1\ \mu\text{m}$ ($R = 240\ \mu\text{m}$, $g = 1.5\ \mu\text{m}$). The Si_3N_4 thickness is $200\ \text{nm}$.

2.3 Part III: Sagnac loop mirrors

Distributed Bragg reflectors (DBRs) are widely employed in waveguide lasers. For example, in rare-earth-ion-doped Al_2O_3 lasers, DBRs are fabricated on the SiO_2 cladding [60] and on the Si_3N_4 underneath [61-64] to make laser cavities. The reflectivity of a DBR depends critically on the grating parameters. The high-resolution lithography tools are usually required to precisely fabricate the gratings, such as laser interference lithography, electron-beam lithography, and stepper lithography. These constraints can be avoided in certain waveguide laser applications by using loop mirrors [7, 8].

Low-loss Si_3N_4 waveguide reflectors based on a Sagnac loop mirror (SLM) are studied. Though the SLM has not been applied in our integrated platform yet, this study is significant to provide preliminary knowledge about the working

principle and the influence of different design parameters on the reflectivity. A schematic of the SLM is shown in Fig. 2.15. Two ports of the directional coupler (DC) at one side are connected to form a loop. The input power is split through the DC region to two counterpropagating modes in the loop. The modes interfere with each other once they return the coupler, giving different portions of the power to the port 1 and 2. For a 50/50 splitting ratio, the reflectivity reaches a theoretical maximum of 100%. The reflectivity and bandwidth of the SLM can be tuned by adjusting the DC length.

Fig. 2.15: Schematic of the Sagnac loop mirror (SLM) proposed. It consists of a directional coupler whose two ports are connected.

The reflectivity of the SLM [65] can be expressed as

$$R_{\text{reflect}} = \sin^2 \left(\frac{L_{SLM}\pi}{L_{100\%}} + \phi \right) = \sin^2 \left(\frac{\Delta n L_{SLM}\pi}{\lambda} + \phi \right) \quad \text{Eq. 2-14}$$

where the $L_{100\%}$ is the length that produces 100% power coupling from one waveguide to the other, L_{SLM} is the coupling length of the DC coupler, Δn is the difference of the refractive indices between the even and odd supermodes. The phase, ϕ , is the additional phase caused by the coupling between waveguide bends located on the both sides of the DC coupling area. To calculate the additional phase, ϕ , we employed the coupled mode theory method combined with the transfer matrix technique (TMT) [66]. The waveguide bend is divided into 100 segments. The coupling of each segment is equivalent to the symmetric coupling. Then, the additional phase, ϕ , of the waveguide bend is calculated by propagating the coupling strength $\kappa(z)$ of each segment by the TMT using Eq. 2-15.

$$\phi = \int_{-R}^R \kappa(z) dz \quad \text{Eq. 2-15}$$

Fig. 2.16(a) shows the contour map of the calculated reflectivity of the SLMs at different coupling length and gap distances. For demonstration, a gap distance of $1.2\ \mu\text{m}$ is selected. Fig. 2.16(b) plots the reflectivity of the SLMs for a gap distance of $1.2\pm 0.1\ \mu\text{m}$. Compared to the coupling length, the reflectivity is much more sensitive to the variation of the gap distance.

Fig. 2.16. (a) Contour plot of the calculated reflectivity of SLMs as a function of the coupling length (L_{SLM}) and gap distance (g). (b) Calculated reflectivity of the SLMs as a function of the length (L_{SLM}). The legend indicates the different gap distances of 1.1 μm , 1.2 μm and 1.3 μm .

Fig. 2.17. Measured reflectivity and transmittance of the SLMs as a function of coupling lengths.

The SLMs are fabricated on a 200 nm thick Si_3N_4 wafer using a similar process as shown in Fig. 2.6. The reflectivity and transmittance of the SLMs are both characterized. For the reflectivity, a circulator (CIR1550PM-FC) is employed to

collect the reflected power. For the transmittance, the output power of the bus waveguides is measured directly. The values are normalized to a straight reference Si_3N_4 waveguide, in which both measurement uncertainties of the SLM and reference waveguide are taken into account. Fig. 2.17 shows the measured reflectivity and transmittance of the SLMs for different lengths of the integrated DC coupler with the propagated measurement errors. The reflectivity shows good agreement with the calculated values for a gap distance of $1.1\text{ }\mu\text{m}$ rather than $1.2\text{ }\mu\text{m}$. This indicates that the gap distance is $\sim 0.1\text{ }\mu\text{m}$ narrower than the design. Although the gap distance varies, the change of the reflectivity is less than 10% in Fig. 2.17. High reflectivity can be realized by adjusting the coupling lengths on a micrometer scale.

2.4 Conclusion

This chapter presented the development of low-loss and broadband MMI-based multi/demultiplexers, reverse characterization of the parameters of ring resonators and the development of Sagnac loop mirrors with tunable reflectivity. In Part I, an optimization process for the MMIs was presented, in which the port dimensions and locations are optimized. The design process provides a fast and reliable way to obtain optimal design parameters regardless of the Si_3N_4 thickness. Optimal MMIs were fabricated and characterized at both 976.2 nm pump and the C-band. The experimental results show good agreement with the simulations. In Part II, Si_3N_4 ring resonators were fabricated and characterized. A reverse characterization method was introduced step by step to extract the parameters of the ring resonators from their spectral characteristics. Low propagation losses ($<0.2\text{ dB/cm}$) were realized for Si_3N_4 waveguides at widths of $0.8\text{ }\mu\text{m}$, $1\text{ }\mu\text{m}$ and $1.4\text{ }\mu\text{m}$ in the C-band, which are employed in the integration work in Chapter 3 to 5. In part III, the reflectivity and transmittance of Sagnac loop mirrors are characterized. High reflectivity can be realized by adjusting the coupling lengths on a micrometer scale.

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3 High-performance optical coupling for polymer-on-Si₃N₄ integration

In this chapter, two integration strategies for the adiabatic coupling between Si₃N₄ and polymer waveguides are studied, namely hybrid integration and monolithic integration. The characteristics of the integration strategies were introduced in Chapter 1. For the hybrid integration, the polymer material SU-8 was utilized for making polymer chips. Polymer waveguides were fabricated on the thermally oxidized SiO₂ substrate. Then the polymer chips were flip-chip bonded onto the Si₃N₄ chip. For the monolithic integration, the polymer was spin-coated directly onto the Si₃N₄ chips to make waveguides. Both schemes developed here also pave the way towards the integration of other materials of similar refractive index onto the Si₃N₄ platform.

Part I of this chapter focuses on the hybrid integration of polymer (i.e., SU-8) and Si₃N₄ waveguides. The width of both the polymer and the Si₃N₄ waveguides are tapered. An efficient design approach combining 2D film mode matching (FMM) method and 3D eigenmode expansion method (EME) is proposed, and its validity is demonstrated. The designed couplers exhibit less than 0.5 dB losses for adiabatic angles and < 1 dB loss for lateral misalignments up to 0.5 μm. Flip-chip bonding is selected to assemble the polymer and Si₃N₄ waveguides, which enables to independently carry out the fabrication processes for the chips and integrate only known-good chips. The low-loss operation has been experimentally demonstrated over a wide spectral window of 1480-1560 nm, with measured coupler losses below <0.8 dB for Si₃N₄ taper angles below 1.2°, in good agreement with the calculated values. Furthermore, thermal shock test (International Standard: IEC 60512-11-4¹) results show less than 0.1 dB degradation, indicating a reliable coupling performance. The main contents of Part I have been published on IEEE Photonics Technology Letters [J. Mu, T. Alexoudi, Y. S. Yong, S. A. Vázquez-Córdova, M. Dijkstra, K. Worhoff, *et al.*, "Low-Loss Highly Tolerant Flip-Chip Couplers for Hybrid Integration of Si₃N₄

¹ International Standard: Connectors for electronic equipment - Tests and measurements - Part 11-4: Climatic tests - Test 11d: Rapid change of temperature, <https://webstore.iec.ch/publication/2313>

and Polymer Waveguides," *IEEE Photon. Technol. Lett.*, vol. 28, pp. 2748-2751, 2016].

Part II introduces the monolithic integration of polymer (i.e., SU-8) and Si₃N₄ waveguides. An adiabatic vertical taper is applied to the Si₃N₄ waveguide. The vertical Si₃N₄ taper is buried inside the polymer waveguide core, which significantly enhances the performance of the optical coupler in terms of loss, bandwidth and tolerance to lateral misalignment. The low-loss operation is experimentally verified at both 976 nm and 1460–1635 nm wavelengths. Measured losses per coupler are as low as 0.12 dB at 976 nm and below 0.16 dB in the 1460–1635 nm wavelength range respectively, and below 0.2 dB at both wavelengths for lateral misalignments between the Si₃N₄ and polymer waveguides up to 1.0 μm . This robust optical coupling solution potentially paves the way for the integration of various active materials onto the Si₃N₄ platform. The main content of Part II has been published in Optics Letters [J. Mu, M. Dijkstra, Y.-S. Yong, F. B. Segerink, K. Wörhoff, M. Hoekman, A. Leinse, S. M. García-Blanco, "Low-loss, broadband and high fabrication tolerant vertically tapered optical couplers for monolithic integration of Si₃N₄ and polymer waveguides," *Opt. Lett.* 42, 3812-3815 (2017)].

3.1 Introduction

Over the past decade, great effort has been spent on the hybrid integration of the passive silicon-on-insulator (SOI) photonic platform with semiconductor materials such as germanium (Ge) and InP to realize active modulators and lasers [1]. Recently, as described in Chapter 1, stoichiometric Si₃N₄ [2] has been widely applied in nonlinear optics, microwave photonics, and bio-sensing due to its excellent optical features such as ultra-low propagation loss, large transparency window ranging from the visible to the mid-IR and highly reproducible fabrication process. The realization of active components in the passive Si₃N₄ photonic platform by means of integration with materials such as polymers [3], InGaAs [4] and rare-earth-ion-doped Al₂O₃ [5] has recently attracted significant interest. Many active devices have been realized using different types of polymers, including efficient tunable filters [3], high speed modulators (> 100 GHz) [6, 7], lasers [8], and amplifiers [9], owing to their low-cost, ease of fabrication, good efficiency for heat insulation, as well as fairly high thermo-optic and electro-optic (EO) coefficients. Particularly, the integration of EO polymers with low-loss silicon nitride and oxynitride waveguides can increase

tunability [3] and lower the attenuation of all-polymer modulators [6]. Still, the low-loss optical coupling between chips and between materials remains a challenge.

Adiabatic vertical couplers have been widely employed for hybrid integration [10, 11] and heterogeneous integration [12, 13] of SOI with III-V devices, and hybrid integration of SOI with polymers [14-16]. The width of the tip of the SOI taper is made to reach the cut-off condition by means of electron-beam or stepper lithography techniques. As a result, the SOI taper tip hardly affects the propagating mode in the coupled waveguide system. Additionally, the highly confined mode in the SOI waveguide is hardly affected at the polymer taper tip. Therefore, the propagation losses of the SOI waveguides dominate over the small mode mismatch loss at both taper tips. Recently, IBM Inc. experimentally demonstrated flip-chip couplers between SOI photonic chips and optical carriers [15], showing high tolerance to lateral misalignment of $\pm 2\ \mu\text{m}$ between the polymer and SOI waveguides. Flip-chip bonding enables the integration of “known-good-dies” without having to develop a new fabrication flow for each new material. It can thus reduce the overall cost and development time. Flip-chip coupling between the polymer and Si_3N_4 chips has not yet been reported and it is the core of Part I of this chapter [17-19].

Furthermore, the monolithic integration of Si and other waveguides have been mainly applied to achieve highly efficient and misalignment tolerant fiber-to-chip coupling [20-24] in recent years. In these works, narrow width Si tapers (tens of nm tip width) fabricated by electron-beam or stepper lithography are employed under the adiabatic condition. The other waveguides are normally fabricated using materials with lower refractive indices such as silicon oxynitride (SiON), polymer and SiN_x which are designed to match the fiber mode size by using the proper dimensions. Previously, optical coupling in multilayer Si_3N_4 platform applied width-tapered Si_3N_4 waveguides [25, 26] which yields a broadband performance. Thickness-tapered waveguide was firstly demonstrated for the coupling between single-stripe and dual-stripe Si_3N_4 waveguides [27] with $\sim 0.5\ \text{dB}$ loss. Therefore, the second part of this chapter concentrates on realizing monolithic integration of the polymer and Si_3N_4 waveguides by utilizing adiabatic vertical Si_3N_4 tapers. Low-loss, broadband and highly fabrication tolerant polymer- Si_3N_4 couplers are demonstrated. Losses per coupler as low as $0.12\ \text{dB}$ at the wavelength of $976\ \text{nm}$ and $0.14\ \text{dB}$ at the wavelength of $1550\ \text{nm}$ are measured.

3.2 Part I: Hybrid integration by flip-chip bonding

3.2.1 Device design

3.2.1.1 Device structure and design method

Linear waveguide tapers are designed to vertically transfer the electromagnetic field between the Si₃N₄ and polymer waveguides. Fig. 3.1 shows a 3D schematic of the vertical coupler and the corresponding cross-sections (CS) at different locations along the propagation direction: (a) at the Si₃N₄ waveguide input/output, (b) at the tip of the polymer taper, (c) at the start of the polymer/Si₃N₄ taper, (d) at the tip of the Si₃N₄ taper, (e) at the polymer waveguide input/output. The coupling region is between the CS at (b) and (d). The device is designed to work for the transverse-electric (TE) polarization.

Fig. 3.1. 3D schematic of the proposed vertical coupler with the cross-sections by hybrid integration: (a) at Si₃N₄ waveguide input/output, (b) at the polymer taper tip, (c) at the start of polymer/Si₃N₄ taper, (d) at the Si₃N₄ taper tip, and (e) at polymer waveguide input/output.

The mode mismatch losses between the CS (a) and (b), and between the CS (d) and (e), can be neglected only when the perturbation of the effective refractive index at the taper tip, is small enough, as it is the case in the tapers between silicon and polymer waveguides studied in [14-16]. However, for the Si₃N₄ waveguides with very low propagation losses, the mode mismatch plays a predominant role in the overall losses of the device. This is especially relevant when using contact UV lithography with a relatively large resolution limit ($>0.8 \mu\text{m}$). The mode mismatch loss, expressed in dB, can be calculated from the mode overlap coefficient, Γ , as $-10 \log_{10} \Gamma$. Under the adiabatic condition,

most of the power of the mode confined in the Si_3N_4 core at the CS (b) will be transferred to the mode confined in the polymer core at the CS (d) without conversion to radiation or higher order modes. Therefore, the coupler loss (α_c) can be estimated by the sum of the mode mismatch at the CS (b), α_1 , and the mode mismatch loss at the CS (d), α_2 (in dB) if the propagation losses can be considered negligible.

To achieve simultaneously a low coupling loss and a high misalignment tolerance for the flip-chip bonded coupler, multiple parameters including the thickness and width of the waveguides, the widths of the taper tips and the lengths of the tapers, the refractive indices of the underfill adhesive and the polymer material, number of modes in the coupled waveguide system and the lateral misalignment (Δx) between the Si_3N_4 and polymer waveguides need to be optimized. Optimizing all taper parameters by means of 3D methods such as EME [28] or beam propagation method (BPM) [15] requires much more computational cost as compared to carrying out the optimization using 2D mode calculations. In this work, the optical lithography (EVG620) tool employed has a resolution of 0.8 μm . Hence, the widths of both Si_3N_4 and polymer taper tips are designed to be 0.8 μm . A UV curable adhesive (NOA 84, Norland Adhesives) is used as underfill material and the epoxy-based negative tone photoresist SU-8 is employed to fabricate the polymer waveguides. The refractive indices of the SiO_2 (thermal), NOA adhesive, SU-8, and the Si_3N_4 layers at a wavelength of 1.55 μm are 1.449 ± 0.001 , 1.51 ± 0.01 , 1.574 ± 0.005 and 1.984 ± 0.001 respectively for TE polarization, as determined experimentally (i.e., Metricon 2010/M and Woollam M-2000UI).

3.2.1.2 2D and 3D simulation results

In the design of the vertical coupler, several considerations need to be taken into account: (i) the vertical coupler should operate under single-mode condition, (ii) the mode should have relatively low confinement (i.e., large mode diameter) to increase the tolerance to lateral misalignments and (iii) the mode mismatch between the CS (a) and the CS (b) at the polymer taper, and that between the CS (d) and the CS (e) should be minimized.

Fig. 3.2(a) shows the mode mismatch loss as a function of the width of the Si_3N_4 waveguide and the thickness of the polymer taper tip for a Si_3N_4 thickness of 90 nm. As expected, the lower the thickness of the polymer layer, the lower the mismatch loss at the polymer taper tip. The opposite occurs at the tip of the Si_3N_4

taper, where the lowest mode mismatch loss requires the largest polymer thickness, as shown in Fig. 3.2(b). The single mode region is at the left of the dotted vertical line in Fig. 3.2(a)-(c). Thicknesses for the Si₃N₄ and polymer layers of 90 nm and 0.5 μm are selected based on the above considerations. The calculated coupler total losses are shown in Fig. 3.2(c).

Fig. 3.2. (a) Mode mismatch loss (in dB), α_1 , at the tip of the polymer taper. (b) mode mismatch loss (in dB), α_2 , at the tip of the Si₃N₄ taper, and (c) total loss, α_c , for 0.5 μm thick polymer layer. The tip widths of both polymer and Si₃N₄ tapers are 0.8 μm . The thickness of the Si₃N₄ layer is 90 nm. Single-mode (SM) and multimode (MM) conditions of the device are separated by the dashed lines.

A minimum coupler loss of 0.40 dB is found for polymer and Si₃N₄ waveguide widths of $\sim 2.9 \mu\text{m}$ and $\sim 2.5 \mu\text{m}$ respectively, for which the coupler is under multimode operation. To fulfil the SM condition, the widths of the Si₃N₄ and polymer waveguides have to be below 2.4 μm and 2.7 μm , respectively. A case in the single-mode region of Fig. 3.2(c) with $W_{\text{Si}_3\text{N}_4} = 2 \mu\text{m}$ and $W_p = 1.5 \mu\text{m}$ is selected, far enough from the multimode condition to leave sufficient room for

process window while keeping the polymer section short to avoid adding propagation losses from the SU-8 waveguide section (i.e., the wider the polymer waveguide, the longer is the taper section from W_p to $0.8 \mu\text{m}$). Typical SU-8 propagation losses are 3.5–5.5 dB/cm at the wavelength of 1550 nm, as measured experimentally.

Fig. 3.3. Coupler losses calculated by EME for different lateral misalignments as a function of Si_3N_4 taper angle. The Si_3N_4 taper lengths are shown in the top axis. The angle and length of the polymer taper are 0.25° and $80 \mu\text{m}$.

The selected values of Si_3N_4 and polymer thicknesses and widths are then used to construct 3D structures to perform EME simulations to determine the propagation losses neglected by the 2D FMM method, namely the taper loss due to conversion to radiation modes and reflections at the taper tip cross-sections. A small value of 0.25° is chosen for the polymer taper angle, which is verified to fulfil the adiabatic condition. The Si_3N_4 taper angles are varied from 0.1° to 1.8° . Fig. 3.3 shows the loss of the vertical couplers as a function of the Si_3N_4 taper angle for different lateral misalignments. The lost power is mainly due to the mode mismatch losses at the taper tips, which is scattered away. When the misalignments are small (e.g. $\Delta x < 1 \mu\text{m}$), the coupler losses converge at the Si_3N_4 taper angle of 0.1° , which is regarded as the adiabatic angle of the Si_3N_4 taper. With the increase of Δx above $1 \mu\text{m}$, the coupler losses dramatically rise and are more significantly affected by the variation of the Si_3N_4 taper angle. At the Si_3N_4 taper angle of 0.1° , the losses of the couplers without misalignment are 0.57 dB. Additionally, less than 0.9 dB losses can be obtained for couplers with

a lateral misalignment range of $\pm 1.4\ \mu\text{m}$, which is well within the capabilities of the flip-chip bonder utilized in this work. If higher bonding tolerance is required, smaller Si₃N₄ taper angles should be utilized. In order to increase the accuracy of the measurements, waveguides with different numbers of cascaded couplers are fabricated.

Further calculations show that the proposed design works for other polymers with refractive indices ranging between ~ 1.53 and 1.8 . Within this range, a polymer width and thickness can be obtained that keeps the coupler losses below 1 dB while maintaining the single-mode condition for the input and output waveguides and the restriction of a minimum taper tip of $0.8\ \mu\text{m}$.

3.2.2 Fabrication process

The Si₃N₄ chip was fabricated by LioniX B.V. [3] based on a single stripe Si₃N₄ layer geometry, with a fabrication process similar to that described in the MMI work of Chapter 2. The Si₃N₄ layer is deposited on a silicon wafer with a $15\ \mu\text{m}$ thick thermal oxide using low-pressure chemical vapor deposition (LPCVD). The thickness of the deposited layer is measured to be $92.1 \pm 0.6\ \text{nm}$ by ellipsometry. In the next step, the Si₃N₄ waveguide structures are patterned by contact UV lithography and then etched by reactive ion etching (RIE) (PlasmaTherm 790). Fig. 3.4(a) shows the profile of a Si₃N₄ taper scanned at different locations along the taper tip by an atomic force microscope (AFM Bruker FastScan). The deformed shape of the taper tip could be caused by a defect of the patterned photoresist during lithography. Additionally, the roughness of the top area of the straight waveguide core and of the taper tip are measured to be less than 1 nm and 10 nm rms respectively. The increased roughness can probably due to the deformation of the photoresist during RIE etching.

To fabricate the polymer waveguides, a SU-8 2000.5 layer is deposited on a borosilicate glass wafer by spin-coating at 3000 rpm (thickness of $0.52\ \mu\text{m}$). The SU-8 film is soft-baked for 3 min at 95°C , and the waveguides are patterned by the same lithography tool. To avoid detachment of the polymer tapers from the substrate, the post-exposure-bake employs multiple steps: 50°C for 1 min, 65°C for 1 min, and 80°C for 3 min with a temperature ramp of $2^\circ\text{C}/\text{min}$. The

unexposed resist is removed with the edge bead remover RER600². Fig. 3.4(b) shows AFM measurements of the fabricated SU-8 taper tip. The thickness of the taper only decreases at the roundly etched taper tip. Additionally, the rms roughness of the top of taper tip is ~ 20 nm and of the straight waveguide core is ~ 4 nm.

Fig. 3.4. AFM scanned profiles of (a) the Si₃N₄ and (b) polymer taper tips at nominal width of 0.8 μm .

The polymer chip is then flip-chip bonded onto the Si₃N₄ waveguides using a flip-chip bonder with a placement accuracy of <0.5 μm (Finetech Lambda). The Si₃N₄ and polymer waveguides are visually pre-aligned with the aid of a Vernier ruler etched on both chips. Subsequently, the UV curable NOA 84 adhesive is applied on top of the Si₃N₄ platform. The bottom stage is heated up to 60°C to

² 1-Methoxy-2-propanol acetate; Propylene glycol monomethyl ether acetate (PGMEA), http://www.smfl.rit.edu/pdf/msds/msds_RER_600.pdf

reduce the viscosity of the underfill adhesive. In order to achieve good contact between the top surfaces of the polymer and the Si_3N_4 waveguides without deforming the polymer waveguide, a 10 N bonding force with a ramping speed of 1 N/s is applied. Full curing of the adhesive is achieved by a high-intensity UV curing source (OmniCure 1500) in a nitrogen environment. The bonded chip is then diced to a dimension of 15 mm $\times$ 8 mm.

Fig. 3.5. (a) Chip bonding by using flip-chip bonder. Vernier rulers on (b) left side and right side of the bonded chip separated by a distance of 0.9 mm.

The flip-chip bonding process and alignment marks are shown in Fig. 3.5(a) and (b). The Vernier rulers (0.25 μm resolution) on both the left and right sides of the chip are separated by a distance of 0.9 mm. Lateral misalignments of -0.75 μm and +1.25 μm can be visually found from the Vernier rulers, where “+” and “-” mean that the polymer chip shifts in either positive or negative x-direction. Furthermore, the couplers at different locations inside the chip have different misalignments, which can be specifically calculated from the mask layout with known locations. The local misalignment values of the cascaded vertical couplers ranging from 0.25 μm to 1.25 μm are determined.

