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Optical amplification and electroluminescence at 1.54 μm in Er-doped zinc silicate germanate on silicon

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Optical amplification and electroluminescence at 1.5 μm is reported in Er-doped $Zn_2Si_{0.5}Ge_{0.5}O_4$ (ZSG:Er) on silicon. ZSG:Er films were deposited by rf sputtering from a composite target in Ar/O_2 mixtures. Channel waveguides were fabricated by plasma etching with Cl/Ar. The refractive index of ZSG:Er was found to be 1.75 at 1.54 μm. Signal enhancement greater than 13 dB and an internal gain of ~2 dB have been achieved by optically pumping a 4.7 cm ZSG:Er amplifier. Electroluminescence at 1.5 μm was achieved using an ac device structure with a ZSG:Er central layer and upper and lower dielectric layers.
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Er-doped waveguide amplifiers (EDWA) combine the potential for large optical gains with small size and the ability to integrate the amplifier with other components such as optical taps (for signal and pump monitoring), splitters, and other common integrated optic components.[1,2] Most waveguide optical amplifier research to date has concentrated on optically pumped rare earth (RE) hosts and semiconductor optical amplifiers, but there has also been interest in electrically pumping impurity based optical amplifiers such as RE-doped Sr.[3] Zinc silicate germanate (ZSG) has been reported[4] to be an excellent host for rare earths and transition metals. We have previously demonstrated[5] the fabrication of optical waveguides and electroluminescent devices using Mn-doped ZSG. In this letter, we report on optically pumped Er-doped ZSG waveguide amplifiers and the achievement of electroluminescence at 1.5 μm.

ZSG:Er films were deposited at room temperature using a Denton Discovery 18 sputtering system. The films were sputtered from a $Zn_2Si_{0.5}Ge_{0.5}O_4$:Er target. The sputtering conditions were 250 W (~5.5 W/cm^2), 40 sccm Ar, 3 sccm Ar/O mixture (80:20), 5 mTorr, and a plasma induced dc bias of −285 V. Films were sputtered at a rate of ~12.5 nm/min. The sputtered films had a 0.1 at.% Er concentration ($\sim 8\times 10^{19}/\mathrm{cm}^3$), as measured by Rutherford backscattering.

ZSG:Er channel waveguides were fabricated using a Cl/Ar-based inductively coupled plasma (ICP) etching. This work was conducted using a PlasmaTherm 790 plasma reactor. The etch mask used consisted of a 1.8-μm-thick layer of Shipley 1818 positive photoresist. An ICP power of 500 W and a rf power of 100 W yielded a smooth morphology (roughness of less than 3 nm), suitable for waveguide testing and material evaluation. The gas flow rates were 15 sccm Cl and 5 sccm Ar. The etch rate under the earlier power conditions and using a 15:5 Cl_2/Ar mixture was ~50 nm/min.

The refractive index variation with wavelength was obtained using a variable wavelength spectroscopic ellipsometer with a 0.27-μm-thick ZSG:Er film on the Si sample. The experimental data were fit using both the Cauchy and Sellmeir models. The Cauchy model is useful for many common dielectric materials and is given by the expression

$$n(\lambda)=A+\frac{B}{\lambda^2}+\frac{C}{\lambda^4}, \quad (1)$$

where A, B, and C are constants to be determined. The Sellmeir model is given by the expression

$$n(\lambda)^2-1=\frac{G_1\lambda^2}{\lambda^2-\lambda_1^2}+\frac{G_2\lambda^2}{\lambda^2-\lambda_2^2}+\frac{G_3\lambda^2}{\lambda^2-\lambda_3^2}, \quad (2)$$

where G_1, G_2, G_3, λ_1, λ_2, and λ_3 are constants to be determined. Both the Cauchy and Sellmeir models delivered standard errors of less than 0.01%, with the Sellmeir model giving a mean standard error approximately 2.5 times greater than the Cauchy model. While the Cauchy coefficients are sufficient for determining the refractive index of ZSG:Er, the Sellmeir coefficients were also determined for comparison with the well known Sellmeir coefficients of pure silica and germanium-doped silica.[6]

The group index of the medium was also determined using the expression

$$N_g=n-\lambda\frac{dn}{d\lambda}, \quad (3)$$

where $dn/d\lambda$ was taken as the derivative with respect to λ of the Cauchy model.

The refractive index and group index of ZSG:Er are shown in Fig. 1 as a function of wavelength, with the Cauchy and Sellmeir coefficients inset. There was no evidence of a point of zero dispersion in the wavelength range of interest; however, the group index is relatively flat in the 1.5 μm regime.

