On-chip integrated lasers in Al_2O_3:Er on silicon

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ABSTRACT

Erbium-doped aluminum oxide channel waveguides were fabricated on silicon substrates and their characteristics were investigated for Er concentrations ranging from 0.27 to 4.2×10^{20} cm^{-3}. Background losses below 0.3 dB/cm at 1320 nm were measured. For optimum Er concentrations in the range of 1 to 2×10^{20} cm^{-3}, internal net gain was obtained over a wavelength range of 80 nm (1500-1580 nm) and a peak gain of 2.0 dB/cm was measured at 1533 nm. Integrated $Al_2O_3:Er^{3+}$ channel waveguide ring lasers were realized based on such waveguides. Output powers of up to 9.5 μW and slope efficiencies of up to 0.11 % were measured. Lasing was observed for a threshold diode-pump power as low as 6.4 mW. Wavelength selection in the range 1530 to 1557 nm was demonstrated by varying the length of the output coupler from the ring.

Keywords: aluminum oxide, rare-earth-ion doping, erbium, channel waveguide, optical gain, waveguide laser, integrated ring laser, tunable laser

1. INTRODUCTION

Over the last two decades there has been significant interest in integrated rare-earth-ion-doped amplifiers and lasers on a chip. Such low-cost, highly compact components can be useful for amplification at the end of an optical link or for signal generation within an integrated optical circuit.[1] In particular, Er^{3+}-doped waveguides are of specific interest because they offer active functionality at the all-important telecom wavelengths. Their applicability has been supported by the availability of low-cost laser-diode pump sources operating at 980 nm and 1480 nm for exciting Er ions. In the past, many different host materials have been investigated for integrated erbium-doped amplifiers[2-8] and lasers.[9-11] Among them, phosphate glass has become the material of choice due to ease of fabrication, high Er solubility without introducing significant quenching effects and, as a result, comparatively high gain per unit length (~3 dB/cm).[12-14]

Previously, Er-doped aluminum oxide ($Al_2O_3:Er^{3+}$) has also been studied as a gain medium for active devices.[15] This material offers several advantages. It exhibits a broad emission spectrum due to the amorphous nature of the host.[16] This makes $Al_2O_3:Er^{3+}$ an interesting material for active devices such as integrated amplifiers which provide gain across a wide wavelength range or integrated tunable and ultrashort-pulse laser sources. Besides, it has a higher refractive index contrast allowing more compact integrated optical devices and smaller waveguide cross sections, resulting in lower gain threshold and total required pump power as compared to phosphate glass. Furthermore, it is fabricated by a straightforward method which results in low background losses and allows deposition on a variety of common substrates. Specifically, it is typically deposited on standard thermally oxidized silicon wafers, introducing the potential for integration with silicon-based photonics technology. Up to now, the main drawback of the material has been that the peak internal net gain was limited to 0.58 dB/cm,[15] which is significantly lower than in other glass materials.

2. Al_2O_3:Er WAVEGUIDES ON SILICON SUBSTRATES

We developed reactive co-sputtering as a reliable and reproducible deposition process for Al_2O_3 layers with different Er concentrations (Fig. 1) and optical losses as low as 0.1 dB/cm (Fig. 2), allowing deposition on a variety of common substrates, e.g. thermally oxidized silicon wafers.[17] We structured these layers by reactive ion etching with a BCl_3/HBr plasma through standard resist masks, thereby obtaining channel waveguides (Fig. 3) with losses as low as 0.2 dB/cm.[18]