3.2.3 Experimental results and discussion

The schematic of the experimental setup is shown in Fig. 3.6. A polarization maintaining (PM) fiber (PM980-XP) was used to couple TE-polarized light from a tunable laser (Agilent 8164B) into the chip. The output is connected to a photodetector by a single-mode fiber (SM-1550). To obtain high-precision alignment, two 3-axes stages (Newport PM-500) are used for the input and output coupling between the waveguide and the fiber. The wavelength of operation is 1.480-1.56 μm . A reliability test of the device is performed according to the standard from the International Electrotechnical Commission (IEC), IEC 60512-11-4: 2002 (i.e., 30 temperature shock cycles from -40 $^{\circ}\text{C}$ to

85° C). In each cycle, the chips are kept at the minimum and maximum temperatures for 30 minutes. The chip is characterized both before and after the thermal shock experiment.

Fig. 3.6. Experimental setup schematic with the optical image of the flip-chip coupler chip.

The transmission measurements inherently include the wavelength dependent losses from the Si_3N_4 waveguide, the polymer waveguide, and the couplers. The propagation loss of the straight Si_3N_4 waveguides is <0.1 dB/cm, whereas the loss of the SU-8 waveguides is 3.5–5.5 dB/cm in the spectral window of interest.

As the chip is only 1.5 cm long, and the length of polymer straight waveguide connecting one polymer taper to the other is 500 μm , the measured loss is dominated by the coupling loss of the vertical couplers. A reference straight waveguide without vertical couplers is tested to extract the in-coupling loss of the chip. This figure is assumed to be the same throughout the chip. Hence, the total loss of N cascaded vertical couplers, $\alpha_{c,total}$, can be calculated by subtracting the reference waveguide loss, α_{ref} , from the total loss of the waveguide with cascaded couplers, α_w . Since each coupler has different misalignment values, the average loss per coupler, $\bar{\alpha}_c = (\alpha_{c,total}/N)$, is utilized as a representative performance metric of the fabricated couplers rather than extracting the coupler loss at a specific misalignment.

Fig. 3.7(a) to (d) demonstrate the average loss per coupler ($\bar{\alpha}_c$) of the fabricated couplers before and after thermal shock tests, as well as the deviation of coupler loss, which includes the uncertainty of the loss measured from the reference waveguides after error propagation. In the spectral window of interest, the average loss for the couplers with Si_3N_4 taper angles between 0.9° and 1.2° is <0.8 dB, which is in good agreement with the losses calculated from the 2D mode solver, which sets the minimum losses. The couplers with Si_3N_4 taper angles of 1.5° and 1.8° are found to have higher losses, probably due to the lower tolerance to misalignment errors shown in Fig. 3.3. Their losses are still below 1 dB. The couplers with the best performance exhibited losses of ~ 0.5 dB for all

wavelengths in the C-band. Finally, the variation of the average losses per coupler before and after thermal shock are small, and no degradation of the couplers is observed after the thermal shock test.

Fig. 3.7. Average loss per coupler ($\bar{\alpha}_c$) before and after thermal shock tests at different Si₃N₄ taper angles and corresponding lengths: (a) 1.8° (19 μm), (b) 1.5° (23 μm), (c) 1.2° (29 μm), and (d) 0.9° (38 μm). The angle and the length of the polymer taper are 0.25° and 80 μm.

3.2.4 Conclusion of Part I

The optimized design of vertical couplers for hybrid integration of Si₃N₄ with polymer waveguides based on flip-chip bonding has been presented. Low-loss highly misalignment tolerant vertical couplers are designed by using a hybrid method that combines 2D FMM mode solver and 3D EME simulations. The proof-of-concept couplers, working under single-mode condition, are experimentally demonstrated in the spectral window of 1.48-1.56 μm. Less than 0.8 dB average losses have been measured for all fabricated vertical couplers with measured lateral Si₃N₄-polymer misalignments within ± 1.25 μm and Si₃N₄ taper angles below 1.2° for all wavelengths in the 1.48-1.56 μm spectral window, both before and after thermal shock tests (IEC 60512-11-4: 2002). The proposed coupling technology holds the credentials for on-chip-scale integration of the Si₃N₄ platform with polymer waveguides.

3.3 Part II: Monolithic integration using vertical Si_3N_4 taper

3.3.1 Device design

Fig. 3.8 shows the 3D schematic as well as the top and side views of the proposed coupler and its cross-sections (CS) at different locations along the coupler. A layer of Norland Optical Adhesive (NOA-84) is deposited as cladding in the final chip to prevent damage to the waveguides (not shown in Fig. 3.8). SU-8 is the polymer employed for this demonstration. The refractive indices of Si_3N_4 , polymer, NOA-84 and SiO_2 are characterized using a prism coupler (Metricon 2010/M) and by an ellipsometer (Woollam M-2000UI) at the two wavelength regions of interest (see Table 3-I).

*

Fig. 3.8. Top: 3D schematic, top and side views of the optical coupler with an adiabatic Si_3N_4 vertical taper. Bottom: Cross-sections at (a) the polymer waveguide core (CS-a), (b) the tip of vertical Si_3N_4 taper (CS-b), (c) the facet of polymer waveguide (CS-c), and (d) the Si_3N_4 waveguide core (CS-d). NOTE: The devices have an upper-cladding of NOA-84 (not shown in the schematics).

Table 3-I. Refractive indices of the materials employed.

λ (nm)	Si_3N_4	Polymer	NOA-84	SiO_2
980	1.994 ± 0.001	1.581 ± 0.005	1.52 ± 0.01	1.449 ± 0.001
1550	1.984 ± 0.001	1.574 ± 0.005	1.51 ± 0.01	1.446 ± 0.001

The adiabatic vertical Si_3N_4 taper plays an essential role in the performance of the optical coupler. The thickness of the Si_3N_4 layer can be gradually tapered down to the desired value with a vertical taper angle θ of $\sim 0.013^\circ$, which is

defined by the optimized wet etching process used to realize the vertical tapers. Hence, tapers with tip height in the nanometer range can be fabricated using an UV contact lithography tool. Adiabatic coupling between the confined modes of the polymer waveguide (CS-a) and the Si₃N₄ waveguide (CS-d) takes place in the region between the Si₃N₄ taper tip (CS-b) and the polymer waveguide facet (CS-c).

The total losses of the optical couplers are given by the loss in the coupling region, which under adiabatic condition is mainly due to the mismatch losses at the abrupt interfaces at the polymer waveguide facet (CS-c) and at the Si₃N₄ vertical taper tip (CS-b) plus the propagation losses caused by material absorption and fabrication errors. The mismatch losses originate from the mode and effective refractive index differences between the modes at the two sides of the discontinuity. The total mode mismatch loss, α_{c1} , is calculated as $\alpha_{c1} = \alpha_{ab} + \alpha_{cd}$, where α_{ab} and α_{cd} are mode mismatch losses at the tip of Si₃N₄ taper and at the facet of the polymer waveguide.

Fig. 3.9. Mode mismatch losses: α_{ab} at wavelengths of (a) 980 nm and (b) 1550 nm with $W_{Si_3N_4} = 1.3 \mu\text{m}$. α_{cd} at (c) 980 nm and (d) 1550 nm with $W_P = 2 \mu\text{m}$. Other parameters: $t_p = 1.8 \mu\text{m}$ and $t_{etch} = 240 \text{ nm}$.

Firstly, the mode mismatch losses are calculated by means of a 2D mode solver and for the optimal parameters of the waveguide cross-section are selected. Then, 3D eigenmode expansion (EME) method simulations are carried out to calculate the losses induced in the coupler region (between CS-c and CS-b) as well as the misalignment tolerance. The propagation loss of the different materials was not included in the calculation model as the objective of this work is to minimize the losses originating from the coupler itself. The couplers are designed for TE polarization. Fig. 3.9(a) and (b) show the mode mismatch losses, α_{ab} , at the wavelengths of 980 nm and 1550 nm. In these simulations, the thickness of the polymer waveguide, t_p , is 1.8 μm . The etched depth into the SiO_2 undercladding at the Si_3N_4 taper tip [Fig. 3.8(b) CS-b] is 200 nm and the width of the Si_3N_4 waveguide, $W_{\text{Si}_3\text{N}_4}$, is 1.3 μm . The design is very tolerant to the variations of the width of both polymer and Si_3N_4 waveguides, as can be seen in Fig. 3.9. The polymer width, W_p , of 2 μm is selected to ensure single-mode (SM) operation at 1550 nm. The width of the Si_3N_4 waveguide was selected to be 1.3 μm for the same consideration as well as to increase the tolerance to lateral misalignment, denoted as Δx , as it will be discussed below. At the polymer facet (CS-c), the thicker the Si_3N_4 core, the more confined the mode is in the Si_3N_4 waveguide, reducing the mode mismatch losses α_{cd} , as shown in Fig. 3.9(c) and (d). A thickness of 200 nm was chosen for the Si_3N_4 waveguide at the CS-c. At the Si_3N_4 taper tip (CS-b), the mode mismatch losses are very sensitive to the thickness of the Si_3N_4 tip (t_{end}). Therefore, the thickness of the Si_3N_4 taper tip at the CS-b is one of the most critical parameters in the coupler design. 3D EME simulations showed negligible intermodal coupling losses at 980 nm, provided that adiabaticity is preserved.

Fig. 3.10(a) shows the simulated total mode mismatch loss α_{c1} as a function of the thickness of the Si_3N_4 tip (t_{end}). It can be seen that α_{c1} is much more tolerant to the variation of t_{end} within the considered range from 20 nm to 60 nm at 1550 nm than that at 980 nm. Nevertheless, as compared to α_{c1} at 1550 nm, α_{c1} at 980 nm is significantly lower for t_{end} values ranging within 30-40 nm where the change of α_{c1} caused by the thickness of the taper tip is also very small.

The influence of total etched depth t_{etch} on α_{c1} is shown in Fig. 3.10(b). The same t_{etch} value is considered for both CS-b and CS-c since the etch rates of Si_3N_4 and SiO_2 are similar in our fabrication process. For a nominal value of t_{end}

of 40 nm, α_{c1} slightly decreases/increases at both wavelengths with the increase/decrease of t_{etch} . The changes are <0.01 dB.

Fig. 3.10. Total mode mismatch loss α_{c1} as a function of (a) Si₃N₄ tip thickness. (b) total etched thicknesses at t_{end} of 20, 30, 40 and 50 nm, and (c) refractive index of the polymer, n_p . The coupler loss α_c including mode mismatch losses and the coupling loss from the vertical region as a function of misalignment, Δx . Other parameters are as shown in Table 3-II.

The design is also very tolerant to the variation of the refractive index of the SU-8 polymer, n_p . Fig. 3.10(c) shows the total mode mismatch loss as a function of the refractive index of the polymer waveguide at $t_{end} = 40$ nm and $t_{etch} = 250$ nm. A wide range of n_p from 1.53 to 1.70 is considered in the calculation. The α_{c1} values at the wavelength of 1550 nm has more obvious growth with the increasing of n_p . This is mainly because the mode mismatch loss α_{cd} grows. For 1550 nm, the mode is less confined in the Si₃N₄ core and feels more impact from the polymer waveguide facet. A variation of refractive index within 0.005 around

the nominal value leads to an increase of α_{c1} , which is below 0.016 dB at 1550 nm. Meanwhile, the increase is negligible at 980 nm.

Table 3-II Optimal design (row A) and fabricated (row B) parameters (units in μm).

	$W_{\text{Si}_3\text{N}_4}$	$t_{\text{Si}_3\text{N}_4}$	t_{end}	W_p	t_p	t_{etch}	L_{taper}
A	1.3	0.2000	0.040	2	1.80	0.250	700
B	1.3	0.2006	0.052	2	1.78	0.267	700

Table 3-II line A shows the selected optimal design parameters based on the above considerations. The corresponding total mode mismatch losses, α_{c1} , are calculated to be 0.0350 dB and 0.092 dB at respectively, 980 nm and 1550 nm. Fig. 3.10(d) shows the total coupler losses α_c as a function of lateral misalignment Δx between the Si_3N_4 and polymer waveguides calculated by a combination of 2D mode solver and 3D EME simulations applied between CS-b and CS-c. At the Si_3N_4 taper tip with a thickness of 40 nm, the losses of a perfectly aligned coupler are calculated as 0.042 dB at 980 nm and 0.095 dB at 1550 nm. The results have good agreement with the total mismatch loss computed by 2D mode solver, confirming the adiabaticity of the vertical Si_3N_4 taper. The coupler losses are more tolerant to the lateral misalignment at 980 nm. This is due to the fact that the coupler losses are dominated by α_{cd} (i.e., mismatch losses at the polymer waveguide facet). The higher confinement of the mode to the Si_3N_4 core at 980 nm, makes α_{cd} more tolerant to lateral misalignments at this wavelength. At 1550 nm, the higher confinement of the mode in the 1.3 μm wide Si_3N_4 waveguide core with respect to the one with $W_{\text{Si}_3\text{N}_4} = 1.1 \mu\text{m}$, makes the coupler with the wider Si_3N_4 more tolerant to lateral misalignment. Alignment accuracy below 1 μm is easily attainable with the lithography machine (EVG620) utilized in this work.

3.3.2 Fabrication results

In this work, the Si_3N_4 waveguides, with adiabatic vertical Si_3N_4 tapers, were fabricated by LioniX B. V. [2]. A 200 nm thick Si_3N_4 layer was deposited by LPCVD at 750-800°C. The vertical tapers were fabricated by UV lithography and isotropic wet etching of the Si_3N_4 layers [29]. The Si_3N_4 waveguide cores were patterned by UV lithography and (RIE) (PlasmaTherm 790). The measured dimensions of the fabricated waveguides are shown in Table 3-II, line B. The mask overlay error between the polymer and Si_3N_4 layers is $0.2 \pm 0.15 \mu\text{m}$, which is determined by on-chip Vernier rulers. The final chip is top-cladded by

NOA-84. Unlike the previous flip-chip bonded case where the adhesive is mostly isolated from oxygen due to the chips on both sides, here, a nitrogen atmosphere and a higher intensity of the UV light are needed to avoid oxygen. The presence of oxygen in the curing environment can quench both the activated photo-initiator radicals as well as the growing chains. This phenomenon is known as “oxygen inhibition”. It can lead to short chain segments, resulting in tacky surface layers and poor mechanical and physical properties. Adhesives are less prone to oxygen inhibition than coatings due to the fact that the substrates on either side of an adhesive isolate the adhesive from oxygen. Higher cure speeds can also lessen the impact of inhibition as faster chain formation allows the polymerization to proceed to completion faster than the quenching can occur. Finally, curing in a nitrogen-rich environment can help to eliminate oxygen inhibition in the most persistent cases. Fig. 3.11(a) and (b) show a focused ion beam image of the cross-section of one of the fabricated waveguides at two locations along the vertical Si₃N₄ taper separated by 300 μm . Tapering effect on the thickness of the Si₃N₄ waveguide can be observed.

Fig. 3.11. Focused ion beam image of the coupler cross-sections: (a) Middle of the taper, (b) Beginning of the taper (CS-c). The images are produced by FEI system by collecting the secondary electrons induced by the incident 30 keV Ga⁺ after the realization of a cleaning cross-section. Imaging angle 52°.

3.3.3 Experimental results and discussion

In the chip layout, groups of waveguides with a different number of cascaded couplers N , with $N = 6, 18$ and 30 , were included. Within each group, different misalignments between the Si₃N₄ and polymer waveguide cores were introduced “by design”. Straight waveguides (i.e., without couplers) were introduced as a

reference. An optical measurement setup similar to that reported in [18] was used, in which a polarization maintaining fiber (PM980-XP) and a single mode fiber (SM-1550) were used for input and output, respectively, at 1550 nm and high numerical aperture fibers (UHNA3) were used for both input and output at 976 nm. The total insertion loss (α_w) is measured for the waveguides with cascaded couplers. The fiber-to-chip edge coupling losses as well as the propagation losses accumulated in the Si_3N_4 waveguide section outside the couplers are almost completely factored out by subtracting the insertion loss of a reference Si_3N_4 straight waveguide on the same chip (α_{ref}), which is measured as 9.7 dB at 976 nm and 16.9 dB at 1550 nm, and assuming identical fiber-to-chip coupling coefficients for each waveguide. An average loss per coupler $\bar{\alpha}$ is obtained from the fitted slope of $\alpha_w - \alpha_{ref}$ over the number of cascaded couplers. The average loss contains the propagation loss of the polymer waveguide sections, which includes the 700 μm long polymer taper plus half of the 300 μm -long section connecting adjacent couplers.

Fig. 3.12. Measured propagation loss of the fabricated SU-8 polymer waveguide in the considered spectral window, i.e., 1460–1635 nm.

Fig. 3.12 shows the propagation losses of the SU-8 polymer waveguide in the spectral window of 1460–1635 nm, which are measured from different lengths of the straight polymer waveguides. The propagation loss at the wavelength of 976 nm and 1550 nm are 0.32 dB/cm and 3.53 dB/cm, respectively. The loss per coupler is obtained by subtracting the total propagation loss of the polymer from the average measured coupler loss. The propagation loss induced by the Si_3N_4 waveguide in the coupler section was considered negligible, due to the low propagation loss achieved from the standard foundry process (<0.1 dB/cm).

Fig. 3.13. (a) Measured loss per coupler at various lateral misalignments at 976 nm and 1550 nm wavelengths. Solid lines are calculated losses for the nominal parameters and dotted lines for the fabricated parameters (Table 3-II); (b) Measured loss per coupler in the spectral window of 1460–1635 nm. The dotted lines are for calculated losses for the nominal structure.

The measured coupler losses as a function of lateral misalignment (fabricated) are shown in Fig. 3.13(a). The coupler with designed zero misalignment has a fabricated Δx of 0.1 μm due to the mask overlay error. The lowest losses are measured to be 0.12 ± 0.04 dB at 976 nm wavelength and 0.14 ± 0.02 dB at 1550 nm. At 976 nm, average measured coupler losses are between 0.12 and 0.20 dB for misalignments < 1 μm and are still below 0.32 dB for misalignments up to 1.6 μm . The insensitive response to the misalignment variation agrees with the simulation shown in Fig. 3.10(d). At 1550 nm, average losses of 0.14–0.19 dB are obtained for misalignments below 1 μm . As clearly seen in Fig. 3.13(a), a deviation between the calculated and measured results of ~ 0.08 –0.15 dB occurs at 976 nm for misalignments below 1 μm . The origin of such deviation is probably caused by the thicker Si_3N_4 taper tip obtained after fabrication (i.e., 52 ± 10 nm versus the 40 nm target), which results in higher mode mismatch loss, α_{ab} . As expected from Fig. 3.9(a), a thicker Si_3N_4 taper tip can account for this difference. At 976 nm, the total mode mismatch loss increases by 0.07–0.13 dB for taper tip thicknesses ranging between 52 and 56 nm, which is within the thickness uncertainty of the measured individual Si_3N_4 taper tips. A smaller effect is expected at 1550 nm, which is confirmed by the experimental data. Additionally, the propagation loss of the vertically tapered Si_3N_4 waveguide is potentially larger than that of the straight Si_3N_4 waveguide due to the extra surface roughness that can lead to increased scattering loss especially at 976 nm. Fig. 3.13(b) shows the measured average losses of mode

converters in the 1460–1635 nm wavelength range for different misalignments. For large misalignments, e.g. Δx of 1.4 μm and 1.6 μm , the mode at shorter wavelengths experiences a lower loss due to its smaller mismatch loss at the tip of the polymer waveguide.

3.3.4 Conclusion of Part II

A low-loss, broadband and highly tolerant vertical coupler between Si_3N_4 and polymer waveguides is presented using adiabatic vertical Si_3N_4 taper. The influence of the different design parameters on the loss of the couplers was reported. The fabricated converters exhibit losses as low as 0.12 dB and 0.14 dB at 976 nm and 1550 nm wavelength respectively. For lateral Si_3N_4 -polymer misalignments $<1 \mu\text{m}$, average losses less than 0.2 dB are achieved at both wavelengths. The measured losses are still below 0.27 dB and 0.38 dB for misalignment $<1.6 \mu\text{m}$. The performance of the converters in the spectral range of 1460–1635 nm agrees with the design. Further performance improvement could be achieved by choosing the optimal value of t_{etch} after measurement of the obtained t_{end} and tapering in both lateral and vertical directions. This robust optical coupling solution potentially paves the way for the integration of various polymer materials onto the Si_3N_4 platform.

3.4 Conclusion

In this chapter, we developed hybrid and monolithic integration technologies for the integration of polymer and Si_3N_4 waveguides. The proposed optical coupling solution for the hybrid integration focuses on using lateral waveguide tapers. The proposed solution for monolithic integration employs a vertical waveguide taper in the Si_3N_4 waveguide. A general design flow combining 2D mode solver and 3D EME simulation methods is described, which enables to efficiently obtain optimal design parameters for the couplers. High-performance features including low-loss, broad bandwidth and high manufacturing tolerance are experimentally demonstrated. Furthermore, thermal shock tests according to the international standard (IEC 60512-11-4: 2002) have been done for the flip-chip bonded couplers, showing no degradation after the temperature shock test. The developed technologies show great potential for the integration of other materials with Si_3N_4 waveguides to form an active-passive platform including on-chip modulators, amplifiers, and lasers.

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4 Double-layer active-passive platforms for Al_2O_3 -on- Si_3N_4 integration

Low-cost, high-performance integration technologies are instrumental for the realization of active-passive integrated photonics devices. Monolithic integration of Al_2O_3 and Si_3N_4 enables to combine the optical features of both materials, increasing the functionalities of the Si_3N_4 passive platform.

In Part I of this chapter, the monolithic integration of Al_2O_3 and Si_3N_4 is studied, enabling to combine the promising optical features of Si_3N_4 with the excellent optical gain characteristics of rare-earth-ion doped Al_2O_3 . The Al_2O_3 and Si_3N_4 layers are separated by a thin SiO_2 film and coupled by adiabatic vertical tapers realized by adiabatically tapering the width of the Al_2O_3 waveguide and adiabatically tapering the thickness of the Si_3N_4 waveguides. In this work, a detailed study of the influence of the different design parameters and fabrication tolerances on the final device performance as well as the full experimental characterization of the fabricated devices is presented. Test structures are characterized under TE polarization. Measured loss per coupler is as low as 0.26 ± 0.03 dB at the wavelength of 1030 nm, and below 0.24 dB in the spectral window of 1460–1635 nm. Lateral misalignment of ± 1 μm results in less than 0.6 dB increase of the coupler loss at 1030 nm, and the tolerance to misalignment goes up to 1.7 μm at the investigated longest wavelength of 1635 nm without introducing extra coupler losses. The reported integration technology paves the way towards a double-layer platform monolithically integrating Si_3N_4 and rare-earth-ion doped Al_2O_3 for active-passive photonic functionalities.

In part II, the active-passive integration is carried out based on the developed double-layer platform technology. For demonstration purposes, an Er^{3+} doped Al_2O_3 layer is grown on the top of the Si_3N_4 wafer. The $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ - Si_3N_4 couplers are characterized at the wavelength of 1306 nm, which lies outside the Er^{3+} absorption band. The same characterization setup as in Part I is used. As expected from the results of Part I, the coupler losses are measured to be as low as 0.23 dB and less than 0.7 dB within the misalignment range of -1.1 μm to +1.6 μm . This demonstration of $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ - Si_3N_4 integration shows the feasibility of realizing various active functionalities in the Si_3N_4 platform by the monolithic integration of rare-earth-ion doped Al_2O_3 .

Part III specifically investigates the resonant coupling effect observed both in the undoped Al₂O₃-Si₃N₄ couplers and the Al₂O₃:Er³⁺-Si₃N₄ couplers for certain lateral shifts between the Si₃N₄ and Al₂O₃ waveguides. The influence of different taper lengths and lateral shifts between the two waveguides on the coupler performance are analyzed. The resonant coupling scheme is found to lower the mode mismatch loss occurring at the taper tips while avoiding the use of high-precision lithograph tools.

The content of Part I has been submitted to the IEEE Journal of Selected Topics in Quantum Electronics, with the title of “Monolithic Integration of Al₂O₃ and Si₃N₄ towards Double-layer Active-passive Platform”. The contents of Part II and III has been accepted by the IEEE Photonics Technology Letters, with the title of “Resonant Coupling for Active-passive Monolithic Integration of Al₂O₃ and Si₃N₄”.

