Fiber-Device-Fiber Gain From a Sol-Gel Erbium-Doped Waveguide Amplifier

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Abstract—An erbium-doped silica-on-silicon planar waveguide optical amplifier is described. The active core is a topographic guide formed from aluminophosphosilicate glass doped with erbium and ytterbium. The buffer is formed from silica deposited by thermal oxidation and the cladding from borophosphosilicate glass obtained by plasma-enhanced chemical vapor deposition. The use of low process temperatures allows relatively heavy doping and careful control of the core etching allows low background insertion losses to be obtained. Spontaneous emission and gain measurements are given and 5.4-dB fiber-device-fiber gain is demonstrated using a 5-cm-long chip pumped using a 980-nm laser diode at 175-mW pump power.

Index Terms—Erbium, optical amplification, sol-gel, waveguides.

THE ERBIUM-DOPED fiber amplifier (EDFA) has been highly successful as a low-noise gain block at 1535-nm wavelength. Er-doped waveguide amplifiers (EDWAs) have also attracted attention, because of their potential for integration with pump lasers and filters [1]. The main difficulty in constructing an EDWA lies in providing suitably high gain in a short length, which requires high Er^{3+} doping without concentration-dependent effects.

Erbium-doped amplifiers and lossless splitters have been formed by ion exchange in silicate [2] or phosphate [3] glass matrixes and by ion implantation into Al_2O_3 [4]. Topographic guides have been formed in Er-doped silicate and phosphate glasses deposited by sputtering [5], [6]. Er-doped guides have also been formed by plasma-enhanced chemical vapor deposition (PECVD) [7], [8]. EDWA performance has been compared in [1]. Internal gains of 4.1 dB/cm have been achieved in ion-exchanged phosphate glass, 1.1 dB/cm in soda-lime silicate glass, and 0.6 dB/cm in implanted Al_2O_3 .

Silica-on-silicon is a useful EDWA configuration because of its low-cost connection to fibers. Unfortunately, Er^{3+} clustering leads to ion-ion effects such as cooperative upconversion [1], resulting in a reduction in the lifetime of the metastable $^4\text{I}_{13/2}\text{Er}^{3+}$ level. Er_2O_3 solubility is improved by codoping with P_2O_5 and Al_2O_3 , with the further advantage in the latter case of broadening the gain spectrum. However, overall gain has so far only been achieved in PECVD EDWAs using low Er^{3+} concentrations, resulting in internal gains of ≈ 0.35 dB/cm [8]. Finally, because of the small absorption cross section of Er^{3+}

at 980 nm, high pump powers are required. However, pump powers are reduced by codoping with Yb^{3+} , which has a large cross section and which may transfer energy nonradiatively to the $^4\text{I}_{11/2}$ level of Er^{3+} .

Although erbium may be incorporated in silica by PECVD, difficulties are caused by the low vapor pressure of erbium compounds. There is, therefore, a need to investigate alternative processes for depositing Er-doped silicate glasses, which can also incorporate the range of codopants needed to tailor the Er^{3+} environment. One possibility is the sol-gel process. Thick layers of silicate glasses can be formed as multilayers, using repetitive cycles of spin-coating and rapid thermal annealing (SC-RTA), with careful control of the annealing temperature [9]. These layers may then be formed into buried channel guides by the conventional route of reactive ion etching and cladding.

Early sol-gel guides were mainly based on TiO_2 - SiO_2 . However, TiO_2 is unsuitable for sol-gel optics, because of its high process temperatures and tendency to form crystalline phases, including erbium titanate. Since then, improved guides have been developed using a range of dopants such as P_2O_5 , B_2O_3 , Al_2O_3 , and Ga_2O_3 . Some dopants have been used to control process temperatures in addition to altering the refractive index. Rare earth dopants such as Nb_2O_5 , Er_2O_3 , and Yb_2O_3 have also been incorporated.

Some progress has been made toward fabricating EDWAs by SC-RTA. For example, relative gains of 1.1 dB/cm have been obtained using Yb-Er-codoped silica-titania, but only in a strip-loaded geometry with fiber coupling and propagation losses so high that no external gain was observed [10]. In this letter, we demonstrate the first practical sol-gel EDWA. The device is based on a buried active core and has low coupling and propagation loss, strong confinement, and a realistic external gain.

To ensure low loss, SC-RTA was used only to deposit the core layer and alternative processes were used for the buffer and cladding, as shown in Fig. 1(a). The buffer was a 19- μm -thick layer of pure silica grown on a 4-in (100) Si wafer by steam oxidation.

The sol-gel core was formed from aluminophosphosilicate glass-doped with erbium and ytterbium. The P_2O_5 dopant served to reduce the SC-RTA process temperature and reduce OH^- contamination (as shown by both optical and FTIR spectroscopy [9], [11]), the Al_2O_3 to control the Er^{3+} environment and the Yb_2O_3 to improve the pump efficiency. Fig. 2 shows the process used to prepare the sol. The silica precursor was a solution of tetraethyl-orthosilicate (TEOS) in isopropanol (IPA), while the dopant precursors were solutions of phosphorus pentoxide and aluminum, ytterbium and erbium salts in IPA.

