Multi-Stage En/Decoders Integrated in Low Loss Si_3N_4–SiO_2 for Incoherent Spectral Amplitude OCDMA on PON

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In this paper, we show and analyze, for the first time, the static performance of integrated multi-stage cascade and tree spectral amplitude OCDMA en/decoders (E/Ds) which are fabricated in the low loss Si_3N_4–SiO_2 material system. Combined with incoherent broad spectral sources these E/Ds enable cost-effective node deployment in an OCDMA passive optical network architecture. We discuss the design of a crucial component, namely the 2x2 3dB multi-mode interference coupler. Finally we show measured spectral codes of two-stage E/Ds and compare these with modeled ones.

Introduction

The current deployment of fiber-optic access networks stimulates the research towards cost-reducing solutions. Photonic integration of optical functions, passive technologies, resource sharing and centralized network management are key issues to be addressed. Optical code division multiple access (OCDMA) on a passive optical network (PON) is considered to be an attractive, cost-effective and complementary technology which, for example, increases the number of users per spectral unit [1]. We propose to use the integrated, incoherent spectral amplitude encoded (SAE) OCDMA technique in order to further reduce deployment costs. The en/decoders (E/Ds) used are Mach-Zehnder Interferometer (MZI) based cascade and tree structures which are passive, tunable and periodic [2]. They filter the broad spectral input of an incoherent source, for example a superluminescent light emitting diode (SLED). The filter pattern and its complementary constitute the spectral code and are both used in binary data transmission (spectral shift keying). We have successfully demonstrated a one-stage tree E/D in InP–InGaAsP [3]. However in this paper, we present E/Ds integrated the Si_3N_4–SiO_2 material system because of the low propagation losses and CMOS-compatible production process [4]. The mask design and actual devices are shown here, for the first time. The parameters of critical components are discussed in detail. We show high-quality optical characteristics for two-stage E/Ds. We report an excellent match with the design and the analytical model.

The rest of the paper is organized as follows. Section 2 describes the E/D design and experimental setup to characterize the chips. Then, Section 3 shows, in detail, the design of the 2x2 MMI coupler. Then, Section 4 reports on the optical characteristics of two-stage cascade and tree E/Ds. Finally, Section 5 concludes the paper.

Design and experimental setup

The E/Ds are designed for a center wavelength of 1550nm where the fabrication process is well-defined. Optical wave guiding is achieved via a thin Si_3N_4 stripe (core) which is surrounded by a thick SiO_2 cladding layer on top of a silicon substrate and a 4µm SiO_2 buffer layer. This causes a polarization dependency of the chips. The TriPleX technology [4] has been further developed to remove that restriction but this has not been applied here. The waveguides are 2µm wide and 145nm high, giving an $n_{eff}=1.54$ for TE@1550nm and single mode operation. The E/Ds can be tuned by phase shifters consisting of a 10µm wide heater on top of the waveguide. A phase shifter is placed in all E/D arms for a red or blue shift of the spectrum. All heater leads are connected to probe pads at a pitch of 250µm. We have designed spot size converters (SSCs) in order to reduce the overlap losses at the fiber-chip interface. The waveguide is horizontally and vertically tapered to a width of 1.5µm and a height of 70nm to match the spot size of a standard single mode fiber (SSMF) with less than 1dB overlap loss. The in- and outputs are at a pitch of 250µm to match fiber-arrays. All E/Ds are modularly constructed as discussed in [2]. The E/D path length differences are calculated for a free spectral range (FSR, or: periodicity) of 5nm because a broad spectral code reduces speckle noise during fiber transmission [5]. The experimental setup is shown in Fig. 1. An SLED is driven with 500mA for a 12.1dBm optical field with an 87.5nm full-width at half-maximum around 1535nm. An isolator is added to block any back-reflections. We optimize the received optical power for TE-mode via the polarization controller (PC). The red Fabry-Perot (FP) laser is used to ease the chip alignment since the Si_3N_4–SiO_2 material system is transparent for visible light. We placed cleaved SSMFs at the input and output of the chip due to the unavailability of anti-reflection coated fibers. The optical field is measured using either a power meter or an optical spectrum analyzer (OSA) with a resolution of 0.05nm.

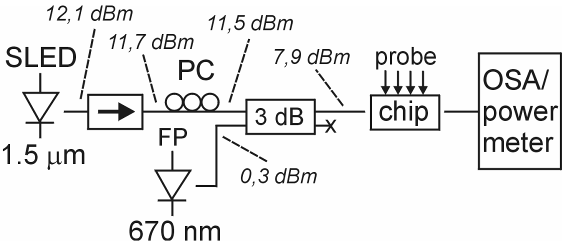
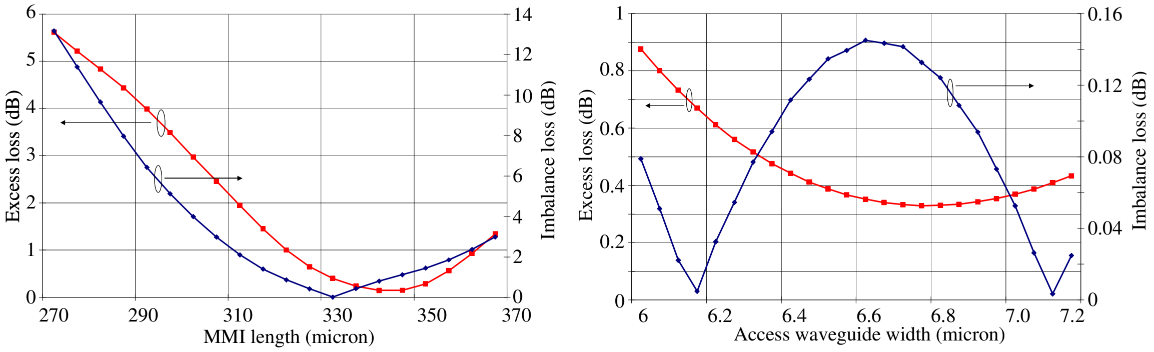