4.1 Introduction

To realize various functionalities, an increasing number of optical components are required for a photonic chip [1]. Amongst the different integrated photonic platforms, silicon nitride shows promising features [2-4] including an intrinsic loss down to 0.1 dB/cm, a wide transparency window covering from the visible to the middle infrared (0.4–2.35 μ m), relatively high refractive index of $\sim$ 2 and compatibility with CMOS technology [5]. Benefiting from these features, Si₃N₄ has been widely studied for microwave photonics applications including beamforming [6] and programmable signal processing [7], for non-linear integrated photonics including optical combs [8] and supercontinuum generation [9], for bio-sensing including interferometric sensors [10], fluorescence imaging [11], and Raman spectroscopy [12, 13], and for other advanced technologies including lidar [14] and gyroscopes [15]. Similarly, as in other commercially available technologies, i.e., InP and silicon-on-insulator (SOI), many standardized building blocks and product development tool kits have been developed for the Si₃N₄ platform to support various manufacturing processes and applications in both industrial and academic scales, e.g. the Triplex platform [2-4]. However, the integration of active devices such as lasers and amplifiers, with Si₃N₄ to expand its functionalities remains a challenge. To overcome it, hybrid integration was studied to realize hybrid lasers by butt-coupling Si₃N₄ and InP waveguides [16]. Although showing very narrow linewidth originating from the high-quality Si₃N₄ external cavity, such integration has small tolerance to the

waveguide misalignment and requires precise packaging technologies, which limits cost-effective assembly and large-scale production.

Besides III-V semiconductors, rare-earth-ion doped aluminum oxide (Al_2O_3) is a good candidate for providing active functionalities to the Si_3N_4 passive platform using a cost-effective monolithic integration approach. Although the III-V semiconductors have excellent optoelectronic value that Al_2O_3 doesn't have. As a host material, the Al_2O_3 can be doped with many rare-earth-ions (RE^{3+}) such as Nd^{3+} , Yb^{3+} , Er^{3+} , Tm^{3+} and Ho^{3+} during the deposition process, covering wavelength ranges from the near-IR to the middle-IR [17-19]. For instance, amplifiers with 20 dB net gain [20] with shallowly etched waveguide spirals (tens of μm) and ring lasers with on-chip couplers [21] have been demonstrated in a fully rare-earth-ion doped Al_2O_3 platform. However, the large loss caused by ground state absorption of the rare-earth-ions limits the integration of other passive components. It can be improved by shallowly etching the waveguides resulting in a large footprint.

To overcome the above issues, monolithic integration of $\text{Al}_2\text{O}_3:\text{RE}^{3+}$ with other passive materials is investigated. For instance, a monolithic integrated amplifier is firstly demonstrated by directly depositing $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ onto SOI waveguides [22]. Monolithic integration of SiO_2 layer on top of ridged $\text{Al}_2\text{O}_3:\text{RE}^{3+}$ waveguides was used to produce an ultra-narrow-linewidth distributed feedback (DFB) laser [23] and a distributed Bragg reflector (DBR) laser [24]. Gratings with precisely controlled coefficients were fabricated on the SiO_2 layer instead of on the $\text{Al}_2\text{O}_3:\text{RE}^{3+}$ layer. These works show the feasibility of realizing scalable light sources with high performance on the $\text{Al}_2\text{O}_3:\text{RE}^{3+}$ platform. An alternative approach with fewer fabrication processes for the monolithic integration of Al_2O_3 and Si_3N_4 was also proposed, where waveguides and gratings were fabricated in a Si_3N_4 layer [25, 26]. Optical modes are guided by the co-integrated ridged waveguide rather than using any waveguide in the gain layer. The method is mostly applied to make DBR or DFB lasers [19, 27, 28]. In this waveguide configuration, the mode field intensity is low with weak mode confinement (especially in the lateral direction) due to the ridged waveguide configuration. Other microring lasers have been reported [29-31]. In these devices, the $\text{Al}_2\text{O}_3:\text{RE}^{3+}$ was deposited into a SiO_2 trench on top of segmented Si_3N_4 waveguides, which guide the resonant pump and laser modes to and from the active ring resonator cavity. This approach requires high-resolution lithography, ultra-precise alignment between the microcavity and the Si_3N_4

structures and high ion concentration to compensate for the large internal resonator loss.

Contrary to the previous approaches, our monolithic integration scheme of Al_2O_3 and Si_3N_4 waveguides forms a double-layer platform, where the waveguides in both the Al_2O_3 and Si_3N_4 layers can guide confined optical modes. The modes couple between the two layers only in a certain coupling region by applying width-tapering to the Al_2O_3 waveguides and thickness-tapering to the Si_3N_4 waveguides. Here, the Si_3N_4 platform with a thin layer of SiO_2 on the top serves, after chemical-mechanical polishing (CMP), as the substrate of the Al_2O_3 layer. This integration scheme is not only available for wafer-scale integration but also capable for selective area growth of active layers [32], providing full freedom to individually integrate optical functions on both layers with high integration density and low propagation losses. In the proposed double-layer configuration, the optical coupling between the Si_3N_4 and Al_2O_3 waveguides remains the key challenge. To make the platform feasible to integrate various optical components, it is significant to achieve broadband and low-loss couplers with high fabrication tolerance to the misalignment between the Si_3N_4 and Al_2O_3 waveguides. This is the main objective of the work presented here.

4.2 Part I: Double-layer platform development

4.2.1 Device design

4.2.1.1 Coupling principles

For the integration of different materials in a photonic chip, there are three common ways to achieve high-performance coupling between two waveguides, namely butt coupling [16], resonant coupling [33] and adiabatic coupling [34]. Butt coupling needs matched effective refractive index of the waveguides from different chips to obtain efficient coupling. The resonant coupling requires phase matching at a certain coupling length to couple the power from one waveguide to the other, which is highly wavelength and polarization dependent. The achievable maximum power transfer relies on the difference of the propagation constants of the two coupled waveguides. The coupling efficiency depends on the precise coupling lengths for which the phase matching condition is satisfied. A more detailed resonant coupling study can be seen in Part III of this chapter. In an adiabatic process, the mode from the first waveguide evolves adiabatically

to the mode of the taper section and eventually evolves to the mode of the second waveguide. There is no power transition from the mode to other modes, such as higher-order modes or radiation modes [35]. It requires a sufficiently slow variation of the geometry of at each position the waveguide taper in the propagation direction. Adiabatic couplers exhibit therefore a broader bandwidth and less polarization dependency than resonant couplers [36]. A general guideline for the design of adiabatic tapers for the fundamental mode is described in [37]. The taper length (z) has to be much larger than the coupling length between the fundamental mode and the higher order mode with a propagation constant closest to that of the fundamental mode in the coupling region, which can be expressed as:

$$z \gg \frac{2\pi}{\beta_0 - \beta_1} \quad \text{Eq. 4-1}$$

where β_0 and β_1 are the propagation constants of the fundamental mode and its first higher-order mode. However, long taper lengths not only reduce the integration density but also introduce additional propagation losses. To shorten the length, delineating curves can be extracted from the wave propagation behavior of the tapers [38]. Instead of this ultimate optimization, most applications such as polymer-Si optical I/Os [39], Si-III-V integration [40] and Si_3N_4 multi-layer platform [41] divide the taper into multiple sections with different angles. Hence, smaller angle can be applied for the section where the mode distribution is more sensitive to its geometric variation. A larger angle can be applied to the sections that are less sensitive to the mode field variation reducing the overall length of the coupler. For example, the work of [42] demonstrates the multi-section design for optical interconnects.

In our previous work [43] (Chapter 3) the thickness-tapered Si_3N_4 tapers (vertical taper) buried inside straight polymer waveguides cores are used for the monolithic integration of polymer and Si_3N_4 waveguides achieving less than 0.2 dB losses over a wavelength range from 976 nm to 1635 nm. Vertically tapering the Si_3N_4 waveguide permits drastically reducing the mode mismatch losses at the Si_3N_4 taper tip, therefore, avoiding the need for nanolithography tools. It also permits monotonically varying the effective index of the hybrid mode to achieve adiabatic power transfer to the Al_2O_3 waveguide. In this work, we apply both width-tapered Al_2O_3 waveguides (lateral taper) and vertical Si_3N_4 tapers to realize adiabatic couplers. The effective refractive index of the fundamental mode in the taper region can be gradually varied to transfer the

mode power between the Al_2O_3 and Si_3N_4 waveguide core. A broadband performance can be achieved by this taper configuration. To make the Si_3N_4 and Al_2O_3 waveguides work independently, a double-layer monolithic integration scheme is proposed. Additionally, multi-section taper scheme is challenging for vertical tapers, but it can be considered in future optimizations.

4.2.1.2 Device structure

A 3D schematic of the double-layer Al_2O_3 - Si_3N_4 platform is shown in Fig. 4.1. A 200 nm thick single-stripe Si_3N_4 layer on a $\sim 8\ \mu\text{m}$ thick thermally-oxidized Si is employed.

Fig. 4.1. 3D schematic of the coupling section of the double-layer Al_2O_3 and Si_3N_4 photonic platform. The cross-sections at (a) the Al_2O_3 waveguide core, (b) the tip of Si_3N_4 vertical taper, (c) the tip of Al_2O_3 lateral taper and (d) the Si_3N_4 waveguide core. The intensity profiles of the fundamental TE mode at the corresponding cross-sections are also shown for the simplicity of illustration.

An important difference compared to previous Si_3N_4 -polymer couplers is that here the top Al_2O_3 layer is separated from the Si_3N_4 bottom layer by a thin LPCVD SiO_2 film. The thin SiO_2 film is polished by chemical-mechanical polishing (CMP) in order to obtain a good surface uniformity for the Al_2O_3 layer

deposition and to protect the Si_3N_4 waveguides during the dry etching process of the Al_2O_3 waveguides. Otherwise, the height variations of the deposited SiO_2 film due to the topology of the Si_3N_4 waveguides underneath can cause misalignment-dependent deformation of the Al_2O_3 waveguide cross-sections leading to less misalignment tolerant and less performant couplers. A SiO_2 film thickness, t_{spacer} , of 200 nm is chosen based on the capabilities of the in-house CMP process. The Al_2O_3 waveguides are fully etched and there is no Al_2O_3 slab layers on top of the Si_3N_4 waveguides except in the coupling region, avoiding influencing the properties of the passive Si_3N_4 waveguides.

Fig. 4.1(a) to (d) show the cross-sections (CS) with corresponding field distributions of the fundamental TE mode in the coupling region at several locations along the adiabatic coupler, namely at the Al_2O_3 waveguide core [CS (a)], the tip of the Si_3N_4 vertical taper [CS (b)], the tip of the Al_2O_3 taper [CS (c)] and the Si_3N_4 waveguide core [CS (d)]. The confined mode in the $\text{Al}_2\text{O}_3/\text{Si}_3\text{N}_4$ waveguide core at both tips [CS(b) and CS(c)] has a slightly different effective refractive index from the mode of the Al_2O_3 [CS(a)] or Si_3N_4 [CS(d)] waveguides. This difference in effective refractive index causes mode mismatch loss, which can be seen from the difference in their field distributions. Afterward, the mode continues propagating inside the coupling region, where the power of the mode is adiabatically transferred from one waveguide to the other. The mode mismatch losses and the losses occurring in the coupling region constitute the total loss of the Al_2O_3 - Si_3N_4 coupler in the double-layer platform.

4.2.2 Simulation results

The same design methodology as reported in [43] was performed to determine suitable parameters for the optical couplers. The methodology combines a 2D mode field calculation with a 3D eigenmode expansion (EME) method. The former calculates the mode mismatch losses at the taper tips and the latter computes the coupling loss originated from the taper region. The 2D mode field calculations were implemented in Phoenix Optodesigner (Synopsys) while the 3D EME calculations were performed using Lumerical Mode Solutions (Lumerical).

In the design, a width of $1.4\ \mu\text{m}$ is used for the Si_3N_4 waveguide and the thickness of the Al_2O_3 layer is 700 nm. The thickness of the Si_3N_4 waveguide is vertically tapered down to $\sim 30\ \text{nm}$ with a taper angle of $\sim 0.013^\circ$ while the width of the Al_2O_3 waveguide is laterally tapered from $1\ \mu\text{m}$ to $0.8\ \mu\text{m}$ with a length of

800 μm . The 0.8 μm Al_2O_3 taper tip width was chosen due to the limit of the standard UV lithography (EVG620). These dimensions support single-mode (SM) condition for both Si_3N_4 and Al_2O_3 waveguides in the wavelength range 1480–1635 nm and satisfy the adiabaticity criteria. The refractive indices of the materials employed are shown in Table 4-I. Three wavelengths are considered in the simulations, 980 nm (i.e., corresponding to the pump wavelength for both Yb^{3+} and Er^{3+}), 1030 nm (i.e., emission wavelength of Yb^{3+}) and 1480–1635 nm (i.e., comprising the Er^{3+} emission band). The tolerance analysis focuses on the influence of the lateral misalignment, Δx , between the Si_3N_4 and Al_2O_3 waveguides, which is introduced by the lithography process, and the thickness variation of the thin SiO_2 spacer film, which depends on the CMP process.

Table 4-I. Refractive indices of the materials in the design

Materials	$\lambda = 980\text{-}1030 \text{ nm}$	$\lambda = 1460\text{-}1635 \text{ nm}$
Al_2O_3	1.65 ± 0.01	1.64 ± 0.01
Si_3N_4	1.994 ± 0.001	1.985 ± 0.001
SiO_2	1.45 ± 0.01	1.445 ± 0.001

4.2.2.1 Mode mismatch losses at taper tips

In Fig. 4.2(a), the mode mismatch loss, α_{ab} , calculated from the field overlap between the fundamental modes of CS (a) and CS (b) is depicted. The loss is below 0.04 dB for all considered wavelengths and misalignments. The smaller wavelengths (i.e., 980 nm and 1030 nm in this study) have a more confined mode in the Al_2O_3 waveguide core and they are therefore less affected by the very thin tip of the Si_3N_4 vertical taper (i.e., 30 nm), which induces a minimal effective refractive index change between the CS (a) and CS (b). Further tapering of the Si_3N_4 thickness (i.e., towards 0 nm) does not bring any further improvement. It is important to highlight that such reduction of the mismatch losses can also be achieved by laterally tapering the waveguide width to a sufficiently small value (i.e., tens of nanometer) [44], which requires a high-resolution lithography technique such as electron-beam lithography or DUV (193 nm) stepper lithography.

As can be seen in Fig. 4.2(a), the trend of the mode mismatch loss with lateral misalignment is different for the different wavelengths. The loss at the shorter wavelengths (i.e., 980 nm and 1030 nm) continuously reduces. However, the loss at the longer wavelengths (i.e., 1480, 1550, 1630 nm) firstly rises and then gradually decreases. As the misalignment increases (i.e., around 0.8 μm of misalignment), the fundamental mode of CS (b) is highly affected by the Si_3N_4

taper tip, which distorts the mode leading to the lowest mode overlap with the mode of CS(a). As the misalignment increases further, the CS (b) mode is less affected by the Si_3N_4 tip due to the fact that the tip is cut-off. The CS (b) increasingly resembles the mode of CS(a) therefore decreasing the mode overlap losses. This indicates that the Si_3N_4 taper tip in the hybrid cross-section [CS (b)] has a non-negligible influence on the mode in the Al_2O_3 waveguide core [CS (b)] at these longer wavelengths.

For larger misalignments (i.e., $>1.5 \mu\text{m}$ for the shorter wavelengths and $>2.2 \mu\text{m}$ for the longer wavelengths) the mode mismatch losses steadily decrease to almost negligible. The reasons are that for such misalignments, the mode is completely confined in the Al_2O_3 waveguide core of the CS (b) since the thin tip of the vertical taper is cut-off.

Fig. 4.2. (a) Mode mismatch loss α_{ab} between the cross-section CS(a) and CS(b) at different wavelengths. The Si_3N_4 taper tip has a width $W_{\text{Si}_3\text{N}_4}$ of $1.4 \mu\text{m}$ and its thickness, t_{end} , is 30 nm . The dimension of the Al_2O_3 waveguide core is: $1 \mu\text{m} \times 700 \text{ nm}$. (b) Mode mismatch loss α_{cd} between the cross-section CS-c and CS-d at different wavelengths. The width of the Si_3N_4 waveguide is $1.4 \mu\text{m}$ and its thickness is 200 nm . The dimension of Al_2O_3 taper is: $0.8 \mu\text{m} \times 700 \text{ nm}$.

At the tip of the Al_2O_3 taper, the mode mismatch loss, α_{cd} , between the CS (c) and CS (d) is found to be bigger than the loss at the tip of Si_3N_4 taper, as shown in Fig. 4.2(b). For instance, α_{cd} is $<0.075 \text{ dB}$ at the short wavelengths and $<0.25 \text{ dB}$ at the long wavelengths for a zero lateral misalignment. Here, the Al_2O_3 taper tip has a relatively large dimension (i.e., $0.8 \mu\text{m}$ width and 700 nm thickness), leading to more impact on the variation of the effective refractive index for the mode transferring between CS (c) and CS (d). Therefore, the mode overlap between the hybrid cross-section and the Si_3N_4 waveguide core is

smaller than that between the CS (a) and CS (b). This can be clearly seen by the more interrupted field distributions shown in Fig. 4.1(c) and (d). Furthermore, the dimension of the Al_2O_3 taper tip has negligible influence on the mode mismatch loss when the Al_2O_3 taper shifts too far away from the Si_3N_4 vertical taper, following a similar trend as at the Si_3N_4 tip.

4.2.2.2 Coupling losses in the taper region

To study the adiabaticity of the coupling region, an EME simulation was carried out based on the 3D structure of the tapers. The fundamental TE modes of the hybrid cross-sections, i.e., CS (b) and CS (c) are regarded as the input/output modes. The power transition loss between them is considered the coupling loss of the taper region, α_{bc} . The length of the taper region is equal to the length of the Si_3N_4 vertical taper, which is $800\text{ }\mu\text{m}$ calculated from the taper angle determined by the tapering process (seen in section III) and the initial and final Si_3N_4 thicknesses. We firstly performed convergence tests for the different simulation parameters. A mesh size of 2 nm in the vertical direction and 5 nm in the lateral direction are employed due to the thin layer of the Si_3N_4 vertical taper.

Fig. 4.3. Coupling loss of the taper region α_{bc} between the cross-section, CS-b and CS-c calculated using 3D EME. The length of both Al_2O_3 and Si_3N_4 tapers is $800\text{ }\mu\text{m}$.

In Fig. 4.3, the calculated coupling loss, α_{bc} , as a function of the lateral misalignment shows that the coupling efficiency and tolerance to lateral misalignment gradually rises towards longer wavelengths. When the Al_2O_3 taper and the Si_3N_4 taper are separated over a certain value of lateral misalignment, i.e., with Δx of $\sim 0.6\text{ }\mu\text{m}$ for 980 nm and 1030 nm , and Δx of $1.3\text{ }\mu\text{m}$ for 1480 nm and 1550 nm , and Δx of $1.4\text{ }\mu\text{m}$ for 1630 nm , the coupling loss raises rapidly. This wavelength dependence of the tolerant range originates from the difference

in mode size at the studied wavelengths, which has an impact on the coupling strength during the mode transition. At the longer wavelengths, further increase of the lateral misalignment leads to resonance coupling [33] due to the large mode size. Eventually, the coupling loss significantly increases when the Al_2O_3 and Si_3N_4 tapers are separated too far away and coupled modes do not spatially overlap anymore.

Fig. 4.4 Intensity profiles of the fundamental TE mode transition in the taper region at the wavelength of 1550 nm: (a) top-view and (b) side-view for the case with zero misalignment; (c) top-view and (d) side-view for the case with misalignment of 1.8 μm .

The power transfer in the taper region is visualized horizontally (top-view) and vertically (side-view) at the wavelength of 1550 nm in Fig. 4.4. For zero-misalignment [Fig. 4.4(a) and (b)], the adiabatic coupling between the Si_3N_4 and Al_2O_3 waveguide cores through the taper region is clearly seen. At the large lateral misalignment of 1.8 μm [Fig. 4.4(c) and (d)], some resonant patterns along the propagation direction can be observed in the intensity profiles. Furthermore, we find that the resonance coupling effect can be reduced while enhancing the tolerance to lateral misalignment by reducing the SiO_2 thin film between the Si_3N_4 and Al_2O_3 waveguides. Nevertheless, the demonstration of the

monolithic integration in this work focuses on utilizing 200 nm SiO_2 film because of our current developed the process.

4.2.2.3 Total losses with different thin SiO_2 film thicknesses

The total loss, α_c , of the Al_2O_3 - Si_3N_4 coupler consists of the mode mismatch losses at the taper tips plus the coupling loss of the taper region. Fig. 4.5(a) to (c) show the total loss as a function of the lateral misalignment for different thicknesses of the thin spacer SiO_2 film, t_{spacer} , of 100 nm, 200 nm and 300 nm. Propagation losses of the materials are not taken into account in the calculations.

Fig. 4.5. Total loss per coupler by adding the mode mismatch losses and the coupling loss from taper region at the thickness of thin SiO_2 film of (a) 100 nm, (b) 200 nm, and (c) 300 nm.

With the increase of t_{spacer} , the range of the tolerance to lateral misalignment decreases. This is more apparent at the shorter wavelengths due to their smaller mode size and less evanescent wave penetration depth. On the other hand, for the thinner SiO_2 film, the mode at the Al_2O_3 taper tip is found to be affected more

by the geometrical changes at misalignments $>0.7\ \mu\text{m}$, giving higher mode mismatch losses especially at the long wavelengths. Nevertheless, the increment of the total coupler loss is less than 0.1 dB within a SiO_2 film thickness range of $200\pm 100\ \text{nm}$. For the proposed case with 200 nm thick SiO_2 film, for zero misalignment, α_c values at the short wavelengths are less than 0.09 dB being still below 0.22 dB at the long wavelengths. Due to the relatively large dimension of the Al_2O_3 taper tip, the mode mismatch loss, α_{cd} , contributes a large portion of the total loss within the tolerant range of the misalignment. To further improve the total loss, this mismatch loss can be overcome by vertically tapering the Al_2O_3 taper tip in future developments.

Regarding simulation results in previous subsections, further-optimization of the waveguide dimensions, taper profiles, and thin SiO_2 film between the two guiding layers could potentially enable to increase the tolerance to lateral misalignment of the adiabatic tapers.

4.2.3 Fabrication results

4.2.3.1 Fabrication processes

The process flow of the monolithic integration of Al_2O_3 and Si_3N_4 is shown in Fig. 4.6(a) to (h). It includes the fabrication of Si_3N_4 waveguides [Fig. 4.6(a) to (c)], the polishing of the thin SiO_2 film [Fig. 4.6(d) to (e)], the fabrication of Al_2O_3 waveguides [Fig. 4.6(f) to (g)] and the deposition of the PECVD SiO_2 cladding [Fig. 4.6(h)]. In the following description of the fabrication processes, a positive photoresist, OiR 907-12 ($\sim 1.4\ \mu\text{m}$ thickness at 3500 rpm), is employed instead of OiR 907-17 ($\sim 1.7\ \mu\text{m}$ thickness at 4000 rpm). We found that the former enables to pattern the taper widths of $0.8\ \mu\text{m}$ reproducibly. This is because lower exposure dose can be applied to the former and avoid undesired exposure of the resist by scattering, diffraction and reflections, which may lead to lifting and deformation of the taper tips.

The $8\ \mu\text{m}$ thick thermal oxide was found to be sufficient to avoid light penetration into the Si substrate during propagation according to the work of the Si_3N_4 and polymer couplers. The Si_3N_4 layer is grown by LPCVD technique in a commercial foundry (Lionix International) on Si wafers with the thermal oxide thickness of $8\ \mu\text{m}$. The Si_3N_4 thickness is characterized to be 199.6 nm by an ellipsometer (Woollam M-2000UI), which is 0.4 nm thinner than the designed value, i.e., 200 nm. Vertically tapering the Si_3N_4 layer is obtained by an isotropic

wet etching technique. The thickness of the taper tip is 30.8 nm. The etching rate difference between the Si_3N_4 and native SiO_2 produces a sidewall angle [45], which is about 0.013° and results in $\sim 800 \mu\text{m}$ taper length, which results in an adiabatic taper.

Fig. 4.6. Process flow of the Al_2O_3 - Si_3N_4 integrated double-layer photonic platform: (a) LPCVD Si_3N_4 film deposition, (b) vertical tapering of Si_3N_4 layer, (c) Si_3N_4 waveguide fabrication after RIE etching and resist removal, (d) SiO_2 intermediate layer deposition by LPCVD TEOS technique, (e) CMP process to ensure surface uniformity, (f) Al_2O_3 deposition, (g) Al_2O_3 waveguide fabrication after RIE etching and resist removal, and (h) PECVD cladding deposition.

After the tapering process, the fabrication of the Si_3N_4 waveguides [Fig. 4.6(c)] is carried out by a reactive ion etching (RIE) process with a suitable CHF_3 - O_2 flow that gives etching rate of 30 nm/min for Si_3N_4 and 32 nm/min for SiO_2 . The etched depth is monitored by an integrated interference camera in the RIE system. The Si_3N_4 waveguides are produced by fully etching into the SiO_2 , and the thickness of etched SiO_2 is less than 50 nm. Photoresist stripping and

standard cleaning procedures are followed to obtain a metal-free surface of the Si_3N_4 wafers for LPCVD SiO_2 deposition on the top.