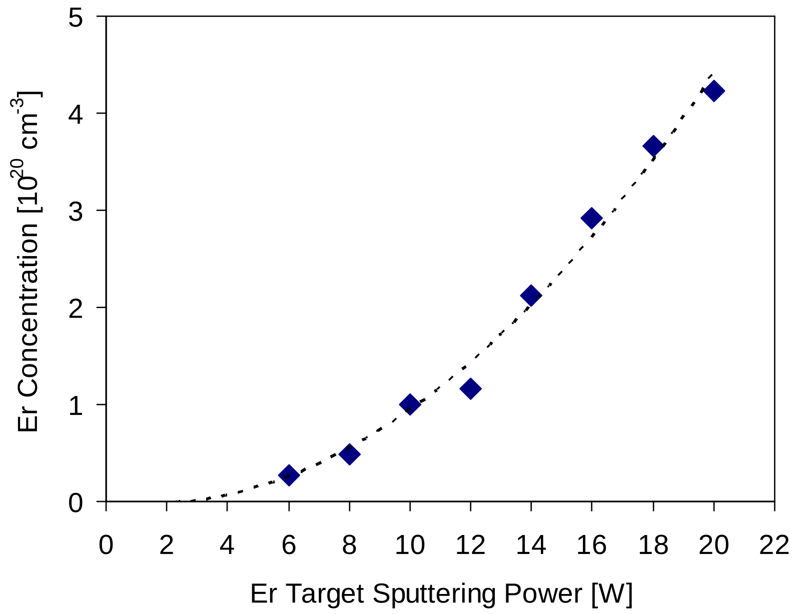

Fig. 1. Er concentration versus Er target sputtering power (Figure taken from Ref. 19)

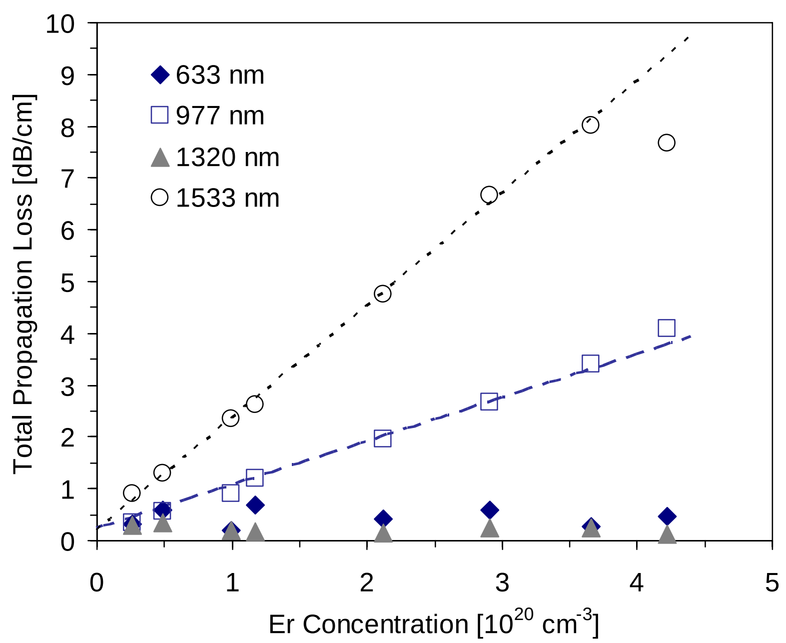

Fig. 2. Total planar waveguide propagation loss at 633 nm, 977 nm, 1320 nm, and 1533 nm as a function of Er concentration. The dashed lines represent the fitted propagation and Er absorption loss at 977 nm and 1533 nm using the average background loss, average confinement factor, and experimentally determined absorption cross sections at each wavelength. (Figure taken from Ref. 19)