Fig. 1. Experimental setup to measure optical characteristics of multi-stage integrated en/decoders.

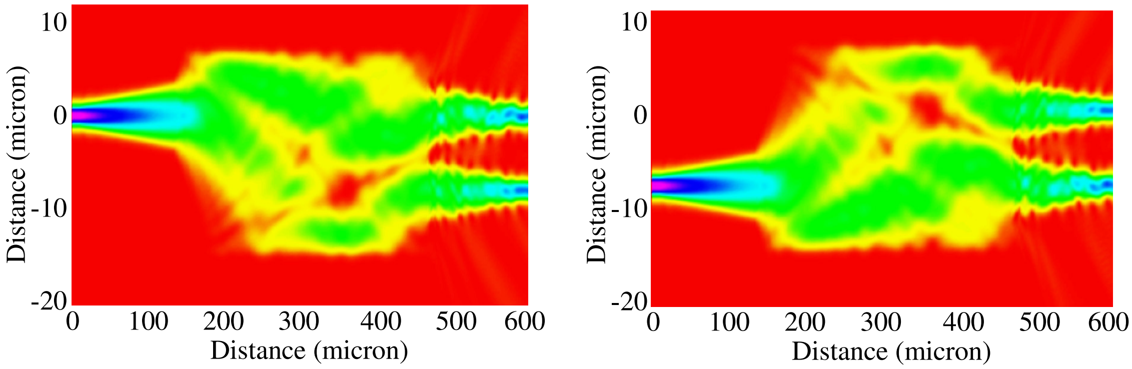
Design of Multi-Mode Interferometer

The 2x2 3dB multi-mode interference (MMI) couplers are designed with reduced reflection losses [6], and optimized on imbalance via the access waveguide (Wa) width [7]. The lithography demanded a minimal gap of 1µm between the access waveguides. We have first determined the width of the MMI to be 22µm which gave the best results in excess and imbalance losses. The corresponding initial dimensions of a paired MMI are L=320.1µm, Wa=6.6µm, x_{c1} = 7.33µm, and x_{c2} = 14.67µm [7]. We then optimize on imbalance loss via first the length of the MMI and then via the access waveguide width as shown in Fig. 2(a) and (b). An MMI with L=330.1µm, W=22µm and Wa=7.1µm shows a negligible imbalance and an excess loss of 0.4dB for TE@1550nm. A 125µm long taper is used to connect the waveguide to Wa which corresponds with values found in [7]. The mode field distribution in the final design is simulated using a beam propagation method in the PhoeniX simulation and visualization tools [8]. This is shown in Fig. 3(a) and (b) for a mode launch in the upper and lower input of the MMI.



(a) MMI length (b) Access waveguide width

Fig. 2. MMI parameter optimization on imbalance loss (excess loss also shown)



(a) Upper input launch (b) Lower input launch

Fig. 3. Mode field distribution in low reflection 2x2 multi mode interference coupler