A thick LPCVD SiO_2 film (~760 nm after annealing) is deposited on the Si_3N_4 wafer to provide sufficient thickness for CMP process. Heaves on the SiO_2 layer exist in the areas where there are Si_3N_4 structures underneath [Fig. 4.6(d)]. They are then polished away during the CMP process with an average SiO_2 removing speed of ~100 nm/min [Fig. 4.6(e)]. Details of the characterization of removing speed during the CMP process are described in Part A of Appendix. Through properly controlling the slurry flow and polishing time, a good uniformity (<40 nm in full wafer scale) surface and a polished SiO_2 thickness of 185 nm are finally obtained.

To fabricate the Al_2O_3 waveguides, the Al_2O_3 layer is deposited on top of the polished wafer by RF-sputtering technique (AJA ATC 1500) [46] [Fig. 4.6(f)]. During the sputtering process, the wafer with the bottom Si_3N_4 layer is heated up to about 650 °C to reduce the incorporation of OH⁻ groups on the layer. The height between the wafer holder and target is set to 6.75 inches and the wafer rotates during the deposition process. In this demonstration, the sputtering power for the aluminum target is 200 W. The measured flows of Ar and oxygen into the reactor are selected to be 30 sccm and 3.8 sccm, respectively. To monitor the thickness of the deposited Al_2O_3 layer in wafer-scale, the Al_2O_3 layer is deposited onto a dummy Si wafer with the above settings for 180 min. A thickness map of the dummy wafer is produced by ellipsometry, as shown in Fig. 4.7 (a). The thickness in the center of the wafer is measured to be ~720 nm, yielding a deposition rate of 4 nm/min. The Al_2O_3 layer thickness gradually decreases from 720 nm in the center to ~670 nm towards the wafer edge. In an area within the 60×60 mm² from the wafer center, a non-uniformity of <7% is achieved, which can be further improved by optimizing the distance between the wafer holder and target.

The Al_2O_3 layer is then deposited on the CMP polished Si_3N_4 wafer afterwards. Its thickness at the center of the wafer is characterized by a prism coupling system (Metricon 2010/M) rather than using the ellipsometer due to the presence of Si_3N_4 waveguides underneath the Al_2O_3 layer. A coupled slab mode propagating at the wavelength of 633 nm in the Al_2O_3 layer is shown in Fig. 4.7(b). The thickness measured by prism coupling is 714 nm at the center of the wafer and 642 nm at the side of the wafer, i.e., the location shown in Fig. 4.7(b),

which shows good agreement with the values obtained from the dummy Si wafer. Therefore, the uniformity of the Al_2O_3 layer on the Si_3N_4 wafer is assumed to be similar to that of the dummy wafer.

To fabricate the Al_2O_3 waveguides, standard UV lithography is applied. The patterned Al_2O_3 layer is then etched by the RIE with a $\text{BCl}_3\text{-HBr}$ flow (2.5:1) (Oxford PlasmaPro 100 Cobra). The photoresist and Al_2O_3 have similar etching rates of 50–55 nm/min. Details of the characterization of the etching rates are shown in Part B of Appendix. The Al_2O_3 waveguides are fully etched with the etching depth is 720 ± 5 nm that is scanned by a profilometer (Veeco Dektak 8).

Eventually, the resulting $\text{Al}_2\text{O}_3\text{-Si}_3\text{N}_4$ double-layer wafer is covered by a thick SiO_2 layer (~ 4 μm), deposited by PECVD technique (Oxford 80) as a cladding layer. After processing, the wafer is diced to individual chips with a dimension of 1.5×1 cm using the dicing system (Loadpoint Micro Ace 3). To demonstrate the optical coupling, an $\text{Al}_2\text{O}_3\text{-Si}_3\text{N}_4$ coupler chip is selected, originating from the area highlighted with a dash line in Fig. 4.7(a). The image of the chip is shown in Fig. 4.8(a).

Fig. 4.7. (a) The thickness profile of the Al_2O_3 layer deposited on a dummy silicon wafer for thickness monitoring using the same settings as the sample wafer. Dots are the scan pattern by the ellipsometer (Woollam 2000UI). Dashed box indicates the location for the test unit of the $\text{Al}_2\text{O}_3\text{-Si}_3\text{N}_4$ couplers in the layout. (b) A slab mode in the Al_2O_3 layer deposited on the top of a CMP polished wafer with fabricated Si_3N_4 structures at the wavelength of 633 nm coupled by the prism coupling system (Metricon 2010/M).

4.2.3.2 Lateral misalignments of fabricated chips

The lateral misalignment in the design ranges from $-1.5\ \mu\text{m}$ to $+1.5\ \mu\text{m}$ with a step of $0.3\ \mu\text{m}$, where the “-” and “+” signs indicate the relative shift direction between the Al_2O_3 and Si_3N_4 waveguides. In the standard optical lithography utilized in this work (i.e., EVG 620), the routinely achievable alignment accuracy is $0.6\ \mu\text{m}$. Therefore, the introduced misalignment in the layout design enables to obtain couplers with less than $0.3\ \mu\text{m}$ alignment accuracy. Furthermore, the misalignment values introduced in the chip design enable the realization of couplers with larger misalignments (i.e., $1.2\text{--}1.8\ \mu\text{m}$), which will be used for the characterization of resonance coupling in the third part of this chapter.

Fig. 4.8. (a) Photograph of the Al_2O_3 - Si_3N_4 integrated coupler chip. Zoom-in optical gradient images at the tip of the Al_2O_3 taper with the lateral misalignment of (b) $1.3 \pm 0.15\ \mu\text{m}$, (c) $1 \pm 0.15\ \mu\text{m}$, (d) $0.1 \pm 0.15\ \mu\text{m}$ and (e) $-1.7 \pm 0.15\ \mu\text{m}$.

To characterize the lateral misalignment between the Al_2O_3 and the Si_3N_4 waveguides, top view images are taken from the fabricated devices by a calibrated microscope. Gradient images extracted directly from the captured optical images permit having a better contrast of the waveguide structures. For example, Fig. 4.8(b) to (e) show gradient images of the couplers with measured misalignment values of $+1.3\ \mu\text{m}$, $+1\ \mu\text{m}$, $+0.1\ \mu\text{m}$ and $-1.7\ \mu\text{m}$. The lowest measured misalignment of $0.1 \pm 0.15\ \mu\text{m}$ appears at the designed $+0.3\ \mu\text{m}$

misaligned coupler after fabrication, indicating a misalignment of $0.2\ \mu\text{m}$ caused by the UV lithography process of the Al_2O_3 layer. This agrees with the misalignment characterized by the analysis of the Vernier ruler in this wafer (optical image not captured).

In order to check the coupler cross-sections by scanning electron microscope (SEM), Al_2O_3 waveguides were fabricated on another Si_3N_4 wafer produced in the same batch. The only difference is that the Al_2O_3 layer in the wafer for SEM imaging is slightly thicker (i.e., $800\ \text{nm}$ in the wafer center). The Al_2O_3 - Si_3N_4 couplers of this monitor wafer are cleaved at different locations along the taper region. A $9\ \text{nm}$ thick gold is sputtered onto the cleaved samples to prevent charging during SEM imaging. Here we show the cleaved cross-sections for lateral misalignments of $\sim 0.1\ \mu\text{m}$ and $\sim 1.3\ \mu\text{m}$. At the side close to the tip of the Si_3N_4 vertical taper, the Al_2O_3 waveguide core and a thin layer of Si_3N_4 buried by the SiO_2 can be clearly seen in Fig. 4.9(a) to (e). At the tip of the Al_2O_3 taper, the narrow Al_2O_3 waveguide core and thick Si_3N_4 waveguide cross-section are shown in Fig. 4.9(c) to (d).

Fig. 4.9. SEM images of the cleaved cross-sections of Al_2O_3 - Si_3N_4 couplers from a monitor Al_2O_3 - Si_3N_4 wafer with the Al_2O_3 thickness of $800\ \text{nm}$ and etched depth of $720 \pm 5\ \text{nm}$; (a) to (e) are taken at locations close to the tip of Si_3N_4 taper; (f) to (h) are taken at locations close to the tip of Al_2O_3 taper. From left to the right, the lateral misalignment increases.

4.2.4 Characterization

4.2.4.1 Propagation loss measurement

The propagation loss of the 200 nm Si_3N_4 waveguides was characterized in Part II of Chapter 2. The propagation loss measurement of the Al_2O_3 waveguides will be described in detail in the following section. A non-conductive method [20, 47] is employed, where top-view intensity images of an Al_2O_3 spiral waveguide are captured by an IR camera (InGaAs camera, Xenics Bocat 320) at different wavelengths. The spiral waveguide has a length of 18 cm and the same width as the Al_2O_3 waveguide of the Al_2O_3 - Si_3N_4 couplers. Its minimal radius, i.e., the radius of the s-bend in the center, is 250 μm , which is designed to have negligible bend loss ($<10^{-4}$ dB/cm). Fig. 4.10(a) shows the light scattering image of the Al_2O_3 spiral integrated with Si_3N_4 waveguides at the wavelength of 1030 nm. The input fiber couples the light into the Si_3N_4 waveguide core. The mode transfers to the Al_2O_3 spiral on the top layer through the Al_2O_3 - Si_3N_4 coupler, which is indicated in cyan color. Due to propagation losses, the intensity of the spiral waveguide decays exponentially along the mode propagation direction [Fig. 4.10 (b)].

To extract the propagation loss, the waveguide channel roughness, which is the main contributor to the propagation loss, is assumed to be uniform along the length of the Al_2O_3 spiral. The scattering intensity is proportional to the power of the mode confined in the waveguide [47]. Thus, the scattering intensity variation along the light propagation direction follows the Lambert-Beer law [20], which enables to obtain the propagation loss of the waveguide. Here the intensity of the pixels in a certain area of the circular path of the spiral Al_2O_3 waveguide included within a yellow column [Fig. 4.10 (a)] are accumulated. Intensities of nine areas at different locations separated by a certain length along the propagation direction of the spiral are extracted. The intensity reduction along the propagation length is plotted in Fig. 4.10(b). These intensity values (in logarithmic scale) at different propagation lengths can be linearly fitted. Its slope determines the propagation loss in dB/cm. A propagation loss of 2.3 dB/cm at the wavelength of 1030 nm is measured. By using this method, the propagation losses at other wavelengths ranging from 1020 nm to 1630 nm are obtained, as shown in Fig. 4.10(c), where the error bars originate from averaging over multiple independently measured intensity images of the same spiral, which are considered as our measurement uncertainty. The wavelength-dependent performance of the propagation loss of the Al_2O_3 spiral is clearly demonstrated.

Since this work focuses on the demonstration of the optical coupling of the double-layer platform, the sputtering of the Al_2O_3 layer has not been optimized yet. The propagation losses shown in Fig. 10(c) are rather high. Lower propagation loss of Al_2O_3 waveguides can be obtained by an optimal sputtering process, as can be seen by the performance of $\text{Al}_2\text{O}_3:\text{Yb}^{3+}$ ring laser sensors [48].

Fig. 4.10. (a) Infrared image of the Si_3N_4 integrated Al_2O_3 spiral at the wavelength of 1030 nm. (b) Intensity measured from certain areas in the infrared image (cyan columns) along the propagation direction. (c) Measured propagation losses of the Al_2O_3 waveguide at various wavelengths.

4.2.4.2 Coupler loss measurement

In the test-unit of the Al_2O_3 - Si_3N_4 couplers, the waveguides of the monolithically integrated double-layer chip are divided into four groups, with an increasing number of cascaded couplers, N , namely 2, 4, 6 and 12, as shown in Fig. 4.8(a). Neighboring couplers are connected by a 300 μm Al_2O_3 waveguide bridge. Each N group contains eleven waveguides with cascaded couplers, the only difference being the lateral misalignment, Δx , which ranges from -1.7 μm to +1.3 μm of

the fabricated device (from $-1.5 \mu\text{m}$ to $+1.5 \mu\text{m}$ in design). The couplers are characterized both at the wavelength of 1030 nm (Toptica CTL1050) and across the spectral window of 1460–1635 nm (Agilent 8164B).

The experimental configuration for the characterization is similar to our previous work [43]. Input light is coupled into the waveguide through polarization maintaining fibers (PM980-XP for 1030 nm and PM1550-XP for the spectral window 1460–1635 nm). Here the input PM fiber facet is positioned at 4° angle with respect to the input Si_3N_4 waveguide facet in order to reduce the influence of the stray light propagating through the cladding layer. Transmission spectra are collected by a high numerical aperture fiber (UHNA3) at all measured wavelengths. Reference Si_3N_4 waveguides are located in the same die. Their facets are assumed to have the same roughness as the other Si_3N_4 waveguides with cascaded Al_2O_3 - Si_3N_4 couplers. Therefore, the fiber-to-chip coupling efficiencies for both the reference waveguide and the cascaded coupler waveguides are assumed to be similar. In addition, an index matching fluid (Diphenyl ether) is employed to all input/output facets to improve the fiber-to-chip coupling and reduce resonances between the fiber and chip facets.

Fig. 4.11. Measured transmission spectra of the reference waveguide and the waveguides with different number of the cascaded Al_2O_3 - Si_3N_4 couplers at misalignments of (a) $0.1 \mu\text{m}$ and (b) $0.2 \mu\text{m}$, respectively. The waveguide transmission with four cascaded couplers (i.e., C4) at Δx of $0.1 \mu\text{m}$ is not shown due to a fabrication defect on the waveguide.

The transmission spectra in the spectral window 1460–1635 nm measured for the couplers with misalignments of $-0.2 \mu\text{m}$ and $0.1 \mu\text{m}$ are shown in Fig. 4.11(a) and (b). This measurement includes all losses from the measurement system including the fiber-to-chip coupling loss, the fiber-to-fiber connecting loss, waveguide propagation losses, and coupler losses. The incident laser power (T_0) is 0 dBm, the insertion loss of the reference waveguide are 14.4 dB and 11.1 dB

at the wavelength of 1460 nm and 1635 nm, respectively, which mainly results from the fiber-to-chip coupling loss (plus the systems losses) since the propagation loss of the reference Si_3N_4 waveguide is low (<0.2 dB for 1 cm length). The size of the mode in the Si_3N_4 waveguide causes the difference of the fiber-to-chip coupling efficiency. Better overlap resulting in lower fiber-to-chip coupling loss is obtained at larger wavelengths.

Insertion losses of the waveguides (α_N) are obtained by directly normalizing the measured transmitted power (in dBm) of the waveguides (T_N) to the one of the reference waveguide (T_r), i.e., subtraction of the insertion loss of the reference waveguide from the one of the waveguide with cascaded couplers, as shown in Eq. 4-2.

$$\alpha_N = (T_0 - T_N) - (T_0 - T_r) \quad \text{Eq. 4-2}$$

The α_N is the lumped losses of the N couplers in the waveguide. In Eq. 4-2, fiber-to-chip coupling loss and system loss are eliminated, providing a remaining loss that only includes the coupler loss and the propagation losses. The latter originates mainly from the Si_3N_4 and Al_2O_3 waveguides in the coupling region with a length of 800 μm and half of the Al_2O_3 waveguide (150 μm) bridge connecting two couplers, which can be estimated by the measured propagation losses of the waveguides (Fig. 4.10). The loss per coupler is therefore extracted as described in [43] by averaging over the number of cascaded couplers and excluding the propagation losses (α_p) corresponding to the coupler region,

$$\alpha_c = \frac{\alpha_N}{N} - \alpha_p \quad \text{Eq. 4-3}$$

Fig. 4.12(a) shows the extracted loss per coupler from the insertion losses of the best-aligned case, i.e., with the measured lateral misalignment of 0.1 μm . The loss per coupler gradually reduces from 0.24 dB to 0.18 dB with the increase of wavelength from 1460 nm to 1635 nm. It can also be seen in Fig. 4.12(b) that the loss per coupler at Δx of -0.2 μm which is about 0.1 dB higher than that at Δx of +0.1 μm in average. Moreover, even lower coupler loss than that of the best aligned case have been achieved under the resonant coupling at larger misalignments, which is specifically described in the third part of the chapter.

To evaluate the tolerance of the fabricated couplers to lateral misalignment as well as the broadband performance of the tolerance, the losses per coupler are measured as a function of lateral misalignment, as shown in Fig. 4.13(a) to (f). At the wavelength of 1030 nm, the coupler shows the lowest loss of 90

0.26±0.03 dB and less than 0.8 dB loss per coupler within a lateral misalignment of ±1 μm. For misalignments larger than 1 μm, the coupler loss rises rapidly. For the long wavelengths ranging from 1480 nm to 1635 nm, the loss values for large lateral misalignment (i.e., -1.7 μm) reduce for increasing wavelengths. This clearly shows that the tolerance to lateral misalignment becomes wider towards longer wavelengths, which agrees with the simulations (shown in subsection 4.2.2.3).

Fig. 4.12. (a) Loss per coupler after averaging over the number of different cascaded couplers at Δx of 0.1 μm and (b) of -0.2 μm, respectively. Measurement uncertainties are obtained from all independent measurements of both reference and coupler cascaded waveguides after error propagation.

Fig. 4.13. Results of measured loss per coupler as a function of lateral misalignment between Al_2O_3 and Si_3N_4 waveguides for the double-layer photonic platform at the wavelength of (a) 1030 nm, (b) 1480 nm, (c) 1510 nm, (d) 1550 nm, (e) 1590 nm and (f) 1635 nm.

4.2.5 Alternative integration scheme without SiO₂ buffer layer

4.2.5.1 Integration scheme

Directly depositing the Al₂O₃ layer onto the Si₃N₄ wafer is also a potential method for active-passive integration. Fig. 4.14 shows the schematics of this integration scheme. As compared to the double-layer platform, the integration by directly depositing Al₂O₃ layer does not require the thin SiO₂ film for the separation of the two layers, which avoids the time-consuming LPCVD SiO₂ and CMP processes. However, an Al₂O₃ ridged waveguide configuration has to be employed. Otherwise, the Si₃N₄ waveguide will be etched away in the full etching of Al₂O₃ layer, with the disadvantage that a thin Al₂O₃ residual film can be left over the Si₃N₄ waveguides [Fig. 4.14(d)], increasing the propagation losses when doped with rare-earth ions.

Fig. 4.14. 3D schematic of the Al₂O₃-Si₃N₄ integration by directly depositing Al₂O₃ layer onto the Si₃N₄ wafer. The cross-sections at (a) the Al₂O₃ waveguide core, (b) the tip of Si₃N₄ vertical taper, (c) the tip of Al₂O₃ lateral taper and (d) the Si₃N₄ waveguide core.

4.2.5.2 Chip design

A vertical Si₃N₄ taper is employed to couple the optical mode between the Al₂O₃ and Si₃N₄ waveguide cores. The Si₃N₄ wafer is from the same batch as in the previous monolithic integration work of Si₃N₄ and polymer (Part II in Chapter 3), where the Si₃N₄ thickness is tapered from 200 nm to ~40 nm with a taper

length of 700 μm . The width of the Si_3N_4 waveguide is also the same as in Chapter 3 i.e., 1.3 μm .

The total coupler loss is found to mainly originate from the total mode mismatch loss both at the vertical Si_3N_4 taper tip and at the facet of the Al_2O_3 ridged waveguide. In the calculation of the coupler losses, the same design flow as described in Section 4.2.2 is employed. The slab thickness (t_{slab}) of the ridged Al_2O_3 waveguide core is set to be the same as the etched depth of Si_3N_4 waveguide core (t_{etch}), which is chosen to be 250 nm. It has to be slightly larger than the thickness of the Si_3N_4 layer in order to fully etch the Si_3N_4 waveguides. The thickness of the deposited Al_2O_3 layer is set to 500 nm. The width of the Al_2O_3 waveguide is 2 μm . The influence of the etched depth of the Al_2O_3 waveguides is investigated by checking the total mode mismatch losses as a function of the etched depth of the ridged Al_2O_3 waveguide, as shown in Fig. 4.15(a). A range of Al_2O_3 slab thickness from 250 nm to 400 nm is investigated. The losses converge to ~ 0.2 dB when the slab thickness reduces to 250 nm for both considered wavelengths, 980 nm and 1550 nm. The main drawback is the propagation loss of the Si_3N_4 waveguide will significantly increase when this scheme is used for the integration of Si_3N_4 and rare-earth-ion doped Al_2O_3 .

4.2.5.3 Experimental results and discussion

To experimentally demonstrate the direct integration scheme, an Al_2O_3 layer with a thickness of 460 nm (in the wafer center) is grown on the 200 nm thick Si_3N_4 wafer. The Al_2O_3 waveguides are etched to a depth of ~ 140 nm resulting in a slab thickness of 320 nm to form a ridge waveguide. The Al_2O_3 waveguide are then cladded by a 2 μm thick PECVD SiO_2 . The measured misalignment of the Si_3N_4 - Al_2O_3 couplers ranges from -0.4 μm to $+2.6$ μm .

The measured losses of the couplers are shown in Fig. 4.15(b) as a function of the lateral misalignment at the wavelength of 1550 nm. For the best aligned case, Δx of -0.1 ± 0.15 μm , the measured coupler loss is 0.67 ± 0.13 dB. As the misalignment increases, the coupler loss slowly increases till a misalignment of ~ 1 μm . Further increase in the misalignment leads to a minimum coupler loss of 0.51 ± 0.19 dB at Δx of ~ 2.3 μm . Such decrease in coupler losses is attributed to resonant coupling between the Si_3N_4 and Al_2O_3 waveguides, the bigger misalignment reducing mode mismatch losses. Further increasing the misalignment, leads to a rapid increase of the coupler losses due to lower overlap

between the Si_3N_4 and Al_2O_3 waveguides in the coupler region, resulting in weak coupling strength.

Fig. 4.15. (a) Total mode mismatch loss at different slab thickness of Al_2O_3 slab layer. (b) Loss per converter for the Si_3N_4 - Al_2O_3 ridge waveguide configuration with the slab thickness t_{slab} of 380 nm. Since the propagation losses were not experimentally characterized, the measured data includes the Al_2O_3 propagation losses. The calculated values do not include propagation losses. The “actual” cross-section, including the effect of the Si_3N_4 topology, has not been included in these calculations. Both measurements and calculations are at the wavelength of 1550 nm.

Fig. 4.16. Schematics of the etched irregular waveguide cross-sections at different lateral misalignments: (a) to (c) at the facet of the ridged Al_2O_3 waveguide, and (d) to (f) at the tip of the vertical Si_3N_4 taper. The heaves of the deposited Al_2O_3 layer due to the underneath Si_3N_4 waveguides are also illustrated. The dashed profiles indicate the original Al_2O_3 layer before etching.

The trend of the measured loss versus misalignment agrees with the simulations. However, the measured values are much larger than the calculated ones. For the best aligned case, the difference mainly results from the increased mode mismatch loss. This is because the Al₂O₃ layer is shallowly etched with the remaining slab thickness of 320 nm, which is thicker than the designed value of 250 nm. Misalignments larger than 0.4 μm lead to irregular waveguide cross-sections, as shown in Fig. 4.16(a) to (f). These irregular waveguide cross-sections lead to the increase of the losses with respect to the simulated rectangular cross-sections. The Si₃N₄ waveguides underneath during the deposition of the Al₂O₃ layer cause heaves on the surface. Therefore, to achieve a good optical coupling as in the double-layer integration described in the previous section, the direct integration requires a properly controlled etched thickness of the Al₂O₃ waveguide as well as a better alignment to achieve adiabatic coupling at zero misalignment or resonant coupling at a small range of misalignments.

4.2.6 Conclusion of Part I

In this part, the monolithic integration of Al₂O₃ and Si₃N₄ towards a double-layer photonic platform is described in detail. Optical couplers in this platform, which remain the key component of the integration, are investigated. In the proposed couplers, the width of the Al₂O₃ waveguide is laterally tapered while the thickness of the Si₃N₄ waveguide is tapered vertically. The influence of the different design parameters on the performance of the Al₂O₃-Si₃N₄ couplers is analyzed. The fabricated couplers exhibit low-loss, broadband behavior and tolerance to misalignments. The developed technology provides a promising way to monolithically combine the outstanding optical features of Si₃N₄ and the properties of rare-earth-ion doped Al₂O₃ for various active-passive photonic functionalities in a double-layer platform.

