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DIODE-PUMPED, ION-EXCHANGED ER/YB WAVEGUIDE LASER AT 1.5 μm IN PHOSPHORUS-FREE SILICATE GLASS

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We demonstrate the first diode-pumped, planar Er/Yb waveguide laser. The device was fabricated by thallium-exchange in a phosphorus-free silicate glass. Lasing was achieved with a low threshold of 15 mW, indicating the absence of the severe backtransfer effects previously reported in Er/Yb bulk laser silicate glasses.

Introduction Diode-pumped, short, Er/Yb waveguide lasers are attractive candidates as low-noise 1.5 μm sources for optical communications. Efficient operation of these devices has already been demonstrated in fibre form [1] using phosphosilicate glasses. From the perspective of planar technology, it is of interest to realise similar devices by ion-exchange. Although this technique can be successfully applied to phosphates [2], silicate glasses have superior chemical resistance and are thus more compatible with this fabrication process, and ion-exchanged silicate glass devices are already being deployed in real systems. Historically, the Er/Yb silicate has been deemed as an inefficient energy transfer system due to the backtransfer problems encountered in the realisation of Er/Yb bulk lasers [3]. These laser glasses, originally pumped at 1060 nm, required pump absorption lengths of about 1 mm and thus had high Yb concentrations. The development of 980 nm laser diodes, together with the waveguide geometry, which allows the pump absorption to be distributed over a few centimetres, have made the use of high Yb concentrations unnecessary. Backtransfer problems may not be present to the same extent at lower Yb concentrations.

In this paper we present the first demonstration, to our knowledge, of a diode-pumped, planar Er/Yb waveguide laser operating at 1.5 μm. The laser was realised by thallium-exchange in a phosphorus-free borosilicate glass codoped with 1% Er_2O_3 and 5% Yb_2O_3 by weight. Lasing was achieved at 1536 nm with 15 mW of coupled pump power at 978 nm. The results show that the backtransfer effects observed in Er/Yb bulk laser silicates [3] are not as severe in our glasses, and that they decrease with decreasing Yb concentration.

Energy Transfer Measurements The silicate glass used in our studies was a borosilicate. To study the transfer efficiency of the glass, two glass samples were made; one glass was doped with 1% wt Er_2O_3 and the other one was codoped with 1% Er_2O_3 and 5% Yb_2O_3. The 1.5 μm fluorescence intensity was measured by pumping samples of equal volume with the same intensity at 978 nm. The energy transfer efficiency, η, was then calculated as $R/\left(\sigma^{Yb}N_o^{Yb}/\sigma^{Er}N_o^{Er}\right)$, where R is the ratio of the measured 1.5 μm fluorescence intensities, $\sigma^{Er(Yb)}$ is the Er (Yb) absorption cross section at 978 nm, and $N_o^{Er(Yb)}$ is the Er (Yb) concentration. At low pumping intensities, we obtained $\eta = 45$ % for our glass. Since the cross section ratio, σ^{Yb}/σ^{Er}, was 5.8 at 978 nm, the results showed that the addition of 5% Yb_2O_3 to this glass enhanced the effective erbium small-signal absorption at 978 nm by a factor of 13.

Raman Spectrum Measurements The enhanced fluorescence intensity in the Yb codoped sample was surprising, as we expected strong backtransfer effects in this silicate glass. Since the absence of backtransfer is usually related to high phonon energies in the glass host, we measured the Raman spectrum for our glass. The recorded spectrum, shown in Fig. 1, reveals no features in the high-phonon energy range (1300-1400 cm^{-1}).

Gain Measurements We fabricated waveguides in our Er/Yb codoped borosilicate glass by thallium-ion exchange. The waveguide was 3.4 cm long and had mode dimensions ($1/e^2$) of 7.1 x 5.4 μm at 1550 nm with a cutoff wavelength of 1580 nm. The measured insertion losses (i.e., coupling plus waveguide losses) were 2.2 dB at 1330 nm. Fig 2 shows the measured gain for the Er/Yb waveguide. An internal gain of 1.7 dB was achieved with 26 mW of coupled pump at 978 nm. Fig.2 also shows the gain measured in a 23 cm long waveguide [4] fabricated in the same glass with 0.5 % Er_2O_3 and 0% Yb_2O_3. The results have been scaled to show the expected gain in 6.8 cm of the 23 cm-long guide. The 6.8 cm length was chosen as twice the length of our device to compensate for the 0.5% erbium concentration, and the scaling implicitly assumes similar gain coefficients for both 6.8 cm and 23 cm-long devices. To verify the accuracy of this scaling, we used a comprehensive Er amplifier model [4] to compute the gain expected in a 3.4 cm waveguide of similar dimensions doped with 1% Er_2O_3; this is shown as a solid line in Fig. 2. The results clearly show that the Er/Yb waveguide achieved similar gains with lower pump powers than the Er waveguide.

Laser Characteristics We butted dielectric mirrors against the waveguide ends and measured the lasing characteristics for the Er/Yb waveguide using a 978 nm laser diode as the pump source. Due to uncertainty in the waveguide losses, we used mirrors with 99% reflectance at 1536 nm. Fig. 3 shows the lasing characteristics; the device achieved lasing with 50 mW of incident pump power. Assuming an optimistic coupling efficiency of 30% (including 12% mirror transmission losses at 978 nm), we obtained a threshold of 15 mW coupled pump power and a slope efficiency of 0.15%.