The refractive index of ZSG:Er was also evaluated using the prism coupling method[7] at a wavelength of 633 nm. A planar waveguide structure consisting of 1 μm of ZSG:Er on a 2.5 μm thermal oxide cladding layer was evaluated for this experiment. The refractive index was found to be 1.773 for a TE polarization and 1.774 for a TM polarization. This value is in good agreement with ellipsometric data and with the previously reported refractive index of Mn-doped ZSG thin

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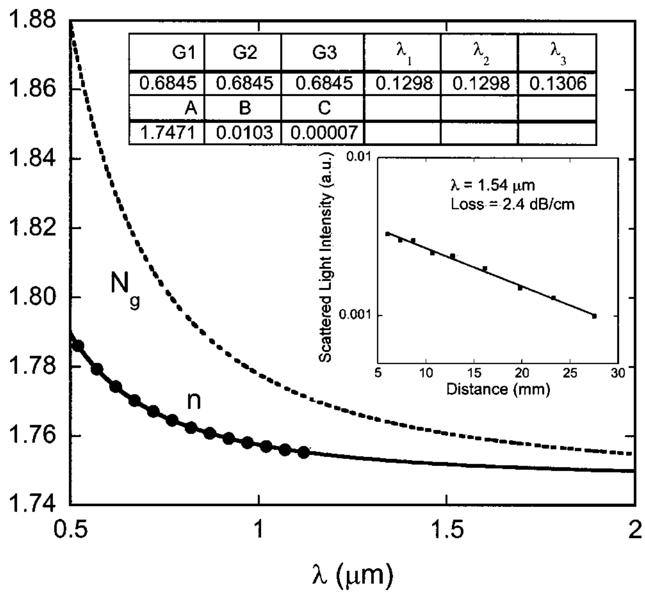

FIG. 1. Refractive index (n) and group index (N_g) of ZSG:Er as a function of wavelength. Inset: Table—Cauchy and Sellmeier coefficients for ZSG:Er; Figure—loss at 1.5 μm is 2.4 dB/cm.

films.[6] High refractive index materials, such as ZSG:Er, are attractive due to the tendency for high index materials to exhibit large emission and absorption cross sections as predicted by the Fuchtbauer–Ladenberg relation and Judd–Ofelt theory.[8] The high index and consequent tighter bending radii will also enable higher density photonic integrated circuits.

Channel waveguide loss measurements were performed at the 1.5 μm peak absorption wavelength with a signal power lying in the small signal gain regime and no applied pump power. The measurement was taken using the well known outscattering technique. The measured loss of 11.3 dB or 2.4 dB/cm (inset Fig. 1) represents the combined effect of absorption and scattering loss of the waveguide amplifier. Similar measurements at 1.3 μm yielded a 0.32 dB/cm loss, which indicates that the effect of absorption is ~2 dB/cm.

A 3.5 μm wide ZSG:Er optical amplifier with a core thickness of 1.1 μm and a length of 4.7 cm was fabricated. The spontaneous emission, signal enhancement, and gain were measured using an optical spectrum analyzer (OSA). The OSA has a resolution of 0.05 nm and exhibits very little polarization dependence. The signal and pump wavelength were combined using a 2×1 multiplexer optimized for the specific wavelengths used. The pump power was supplied by a 974 nm laser diode with a maximum output power of 250 mW. A tunable laser was used to vary the signal wavelength from 1510 to 1570 nm. The input fiber delivering both pump and signal terminates in a fiber lens with a mode field diameter of 9. After traversing the amplifier, the pump and signal are coupled to the OSA through a second lensed fiber focused on the output of the guide. The emission lifetime was measured to be 2.8 ms using time resolved spectroscopy. No evidence of quenching was observed in power dependence measurements.

The ZSG EDWA gain and signal enhancements are shown in Fig. 2 as a function of optical pump power in the input fiber and in the waveguide. The measurements were taken at a wavelength of 1535 nm to achieve a high signal