4.3 Part II: Active-passive integration

In this section, the active-passive integration is experimentally studied based on the developed double-layer platform technology in Part I using an Er^{3+} doped Al_2O_3 layer. The purpose is to verify the feasibility of active-passive integration and figure out the performance of the optical coupling between the $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ and Si_3N_4 waveguides, which is significant for the monolithically integrated $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ - Si_3N_4 amplifiers in Chapter 5.

4.3.1 Fabrication results

The fabrication of active-passive chips follows the process flow demonstrated in Fig. 4.16. The LPCVD Si_3N_4 wafer is fabricated from the same batch as in Part I, with the Si_3N_4 thickness being tapered from 199.6 nm to 30.8 nm and the thin SiO_2 buffer film being polished to 185 nm.

Fig. 4.17. The thickness profile of the $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ layer deposited on a dummy $8\text{ }\mu\text{m}$ thermally oxidized wafer for thickness monitoring of the $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ - Si_3N_4 wafer using the same settings as the sample wafer. The thickness was measured using an ellipsometer (Woollam 2000UI).

To co-sputter the $\text{Al}_2\text{O}_3:\text{Er}^{3+}$, the sputtering machine (with replaced Al target) is calibrated at a measured oxygen flow of 4.0 sccm. An RF-power of 14 W is applied to the erbium sputtering gun. To monitor the co-sputtering process, a silicon wafer with $8\text{ }\mu\text{m}$ of thermal oxide is used. The layer thickness after sputtering for 300 minutes is characterized by the ellipsometer and plotted in Fig. 4.17. The thickness in the wafer center is 815 nm, implying a sputtering rate of 2.71 nm/min. The same setting of the parameters is applied to deposit $\text{Al}_2\text{O}_3:\text{Er}^{3+}$

in the next run. The fabricated $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ layer on the Si_3N_4 wafer is then measured by prism coupling (Metricon Model 2010/M) to be 819 nm. The Al_2O_3 waveguides are then etched to a depth of 840 nm utilizing the same reactive ion etching process as in section 4.2.3.1.

To determine the lateral shifts, Δx , of the fabricated couplers, calibrated top-view gradient images are employed. In the active-passive integrated wafer, the misalignment due to mask overlap variation is found to be $0.4 \mu\text{m}$. For instance, Fig. 4.18(a) shows the matched teeth of a Vernier ruler, indicating a misalignment of $0.45 \pm 0.15 \mu\text{m}$ at the wafer scale. The lateral shift of the local chip can also be measured. For simplicity, “+” and “-” signs are used to indicate the shifting direction. As shown in Fig. 4.18(b) and (c), the “+” sign is used when the Si_3N_4 waveguide is shift upwards the Al_2O_3 waveguide, and vice versa. Lateral shift values of $+1.3 \pm 0.15 \mu\text{m}$ and $+1.6 \pm 0.15 \mu\text{m}$ are found from the couplers with the designed values, i.e., $+0.9 \mu\text{m}$ and $+1.2 \mu\text{m}$, respectively. This indicates a misalignment of $0.4 \mu\text{m}$ caused by the mask overlay can be extracted, which agrees with the results from the Vernier ruler.

Fig. 4.18. Zoom-in optical gradient images for lateral shift measurement. (a) Vernier ruler with a teeth resolution of $0.15 \mu\text{m}$. The image at the Al_2O_3 taper tip with a measured shift of (b) $+1.3 \pm 0.15 \mu\text{m}$ and (c) $+1.6 \pm 0.15 \mu\text{m}$.

4.3.2 Characterization results

Fig. 4.19(a) illustrates a Si_3N_4 waveguide with cascaded $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ - Si_3N_4 couplers with a lateral shift of $1.3 \mu\text{m}$, where the 976 nm pump light and red light are launched together. The green light generated due to the energy transfer up-conversion of Er^{3+} clearly demonstrates the resonant coupling effect. The loss per coupler at 1306 nm (i.e., outside the absorption band of erbium) is measured for different misalignments, Fig. 4.19(b). The propagation loss of the Si_3N_4 waveguides (0.12 dB at 1550 nm) is reversely characterized using the ring

resonators, and the propagation loss of the $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ waveguide (0.4 dB/cm) is measured using the non-deductive method at the wavelength of 1306 nm. Both propagation losses are excluded in the loss per coupler. The lowest loss is found to be 0.23 ± 0.06 dB, obtained at the lateral shift of -0.8 ± 0.15 μm , for which resonant coupling occurs. The coupler loss significantly raises when the misalignment increases to 1.9 μm due to the weaker coupling strength at this lower wavelength.

Fig. 4.19. (a) Waveguide with cascaded $\text{Al}_2\text{O}_3:\text{Er}^{3+}\text{-Si}_3\text{N}_4$ couplers with a lateral shift of 1.3 μm . Green light is produced by energy transfer up-conversion of Er^{3+} by launching a 976 nm pump laser into one side. Red light is coupled to the other side for alignment. Zoom-in of the coupler is also shown with only pump light. (b) Measured coupler loss of the fabricated $\text{Al}_2\text{O}_3:\text{Er}^{3+}\text{-Si}_3\text{N}_4$ couplers as a function of the measured misalignments ranging from -1.1 μm to +1.9 μm at the wavelength of 1306 nm.

4.3.3 Conclusion of Part II

We firstly demonstrated the active-passive integration of $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ and Si_3N_4 based on the double-layer photonic platform. Fabricated $\text{Al}_2\text{O}_3:\text{Er}^{3+}\text{-Si}_3\text{N}_4$ couplers show as low as 0.23 ± 0.06 dB losses at a lateral misalignment of 0.8 ± 0.15 μm at 1306 nm wavelength and a large tolerant range for the lateral misalignment, proving the feasibility realization of active functionalities in the Si_3N_4 platform using rare-earth ion doped Al_2O_3 .

4.4 Part III: Investigation of resonant coupling effect

From Part I and Part II, we have found that the mode mismatch loss at the taper tips is the higher contributor to the total loss in the adiabatic couplers proposed in this work. To overcome it, several approaches can be followed, including the fabrication of tiny (i.e., tens of nanometers) taper tips, the use of vertical tapers

at both ends of the coupler and the design of resonant couplers [33, 34]. The use of resonant couplers avoids the need for high precision lithography tools such as a stepper lithography or electron-beam lithography to produce the vertical tapers in the Al_2O_3 waveguides.

This part firstly explains the principle of resonant coupling based on coupled mode theory [49]. The simulation follows the same method used in Part I. Here, the separation between the Al_2O_3 and Si_3N_4 waveguides is named as lateral shift. The experimental results of the undoped Al_2O_3 - Si_3N_4 couplers with lateral shifts of 1–1.7 μm (from Part I) and the $\text{Al}_2\text{O}_3\text{:Er}^{3+}$ - Si_3N_4 couplers with lateral shifts of 1–1.9 μm (from Part II) are utilized to analyze the resonant coupling. Both simulated and experimental results demonstrate that resonant coupling can achieve low-loss performance by minimizing the influence of mode mismatch losses at the taper tips. Additionally, the broadband performance is still preserved in the resonant coupling in the taper section because there is always a region of the phase matching with sufficient length to couple the power from one waveguide taper to the other.

4.4.1 Resonant coupling effects

4.4.1.1 Basic principle

The optical modes in the Al_2O_3 and Si_3N_4 waveguides spatially overlap for a certain lateral shift value. This spatial overlap makes the mode propagating in one waveguide “sense” the dielectric permittivity of the other waveguide, which is regarded as a perturbation of the permittivity, $\Delta\epsilon$. The perturbation can be described by a coupling strength, κ (unit: m^{-1}), between the Al_2O_3 and Si_3N_4 waveguides. To calculate the coupling strength, an integral of the normalized mode fields at the cross-sections is performed using the perturbation of the permittivity [49],

$$\kappa(z) = \frac{\omega}{4} \iint E_1(x, y) \Delta\epsilon(x, y, z) E_2(x, y) dx dy \quad \text{Eq. 4-4}$$

where $E_1(x, y)$ and $E_2(x, y)$ represent the mode fields of the lateral Al_2O_3 taper and vertical Si_3N_4 taper.

The coupling strength reduces when the two waveguides separate away due to the decrease of the perturbation of the permittivity. The coupling strength determines the ability of power transfer between the two coupled waveguides. The amount of optical power transferred from one waveguide to the other

depends on the phase matching condition. Perfect phase matching condition enables to completely transfer the power between the coupled waveguides [33, 34, 49]. It normally requires synchronized modes with equal propagation constants. The application is mostly seen in identical directional couplers, in which the two waveguides are designed to be identical. This means the effective refractive indices for the individual waveguides have to be identical. However, fabrication of synchronous waveguides has practical difficulties, especially for waveguides made of different materials. Therefore, the maximum of the achievable coupling efficiency from waveguide I to waveguide II has to be taken into account, which includes not only the coupling strength but also the difference of the propagation constants ($\Delta(z)$) at coupling length z :

$$\Delta(z) = \frac{\beta_1 - \beta_2}{2} \quad \text{Eq. 4-5}$$

where β_1 and β_2 are the propagation constants of the Al_2O_3 and Si_3N_4 waveguides respectively. The maximum power transferred can be expressed as

$$\frac{P_{I \rightarrow II}}{P_I} = \frac{1}{1 + (\Delta/\kappa(z))^2} \sin^2 \gamma z \quad \text{Eq. 4-6}$$

where the parameter $\gamma(z)$ is defined as $\gamma(z) = \sqrt{\kappa(z)^2 + \Delta(z)^2}$. Eq. 4-6 enables us to quickly calculate the coupling length that leads to full power transfer, i.e. $L_{100\%} = \frac{\pi}{2\gamma_{100\%}}$. The amplitude of Eq. 4-6, i.e., $1/[1 + (\Delta/\kappa)^2]$, shows that the same propagation constants (i.e., phase matching) are required in order to realize complete power transfer within the length $L_{100\%}$ under phase matching.

4.4.1.2 Simulation results

To overcome the practical difficulties of fabricating synchronized waveguides, both Al_2O_3 and Si_3N_4 waveguides are specifically tapered to obtain phase matching at different wavelengths within the taper region, therefore leading to broad bandwidth and tolerance to length variations. Fig. 4.20 shows the effective refractive indices of both the Al_2O_3 (blue) and Si_3N_4 (black) waveguides as a function of their widths for three wavelengths along the operating range. Phase matching can be observed at all three wavelengths at different taper locations. The coupling strength can be tuned by the lateral shift. The sufficiently small taper angle is required to maintain the coupling strength for the full wavelength range for a given lateral shift.

Fig. 4.20. Effective refractive indices of the lateral Al_2O_3 and vertical Si_3N_4 tapers at the wavelengths of 1460 nm, 1550 nm and 1630 nm.

Fig. 4.21. (a) Top-view and (b) side-view intensity fields of the couplers at a lateral shift of 1.4 μm at a wavelength of 1550 nm.

Fig. 4.21(a) and (b) show the top-view and side-view intensity fields of the resonant coupler at a lateral shift of 1.4 μm . Strong coupling occurs within the taper length of 300–350 μm , which corresponds to the phase matching point (Fig. 4.20) at the Si_3N_4 taper thickness of 135 nm (i.e., taper length of 306 nm). The

coupler with a lateral shift of $1.8 \mu\text{m}$ requires longer coupling length, as expected, due to a smaller coupling parameter $\kappa(z)$. This can be seen in Fig. 4.4(c) and (d) by the presence of power still resonating between the waveguides.

The reduction of mode mismatch losses at the taper tips due to the lateral shift can be seen in Fig. 4.22(a). Physically, a larger shift reduces the influence of the taper tip on the confined mode in the other waveguide, reducing the induced losses. However, larger shifts weaken the coupling strength, increasing the length required to fully transfer the power from one waveguide to the other. Additionally, for all considered lateral shifts, the mode mismatch loss increases with wavelength, due to a larger mode size.

Fig. 4.22. (a) Total mode mismatch losses at the taper tips for lateral shifts of 1.4, 1.6 and $1.8 \mu\text{m}$. Coupler losses as a function of the taper length and wavelength for different lateral misalignments of (a) $1.4 \mu\text{m}$, (b) $1.6 \mu\text{m}$ and (c) $1.8 \mu\text{m}$. The color bar indicates the value of coupler loss in dB. The Al_2O_3 thickness is 720 nm and the thin SiO_2 buffer layer is 180 nm .

The total coupler loss combines the coupling loss in the taper region and the mode mismatch losses at the taper tips. Taper lengths from $20 \mu\text{m}$ to $800 \mu\text{m}$ and a spectral window of $1460\text{--}1640 \text{ nm}$ are considered in the EME simulation. Fig.

4.22(b) to (d) show the total coupler loss as a function of coupler length and operating wavelength for lateral shifts of 1.4 μm , 1.6 μm and 1.8 μm . As the lateral shift increases, the coupler shifts from adiabatic [50] to resonant. For a 1.4 μm lateral shift, the coupler loss remains less than 0.12 dB for the whole spectral window of interest for taper lengths larger than 200 μm . When the lateral shift rises to 1.8 μm , the coupling strength between the Al_2O_3 and Si_3N_4 tapers weakens, requiring longer coupling length [Fig. 4.22(b) and (c)]. Furthermore, the wavelength range for which such low losses can be achieved is also reduced.

4.4.2 Experimental results and discussions

The experimental setup and loss extraction method have been described in the loss measurement of Part I (4.2.4.2). In this subsection, the average loss per coupler at the lateral shifts ranging from 1–1.7 μm is shown in Fig. 4.23(a) and (b) after subtraction of the propagation losses of the materials. For lateral shifts of 1 μm and -1.1 μm , the couplers are still working in the adiabatic regime. The higher total coupler losses are due to the larger mode mismatch loss at the taper tips, as discussed above. At the lateral shift of +1.3 μm and -1.4 μm , the couplers are operating in the resonant regime. The loss per coupler in the studied spectral window is below 0.2 dB, mostly centered around 0.15 dB. For a lateral shift of -1.7 μm , the coupler loss increases notoriously at shorter wavelengths.

Fig. 4.23. (a) Measured coupler loss of the fabricated undoped Al_2O_3 - Si_3N_4 couplers for lateral shifts of -1.7 μm , -1.4 μm , -1.1 μm , 1 μm and 1.3 μm for the wavelength range of 1460-1635 nm. (b) Measured coupler loss of the fabricated Al_2O_3 : Er^{3+} - Si_3N_4 couplers at the measured lateral shifts of +1 μm , +1.3 μm , +1.6 μm and 1.9 μm at the wavelength of 1306 nm.

Furthermore, the losses of the Al_2O_3 : Er^{3+} - Si_3N_4 couplers for lateral shifts of +1 μm , +1.3 μm , +1.6 μm and 1.9 μm are plotted in Fig. 4.23(b). In the resonant

coupling region, the lowest loss of 0.35 ± 0.03 dB is obtained at the lateral shift of $1.3 \mu\text{m}$, also excluding the propagation losses of the materials. It is important to note that the coupler losses measured for the $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ at 1306 nm are slightly higher than the ones for the passive waveguides characterized in the C-band. This could be because that the coupler length (i.e., $800 \mu\text{m}$) is not the most optimal value for the $\text{Al}_2\text{O}_3:\text{Er}^{3+}\text{-Si}_3\text{N}_4$ couplers. It is expected that a similar value as the one obtained for the passive couplers [Fig. 4.23(a)] should be achieved in the active ones for the C-band wavelengths by properly choosing the taper lengths.

4.4.3 Conclusion of Part III

Part III presents resonant couplers in the monolithic integration of Al_2O_3 and Si_3N_4 by laterally shifting the lateral Al_2O_3 and vertical Si_3N_4 waveguide tapers, which further explains the resonant coupling effects found in Part I and Part II. With this coupling scheme, even lower losses can be experimentally achieved (<0.2 dB) in the spectral window of 1460–1635 nm for the undoped $\text{Al}_2\text{O}_3\text{-Si}_3\text{N}_4$ couplers for a lateral shift of $1.4 \pm 0.15 \mu\text{m}$. Furthermore, 0.35 ± 0.03 dB loss is obtained for the resonant $\text{Al}_2\text{O}_3:\text{Er}^{3+}\text{-Si}_3\text{N}_4$ couplers at the lateral shift of $1.3 \pm 0.15 \mu\text{m}$ at 1306 nm wavelength. These results demonstrate that resonant coupling can achieve low-loss performance by minimizing the influence of mode mismatch losses at the taper tips while avoiding high-resolution lithography.

4.5 Conclusion

This chapter introduces our work on the development of the double-layer photonic platform enabling to combine the outstanding optical features of Si_3N_4 and the properties of rare-earth-ion doped Al_2O_3 for various active-passive photonic functionalities by monolithic integration. The fabrication processes of the double-layer platform were developed. High-performance optical coupling between the Al_2O_3 and Si_3N_4 waveguides was achieved based on the double-layer platform using both adiabatic and resonant coupling schemes, leading to low-loss and broadband response, highly tolerant to misalignment errors. Furthermore, the first active-passive integration based on the double-layer platform was successfully demonstrated using $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ and Si_3N_4 . The developed technologies provide a promising way towards the realization of active functionalities on the Si_3N_4 platform such as integrated $\text{Al}_2\text{O}_3:\text{Er}^{3+}\text{-Si}_3\text{N}_4$ amplifiers in Chapter 5.

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5 $\text{Al}_2\text{O}_3\text{:Er}^{3+}\text{-Si}_3\text{N}_4$ amplifiers based on the double-layer active-passive platform

5.1 Introduction

Integrated amplifiers and light sources are important components for integrated photonic circuits that combine various functionalities into a single chip [1]. In silicon photonics, semiconductor materials are widely used for the realization of amplifiers and lasers either by hybrid integration [2-4] or by direct growth onto silicon substrates [5-7]. Semiconductor materials have a carrier lifetime of a few hundred picoseconds [8], which may cause cross-talk between different wavelength channels during the high bit-rate amplification under saturation region. Furthermore, semiconductor gain materials suffer from large refractive index changes caused by carrier-induced index-gain coupling. Compared to III-V materials, rare-earth-ion doped materials have a much higher intrinsic lifetime (0.1–10 ms) [9]. The excitation of the doped ions induces less refractive index change ($\sim 10^{-6}$) [10-12]. These features lead to a more thermally and spatially stable gain, making them promising candidates for high-speed optical amplifiers (i.e., distortion free amplification has been demonstrated experimentally to 170 Gbit/s, limited by the measurement equipment) [13] and narrow linewidth lasers [14, 15]. High gain per unit length has been obtained for crystalline host materials, in which a high rare-earth ion concentration can be achieved. For instance, Yb^{3+} doped monoclinic potassium double tungstates [16] have provided ~ 935 dB/cm modal gain at 1 μm wavelength, which is comparable to the modal gain achieved in III-V materials. However, scalable fabrication of high contrast waveguides on monoclinic potassium double tungstates is challenging [17]. More compact structures with high gain per unit length are also investigated using high doping concentrations in other crystalline host materials. A net material gain of ~ 100 dB/cm for an Er^{3+} doped single-crystal chloride silicate nanowire 56.2 μm long [18] has been demonstrated. A net modal gain of 20 dB/cm was shown recently for a 250 μm long slotted- Si_3N_4 waveguide filled with $\text{Al}_2\text{O}_3\text{:Er}^{3+}$ grown by atomic-layer deposition (ALD) with organic ligand exchange scheme to obtain high doping [19]. Although high gain per unit length is achieved, the net gain in the previous demonstrations is very low (< 1 dB), for a narrow bandwidth. Furthermore, the fabrication processes is time-consuming

[19] and not scalable to mass production [18]. It is challenging for those devices to achieve higher net gains by increasing the length due to quenching processes (i.e., energy-transfer up-conversion (ETU)), and to insufficient inversion because of the high pump absorption for such high rare-earth ion concentrations.

Erbium ion doped amorphous Al_2O_3 deposited by RF co-sputtering on thermally oxidized silicon wafers shows promising features including broadband gain (~ 80 nm), high net gain (~ 20 dB) and highly tolerant, scalable and fast fabrication process [20-22]. Several concepts have been proposed in the literature aiming at the integration of erbium ion doped dielectrics onto the SOI platform. In a theoretical paper, Er^{3+} doped SiO_2 was introduced into a SOI slot waveguide consisting of heavily doped silicon stripes to achieve current injection through the doped material [23]. Direct deposition of co-sputtered $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ onto the SOI platform has been experimentally demonstrated [24], unfortunately without net gain due to the high coupling loss and high propagation loss of the SOI waveguide.

Recently, tremendous progress has been made on applications using silicon nitride (Si_3N_4) photonics, such as beamforming [25] and programmable signal processing [26] in microwave photonics, optical combs [27] and supercontinuum generation [28] in non-linear photonics, interferometric sensors [29], fluorescence imaging [30] and Raman spectroscopy [31, 32] in bio-sensing, and lidar [33, 34] and gyroscopes [35] in autonomous drive technologies. These applications mainly benefit from the excellent optical properties of Si_3N_4 , namely a wide transparency window from the visible to the near-infrared wavelengths (~ 400 nm to 4 μm), and low propagation loss. The propagation loss can be as low as ~ 0.1 dB/cm for LPCVD Si_3N_4 at the C-band [36-38]. The Si_3N_4 platform and many design building blocks are commercially available from providers such as Lionix [39], Ligentec [40], IMECs BioPIX [41] and IMB-CNM [42] both via multiwafer project runs (MPWs) or dedicated production runs. However, the integration of light sources onto the Si_3N_4 platform remains challenging. At the telecommunication bands, efforts are mainly aimed to the integration of III-V optical amplifiers with external high-Q cavities on Si_3N_4 by butt-coupling [43, 44]. RE^{3+} doped Al_2O_3 has also been directly sputtered onto Si_3N_4 waveguides or sputtered into a SiO_2 trench on top of the Si_3N_4 [45-52] to form hybrid waveguides. Compared to the former butt-coupled laser, the latter shows better performance, achieving relatively narrow lasing linewidth with higher temperature stability and lower noise. Moreover, the RE^{3+} doped Al_2O_3

can cover broadband wavelengths ranges from the near- to middle-infrared by doping with different rare-earth-ions such as Nd^{3+} , Yb^{3+} , Er^{3+} , Tm^{3+} and Ho^{3+} during the deposition process [11, 45, 46, 51, 53].

The monolithic integration of RE^{3+} doped Al_2O_3 and Si_3N_4 enables the combination of the advantageous properties of both materials for scalable fabrication. In the previous chapter, the active-passive integration between the $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ and the Si_3N_4 has been investigated based on the double-layer platform. Compared to the active-passive integrations in the works of [45-52], the optical modes based on the double-layer platform are guided independently in the Si_3N_4 and $\text{Al}_2\text{O}_3:\text{RE}^{3+}$ waveguides located in two individual photonic layers that only interact and couple in the adiabatic tapered region. This allows our platform to integrate various RE^{3+} doped materials and realize different active functionalities on the Si_3N_4 platform.

Here, we present high net gain optical amplifiers by monolithic integration of $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ onto the Si_3N_4 platform based on our double-layer platform. Two batches of $\text{Al}_2\text{O}_3:\text{Er}^{3+}\text{-Si}_3\text{N}_4$ amplifiers have been fabricated using our in-house process in MESA+ Nanolab. The first batch has a Er^{3+} concentration of $(1.2\text{--}1.5)\times 10^{20}\text{ cm}^{-3}$ (type Amp-I) while the second batch has a higher Er^{3+} concentration of $(1.8\text{--}2.3)\times 10^{20}\text{ cm}^{-3}$ (type Amp-II). In previous reported work [18-22], the optical net gain of the waveguide amplifiers was calculated from the signal enhancement (SE) measurement (i.e., ratio of the output signal power with pump-on and the output signal power with pump-off) by subtracting the measured (or calculated in some reports) absorption losses and background propagation losses. For simplicity, we denoted this net gain as g_{SE} . In this method, additional optical losses of the waveguide amplifiers induced by waveguide defects are not considered since the output signal power in the pump-on and pump-off cases are both affected. Furthermore, the precision of the measurement of absorption and propagation losses affects the extracted optical gain significantly, which is especially critical at high doping concentrations [18, 19]. Therefore, a different gain characterization method is studied here that uses a passive reference Si_3N_4 waveguide on the Amp-I type chips under the assumption that these have the same fiber-to-chip coupling loss as the amplifier device. A global gain (g_{global}) is demonstrated by comparing the amplified signal in the pump-on case to the output of the reference waveguide (undoped). The global gain takes into account all losses occurring on the amplifier chip. The

analysis of the same amplifier using both methods leads us to an improved signal-enhanced method.

