$Al_2O_3:Er^{3+}$ as a broad gain medium for 1.53-µm integrated optical applications

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Novel on-chip devices, suitable for integrated optical applications around 1.53 µm, have been realized by applying $Al_2O_3:Er^{3+}$ as a broad gain medium. A zero-loss optical power splitter operating over the entire C-band (1525-1565 nm) and requiring < 50 mW of 977 nm pump power has been demonstrated. Peak net gain of up to 11 dB at 1532 nm and signal transmission at 170 Gbit/s without added bit-error penalty have been measured in an $Al_2O_3:Er^{3+}$ amplifier. Finally, the first integrated $Al_2O_3:Er^{3+}$ ring laser has been realized. Laser emission was demonstrated over the wavelength range 1530-1557 nm by tuning the output coupler length.

Introduction

$Al_2O_3:Er^{3+}$ has been investigated as a gain material due to its low absorption, higher refractive index compared to other Er-doped glasses (thus allowing higher integration density) high Er^{3+} solubility and broad emission spectrum around 1.53 µm [1]. We have recently demonstrated higher gain of up to 2.0 dB/cm and over a wavelength range of 80 nm in $Al_2O_3:Er^{3+}$ waveguides [2]. This high and broad gain around the all-important telecom wavelengths allows for the application of $Al_2O_3:Er^{3+}$ in active on-chip devices.

In this paper various applications of $Al_2O_3:Er^{3+}$ are reported. The first device is a zero-loss splitter operating over the entire C-band (1525-1565 nm). The second application is the demonstration of amplification of a 170 Gbit/s encoded 1550 nm signal. In addition to being the first high-bit-rate transmission measurement in $Al_2O_3:Er^{3+}$ waveguides, it is the first time to our knowledge that 170 Gbit/s data transmission has been demonstrated in an erbium-doped waveguide amplifier (EDWA). Finally, a fully-integrated $Al_2O_3:Er^{3+}$ ring laser is reported. The laser produces several wavelengths over a 27-nm-range and could in future be applied as a tunable on-chip light source.

Zero-loss Optical Power Splitter

A ~500-nm-thick $Al_2O_3:Er^{3+}$ film was deposited using the optimized growth recipe described in [3] and 1.5-µm-wide $Al_2O_3:Er^{3+}$ channel waveguides were prepared by reactive ion etching [4]. A 5-µm-thick SiO_2 top-cladding layer was deposited by plasma-enhanced chemical vapour deposition, and end facets were prepared by dicing.

The $Al_2O_3:Er^{3+}$ lossless splitter design [5] consists of two pump inputs in order to ensure sufficient pump power to excite the 8.6-cm-long $Al_2O_3:Er^{3+}$ waveguides. To facilitate this two couplers were applied which were designed to selectively couple signal light (> 90%), while coupling minimal pump light (≤ 10%). The couplers and waveguides were designed for TE-polarized signal light and randomly polarized pump light. The two pumped $Al_2O_3:Er^{3+}$ waveguide sections were folded so that the entire device fits in an area of 4.2 × 30 mm.

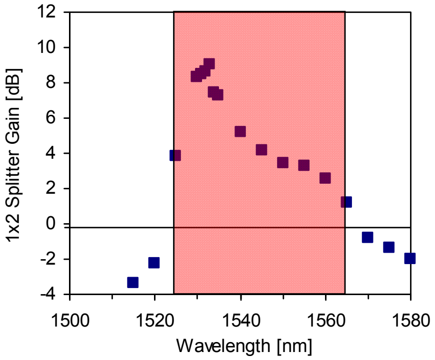

Fig. 1. Internal net gain vs. wavelength at each output waveguide of the $Al_2O_3:Er^{3+}$ on-chip lossless splitter

In order to characterize the $Al_2O_3:Er^{3+}$ splitter separate optical loss measurements and signal enhancement measurements were carried out. The optical propagation losses were measured by launching signal light from a tunable laser source into straight waveguides on the same chip and analyzing the change in light intensity captured by an infrared camera. To measure the signal enhancement, fiber-array units (FAUs) were aligned simultaneously to the input and output ports of the chip using piezoelectric computer-controlled stages. The FAUs consisted of Nufern UHNA3 fibers and standard 1550-nm single-mode fibers for the pump and signal inputs, respectively. 976-nm pump light from diode laser and Ti:Sapphire laser sources and modulated TE-polarized signal light from a tunable laser source (1500-1580 nm) were launched into the device. The output signal was coupled to an InGaAs detector followed by a lock-in amplifier to eliminate residual pump light and amplified spontaneous emission.

Approximately 27 mW and 19 mW of pump power were launched into each waveguide while 1 µW was launched at the signal input. The net gain was calculated per output branch of the splitter and is shown in Fig. 1. Net internal gain of up to 9.0 dB and over a wavelength range of 1525 to 1565 nm, covering the entire C-band (shaded area in Fig. 1), was achieved.