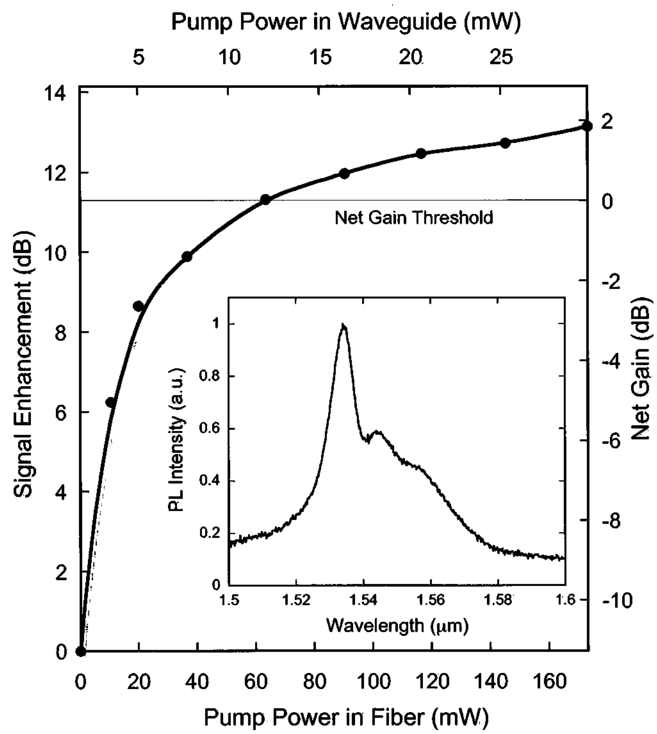

FIG. 2. Signal enhancement and net gain for a 4.7 cm long ZSG:Er EDWA. Inset—spontaneous emission spectrum.

enhancement of 13 dB and an internal gain of 1.86 dB. The spontaneous emission spectra from ZSG:Er are shown in the inset of Fig. 2.

To determine the behavior of the amplifier as a function of input signal power the signal was attenuated over 4 decades. As shown in Fig. 3, the signal enhancement is reduced by 3 dB when the input signal power in the fiber is ~0.4 mW. After accounting for coupling losses it is estimated that the signal saturation power (point of 3 dB gain compression) in the waveguide is ~32 μW. The relatively low saturation power is mainly due to the low Er doping concentration in the ZSG film. Significant increases are expected at higher Er concentrations.

To evaluate the prospects of electrically pumped optical gain, ZSG:Er electroluminescent devices (ELD) were inves-

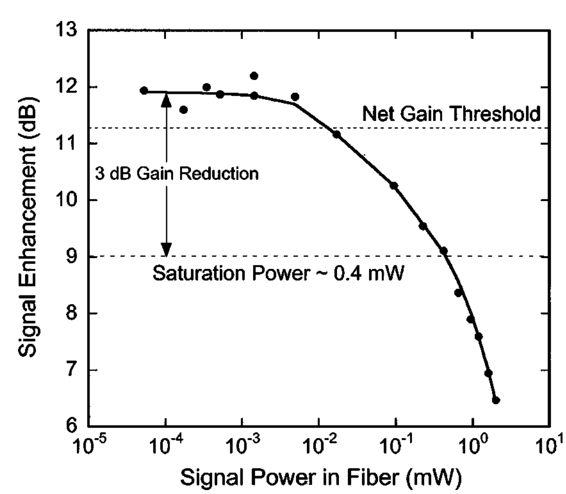

FIG. 3. Signal enhancement as a function of signal strength for a 4.7 cm long ZSG:Er waveguide amplifier.

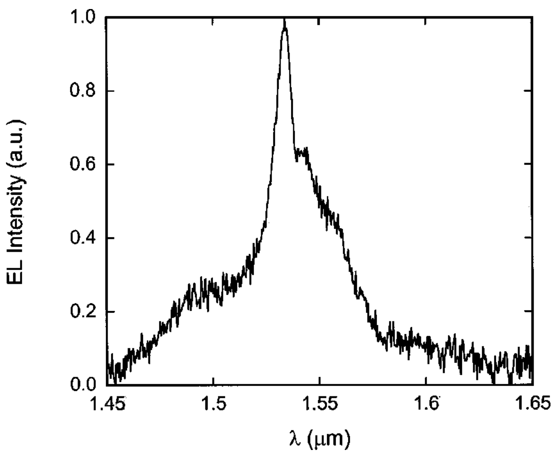

FIG. 4. Electroluminescence spectra for ZSG:Er ELD operated 1 kHz at 280 V.

tigated. The ELD has an ac-coupled structure which is similar to the amplifier structure. ELDs were fabricated using a thick dielectric ($BaTiO_3$) upper layer and a thin dielectric (Al_2O_3) lower layer. The EL spectrum in Fig. 4 was obtained under bias conditions of 280 V and 1 kHz. The electrically pumped emission spectrum is very similar to the optically pumped spontaneous emission spectrum given in Fig. 2. This indicates the electroluminescent optical amplifiers in ZSG:Er are a definite possibility.

In conclusion, we have reported an electroluminescent amplifying medium suitable for integrated optics on a Si platform with an internal gain of ~0.4 dB/cm. We expect that a significantly higher optical gain can be achieved for the $Zn_2Si_{0.5}Ge_{0.5}O_4$:Er system since the Er concentration of our films was 5–10× times smaller than the typical optimum concentration. The ability to fabricate waveguide amplifiers on a Si platform is important for the development of future phonic integrated circuits that incorporate light emitters, photodetectors, signal monitoring devices, and other passive and active components.

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