We demonstrated a net gain up to 9 ± 0.28 dB for the g_{global} and 10.2 ± 0.8 dB for the g_{SE} for an integrated amplifier (Amp-I type) with a 7.2 cm long $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ spiral where both reported gains include the coupling losses between the $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ and Si_3N_4 waveguides. For the higher ion concentration samples, i.e., Amp-II type, a net gain, g_{SE} , as high as 18.1 ± 1 dB is obtained for an integrated amplifier with a 10 cm long gain section, which corresponds to 19.1 dB net gain of the integrated $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ spiral (i.e., eliminating the losses of the input and output vertical taper couplers). A broad bandwidth of net gain of more than 70 nm, is achieved.

5.2 Simulation

5.2.1 Waveguide design

The integrated $\text{Al}_2\text{O}_3:\text{Er}^{3+}\text{-Si}_3\text{N}_4$ amplifier is developed based on our double-layer active-passive photonic platform (Chapter 4) where the Al_2O_3 and Si_3N_4 waveguides support confined modes independently except in the coupling region. The waveguide design for the amplifier thus focuses on the Al_2O_3 waveguides.

Fig. 5.1. Ridge Al_2O_3 waveguide cross section for the single-mode condition checking and bending loss calculation.

5.2.1.1 Mode calculations

Single-mode (SM) operation is important in our application. Transverse electric (TE) polarization is employed in the integrated amplifier design since the double-layer platform is designed to work under TE polarization. The fundamental TE modes at both the pump wavelength (980 nm) and the signal wavelength

(1550 nm) are considered. Compared to the higher order modes, the fundamental modes have a better mode overlap and lower losses due to the higher confinement inside the waveguide core. Mode calculations are performed using Phoenix Optodesigner (Synopsys). To study the SM condition, a ridge waveguide cross-section is used, as shown in Fig. 5.1. The calculation aims to investigate the maximum values of the Al_2O_3 width ($W_{\text{Al}_2\text{O}_3}$) allowed to only guide fundamental TE mode, for different deposited thickness (t_g) and etched thickness ($t_{\text{Al}_2\text{O}_3}$). A deposited thickness of 0.6–1.2 μm is considered. The etched thickness ranges from 0.2 μm to the value that is available to fully etch the Al_2O_3 waveguide.

Fig. 5.2. Maximum width of the Al_2O_3 waveguide under single-mode condition as a function of the etched thickness at the wavelengths of (a) 980 nm and (b) 1550 nm. The legends represent the thickness of deposited Al_2O_3 (t_{grow}) varying from 0.6 μm to 1.2 μm .

The maximum width values are shown in Fig. 5.2(a) and (b) for the wavelengths of 980 nm and 1550 nm, respectively. At each deposited thickness, possible ranges of the width and etched thickness within the SM condition can be readily achieved for the wavelength of 1550 nm. To fulfil the SM condition at the pump wavelength the ridge needs to be shallowly etched, which is not compatible with the double layer platform. However, given the adiabaticity of the couplers described in Chapter 4, the pump fundamental mode travelling in the Si_3N_4 waveguide should evolve into the fundamental mode of the Al_2O_3 waveguide. A tightly confined field with high optical intensity and good overlap between the pump and signal modes can be achieved in the Al_2O_3 waveguide core. This is not only beneficial to reduce the pump threshold for a given net gain but also makes a more compact device achievable due to its strong lateral confinement of the

propagating mode. In the previous chapter, the phase matching condition between the TE₀ mode and higher order mode at the wavelength of 980 nm is not satisfied, meaning that the TE₀ mode of the pump can be maintained according to the coupled mode theory [54]. Therefore, the Al_2O_3 waveguide width has to be less than 1.4 μm for all considered deposited thicknesses from 0.6 μm to 1.2 μm in the design.

5.2.1.2 Bend design

For bent Al_2O_3 waveguides, the effective refractive index $n_{eff} = n_{eff}^0 + in_i$ is calculated, where the imaginary part n_i is employed to estimate the bend loss α_{bend} (dB/cm) using the equations of Eq. 2-3 and Eq. 2-4.

Fig. 5.3. Bend loss for the fully etched Al_2O_3 waveguides for different deposited thicknesses (i.e., 0.6 μm , 0.8 μm and 1 μm) and different waveguide width (i.e., 1 μm , 1.2 μm and 1.4 μm).

Under the SM condition, a width range of 1–1.4 μm is considered in the calculation at a wavelength of 1550 nm. Fig. 5.3 shows the losses for the different deposited thicknesses and waveguide widths as a function of the bend radius. For each width, a suitable range of bend radii for a bend loss below 0.02 dB is demonstrated, which is within the measurement error of the Si_3N_4 propagation loss. Larger width and thickness significantly reduce the bend radius required due to the higher mode confinement in the waveguide core. At a deposited thickness of 0.6 μm , the bend radius is sensitive to the width variation. A waveguide width of 1.4 μm was chosen for the design. The minimum bend radius was set to 250 μm . The chosen width and bend radius are suitable for a

deposited thickness ranging from 0.6 μm to 1 μm with a bend loss below 0.02 dB.

5.2.1.3 Confinement factor and overlap

The confinement factor indicates how much of the mode power is confined inside the Al_2O_3 waveguide core, which determines how strong the interaction of the pump and signal modes with the rare-earth-ions in the Al_2O_3 waveguide core can be.

Fig. 5.4. Intensity profiles of the mode fields at the wavelength of (a) 980 nm and (b) 1550 nm for Al_2O_3 waveguide dimension: $1.4\text{ }\mu\text{m} \times 0.8\text{ }\mu\text{m}$. (c) Mode confinement factor within the Al_2O_3 waveguide core for both wavelengths. (d) The spatial overlap between the mode fields of the two wavelengths. The Al_2O_3 waveguide width is 1.4 μm in (c) and (d).

With the selected width (1.4 μm) and minimum bend radius (250 μm), the mode field profiles for the Al_2O_3 waveguides with different thickness were calculated. For instance, the intensity profiles of the modes at 980 nm and 1550 nm are shown in Fig. 5.4(a) and (b), respectively. It can be seen that the mode of the pump is more confined inside the waveguide core than that of the signal. To calculate the confinement factor, the power within the core area (i.e., gray

region) is integrated and divided by the integrated power in the full calculation window with the dimension of $6\text{ }\mu\text{m} \times 6\text{ }\mu\text{m}$. Fig. 5.4(c) shows the confinement factors (Γ) as a function of the waveguide thickness. When the waveguide thickness increases from $0.8\text{ }\mu\text{m}$ to $1.2\text{ }\mu\text{m}$, the confinement rises from 77% to 93% for the pump and from 45% to 82% for the signal. The spatial overlap between the pump and signal modes were also calculated and are shown in Fig. 5.4(d). More than 80% overlap can be realized for the considered thickness.

5.2.2 Gain simulation

5.2.2.1 Energy transitions in $\text{Al}_2\text{O}_3:\text{Er}^{3+}$

Since the work focuses on demonstrating amplifiers by active-passive integration of the $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ and Si_3N_4 waveguides based on the developed double-layer platform, the basic principle of the energy level transitions in Er^{3+} is introduced below.

The Er^{3+} ion is formed when the erbium atom loses the electrons in the $6s^2$ electronic shell and one electron of the $4f$ electronic shell. Energy transitions within the partially filled $4f$ shell become available and these are well-defined since the $4f$ shell is shielded from the environment by the electronic clouds of the $5s$ and $5p$ orbitals. The energy levels of the $4f$ electronic shell are described with the Russell-Saunders notation, $^{2S+1}L_J$, with respective spin-orbit coupling splitting, where L represents the total orbital angular momentum that is the sum of orbital angular momentum of the individual electrons, S is the total spin angular momentum summed from the spin angular momentum of each electron and J is the total angular momentum combining the L and S .

Fig. 5.5 shows the simplified diagram of the energy levels of Er^{3+} in Al_2O_3 for operation at $\sim 1.5\text{ }\mu\text{m}$ wavelength. The energy level and emission wavelengths are from [55, 56], and intrinsic lifetime data is from [57]. Pumping at the wavelength of 980 nm or 1480 nm enables ground state absorption (GSA) and excites the ion from ground state ($^4\text{I}_{15/2}$) to the $^4\text{I}_{11/2}$ or $^4\text{I}_{13/2}$ level. At 980 nm, the excited ions in the $^4\text{I}_{11/2}$ level can be further excited to the $^4\text{F}_{7/2}$ level by excited state absorption (ESA), resulting in additional attenuation of the pump power. Non-radiative decay occurs for these ions through phonon-assisted transitions. This contributes to the quenching process of the ions. Relaxing excited ions from higher-lying levels to lower ones also generates spontaneous emission of photons at other wavelengths. For example, the green light that can be seen in Er^{3+} doped

devices is mainly due to spontaneous emission of ions from the $^2H_{11/2}$ and $^4S_{11/2}$ levels to the ground state.

Fig. 5.5. Schematic of the energy level diagram of $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ [55] with updated energy data from the work of [56], and intrinsic lifetime data from [57].

The excited ions at the $^4I_{13/2}$ level with long lifetime ($\sim 7.55 \text{ ms}$) produce a population inversion with respect to the ground state. This enables stimulated emission of the ions from the $^4I_{13/2}$ level to the ground state so that the input signal can be amplified. The amplified spontaneous emission (ASE) from the $^4I_{13/2}$ level to the ground state can introduce noise to the amplified signal.

The energy-transfer up-conversion (ETU) process of the excited ions significantly affects the population at the excited levels. In the ETU, two excited ions transfer energy between them to promote one ion to a higher energy level while returning the other to the ground state. The ETU effect coefficient of Er^{3+} at the $^4I_{13/2}$ level is found to be proportional to the ion concentration [57]. The ETU process can also occur to the ions in the level $^4I_{11/2}$, but it is weaker due to the short lifetime and fast decay of the ions at this level to the $^4I_{13/2}$ level. ETU leads to the depopulation of the excited states and contributes to the quenching of the Er^{3+} ions. Moreover, a cross-relaxation (CR) process can occur for the ions in $^4I_{9/2}$. The excited ion promotes an ion at the ground state to be excited to the

level $^4I_{13/2}$ while relaxing itself to the level energy level $^4I_{13/2}$. This is the reverse of the ETU process but is neglected due to the short lifetime at the level $^4I_{9/2}$.

5.2.2.2 Three-level rate-equation model

To calculate the optical gain of the integrated amplifiers, a rate-equation model incorporating the quenching effects of the Er^{3+} ions [21] is utilized in this work. The rate-equation model is based on a simplified three-level system including the $^4I_{15/2}$, $^4I_{13/2}$ and $^4I_{11/2}$ levels for the 980 nm wavelength pump. Besides the non-radiative decay and the ETU, active ion-pairs or clusters, undesired impurities and other host material imperfections could lead to quenching effects [21, 57]. The quenching effect is taken into account in this model by introducing f_a and f_q , which represent the fractions of active and quenched ions, respectively. The ESA and waveguide propagation loss contribute to the attenuation of the pump power. The population densities of each level are expressed in the following equations:

$$\frac{dN_{2,a/q}}{dt} = R_p + W_{ETU}N_{1,a/q}^2 - \frac{1}{\tau_2} N_{2,a/q} \quad \text{Eq. 5-1}$$

$$\frac{dN_{1,a/q}}{dt} = -R_s - \frac{1}{\tau_1} N_{1,a/q} - 2W_{ETU}N_{1,a/q}^2 + \frac{1}{\tau_2} N_{2,a/q} \quad \text{Eq. 5-2}$$

$$f_{a/q}N_d = N_{0,a/q} + N_{1,a/q} + N_{2,a/q} \quad \text{Eq. 5-3}$$

$N_{i,a/q}$ is the population density of the energy level i ($0-^4I_{15/2}$, $1-^4I_{13/2}$ or $2-^4I_{11/2}$). The subscript a/q denotes active or quenched ions. The ETU coefficient is denoted as W_{ETU} in unit of cm^3/s . τ_1 and τ_2 are the lifetimes of the level 1 and 2. Their reciprocals indicate the rates of the ions de-exciting to the ground state and the level 1. The pump and signal rates are represented as R_p and R_s ($cm^{-3}s^{-1}$). They are calculated using the following equations:

$$R_p = \frac{\lambda_p}{hc} I_p (\sigma_{a,p} N_{0,a/q} - \sigma_{e,p} N_{2,a/q}) \quad \text{Eq. 5-4}$$

$$R_s = \frac{\lambda_p}{hc} I_p (\sigma_{e,s} N_{1,a/q} - \sigma_{a,s} N_{0,a/q}) \quad \text{Eq. 5-5}$$

Here, the $\sigma_{a,p/s}$ and $\sigma_{e,p/s}$ are the effective cross-sections for absorption and emission at the pump and signal wavelengths in unit of cm^2 . $I_{p/s}$ is the intensity of the pump or of the signal, which is determined by the field intensity distribution inside the waveguide core. This can be calculated by the product of

the pump/signal power $P_{p/s}$ and the corresponding normalized field distribution $\psi_{p/s}$.

At the steady state, the left terms in Eq. 5-1 and Eq. 5-2 are 0. Combining the equations of Eq. 5-1, Eq. 5-3 and Eq. 5-4, the population density $N_{2,a/q}$ can be expressed using the ion density N_a and $N_{1,a/q}$, which can be further used to replace the $N_{2,a/q}$ in Eq. 5-5 and Eq. 5-2, resulting in a quadratic equation for the $N_{1,a/q}$. Therefore, the rate-equation model can be built based on the iteration of solving the population densities until they become steady.

In the gain calculation for the amplifier with forward pumping, i.e., where the signal and pump are launched at the same side, the model is mainly based on the work of [56]. The length of the gain section is separated into multiple segments, in this case 20. In each segment, the pump and signal powers are updated by considering the absorption, emission, excited state absorption, and waveguide propagation loss along the propagation direction, as shown in equations Eq. 5-6 and Eq. 5-7 respectively and are used as input of the next segment. The iteration is carried out until the steady state of the population densities is reached.

$$\frac{dP_p}{dz} = P_p \iint (\sigma_{e,p} N_{2,a/q} - \sigma_{a,p} N_{0,a/q} - \sigma_{ESA,p} N_{2,a/q}) dx dy - \alpha_{0,p} \quad \text{Eq. 5-6}$$

$$\frac{dP_s}{dz} = P_s \iint (\sigma_{e,s} N_{2,a/s} - \sigma_{a,s} N_{0,a/s}) dx dy - \alpha_{0,s} \quad \text{Eq. 5-7}$$

The propagation loss of the waveguides is denoted as $\alpha_{0,p/s}$ for the pump and signal.

5.2.2.3 Influence of different parameters on the gain

The influences of parameters such as waveguide dimensions, ion concentration, propagation losses, launched pump power and launched signal power on the gain are investigated.

5. $\text{Al}_2\text{O}_3:\text{Er}^{3+}\text{-Si}_3\text{N}_4$ amplifiers based on the double-layer active-passive platform

Fig. 5.6. Net gain simulation results at the wavelength of 1532 nm as a function of the gain section length L_g (0–20 cm) for several thickness of the Al_2O_3 layer (a) 0.6 μm , (b) 0.8 μm , (c) 1.0 μm and (d) 1.2 μm . The launched pump power is set to 100 mW that reaches gain sturation. The legend represents the ion concentrations used, ranging from $0.5 \times 10^{20} \text{ cm}^{-3}$ to $2.5 \times 10^{20} \text{ cm}^{-3}$. Propagation losses of 0.5 dB/cm and 1 dB/cm are considered for the signal and pump respectively. (e) Maximum values of the gain as a function of the waveguide thickness extracted from (a-d). (f) Maximum values extracted at the propagation loss of 0.8 dB/cm for the signal and 1.6 dB/cm for the pump.

Fig. 5.6(a) to (d) shows the calculated gain values as a function of the length of the $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ spiral (L_g) for different thicknesses of the Al_2O_3 layer and various ion concentrations. In these simulations, the propagation losses are set to

1 dB/cm at 980 nm and 0.5 dB/cm at the wavelength of 1532 nm. A pump of 100 mW that reaches gain saturation and a signal of 1 μ W (small signal regime) are launched at the same side. For each thickness, the gain is sensitive to the variation of ion concentration. As shown in Fig. 5.6(e), the sensitivity converges when the ion concentration is above $1.5 \times 10^{20} \text{ cm}^{-3}$, showing less than 1 dB difference on the maximum gain values. The power confinement grows with the increasing thickness, while the field intensity distribution becomes less dense due to the increased mode size. For a thickness above 0.8 μm , the achievable maximum gain within $L_g = 20 \text{ cm}$ also converges, implying that an increased confinement factor does not increase the achievable gain. In addition, the maximum values for the case with propagation losses of 0.8 dB/cm for the signal and 1.6 dB/cm for the pump are presented in Fig. 5.6(f). The propagation losses are found to have a substantial effect on the maximum values due to the attenuation of the power and signal powers along the propagation direction. Optimized processes of the Al_2O_3 deposition with lower propagation losses are clearly required for these integrated amplifiers.

5.3 Fabrication results

Fabrication of the monolithically integrated amplifiers follows the process flow presented in Fig. 4.6 of Chapter 4, including the fabrication of Si_3N_4 waveguides, the CMP polishing of the thin SiO_2 spacer film, the fabrication of Al_2O_3 waveguides and the deposition of the PECVD SiO_2 cladding. The integrated amplifiers are separated into two types: Amp-I and Amp-II, according to two different ion-concentrations. The fabricated chips of the Amp-I and Amp-II types amplifiers are shown in Fig. 5.7(a) and (b).

Fig. 5.7. Fabricated amplifier chips for (a) the Amp-I type and (b) the Amp-II type.

5. $\text{Al}_2\text{O}_3:\text{Er}^{3+}\text{-Si}_3\text{N}_4$ amplifiers
based on the double-layer active-passive platform

The waveguide dimensions are listed in Table 5-I. For the Amp-II type amplifiers, the fabrication is carried out in the same batch as the chips for active-passive integration, which has been described in the Part II in Chapter 4. These amplifiers have 1×2 MMI-based multi/demultiplexers for combining and splitting the pump and signal. The $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ thickness of Amp-II is 785–810 nm. The following section focuses on the description of the fabrication processes for the Amp-I type amplifiers.

Table 5-I. Waveguide dimensions of the Amp-I and Amp-II type amplifiers.

TYPES	Amp-I		Amp-II	
SiO ₂ thin film thickness (nm)	60		185	
LAYERS	Si ₃ N ₄	Al ₂ O ₃	Si ₃ N ₄	Al ₂ O ₃
Width (μm)	1.4±0.08	1.4±0.1	1.4±0.08	1.4±0.12
Tapered Width (μm)	0.8	0.8±0.13	--	0.8±0.11
Tapered Length (μm)	222±8	800	800	800
Thickness (nm)	200.2±0.12	870–880	199.6±0.13	785–810
Tapered Thickness (nm)	<10	--	30.8	--
Min. Radius of Spiral (μm)		400		250

Fig. 5.8. For the Amp-I: (a) optical image of the thickness-tapered Si_3N_4 layer and (b) fabricated vertical Si_3N_4 taper profiles.

In the Amp-I, the vertical tapering process of Si_3N_4 layer is different from the one demonstrated in the Chapter 4. Here, a 78 nm thick PECVD SiO_2 (measured by the ellipsometer) is utilized as the sacrificial layer. After etching using buffered hydrofluoric (BHF) acid, the vertical Si_3N_4 taper profiles are scanned at different locations with the profiler (Veeco Dektak 8). For instance, Fig. 5.8(a) shows the tapered thickness of the Si_3N_4 layer around an etching window with a

dimension of $300\text{ }\mu\text{m} \times 380\text{ }\mu\text{m}$. Two scanned profiles of the Si_3N_4 tapers along the length direction are plotted in Fig. 5.8 (b). Good linearity can be seen, indicating a good stability of the BHF concentration and etching rates during the process. The thickness is tapered from 200 nm to less than 10 nm with a taper length of $222 \pm 4\text{ }\mu\text{m}$, i.e., with a taper angle of 0.05° .

Due to the shorter vertical Si_3N_4 taper of the Amp-I, the thin SiO_2 film is polished to $\sim 60\text{ nm}$ in the CMP process, which is thinner than that in the Amp-II (i.e., $\sim 185\text{ nm}$). This is because the thinner SiO_2 buffer layer benefits the tolerant range of the misalignment between Al_2O_3 and Si_3N_4 waveguides in the monolithic integration [Fig. 4.5]. In the $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ layer deposition, some parameters are also adjusted. First, the distance between the wafer and plasma gun is modified to 6 inches to improve the uniformity. The Oxygen flow is set to 3.6 sccm and the temperature of the chamber is $\sim 580^\circ\text{C}$. The deposition rate is characterized by the monitor wafer to be 5.4 nm/min. The thickness of the deposited $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ on the integrated amplifier dies are characterized by the prism coupling system (Metricon Model 2010/M). It varies from 880 nm in the wafer center to 850 nm on the side of the wafer, from which the thickness of $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ of the integrated amplifiers are extracted to be 870–880 nm. The positive photo-resist of OiR907-17 is spin-coated at 4000 rpm. The $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ waveguides are fully etched using the RIE process with a $\text{BCl}_3\text{-HBr}$ flow (Oxford PlasmaPro 100 Cobra). The wafer is finally cladded by a $\sim 4.5\text{ }\mu\text{m}$ thick PECVD SiO_2 and diced to individual chips in the dicing system (Loadpoint Micro Ace 3).

Fig. 5.9. In the Amp-I: Vernier ruler with a teeth resolution of $0.15\text{ }\mu\text{m}$ at (a) the left side and (b) the right side of the 4-inch wafer. The Al_2O_3 and Si_3N_4 structures are indicated with different gray colors.

The lateral misalignment between the Al_2O_3 and Si_3N_4 waveguides is determined by the alignment markers on both sides of the wafers. Mask overlay of $0.15\ \mu\text{m}$ and $-0.15\ \mu\text{m}$ are found on the left and right sides of the wafer respectively, as demonstrated in Fig. 5.9(a) and (b), implying a better mask alignment accuracy for the dies in the center areas of the wafer.

5.4 Measurement principle and setups

5.4.1 Gain measurement principles

In previous reports [18-22], the net gain (in dB unit) was extracted from the signal enhancement (SE) after subtracting the absorption and propagation loss of the gain waveguide. At the pump-off case, the output signal (P_1^S) is equal to the input signal (P_s^0) subtracting the fiber-to-chip coupling loss, the absorption loss ($\alpha_{a,s}$), the propagation loss (α_0) and the $\text{Al}_2\text{O}_3:\text{Er}^{3+}\text{-Si}_3\text{N}_4$ coupler loss (α_c). At the pump-on case, the net gain is equal to the ratio of the output signal (P_A^S) to the input signal (P_s^0). The SE is defined as the ratio of output signals from the integrated amplifier in pump-on and pump-off cases, as shown in Fig. 5.10(a). The net gain for integrated amplifiers can be calculated from the measured SE, and the input signal at the pump-off case is not required. The calculation is expressed as,

$$g_{SE} = 10 \log_{10} \frac{P_A^S}{P_1^S} - \alpha_{a,s} - \alpha_0 - 2\alpha_c \quad \text{Eq. 5-8}$$

, where the absorption loss, the propagation loss, and the $\text{Al}_2\text{O}_3:\text{Er}^{3+}\text{-Si}_3\text{N}_4$ coupler loss must be individually characterized. The quality of waveguide facets contributes equally to the signal powers in pump-on and pump-off cases. Hence, the SE measurement is not affected by the waveguide facets and it is insensitive to the variation of the fiber-to-chip coupling. If additional losses occur due to waveguide imperfections, the SE measurement will not be disturbed either. These features enable identification of the amplification capability of the integrated amplifiers in a way that is insensitive to waveguide defects. However, waveguide defects will lower the amplified power at the output of the amplifier, leading to a lesser net gain from the integrated amplifier. Furthermore, for amplifiers with high absorption loss or long propagation distances, the output signal power in pump-off case, P_1^S , can be very weak. This requires highly sensitive detectors and other technologies to enhance the signal-to-noise ratio (SNR). Moreover, the measurement error of each parameter propagates during

the extraction of the gain using Eq. 5-8, which could cause more uncertainties in the gain measurement.

Fig. 5.10. Schematics of the integrated $\text{Al}_2\text{O}_3:\text{Er}^{3+}\text{-Si}_3\text{N}_4$ amplifiers (a) without passive reference waveguide and (b) with passive reference waveguide.