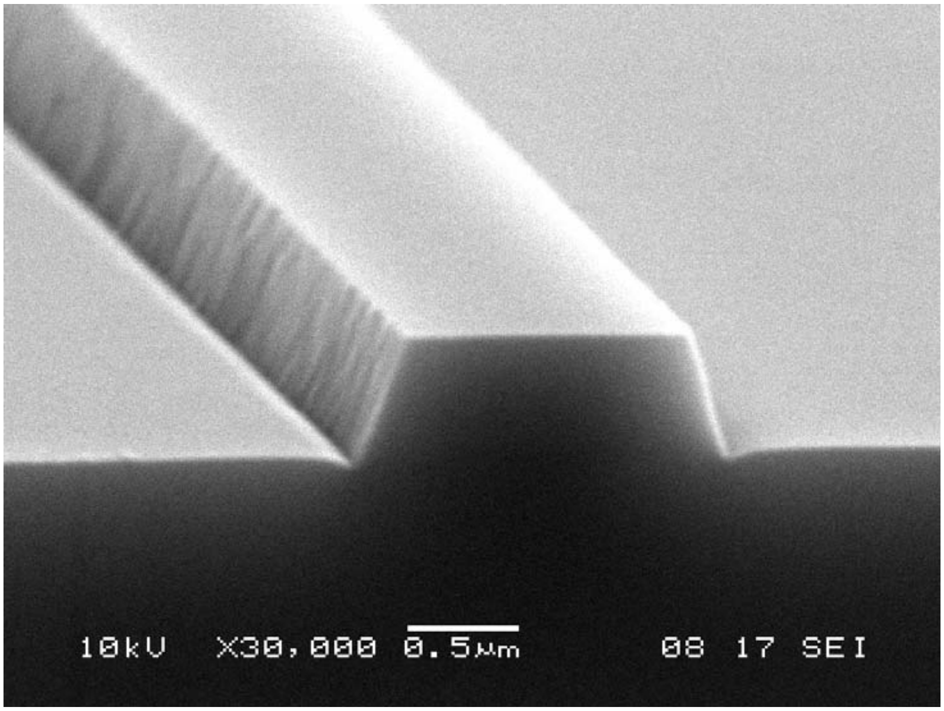

Fig. 3. SEM micrograph profile of a 1.3-μm-wide and 530-nm-deep channel waveguide in Al_2O_3 (Figure taken from Ref. 18)

The characteristics of the $Al_2O_3:Er^{3+}$ channel waveguides were investigated for Er concentrations ranging from 0.27 to 4.2×10^{20} cm^{-3}.[19] $Al_2O_3:Er^{3+}$ exhibits a broad emission spectrum (Fig. 4). This makes $Al_2O_3:Er^{3+}$ an interesting material for active devices such as integrated amplifiers which provide gain across a wide wavelength range, as well as integrated tunable and ultrashort-pulse laser sources. For optimum Er concentrations in the range of 1 to 2×10^{20} cm^{-3}, internal net gain of up to 2.0 dB/cm was obtained. For an amplifier length of 5.4 cm, Er concentration of 1.17×10^{20} cm^{-3}, and a launched 977-nm pump power of 80 mW, gain was obtained over a large wavelength range of 80 nm (1500-1580 nm) and a peak gain of 9.3 dB was measured at 1533 nm (Fig. 5). The broadband and high peak gain is attributed to an optimized fabrication process, improved waveguide design, and pumping at 977 nm as opposed to 1480 nm. By use of a rate-equation model, internal net gain of 33 dB at the 1533-nm gain peak and more than 20 dB for all wavelengths within the telecom C-band (1525-1565 nm) is predicted for a launched signal power of 1 μW, when launching 100 mW of pump power into a 24-cm-long amplifier. The high optical gain demonstrates that $Al_2O_3:Er^{3+}$ is a competitive technology for active integrated optics.

Signal transmission experiments were performed at 170 Gbit/s in an integrated $Al_2O_3:Er^{3+}$ waveguide amplifier to investigate its potential application in high-speed photonic integrated circuits.[20] A differential group delay of 2 ps between the TE and TM fundamental modes of the 5.7-cm-long amplifier was measured. When selecting a single polarization, open eye diagrams and bit error rates equal to those of the transmission system without the amplifier were observed for a 1550 nm signal encoded with a 170 Gbit/s return-to-zero pseudo-random 2^7-1 bit sequence, showing that the EDWA does not add any penalty to the system.