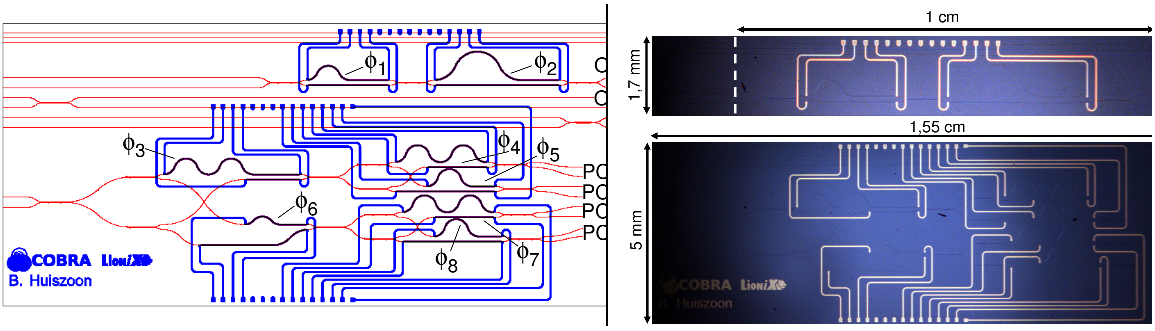
Two-Stage Cascade and Tree En/Decoders

The mask and the actual two-stage cascade and tree E/Ds are shown in Fig. 4(a) and (b). An output power of -2.2dBm +/- 0.1dB was measured at the 2x2 two-stage cascade E/D, and -9.9dBm +/- 0.4dB was measured at the 2x8 two-stage tree E/D. The loss of the cascade can be estimated as follows: 2x connector losses of 0.8dB, 2x fiber-chip losses of 1.8dB, 2x SSC losses of 1.6dB, 3x MMI excess losses of 1.8dB, a 3dB splitting loss and propagation losses of 1.1dB. The two-stage tree additionally has a 6dB splitting loss, 2x MMI excess losses and higher propagation losses. The four measured and modeled spectral codes of a two-stage cascade and tree are shown in Fig. 5(a)-(d). The spectral codes are labeled via the settings of the phase shifters (or phase code identifiers (PCIs) [2]) as shown in Fig. 4(a). Thus PCI 00, 01, 10 and 11 are represented by the following dissipated powers of the phase shifters, namely (ϕ_1=31mW, ϕ_2=0mW), (ϕ_1=31mW, ϕ_2=124mW), (ϕ_1=148mW, ϕ_2=0mW) and (ϕ_1=148mW, ϕ_2=124mW) at the two-stage cascade E/D and (ϕ_3=26mW, ϕ_5=0mW), (ϕ_3=26mW, ϕ_5=171mW), (ϕ_6=268mW, ϕ_7= 47mW) and (ϕ_5=268mW, ϕ_8=41mW) at the two-stage tree E/D. We have measured a thermal crosstalk of around 0.3 pm/mW between ϕ_4,ϕ_5 and ϕ_7,ϕ_8 due to a narrow spacing of 35µm. This effect is not noticeable at the low thermal tuning powers used. The spectral codes in Fig. 5 show an excellent match with the modeled codes in [2]. Moreover, the tree and cascade have a comparable performance.

Conclusions

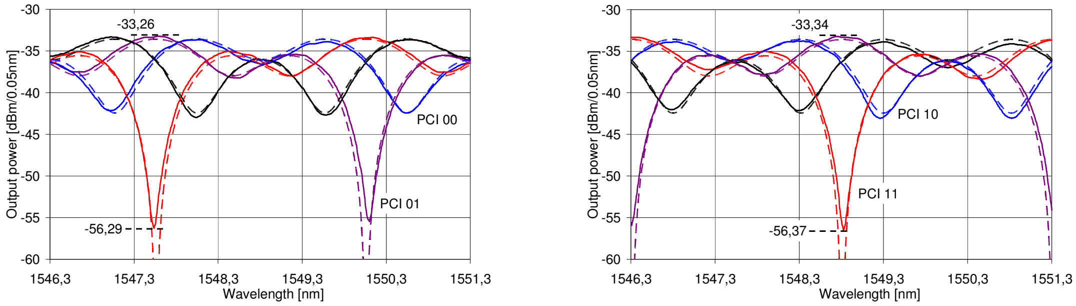
The passive, periodic and low-loss en/decoders presented in this paper enable a cost-efficient multi-user incoherent spectral amplitude OCDMA deployment on a (coarse-)

wavelength division multiplexing passive optical network. We have integrated multiple multi-stage cascade and tree E/Ds in the Si_3N_4–SiO_2 material system. The design, fabrication method and optical characteristics are shown here for the first time. We report an excellent match with the modeled spectral codes for two-stage en/decoders. The tree structure shows a performance comparable to the cascade.

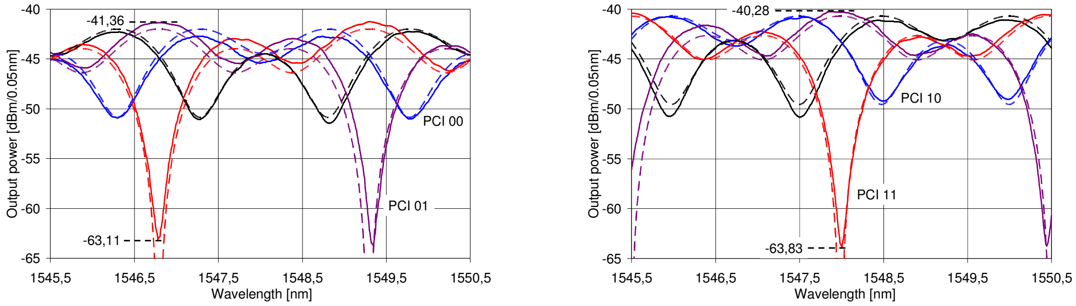


(a) Mask of cascade (up) and tree (down) (b) Fabricated cascade (up) and tree (down)

Fig. 4. Integrated two-stage en/decoders



(a) PCI 00 and PCI 01 at cascade E/D (b) PCI 10 and PCI 11 at cascade E/D



(c) PCI 00 and PCI 01 at tree E/D (d) PCI 10 and PCI 11 at tree E/D

Fig. 5. Spectral codes corresponding with PCIs for two-stage integrated en/decoders; model (dashed) and experiment (solid)

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