Benefiting from the active-passive integration based on the developed $\text{Al}_2\text{O}_3\text{-Si}_3\text{N}_4$ photonic platform, a new method for gain measurement is proposed. It overcomes the challenges of the previous method based on SE measurements. Here, a passive reference Si_3N_4 waveguide is added to the amplifier chips. It has the same dimension as the Si_3N_4 waveguide integrated gain spirals, as shown in Fig. 5.10(b). Waveguide facets on the same chip after dicing are assumed to be identical, resulting in same fiber-to-chip coupling efficiencies between the reference waveguide and the integrated amplifier. The net gain can be directly characterized by comparing the amplified signal of the amplifier in the pump-on case (P_A^s) to the signal of the reference waveguide that is passive (P_r^s) using the following expression:

$$g_{\text{global}} = 10 \log_{10} \frac{P_A^s}{P_r^s} \quad \text{Eq. 5-9}$$

For simplicity, it is denoted as g_{global} to distinguish from the gain g_{SE} measured from the signal enhancement method.

Therefore, the integrated amplifier in our platform serves as a building block. When the signal light passes through the building block, the measured gain according to Eq. 5-9 directly indicates the performance of the integrated amplifier, i.e., how much the input signal can be amplified. The unabsorbed signal power from the reference waveguide and the amplified power are relatively large, making the detection of these signals easier, as compared to the gain with the SE measurements. All types of on-chip losses are taken into account by the gain, g_{global} . Individual characterizations of the absorption loss, the propagation loss and the coupler loss, and other losses from the waveguide defects in the building block are not required.

combined or split using polarization maintained (PM) wavelength division multiplexers (980/1550 WMD, WP9850F). This setup is also applied to the characterization of the Amp-II type amplifiers. The only difference is that the output signal and pump are collected by a fiber array (127 μm pitch), as demonstrated in Fig. 5.11(b). Because the Amp-II type amplifiers have on-chip 1×2 MMI-based multi/demultiplexers, in order to launch more pump at the input, the pump and signal are first combined by an external WDM and then launched into the pump port of the on-chip multiplexer. At the output, the pump and signal are first split by the on-chip demultiplexer. Then, they are collected by different channels of the fiber array. Eventually, the signal is connected to the OSA where the residual pump is further removed.

Amp-II type amplifiers are also characterized using a setup similar to the work in [56] with a lock-in amplifier (Stanford Research System, SR810PSP), as shown in Fig. 5.11(c). The signal of the tunable laser is internally modulated with a frequency of 283 Hz to discriminate it from the influence of the ASE at the signal wavelength. The output signal is measured by a spectrometer (HORIBA, iHR 550) with a cooled InGaAs detector (-20°C), where the voltage signal is amplified by the lock-in amplifier.

5.4.3 Approaches for measuring absorption and propagation losses

To characterize the absorption and propagation losses, two approaches based on the insertion loss measurement (employed in Chapter 2 to 4), and the non-deductive method [58] (employed in Chapter 4) are employed.

5.4.3.1 Insertion loss measurements

The first approach considers all kinds of losses originated from the integrated amplifiers. A spectral window of 1460–1638 nm is used for this approach. The insertion loss of the integrated amplifiers includes the absorption loss, propagation loss, $\text{Al}_2\text{O}_3\text{:Er}^{3+}\text{-Si}_3\text{N}_4$ coupler loss and the fiber-chip-coupling loss. The fiber-to-chip coupling loss can be eliminated after normalizing the insertion loss to the one of the passive Si_3N_4 waveguides as the reference waveguide. However, it requires that the fiber-to-chip coupling losses of the waveguides on the same chip are assumed to be equal. The facets of the Si_3N_4 waveguides with integrated amplifiers and the reference Si_3N_4 waveguides on each amplifier chip are diced at the same time. In our cases, the errors from the reference waveguides did not seem to present major problems.

This method separates the absorption spectra from the insertion loss by normalizing the values at wavelengths above 1630 nm, where the propagation loss dominates the integrated $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ waveguide due to the relatively weak absorption of Er^{3+} [20]. However, the wavelength-dependent variation of the fiber-to-chip coupling loss (<0.1 dB/cm) in this spectral window thus contributes to the extracted absorption spectra. For example, the calculated fiber-to-chip coupling loss for the Si_3N_4 waveguide dimension of $1.4 \mu\text{m} \times 0.2 \mu\text{m}$ at the wavelength of 1460 nm is 1.8 dB smaller than that at the wavelength of 1630 nm when using the small core fiber (UHNA3).

5.4.3.2 The non-deductive method

The second approach, i.e., the non-deductive method, focuses on the intensity profiles along the integrated $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ spiral. The scattering intensity is proportional to the mode power confined in the waveguide [58]. Thus, the scattering intensity as a function of distance along the light propagation direction is correlated to the Lambert-Beer law, which enables extraction of the propagation loss along the waveguide. The loss extracted using the non-deductive method is independent of the fiber-to-chip coupling efficiency between the amplifier and reference waveguides. However, scattering intensity reaching to the waveguide defects after long-distance propagation can be too weak to be detected reliably by the IR camera. Therefore high propagation losses within these areas with waveguide defects cannot be characterized well. Moreover, the performance of the $\text{Al}_2\text{O}_3:\text{Er}^{3+}\text{-Si}_3\text{N}_4$ couplers cannot be considered either. Therefore, the non-deductive method can only characterize the propagation plus absorption losses of the full device.

In this work, both approaches are employed and compared to each other to provide a reliable result. The absorption and propagation losses are presented in the experimental sections for the Amp-I (5.5.1) and Amp-II type amplifiers (5.6.1).

5.4.4 Estimation of ion concentration

The wavelength-dependent absorption cross-section of $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ (cm^2), σ_{abs} , can be deduced from the absorption losses using the following expression [20, 59]:

$$\sigma_{abs} = \frac{\alpha_{a,s}}{N_0 \cdot 10 \log_{10} e \cdot l} \quad \text{Eq. 5-10}$$

where the N_0 is the ion concentration and Γ is the confinement factor of the mode inside the waveguide core. The calculated confinement factors at the wavelength of 1532 nm, as shown in Fig. 5.4(c), are 68.4% and 73% for the integrated $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ spiral with the thickness of 0.8 μm and 0.9 μm , respectively. The absorption cross-sections of the $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ are presented in the work of [20], in which the values within the wavelengths of 1480–1580 nm are experimentally characterized and the remaining wavelength region has been filled using the McCumber theory [60]. With these parameters, the ion concentration can be estimated. In the previous subsection, the absorption and propagation losses, as characterized using both the insertion loss method and the non-deductive method, showed good agreement. For simplicity, the calculated absorption spectra are plotted from the measured spectra using the insertion loss method, as shown in dashed lines in Fig. 5.12(b) and Fig. 5.18(c). The ion concentration is $(1.2\text{--}1.5)\times 10^{20} \text{ cm}^{-3}$ for the Amp-I type amplifiers and $(1.8\text{--}2.3)\times 10^{20} \text{ cm}^{-3}$ for the Amp-II type amplifiers.

5.5 Results I: The Amp-I type integrated amplifiers

In the Amp-I type amplifiers, the $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ - Si_3N_4 couplers have a vertical Si_3N_4 taper length of $222\pm 4 \mu\text{m}$. The coupler loss refers to the couplers from the reference coupler chip with the same design parameters. The loss is measured to be $0.64\pm 0.2 \text{ dB}$ at 1306 nm including the propagation losses that lies outside the ground state absorption band of Er^{3+} ions. For simplicity, the integrated amplifiers fabricated in this batch are numbered according to the integrated spiral length, as listed in Table 5-II.

Table 5-II. The index of the Amp-I type amplifiers.

Diced Chip	C4		C6		C12			C13			C15	
Gain Length (cm)	18.2	9.1	13.4	3.9	7.2	11.1	3.7	7.2	11.1	9.1	13.4	
Amplifier Index, i-	1	2	3	4	5	6	7	8	9	10	11	

5.5.1 Absorption and propagation losses

5.5.1.1 Based on insertion loss measurements

The insertion loss of the integrated amplifier contains the absorption loss, the propagation losses, and the coupler loss. With the measured coupler loss, the absorption plus propagation losses can be extracted from the insertion losses. They are expressed in units of dB/cm by dividing the length of the integrated $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ spiral.

5. $\text{Al}_2\text{O}_3:\text{Er}^{3+}\text{-Si}_3\text{N}_4$ amplifiers based on the double-layer active-passive platform

Fig. 5.12(a) shows the measured absorption plus propagation losses in the spectral window of 1460–1638 nm under different incident powers ranging from 0 dBm to -30 dBm (output powers from the laser). Two integrated amplifiers with an active spiral length of 7.2 cm from the chips of C12 (i-5) and C13 (i-8) are taken as examples in Fig. 5.12(a). For both chips, their loss spectra converge for incident powers below -20 dBm. However, the converged spectra shift between the two chips, implying a variation of the propagation loss for the chips at different locations on the same wafer.

Fig. 5.12. (a) Absorption plus propagation loss (α_{ap}) of the integrated amplifier i-5 (from the chip C12) and i-8 (from the chip C13) with different incident powers in the spectral window of 1460–1638 nm. (b) Absorption losses (solid lines) extracted from the α_{ap} spectra after normalizing to the loss at a wavelength of 1638 nm. Dashed lines are the calculated values from the absorption cross-sections presented in the work of [20] at different ion concentrations.

To exclude the influence of the propagation loss, the absorption plus propagation spectra at -30 dBm incident power are normalized to the loss at 1638 nm where it is dominated by the propagation loss. The absorption spectra are plotted in the real lines in Fig. 5.12(b). M1 and M2 represent the use of small core fibers (UHNA3) and normal SM fibers in the characterization, respectively. The absorption losses show good overlap with each other and less than 0.15 dB/cm deviation. At 1532 nm (absorption peak), the loss varies from 2.4–2.6 dB/cm between the two amplifiers. There are several factors that could cause the change of absorption spectra such as the polarization, measurement uncertainties, and fabrication variations like the non-uniformity of layer thickness and ion density during the co-sputtering process. In addition, the absorption spectra enable estimation of the ion concentration. The calculated data from the absorption

cross-sections [20] is shown in the dashed lines for comparison. More details are described in the next subsection.

5.5.1.2 Based on the non-deductive method

The absorption and propagation losses are investigated using non-deductive method [21, 58]. For this study, an 18.2 cm long integrated $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ spiral from the amplifier chip C4 (i-1) is chosen. Its intensity profile at different incident powers is captured by the InGaAs camera (Xenics Bocat 320). The losses are extracted from the decay of the intensity along the propagation distance, as plotted in Fig. 5.13(a). Here, the index matching fluid (Diphenyl ether) is not applied to the fiber-to-chip coupling. The measured data converge when the incident laser power is below -17 dBm. The loss at 1532 nm is 2.75 ± 0.08 dB/cm. The loss reduces to 0.4 ± 0.12 dB/cm at 1630 nm. About 2.35 dB loss for the absorption peak can be estimated, which matches the value obtained from the insertion loss measurements.

Fig. 5.13. (a) The absorption plus propagation losses α_{ap} at multiple wavelengths in the spectral window of 1460–1638 nm for the integrated amplifier i-1. (b) The propagation losses α_0 characterized at the wavelength of 1306 nm for different integrated amplifiers. Both results are characterized using the non-deductive method [58].

Previously, the propagation loss at wavelengths longer than 1630 nm was considered as the propagation loss due to the low absorption at these wavelengths. To verify these results, the propagation losses are also characterized at 1306 nm using the non-deductive method. This wavelength is selected because of the absence of ground state absorption of the Er^{3+} ion. The losses are plotted in Fig. 5.13(b) for the fabricated devices. The propagation loss varies between the integrated amplifiers. A range from 0.2 dB/cm to 0.8 dB/cm

can be seen. The propagation losses of the amplifiers i-1, i-5 and i-8 are 0.31 ± 0.06 dB/cm, 0.78 ± 0.12 dB/cm and 0.23 ± 0.01 dB/cm. They are comparable to the results in Fig. 5.12(a) and Fig. 5.13(a) at the long wavelengths (>1630 nm), which are 0.4 ± 0.12 dB/cm for the i-1, 1.13 ± 0.13 dB/cm for the i-5, 0.43 ± 0.13 dB/cm for the i-8, showing good agreement of obtaining absorption and propagating losses between the insertion loss method and non-deductive method. Further reduction of these propagation losses can be carried out by improving the dry etching of the Al_2O_3 waveguides to reduce the side wall roughness, and better cleaning before and after etching to minimize the particle contamination on the waveguide spirals.

5.5.2 Transmission spectra and the amplifier losses

Fig. 5.14(a) to (c) shows the transmission spectra of the reference Si_3N_4 waveguide (T_r), the pump-off case (T_{off}) and pump-on case (T_{on}) for the amplifiers i-5, i-8 and i-10. Transmission values (plotted by dots) are extracted after eliminating the ASE from the spectra. The incident power at 1532 nm is -30 dBm. Insertion losses of the reference Si_3N_4 waveguide (T_r) can be obtained by subtracting the incident power from its transmission. The insertion loss is composed of the fiber-to-chip coupling loss, the fiber-to-fiber connecting loss, the insertion loss from the WDM, and fiber-to-OSA connecting loss. The fiber-to-chip coupling losses are characterized from the reference waveguides by connecting the output fiber directly to a detector. The measured values per facet are 8.5 ± 2 dB for the 976.2 nm pump and 5.5 ± 1 dB for the signal at 1532 nm for TE polarization, in which the deviation represents the variation among different amplifier chips. The integrated amplifier chips are measured at different periods. Before each period the fiber is reconnected to the OSA and the connection is kept fixed during the measurements. Therefore, the insertion loss from the fiber-to-OSA connection differs for different amplifiers and contributes as a constant value to the transmission spectra.

Fig. 5.14. Examples of the measured spectra from the OSA including the signal of the reference Si_3N_4 waveguide, and the signal of the integrated amplifier in pump-on and pump-off cases for the amplifier chips: (a) i-5 ($L_g = 7.2$ cm), (b) i-8 ($L_g = 7.2$ cm) and (c) i-10 ($L_g = 9.1$ cm). The incident power of the tunable laser is set to -30 dBm (1 μW) to satisfy the small signal regime. For the pump-on case, the incident power from the pump laser is tuned to ~ 750 mW at 976.2 nm. The OSA resolution is adjusted to 0.5 nm and the scanning wavelength range is 1531–1533 nm. (d) The insertion loss of the available amplifiers extracted from the OSA spectra that includes all kinds of losses on the chip. They are presented in dB/cm after dividing by the gain length.

The amplifier loss can be easily deduced by comparing the transmission data (in dBm) under the pump-off case to that of the reference waveguide, i.e., $\alpha_{off} = T_{ref} - T_{off}$. The absorption loss, the propagation loss, and the $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ - Si_3N_4 coupler loss, and other losses caused by the defects are all taken into account in the pump-off amplifier loss. This is extremely beneficial to practically examine how much influence the waveguide defects have. A quantitative evaluation of additional loss from the defects can be carried out by comparing to the previous absorption spectra normalized at the long wavelengths [Fig. 5.12(b)] and measured with the non-deductive method [Fig. 5.13(a)]. Fig. 5.14(d) plots the

amplifiers losses in dB/cm. In these plots, the coupler loss of 0.64 ± 0.2 dB and the propagation loss are excluded using previous measured data at 1306 nm [Fig. 5.13(b)]. Therefore, the remaining amplifier loss consists of the absorption loss and other losses from the defects, as shown in Fig. 5.15. Most amplifiers have a loss of 2.7 ± 0.15 dB/cm that matches the absorption losses obtained in Fig. 5.12(b) and Fig. 5.13(a). Hence, a good quality of these amplifiers can be implied. However, there are some exceptional cases. The amplifiers i-3 and i-9 have obviously higher losses than the others. The additional loss might be introduced by waveguide defects. Moreover, amplifier i-5 tends to be lower than the others. This might be caused by a change of the ion concentration due to non-uniformity of Er^{3+} during the co-sputtering process.

Fig. 5.15. The amplifier losses in the pump-off case after excluding the propagation losses at 1306 nm wavelength [Fig. 5.13(b)] and the coupler loss. Here, the standard deviations have been propagated during the data processing. The number on x-axis is used to represent the index of the amplifier. The missing data is because the samples of i-1, i-6 and i-7 are damaged.

To check the waveguide defects in the amplifiers i-3 ($L_g = 13.4$ cm) and i-9 ($L_g = 11.1$ cm), the profile images of the integrated $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ spirals are captured using a camera (FLIR, ptgrey), as shown in Fig. 5.16(a) and (b), respectively. The amplifiers are pumped at 976.2 nm where the green light is generated by energy transfer up-conversion of Er^{3+} on the top $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ layer. The waveguide defects can be clearly seen. In the amplifier i-3, the pump launched from the right side has an apparent attenuation. In the amplifier i-9, there is a clear scattering point. By using bidirectional pumping, the losses caused by such defects could have less influence on inverting the amplifier or the SE gain. However, the losses for the signal will lower the output signal and

reduce the global gain. Furthermore, the $\text{Al}_2\text{O}_3:\text{Er}^{3+}\text{-Si}_3\text{N}_4$ couplers with modified vertical Si_3N_4 taper length, i.e., $222\pm 4\ \mu\text{m}$, also exhibit sharp but short “green tapers”. There is no green light on the top of the Si_3N_4 waveguide on the bottom layer since the $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ is fully etched in the fabrication.

Fig. 5.16. The defects observed from the amplifier (a) i-3 ($L_g = 13.4\ \text{cm}$), and (b) i-9 ($L_g = 11.1\ \text{cm}$). The green light is generated by energy transfer up-conversion of Er^{3+} on the top $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ layer.

5.5.3 Net gain

The characterized net gains of the type Amp-I amplifiers are shown in Fig. 5.17(a) as a function of the length of the integrated $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ spiral. To calculate the gain, we first exclude the ASE in the values of T_{on} . According to Eq. 5-8, the net gain g_{global} is achieved by subtracting the signal power (in dBm) of the reference waveguide in the pump-off case from the one of the integrated amplified in pump-on case, i.e., $T_{on} - T_r$. The SE values are directly extracted by the difference between the signal powers in the pump-on and pump-off cases, i.e. $SE = T_{on} - T_{off}$, to calculate the net gain g_{SE} (SE gain) by Eq. 5-8. The highest g_{global} of $9\pm 0.28\ \text{dB}$ is obtained by the amplifier i-8 at with a gain length of $7.2\ \text{cm}$. It matches with a corresponding g_{SE} of $10.2\pm 0.8\ \text{dB}$. The amplifier i-9 with a length of $7.2\ \text{cm}$ showed the highest SE gain of $16.5\pm 1.5\ \text{dB}$. The corresponding global gain comes to $8.5\pm 0.4\ \text{dB}$, implying about $8\ \text{dB}$ loss due to waveguide defects [Fig. 5.16(b)]. Similar numbers are found for the amplifier i-3 ($L_g = 13.4\ \text{cm}$), where the global gain is $7\pm 0.56\ \text{dB}$ with a net gain g_{SE} of $15.7\pm 1.53\ \text{dB}$, due to the loss at the waveguide defect [Fig. 5.16(a)]. The global gains from other amplifiers such as i-1, i-2 and i-11 are $4\text{--}6\ \text{dB}$ lower than the related SE gain values. For the other amplifiers, the global gain and the SE gain

5. $\text{Al}_2\text{O}_3:\text{Er}^{3+}\text{-Si}_3\text{N}_4$ amplifiers
based on the double-layer active-passive platform

match each other closer, indicating a good waveguide quality for these amplifiers.

The standard deviations are separately plotted in Fig. 5.17(b) for the global and SE gains. The standard deviation of the global gain ($\delta_{g,global}$) can be obtained by propagating the measurement errors of the signal power from the reference waveguide (δ_r) and from the integrated amplifier (δ_A), as expressed in Eq. 5-11. While the error propagation in the SE gain measurements contains the measurement uncertainty in SE (δ_{SE}), the absorption loss ($\delta_{a,s}$ in dB/cm), the propagation loss (δ_o in dB/cm) and the coupler loss (δ_c). The measurement error of the SE gain ($\delta_{g,SE}$) is calculated via Eq. 5-12. For each integrated amplifier, the measurement error of the global gain is lower than that of the SE gain, as it originates from fewer steps of error propagation. The $\delta_{g,global}$ values remain below 0.5 dB for all measured amplifiers. A strong dependence on the gain length can be seen in the δ_{SE} values of the integrated amplifiers. As expected in Eq. 5-12, where the gain lengths are multiplied by the absorption and propagation losses. For example, the δ_{SE} rises from 0.65 dB to ~1.6 dB when the gain length increases from 3.9 cm to 13.4 cm.

$$\delta_{g,global} = \sqrt{\delta_A^2 + \delta_r^2} \quad \text{Eq. 5-11}$$

$$\delta_{g,SE} = \sqrt{\delta_{SE}^2 + (\delta_{a,s} \cdot L)^2 + (\delta_o \cdot L)^2 + \delta_c^2} \quad \text{Eq. 5-12}$$

Fig. 5.17. (a) Net gains of the $\text{Al}_2\text{O}_3:\text{Er}^{3+}\text{-Si}_3\text{N}_4$ amplifiers at the wavelength of 1532 nm. (b) The corresponding standard deviations of the measurement data extracted in different ways.

5.6 Results II: The Amp-II type integrated amplifiers

The Amp-II type integrated amplifiers are fabricated in the same batch as the chips for demonstrating active-passive integration (Part II of Chapter 4), where the length of the vertical Si_3N_4 taper is 800 μm . The integrated amplifiers with different lengths of integrated $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ spirals are listed in Table 5-III. For the $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ - Si_3N_4 couplers, the coupler loss refers to those measured values from the coupler chip with the same designed misalignment between the $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ and Si_3N_4 waveguides, which is 0.47 ± 0.02 dB. As described in the measurement setup, the Amp-II type amplifiers have on-chip integrated MMI-based multi/demultiplexers to combine and split the pump and signal lights. The MMI losses are separately characterized from the neighboring chips to indicate the MMI performance on the integrated amplifiers. There is no reference waveguide on the amplifier chip. To measure the net gain by Eq. 5-8, the absorption and propagation losses have to be precisely characterized using both insertion loss measurement and non-deductive methods and compared each other.

Table 5-III. The index of the Amp-II type integrated amplifiers

Length of gain section L_g (cm)	5.9	15	19	10	10	10	10
Amplifier Index, ii-	1	2	3	4	5	6	7

5.6.1 Absorption and propagation losses

To study the absorption losses of the Amp-II type amplifiers fabricated with higher ion concentration than the Amp-I type, the amplifier ii-1 with a 5.9 cm long integrated $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ spiral is selected. Compared to the Amp-I type amplifiers, the insertion losses of the Amp-II type amplifiers have additional losses caused by the on-chip MMI multi/demultiplexers. The MMIs on the integrated amplifiers are assumed to have similar losses as those on the reference chips. The measured MMI losses are demonstrated in Fig. 5.18(a) with their measurement errors displayed with shadows. Both launching the light through the pump port and signal port of the MMI are presented, showing 9.2 ± 0.15 dB and 1.4 ± 0.12 dB losses at 1532 nm respectively.

Fig. 5.18(b) demonstrates the output power of amplifier ii-1 for different incident powers in the spectral window of 1460–1635 nm. In these absorption measurements, to avoid the external WDMs and 3dB couplers that introduce extra losses, the tunable laser is directly connected with the PM fiber to the chip input, and the output is collected by another PM fiber directly to the detector. Due to a lack of reference waveguides, the absorption losses are normalized to

5. $\text{Al}_2\text{O}_3:\text{Er}^{3+}\text{-Si}_3\text{N}_4$ amplifiers
based on the double-layer active-passive platform

the minimum at 1615 nm including the losses of the MMIs, as shown in Fig. 5.18(c). The absorption spectra converge for incident powers below -20 dBm. The peak absorption at 1532 nm is 3.26 ± 0.13 dB/cm. The loss tends to rise for wavelengths longer than 1620 nm. This could be due to multiple factors such as the wavelength-dependent loss of the MMIs and the bend losses. Here, a minimum radius of 250 μm is used for the $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ spirals. However, this effect is not observed for the Amp-I type amplifiers where the minimum radius is 400 μm . This implies that 250 μm could be a potential issue resulting in bend losses especially at wavelengths above 1620 nm. The calculated absorption spectra are plotted with dashed lines in Fig. 5.18(c). The ion concentration of the Amp-II type amplifiers is probably within $(1.8\text{--}2.3) \times 10^{20} \text{ cm}^{-3}$.

Fig. 5.18. (a) The MMI losses in the spectral window of 1460–1635 nm. (b) Measured transmissions of the integrated amplifier ii-1 with different incident powers from 0 dBm down to -40 dBm. (c) The absorption spectra extracted from the transmission spectra after normalizing to the loss at 1635 nm. The $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ spiral length is 5.9 cm.