By use of this technology a lossless 1×2 power splitter has been realized in $Al_2O_3:Er^{3+}$ on silicon.[21] Net gain was measured over a wavelength range of 40 nm (1525-1565 nm) across the complete telecom C-band. Using a similar design, calculations predict a 1×4 lossless splitter over the same wavelength range when launching a total of 30 mW into the amplifying sections of the splitter.

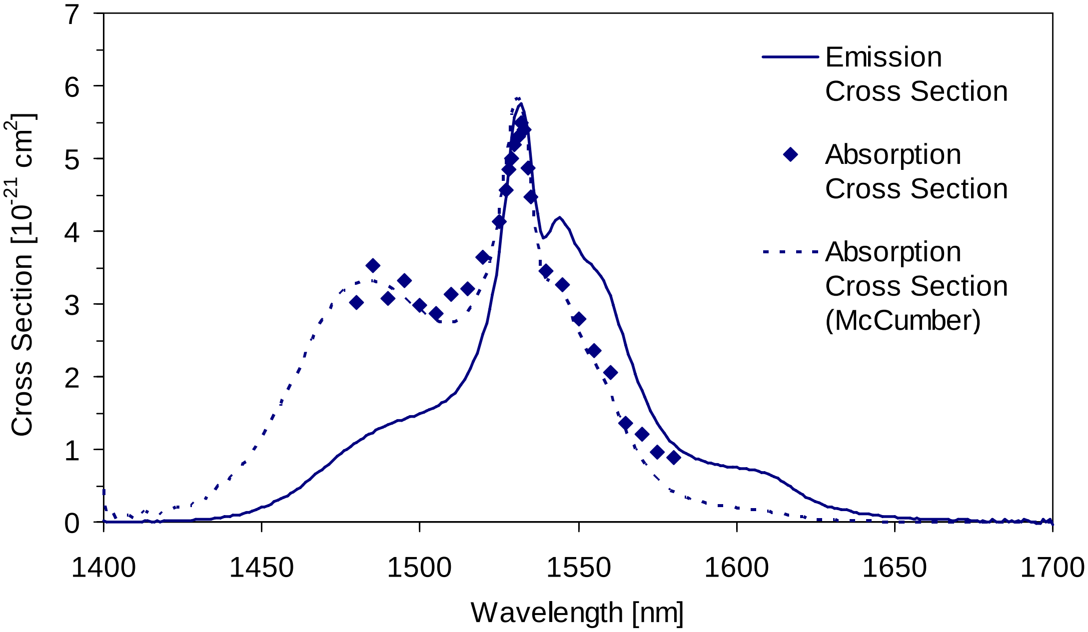

Fig. 4. Emission cross section determined from the luminescence spectra of samples with Er concentrations of 1.00 to 4.22 × 10^{20} cm^{-3}. The absorption spectrum calculated using McCumber theory and measured at single wavelengths in the range 1480-1580 nm are indicated by the dashed line and the plotted points, respectively. (Figure taken from Ref. 19)

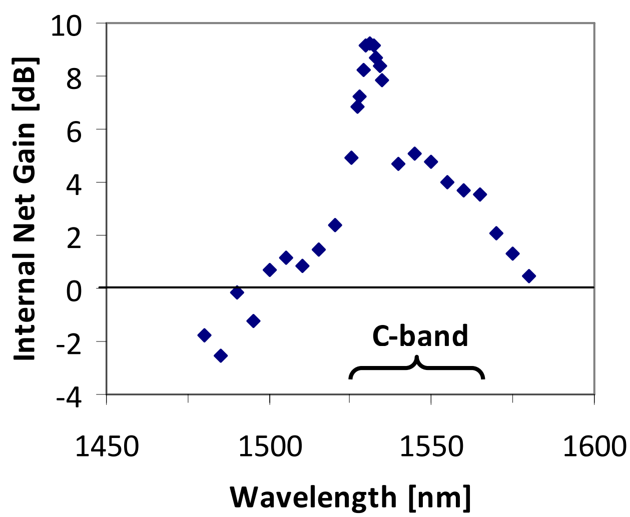

Fig. 5. Internal net gain as a function of wavelength for an amplifier length of 5.4 cm, Er concentration of 1.17 × 10^{20} cm^{-3}, and a launched 977-nm pump power of 80 mW (Figure taken from Ref. 19)