The sol itself was prepared in stages. A phosphosilicate (PSG) sol was first formed by combining TEOS and P_2O_5 solutions

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Fig. 1. Schematic of the overall fabrication process.

Fig. 2. Preparation process for multicomponent silicate sol.

with H_2O and refluxing to hydrolyze on average two OR groups per TEOS molecule ($R = 2$) using HCl as a catalyst. The PSG sol was then stabilised to avoid gelation of the mixture. AlPSG, ErAlPSG and YbErAlPSG sols were then obtained by successive additions of IPA solutions of phosphorus pentaoxide and aluminum, ytterbium and erbium salts, in ratios needed to obtain the final composition.

Experimentally, an upper limit to the total concentration of rare earth precursor was found, to avoid precipitation of the sol. A compromise was therefore required between the target Er concentration and the target Yb : Er ratio. In the demonstration here, the core was doped with 10 mol% P_2O_5 , 2.5 mol% Al_2O_3 , 0.25 mol% Er_2O_3 , and 0.25 mol% Yb_2O_3 , giving an

Fig. 3. Spontaneous emission measurements for a 5-cm-long EDWA with a 4- μm core width, for different values of 980-nm pump power.

asymmetric guide with an index step of $\Delta n \approx 1.5 \times 10^{-2}$ and an Yb : Er ratio of 1 : 1. Amplifiers were also fabricated with an Yb : Er ratio of 3 : 1, but the Er concentration had to be reduced to allow an increased Yb concentration, causing a reduction in overall gain.

Rapid thermal processing was performed in O_2 using an AG Associates Heatpulse 610 rapid thermal annealer. Multiple layers were deposited to yield an overall core thickness of 4 μm and the core was then consolidated at 1000 $^\circ\text{C}$ in a conventional furnace. A surface mask containing guide widths of 3 to 6 μm was then formed from Cr metal and hard baked resist. The cores were then etched in a load-locked reactive ion etching (RIE) system using a mixture of C_4F_8 and He. The etching was carried out at low (1 mtorr) pressure to assist removal of involatile by-products, and hence avoid micromasking. The etch rate of the sol-gel cores was around 300 $\text{\AA}/\text{min}$. Examination of the cross section of the cores showed that a small sidewall slope had arisen from the low-pressure etching.

The cladding was a 16- μm -thick layer of borophosphosilicate glass (BPSG) deposited by PECVD and then consolidated at 950 $^\circ\text{C}$ for 6 h. The maximum overall process temperature was therefore limited to 1000 $^\circ\text{C}$ and the wafer was only exposed to this temperature for a short time. As a result, no crystalline phases appeared to be formed, as evidenced by the low scattering of the guide at visible wavelengths. A transparent layer with a uniform dispersion of Er^{3+} ions was therefore obtained.

Characterization was performed using an optical spectrum analyzer equipped with an internal 1550-nm edge-emitting light-emitting diode (ELED) source (Agilent 86142B). Fig. 3 shows spontaneous emission spectra obtained from 5-cm-long EDWA with a 4- μm -wide core, by pumping using a 980-nm laser diode at different powers. Strong fluorescence was observed, which did not completely saturate even at powers as high as 200 mW. The fluorescence bandwidth was 19 nm [full-width at half-maximum (FWHM)]. Fig. 4 shows single-mode fiber-device-fiber transmission measurements

Fig. 4. Transmission measurements for a 5-cm-long EDWA with a 4- μ m core width, for different values of 980-nm pump power.

Fig. 5. (a) Variation of signal power and spontaneous emission power. (b) Variation of apparent gain and corrected gain, for a 5-cm-long EDWA with a 4- μ m core width.

for the same device, obtained using the ELED source. The background insertion losses are ≈ 1.0 dB and the Er^{3+} ions contribute an additional 7.6-dB loss (corresponding to

1.52 dB/cm) at 1535-nm wavelength. Almost complete inversion is obtained at a pump power of ≈ 175 mW, giving an apparent fiber-device-fiber gain of 5.75 dB and an internal gain of 1.35 dB/cm.

Fig. 5(a) shows the variation of total signal power and spontaneous emission with pump power, for the same device as before. Clearly, the spontaneous emission is a small fraction of the total. However, some correction is required to obtain accurate gain figures. Fig. 5(b) shows the apparent fiber-device-fiber gain obtained from Fig. 4 and the corrected gain after subtraction of the spontaneous emission. Transparency is obtained at a pump power of ≈ 25 mW and a corrected gain of ≈ 5.4 dB is obtained at ≈ 175 mW.

In conclusion, a hybrid sol-gel/PECVD fabrication process has been used to demonstrate a compact silica-on-silicon EDWA with a useful fiber-device-fiber gain. The results obtained represent both the highest external gain for a sol-gel EDWA and the highest internal gain per centimeter to date for a silica-on-silicon device. The high internal gain suggests that this approach may be used to construct modest amplifiers suitable for Metro applications in an in-line configuration, without the need for a folded optical path. Further work is underway to optimize the guide design and the active layer composition to reduce the pump power requirements and tailor the gain spectrum.

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