Fig. 5.19. The absorption plus propagation losses of type Amp-II amplifiers (a) ii-1 ($L_g = 5.9$ cm), (b) ii-3 ($L_g = 19$ cm) and (c) ii-5 ($L_g = 10$ cm), at different incident powers. (d) The propagation losses at 1306 nm. All the results are characterized using the non-deductive method [58].

Normalized absorption losses cannot fully represent the performance of the integrated $\text{Al}_2\text{O}_3\text{:Er}^{3+}$ spiral since the on-chip MMI losses are not locally determined. Therefore, the integrated amplifiers are characterized using the non-deductive method. The absorption plus propagation losses are directly extracted from the intensity profiles of the integrated spirals as shown in Fig. 5.19(a) to (c) for the lengths of 5.9 cm (ii-1), 19 cm (ii-3) and 10 cm (ii-5). With the reduction of the incident signal power below -15 dBm, the absorption spectra trends to converge. Among the measured devices, the peaks at 1532 nm vary from 3.5 dB/cm to 3.9 dB/cm at the incident power of -20 dBm. The propagation losses are locally determined for each integrated amplifier at 1306 nm (outside the ground state absorption band of Er^{3+}). Fig. 5.19(d) illustrates the propagation losses with their standard deviation. Among the integrated amplifiers, the mean values for the propagation losses are within 0.35–0.65 dB/cm. Given the

5. $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ - Si_3N_4 amplifiers based on the double-layer active-passive platform

measurement uncertainties, the propagation losses at 1306 nm are in good agreement with those at longer wavelengths, such as 0.5 ± 0.1 dB at 1620 nm for the ii-1, 0.6 ± 0.05 dB at 1630 nm for the ii-3, and 0.84 ± 0.03 dB at 1590 nm for the ii-5. This further verifies that the loss at longer wavelengths is dominated by propagation loss.

Furthermore, the fiber-to-chip coupling loss can be estimated based on the MMI loss and the transmission spectra of the amplifiers. For instance, at an incident power of 0 dBm, the measured insertion loss of the amplifier ii-1 is 20 dB for the wavelengths above 1610 nm. At these wavelengths, the losses from the MMIs (2.2–2.8 dB per MMI), the couplers (0.47 dB/per coupler), the propagation loss of the integrated amplifiers ($0.5 \text{ dB/cm} \times 5.9 \text{ cm}$) can be subtracted, resulting in a remaining insertion loss of 10–12 dB which is dominated by the fiber-to-chip coupling losses. A more accurate characterization of the fiber-to-chip coupling losses requires reference Si_3N_4 waveguides. Therefore, the incident powers from the pump and signal lasers are listed to present the gains instead of launched powers.

5.6.2 Signal enhancement and net gain

Due to lack of reference Si_3N_4 waveguides, the gain of the Amp-II type amplifiers are characterized from the measured signal enhancements by the Eq. 5-8. To obtain the net gain from the SE measurement, the absorption plus propagation losses characterized using the non-deductive method [Fig. 5.19(a) to (c)] are employed, which is more precise than the normalized absorption losses.

Fig. 5.20. Optical image of the amplifier ii-1 ($L_g = 5.9 \text{ cm}$) for demo purpose at the incident 976.2 nm pump power of 15 mW. The pump and red lasers are launched through the input and output ports separately. The green light is generated by energy transfer up-conversion of Er^{3+} on the top $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ layer.

For the shortest amplifier ii-1, the forward pumping scheme is used in the setup shown in Fig. 5.11(c), which is found to sufficiently invert the amplifier. The signal and pump light are combined and split by the on-chip MMIs. To demonstrate the integrated amplifier, in Fig. 5.20, an optical image is taken by launching the pump at one side and a red laser at the other (for alignment). The SE is measured by comparing the output signal powers in pump-on and pump-off cases.

Fig. 5.21. (a) Measured signal enhancement of the amplifier ii-1 as a function of incident pump power for different incident signal powers. (b) Maximum achievable values of the net gain g_{SE} obtained from the saturated SE measurements as a function of the incident signal power at 1532 nm. (c) Net gain for multiple wavelengths with the incident signal power of -30 dBm. For (b) and (c), the incident pump power is about 380 mW.

The results are plotted in Fig. 5.21(a) as a function of the incident pump power. With increasing incident pump power, first, the SE rises rapidly and then saturates. At high pump power, a large fraction of the Er^{3+} ions are already excited, bleaching the concentration of ions in the ground state. Further

increasing the pump power cannot excite more ions, resulting in no more gain. To calculate the gain, an absorption plus propagation loss of 3.73 ± 0.14 dB/cm at 1532 nm [Fig. 5.19(a)] is used for amplifier ii-1.

The net gain is shown in Fig. 5.21(b) as a function of incident signal power from -40 dBm to 2 dBm. A measurement uncertainty of 0.8 dB is obtained after propagating the uncertainties of the absorption plus propagation loss and the SE. At an incident pump power of 380 mW, 10 dB net gain is achieved. This corresponds to 1.85 dB/cm gain provided by the integrated $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ spiral on amplifier ii-1. The net gain per unit length is affected by the incident signal power. It starts to decrease when the incident signal power is larger than -20 dBm, implying gain saturation probably happen at the end length of the gain spiral that lower the total gain. The higher incident signal powers introduce additional decay leading to a lower density of excited ions. The saturation power of the signal light depends on many factors such as the photon energy, the upper state lifetimes, the absorption and stimulated emission cross-sections, mode intensity profiles and spatial overlapping of the modes, which can be specifically studied in the future.

For the integrated amplifier ii-5 with the gain section length of 10 cm, bidirectional pumping is used for the characterization using the setup of Fig. 5.11(b). A demo of the amplifier is shown in Fig. 5.22(a) with green light produced by energy transfer up-conversion of Er^{3+} at the incident pump power of about 750 mW. There are no obvious scattering points or other imperfections. Fig. 5.22(b) demonstrates the net gains at 1532 nm as a function of the incident signal power. The corresponding net gain are extracted from the SE values using the measured coupler loss, and the measured absorption plus propagation losses [Fig. 5.19(c)]. The signal is input through the pump port of the MMI. The output signals are collected by both an OSA and a spectrometer with a lock-in amplifier. After removing the ASE from the OSA spectra, the net gain match with the ones read from lock-in amplifier. Gain saturation happens when the incident power is above -6 dBm. Furthermore, the net gain at other wavelengths from the telecommunication bands, i.e., S-band, C-band and L-band, are characterized, as shown in Fig. 5.22(c). Optical gain has been realized for the integrated amplifier within the bandwidth of 1510–1580 nm. A maximum gain of 18.9 ± 1 dB has been obtained at 1532 nm, which indicates that the integrated $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ spiral can generate a gain of 1.97 dB/cm under bidirectional pumping after excluding the coupler losses.

Fig. 5.22. (a) Optical Image of amplifier ii-5 ($L_g = 10 \text{ cm}$) for demo purpose with bidirectional pumping with an incident power of 60 mW for both sides. (b) At 1532 nm, the measured net gain of the amplifier ii-5 as a function of incident pump power for different incident signal powers. (c) Maximum achievable net gains within the small-signal regime and the net gain obtained at multiple wavelengths for 1500–1580 nm. The incident pump power is $\sim 750 \text{ mW}$ split by the 3dB coupler during the bidirectional pumping.

5.7 Conclusion

In this chapter, we introduced integrated optical amplifiers based on our double-layer photonic platform. Optical $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ - Si_3N_4 amplifiers were designed, fabricated and characterized. Net gain as high as $18.9 \pm 1 \text{ dB}$ was obtained for an integrated amplifier with a 10 cm gain length, yielding gain per unit length of 1.97 dB/cm . The results are comparable to the highest net gain in $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ from previous work in our group [21]. A broad bandwidth gain operation over 70 nm wavelength was also realized. Furthermore, we introduced a new approach to characterize the optical gain considering all on-chip losses. This approach shows good agreement with commonly used gain characterization method based on the signal enhancement data, and turns out to be more realistic

*5. $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ - Si_3N_4 amplifiers
based on the double-layer active-passive platform*

for the amplifiers with waveguide imperfections. The demonstration of these integrated amplifiers shows the potential for ultra-high optical gain in our double-layer active-passive photonic platform by using high gain material. Currently, the layer growing technologies to obtain high ion concentration in Al_2O_3 with controllable quenching effect are being investigated.

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6 Summary

The integration of active devices such as lasers, amplifiers, and modulators in the Si_3N_4 platform is significant to realize diverse functionalities in photonic integrated circuits. In this thesis, a generic integration technology as well as building blocks that enable the integration of active functionalities into Si_3N_4 platform are designed, fabricated and experimentally demonstrated. Two materials, the SU-8 polymer and amorphous aluminium oxide (Al_2O_3) have been used in the demonstrations. In particular, Er^{3+} doped Al_2O_3 has been utilized to demonstrate an active-passive application, i.e., optically pumped integrated $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ - Si_3N_4 amplifiers.

Chapter 2 of this thesis presents the development of building blocks based on the passive Si_3N_4 platform. These building blocks are needed for the realization of integrated active-passive devices and yield low losses due to the low-loss feature of Si_3N_4 . We proposed an optimization process that provides a fast and reliable way to obtain optimal design parameters for MMI multi/demultiplexers regardless of the Si_3N_4 thickness. The devices were fabricated and characterized and showed low-loss and broadband behavior [1]. Another building block, i.e., Si_3N_4 ring resonator, was also studied as a precise tool to characterize the propagation losses of the Si_3N_4 waveguides. The third building block developed was a Sagnac loop mirror, widely employed in the realization waveguide laser cavities [2, 3]. The measurements of the loop mirrors show that tunable reflectivity can be realized by adjusting the coupling lengths on the micrometer scale, which can be applied for the future lasers.

After investigating the above basic building blocks, hybrid and monolithic integration technologies were studied between the Si_3N_4 platform and the SU-8 polymer in **Chapter 3**. Hybrid integration based on flip-chip bonding is developed in Part I by using adiabatically width-tapered waveguides. The devices were environmentally tested according to the international standard (IEC 60512-11-4: 2002) and showed robust optical coupling between the polymer and Si_3N_4 waveguides after several thermal shock cycles [4]. To further improve low-loss, ultra-broadband, and ultra-high fabrication tolerant features of the optical coupling, Part II studies the monolithic integration between the Si_3N_4 platform and polymer, by employing thickness-tapered Si_3N_4 waveguides [5]. These works show great potential for the integration of other polymer (or dielectric)

materials onto the Si_3N_4 platform to form various active-passive applications such as on-chip electro-optic (EO) polymer modulators, to enable, for example, the realization of integrated gyroscope in Si_3N_4 platform [6].

Based on the developed optical coupling solutions in **Chapter 3**, to enable the realization of various active photonic functionalities using active-passive integration, **Chapter 4** developed a double-layer photonic platform that combines the outstanding optical features of Si_3N_4 and the properties of rare-earth-ion doped Al_2O_3 . In the developed double-layer photonic platform, the optical modes are guided independently in the Al_2O_3 layer and in the Si_3N_4 layer, which are separated by a Si_3N_4 buffer. High-performance optical coupling between the Al_2O_3 and Si_3N_4 waveguides is achieved based on both adiabatic [7, 8] and resonant coupling schemes [9], leading to a low-loss, broadband response highly tolerant to misalignment errors. Such optical coupling solution was further tested for active-passive integration between $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ and Si_3N_4 . The technologies developed in this chapter provide a promising way towards the realization of active functionalities on the Si_3N_4 platform by scalable monolithic integration and show great potential for the realization of low-cost, mass-produced integrated lasers and amplifiers.

Chapter 5 introduces the first integrated optical $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ amplifier with a high net gain (i.e., from Si_3N_4 input- Si_3N_4 output waveguide) on the Si_3N_4 platform with a high net gain (i.e., circa 18 dB), which is our first application based on the double-layer platform. In this work, we leverage the previous studies on the $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ gain material [10-12] carried out in previous years at the MESA+ Institute at the University of Twente. In this work, integrated optical $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ - Si_3N_4 amplifiers were designed, fabricated and characterized based on the developed double-layer active-passive integrated platform. Previously, Vázquez-Córdova et. al. [13] reported the $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ amplifiers on thermally oxidized silicon substrate by shallowly etching technique achieving a record high 20 dB net gain for a 12.9 cm long spiral. Different from their waveguide configuration, the $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ waveguides in our integrated amplifiers were fully etched. Comparable net gain as high as 18.1 ± 1 dB was obtained from the Si_3N_4 -to- Si_3N_4 for an integrated amplifier with a 10 cm spiral length, with operation over a 70 nm wavelength range. We proposed an improved way to characterize the optical gain considering all on-chip losses. This approach was experimentally demonstrated and showed good agreement with commonly used gain characterization method based on signal enhancement. Furthermore, the

proposed method gave us further insight into the methodology based on signal-enhancement, letting to an improved more robust signal-enhancement method that takes into consideration potential waveguide imperfections.

Based on the findings in the above amplifiers using the developed double-layer active-passive platform, the main challenge is the optical gain per unit length provided by the $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ is low (below 2 dB/cm). Further work can be done to increase the optical gain in $\text{Al}_2\text{O}_3:\text{RE}^{3+}$ materials by developing proper co-sputtering processes, and reduce the propagation losses by improving fabrication processes.

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Appendix

A. CMP polishing rates

Our chemical mechanical polishing (CMP) processes are carried out using the Mecapol E460 CMP system with the IC1000 Dow polishing pad. The slurry is a silica and potassium hydroxide slurry mixed with Semi-Sperse 25 and deionized (DI) water by a ratio of 2:1. The removal rate of dielectric material in the CMP process is affected by various parameters such as the working-pressure between the wafer and pad surfaces, the velocities of the pad plate and wafer holding head, the concentration of the slurry and the surface condition of the pad [1, 2]. The uniformity of the removal rate is mostly influenced by the uniformity of the layer before polishing and the back-pressure between the wafer and its holding head. The latter enables to compensate its original non-uniformity by slightly bending the wafer (from nm to tens of nm scale) in order to obtain less deviating removal speed over the wafer.

The removal rate and surface uniformity are characterized using dummy Si wafers with annealed LPCVD SiO₂ before polishing the sample wafer in each batch. Some of the monitor wafers during the processes are checked in details by measuring the thickness pattern over the full wafer after each polishing. CMP parameters of these wafers, i.e., the back-pressure and working-pressure, are illustrated in Table A-I. Each monitor wafer is from a different CMP batch (at different date).

Table A-I. Pressures settings of the monitor wafers in different CMP batches.

Wafer indices	Backpressure (Bar)	Working-pressure (Bar)
i-2166	0	0.8
i-3302	0.2	0.8
i-1107	0.05	0.8
i-3100	0	0.8
i-2223	0	0.75

For example, the thickness and removal rates monitored from the wafer i-1107 are demonstrated in Fig. A.1(a) to (f). The thickness is measured by the ellipsometer (Woollam M-2000UI). The removal rates are calculated by diving the thickness differences from the original values by the polishing time, as shown

in Fig. A.1(c) to (f). These rates enable us to estimate the required polishing time for the sample wafer. In addition, to estimate the planarity, a zoom-in figure of the final thickness profile of the monitor wafer i-1107 is plot in Fig. A.2. The thickness of the majority area ($>80\%$) on the wafer is within 395 ± 20 nm.

Fig. A.1. For the monitor wafer i-1107: (a) SiO_2 thickness before polishing and (b) final thickness after polishing. Removal rates monitored at different polishing times of (c) 55 s, (d) 125 s, (e) 175 s and (f) 225 s.

Fig. A.2. Zoom-in the final thickness profile of the monitor wafer i-1107.

Fig. A.3. (a) Monitored SiO_2 thicknesses calculated for the area within 3 cm radius at different polishing times and the corresponding standard deviation that indicates the uniformity of the surfaces. (b) Monitored removal rates at different polishing times.

Fig. A.3(a) and Fig. A.3(b) show the average thickness and removal rates of the monitor wafers from the batches. Each monitor wafer is employed in a fabrication batch that is carried out at a different fabrication date. The standard deviations of both the thickness and removal rates are extracted from the values at different locations within 3 cm radius from the wafer center, which can be used to indicate the uniformity of the surfaces. In Fig. A.3(a), the standard

deviation of the thickness firstly increases and then trends to be stable or even reduce. This implies the surface uniformity can be potentially improved by applying longer polishing time or using multiple polishing steps. In Fig. A.3(b), the removal rates vary between the batches, originating from various uncertainties caused by the pre-condition of the polishing pad, the slurry mixing, and the roughness change of the polishing pad after using multiple times. Nevertheless, the removal rates are found to be stable in each batch for the estimation of polishing time and surface roughness of the sample wafer. In the future, more efforts can be spent on modifying the CMP process to achieve more accurate removal rates and more uniform polished surfaces.

B. Etching rates

Knowing the etching rates of Al_2O_3 and photoresist is important for controlling the etching depth of the Al_2O_3 waveguides. The height profiles of the alignment marks at both sides of the wafers, scanned by a profiler (Veeco Dektak 8) include the height of the photoresist before etching (H_0), the total height (waveguide plus photoresist) after etching (H_1), and the waveguide height after a quick resist stripping using acetone (H_2). This data enables to characterize the etching rates. The resist etching rate is equal to $H_0 - (H_1 - H_2)$ divided by the etching time. The Al_2O_3 etching rate is equal to H_2 divided by etching time.

Fig. A.4. Profiles of alignment structures in the wafer are scanned before etching, after 12.5 minutes etching, and after a resist stripping using Acetone for: (a) undoped Al_2O_3 layer (in Part I of Chapter 4) and (b) $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ layer with 14W-RF sputtering power for Erbium gun (in Part II of Chapter 4).

For example, Fig. A.4(a) and (b) show the monitored profiles during the etching process of undoped Al_2O_3 in the Part I and the $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ in the part II of Chapter

4. Both cases use the high resolution i-line photoresist (Fujifilm) OiR 907-12. The thickness of photoresist is characterized to be $1.18 \pm 0.01 \mu\text{m}$ and $1.39 \pm 0.01 \mu\text{m}$ at a spin coating speed of 4500 rpm and 3000 rpm, respectively. Due to the larger thickness of the $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ layer, the etching process uses the photoresist with a lower spin coating speed (i.e., 3000 rpm). In Fig. A.4(a), the etching rates are 47 nm/min for the photoresist and 55.36 nm/min for the undoped Al_2O_3 . The values in Fig. A.4(b) are 44.9 nm/min for the photoresist and 56 nm/min for the $\text{Al}_2\text{O}_3:\text{Er}^{3+}$. The small variation can be caused by various uncertainties during the fabrication processes. Nevertheless, in order to precisely control the etching depths of the waveguides in our work, the etching rates are characterized in each process. The etching time is then calculated to obtain the target depth.

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Samenvatting

De integratie van actieve componenten zoals lasers, optische versterkers en modulatoren zijn van uitermate belang voor de realisatie van diverse optische functionaliteiten op een fotonische chip. Dit proefschrift beschrijft het ontwerp, productie en de experimentele toetsing van zowel een generieke integratie methode als de bouwstenen om een dergelijke integratie te bewerkstelligen op het Si_3N_4 golfgeleider materiaal platform. Hiervoor zijn de materialen SU-8 polymeer en aluminium oxide (Al_2O_3) gebruikt. Met name Er^{3+} gedoteerd Al_2O_3 was benut om een actieve-passieve toepassing te demonstreren: een geïntegreerde, optische $\text{Al}_2\text{O}_3:\text{Er}^{3+}\text{-Si}_3\text{N}_4$ versterker.

Hoofdstuk 2 presenteert de ontwikkeling van de bouwstenen op het passieve Si_3N_4 platform. Deze materiaalkeuze voor de bouwstenen is gebaseerd op de lage optische verliezen, wat van belang is voor de realisatie van actieve-passieve componenten. Een optimalisatieproces is geïntroduceerd voor een snelle en betrouwbare berekening van de ontwerpparameters voor MMI multi/demultiplexers, ongeacht de dikte van Si_3N_4 . Deze bouwstenen zijn geproduceerd en metingen toonden aan dat ze lage verliezen bevatten en over een breed golflengtebereik werken. Si_3N_4 ring resonatoren waren bestudeerd als middel om de propagatieverliezen van Si_3N_4 golfgeleiders te bepalen. Verder is een Sagnac spiegel als derde bouwsteen ontwikkeld voor implementatie in golfgeleider lasers. De metingen van de Sagnac spiegel tonen aan dat de reflectiviteit gecontroleerd kan worden door de koppellengte te variëren, wat mogelijk toegepast kan worden in lasers.

Hybride en monolithische integratietechnieken van de SU-8 polymeer en Si_3N_4 platformen zijn bestudeerd in **Hoofdstuk 3**. Deel I beschrijft de ontwikkeling van hybride integratie gebaseerd op flip-chip bonden en het gebruik van adiabatisch vernauwde golfgeleiders. De gerealiseerde structuren zijn getoetst via internationale standaarden en toonden robuuste optische koppeling tussen de SU-8 polymeer en Si_3N_4 golfgeleiders na verscheidene thermische schok cycli. Voor de verdere verbetering van lage verliezen, breedband werking en uitstekende fabricatie tolerantie voor optische koppeling, beschrijft Deel II de monolithische integratie tussen het Si_3N_4 en SU-8 polymeer platform via Si_3N_4 golfgeleiders die in de hoogte afgevlakt zijn. Dit werk heeft veel potentiaal voor de integratie van andere polymeer of diëlektrische materialen op het Si_3N_4

platform voor actieve-passieve toepassingen, zoals elektro-optische modulatoren voor, bijvoorbeeld, een gyroscoop.

Gebaseerd op het werk beschreven in **Hoofdstuk 3**, wordt in **Hoofdstuk 4** de ontwikkeling besproken van een fotonisch platform bestaande uit twee lagen dat de excellente optische eigenschappen combineert van zowel Al_2O_3 gedoteerd met zeldzame aardmetalen als Si_3N_4 . Dit dubbel gelaagde platform staat de geleiding van licht toe in beide de Si_3N_4 en Al_2O_3 laag, welke van elkaar gescheiden zijn door een SiO_2 buffer laag. Goede optische koppeling tussen de Si_3N_4 en Al_2O_3 golfgeleiders is behaald via adiabatische of resonante koppeling, met als resultaat een koppelingsmethode met lage verliezen, een breed golflengtebereik en tolerantie onder verschuivingsfouten. De koppelingsmethode was verder ontwikkeld voor actieve-passieve integratie van $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ en Si_3N_4 . De technieken ontwikkeld in dit hoofdstuk zijn veelbelovend voor actieve functionaliteit op het Si_3N_4 platform via schaalbare, monolithische integratie en bevatten veel potentiaal voor de realisatie van goedkope, massa produceerbare lasers en optische versterkers.

Hoofdstuk 5 introduceert de eerste geïntegreerde $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ optische versterker op het Si_3N_4 platform met een hoge netto versterking van 18 dB (dat wil zeggen, van Si_3N_4 input- naar Si_3N_4 output golfgeleider), wat de eerste getoonde toepassing is op dit dubbel gelaagde platform. Dit werk bouwt voort op eerdere studies uitgevoerd in het MESA+ instituut van de Universiteit Twente over optische versterking in $\text{Al}_2\text{O}_3:\text{Er}^{3+}$. Eerder rapporteerden Vázquez-Córdova en anderen (onze groepsleden) een record versterking van 20 dB in een 12.9 cm lange spiraal op thermisch geoxideerde silicium substraten door middel van een korte ets techniek van $\text{Al}_2\text{O}_3:\text{Er}^{3+}$. Echter, het hier gepresenteerde werk is gebaseerd op een volledig geëtste golfgeleider. Een vergelijkbare versterking van 18.1 ± 1 dB was behaald over een golflengtebereik van 70 nm voor een spiraal met lengte van 10 cm. Verder werd er een verbeterde methode voorgesteld om de optische versterking te bepalen met in acht name van alle verliezen op de chip. Deze methode is experimenteel getoetst en toonde een goede overeenkomst met de gebruikelijke manier om optische versterking te karakteriseren. De nieuw geïntroduceerde methode verschaft dieper inzicht in de methodologie gebaseerd op signaal versterking en resulteert in een robuustere signaal versterking die rekening houdt met imperfecties van de golfgeleider.

Ondanks de uitstekende resultaten behaald in de optische versterkers gebaseerd op het dubbel gelaagde actieve-passieve platform, is de technologie beperkt door de lage intrinsieke versterkingscapaciteit van $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ van 2 dB/cm. Toekomstig werk zou gericht kunnen worden op verhoging van de optische versterking door middel van verdere ontwikkeling van het cosputter proces en de verlaging van propagatieverliezen geïntroduceerd tijdens het fabricatieproces.

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