3. Al_2O_3:Er WAVEGUIDE LASERS

By use of this technology, we have demonstrated an integrated $Al_2O_3:Er^{3+}$ laser based on a novel ring-resonator design (Fig. 6) which allows strong coupling of pump light into the ring while simultaneously allowing only a small percentage of output coupling at the signal wavelength.[22,23] Directional couplers 1 and 2 were designed to strongly couple TE-polarized ~1550 nm signal light while minimally coupling randomly polarized 980 nm pump light. The coupler gaps were 2 µm and adiabatic sine bend transitions were used at the input and output of each coupler. The coupler lengths were varied from 350 to 600 µm in increments of 50 µm. This was to ensure a range in which the out-coupled power and the total cavity roundtrip losses were sufficiently low for laser action. The resonator length ranged from 2.0 to 5.5 cm.

In order to characterize the $Al_2O_3:Er^{3+}$ ring laser devices, a fiber array unit (FAU) consisting of high numerical aperture fibers was aligned simultaneously to the input and output ports of the chip. Pump light from a 980-nm diode laser was coupled to the chip through one fiber of the FAU and the output signal was collected in a second fiber of the FAU. The laser power was measured using a lightwave multimeter and the laser spectra were measured using a spectrometer.

Lasing was observed in devices with coupling lengths in the range 400-550 µm. In Fig. 7 the laser output power is shown as a function of launched pump power for devices with three different coupling lengths. The highest slope efficiency of 0.11% was observed in a 5.5-cm-long resonator, with an output power of up to 9.5 µW measured at 19 mW launched pump power. A low minimum threshold pump power of 6.4 mW was measured.

Normalized laser output spectra for three devices are shown in Fig. 8. The spectra include several longitudinal modes due to the cm-long resonator length, which results in a free spectral range of between 0.3 and 0.8 pm. The calculated coupled power for TE polarization is shown in Fig. 9 for the three observed lasing wavelengths. Lasing tends to occur at wavelengths where the coupled power is highest, thus the total round-trip losses of the resonator are lowest. Lasing occurs most frequently around 1532 nm, where the gain of the material is highest.[19]

In another approach, a distributed-feedback (DFB) laser was demonstrated.[24] The grating pattern was defined by laser interference lithography (LIL) and etched into a cladding layer which was deposited on top of the waveguides. The laser operated in a single longitudinal mode and single polarization (TE) where a maximum output power of 165 µW was achieved.

4. CONCLUSIONS

$Al_2O_3:Er^{3+}$ optical waveguides have been fabricated on silicon substrates. Due to an optimized deposition procedure, resulting in low background losses, and an improved waveguide design, internal net gain of up to 2.0 dB/cm was measured at 1533 nm. In addition, internal net gain was achieved over a bandwidth of 80 nm between 1500-1580 nm, with a maximum of 9.3 dB at the gain peak at 1533 nm. By use of this technology we have demonstrated an $Al_2O_3:Er^{3+}$ laser based on a novel ring-resonator design which allows strong coupling of pump light into the ring while simultaneously allowing only a small percentage of output coupling at the signal wavelength. Output powers of up to 9.5 µW were observed with threshold pump powers as low as 6.4 mW. Due to the broad gain spectrum in $Al_2O_3:Er^{3+}$, the output wavelength varied between 1530 to 1557 nm in devices with different output coupler lengths.