High Bit Rate Amplification Experiments

Transmission experiments were performed in a 5.7-cm-long $Al_2O_3:Er^{3+}$ straight channel waveguide amplifier [6]. Net internal gain of up to 11 dB was measured at 1532 nm for a launched pump power of 63 mW, while 6.6 dB gain was measured at 1550 nm. The threshold launched pump power for internal net gain was 4 mW and 3 mW at 1532 nm and 1550 nm, respectively. A 170-Gbit/s data stream consisting of 1.5-ps pulses was generated by a 42.5-GHz optical clock (a filtered, chirp-compensated quantum dash Fabry-Perot mode-locked 1550-nm laser) [7], followed by a $LiNbO_3$ Mach-Zehnder Interferometer (MZI) modulated electronically by a pattern generator to obtain a 42.5-Gbit/s 2^7-1 return-to-zero pseudo-random bit sequence (PRBS) and an optical time division multiplexing (OTDM) bit-rate multiplier which multiplexed four delayed versions of the signal. After amplification in an erbium-doped fiber amplifier (EDFA), power and polarization control and eliminating back-scattered light by an optical isolator, the signal was coupled to and from the chip via microlensed fibers. A 1480-nm Raman laser pumped the chip via a fiber multiplexer (MUX) in a counter-propagating scheme. After amplification the signal was propagated through a 170-to-42.5-Gbit/s optical demultiplexer based on an electro-optic phase-locked loop, also recovering the optical clock, and detected by a 42.5-Gbit/s electrical time division demultiplexing receiver (ETDM). An optical sampling oscilloscope (1-ps resolution) visualized the signal.

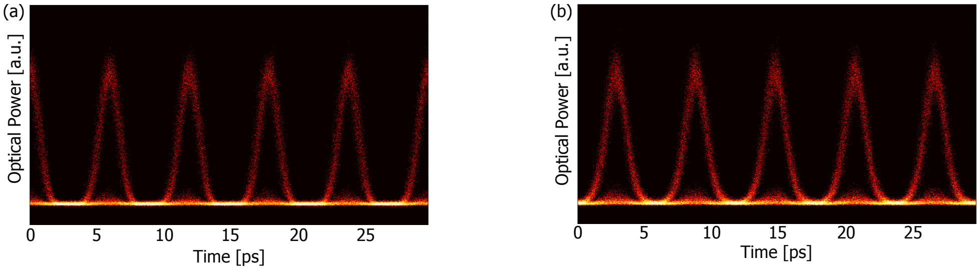

Fig. 2. Transmission eye diagrams at 170 Gbit/s (a) without EDWA and (b) with EDWA and a launched signal power of 0.5 mW and counter-propagating pump power of 65 mW

For all measurements a single polarization state was selected by adjusting the polarization controller on one fundamental mode to avoid group delay dispersion between the TE and TM modes. Typical eye diagrams without the EDWA and with the EDWA and a single polarization are shown in Fig. 2a and Fig. 2b, respectively. The eye pattern is open and the pulse FWHM is 2 ps in both cases. Bit error rate (BER) assessments were also performed with and without the device in the transmission setup. Identical bit error rate vs. received optical power curves were obtained with and without the EDWA in the system, verifying that negligible noise is added by the amplifier.

Integrated Ring Laser

A schematic of the Al_2O_3:Er^{3+} ring laser [8] is shown in Fig. 3 Cladded Al_2O_3:Er^{3+} waveguides were prepared with the same dimensions as described for the zero-loss power splitter. Coupler 1 in Fig. 4a was designed such that strong coupling at the signal wavelength around 1550 nm of > 95 % for TE-polarization and weak coupling of < 10% at the pump wavelength of 980 nm was achieved. The coupler lengths were varied from 350 to 600 μm in increments of 50 μm while the resonator length was varied from 2.0 to 5.5 cm.

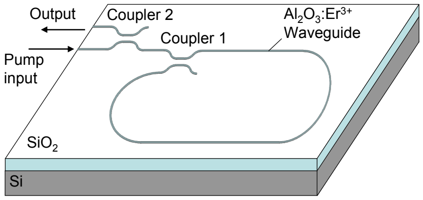

Fig. 3. Schematic of Al_2O_3:Er^{3+} ring laser

In order to characterize the Al_2O_3:Er^{3+} ring laser devices, a FAU was aligned simultaneously to the input and output ports of the chip using piezoelectric computer-controlled stages. Pump light from a 980-nm diode laser was coupled to the chip and the output signal was collected and the laser power was measured using a lightwave multimeter. The laser spectra were measured using a spectrometer.

Devices with coupling lengths ranging from 400 to 550 μm were observed to lase. 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. The threshold pump power varied from 6.4 to 15.5 mW. Lasing was observed at wavelengths ranging from 1530-1557 nm. Because of the long resonator length, which results in a free spectral range of between 0.3 and 0.8 pm, the spectra include several longitudinal modes.

Conclusions

Various active devices applying $Al_2O_3:Er^{3+}$ have been demonstrated, including a zero-loss power splitter, a high-bit-rate amplifier, and an integrated ring laser.

Acknowledgments

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