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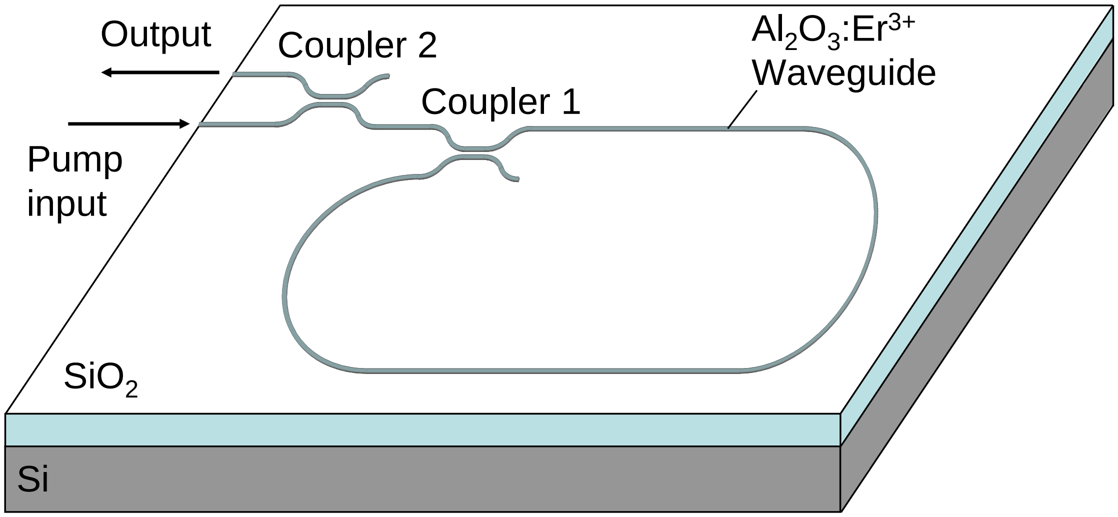

Fig. 6. Schematic of Al_2O_3:Er^{3+} ring laser (Figure taken from Ref. 22)

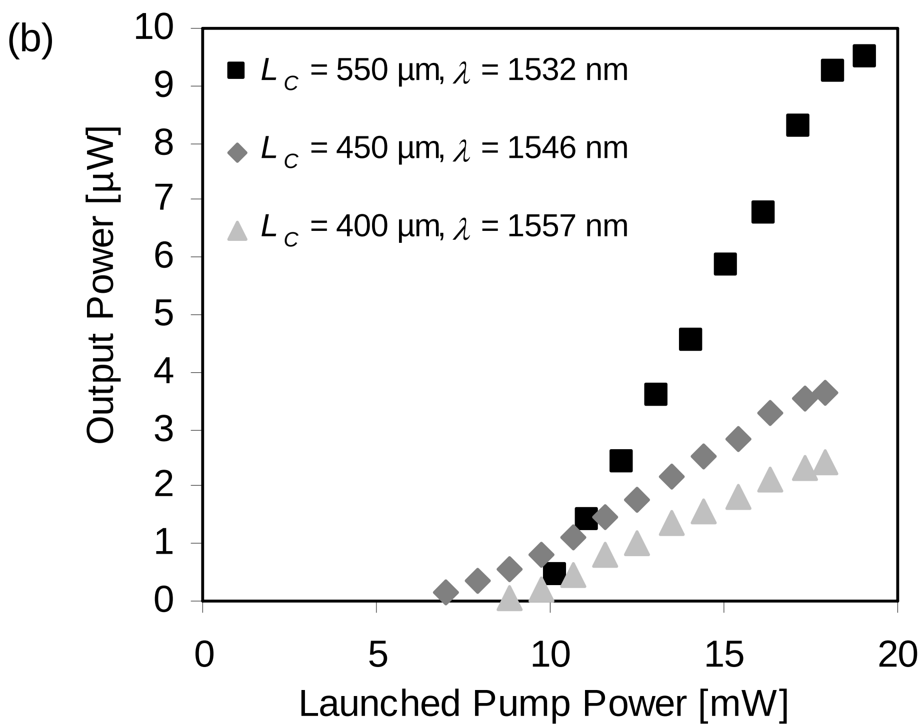

Fig. 7. On-chip integrated laser output power vs. pump power launched into the chip for varying resonator and output coupler length. The resonator length, coupler length, and main lasing wavelength are indicated. (Figure taken from Ref. 23)

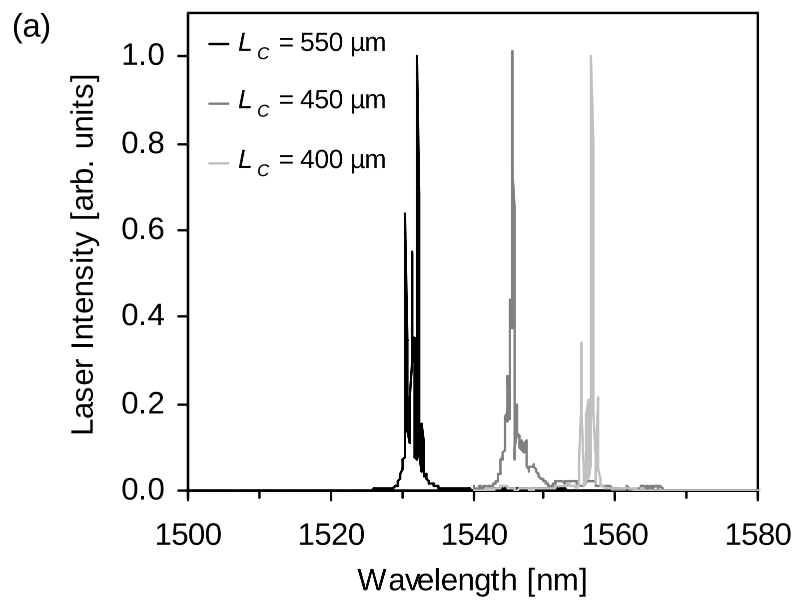

Fig. 8. Laser output spectra for coupler lengths L_C of 550, 450, and 400 µm (Figure taken from Ref. 23)

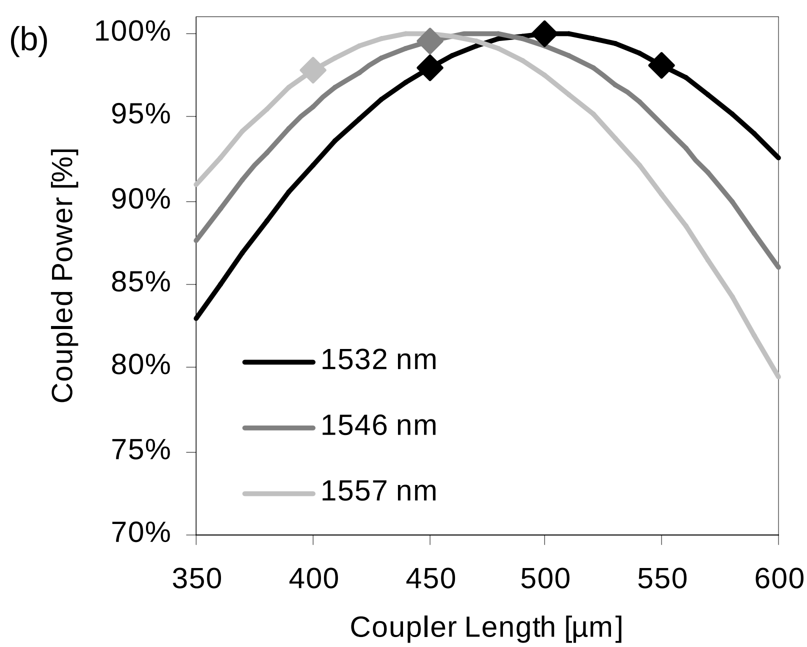

Fig. 9. Simulated coupled power in Coupler 1 vs. coupler length for the observed laser wavelengths and TE polarization. The coupler lengths for which lasing was observed are indicated by the diamonds on the curves. (Figure taken from Ref. 23)

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