Discussion The measurements presented here indicate that backtransfer effects are not as severe as those reported in Er/Yb bulk laser silicate glasses [3]. To further investigate this issue, we modelled the fluorescence experiments described above, taking into account backtransfer effects. For weak excitations, we find that the energy transfer efficiency is given by

$$\eta \approx \frac{k_{tr} N_o^{Er} \tau_2^{Yb}}{1 + k_{tr} N_o^{Er} \tau_2^{Yb} \left(1 + \tau_{32}^{Er} N_o^{Yb} / \tau_2^{Yb} N_o^{Er}\right)}$$

where k_{tr} is the energy transfer rate (in $cm^3 s^{-1}$) between Yb and Er, τ_{32}^{Er} is the nonradiative lifetime of the ${}^4I_{11/2}$ level in Er, and τ_2^{Yb} is the lifetime of the ${}^2F_{5/2}$ level in Yb. The term $\gamma \equiv \tau_{32}^{Er} N_o^{Yb} / \tau_2^{Yb} N_o^{Er}$ represents the effect of backtransfer, clearly showing that backtransfer decreases with decreasing Yb/Er ratio. This behaviour was confirmed by repeating the energy transfer measurements described above for glasses with different Yb to Er ratios; the results are shown in Fig. 4. We note that this behaviour is not seen in phosphates because $\tau_{32}^{Er} / \tau_2^{Yb}$ in this host is much lower than in silicates [3].

It is clear from Fig. 2 that 15 mW of coupled pump power would not be sufficient to achieve lasing without Yb, thus ruling out the possibility that the laser action is due to direct pumping of Er ions. The low slope efficiency is expected due to the 99% reflectance of the mirrors. From Fig. 2, a 15 mW threshold corresponds to a single-pass cavity loss of 0.7 dB, which for 99% mirrors (0.04 dB loss) yields waveguide losses of about 0.2 dB/cm. With these waveguide losses, it is expected that replacing the 99% mirrors for 90% mirrors will increase the slope efficiency tenfold while still achieving a pump threshold below 20 mW. Optimisation of the Er concentration, Yb/Er ratio, and waveguide length and losses should lead to further improvements in the performance of the device.

Conclusion We have demonstrated the first diode-pumped, planar Er/Yb waveguide laser. The low pump threshold, together with fluorescence intensity and gain measurements, indicate that there are no severe backtransfer effects in these glasses. Raman measurements rule out the possibility that the lack of severe backtransfer effects is due to high-phonon energy components present in this glass.

Thus, our results demonstrate that we can potentially achieve efficient operation of diode-pumped waveguide lasers through energy transfer in silicates using low ratios of Yb to Er concentration. Although it is possible that phosphates may still provide more efficient operation of such devices, the chemical durability of the silicate host may offer many advantages.

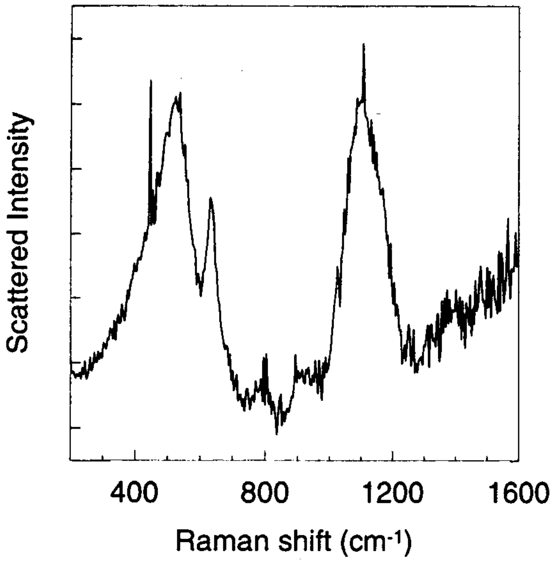

Figure 1. Measured Raman spectrum.

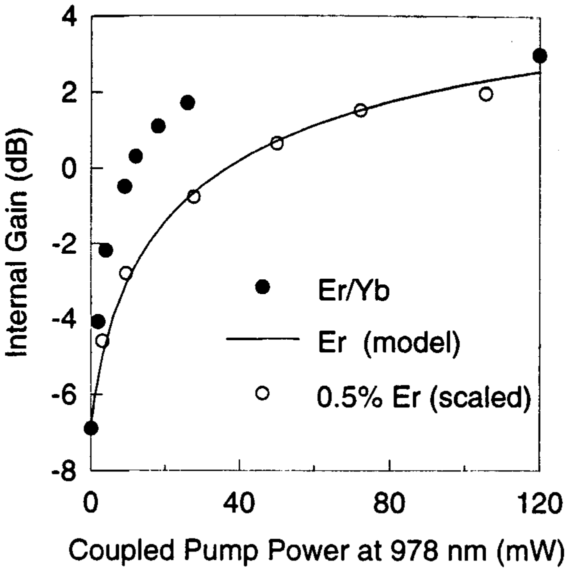

Figure 2. Gain measurement.

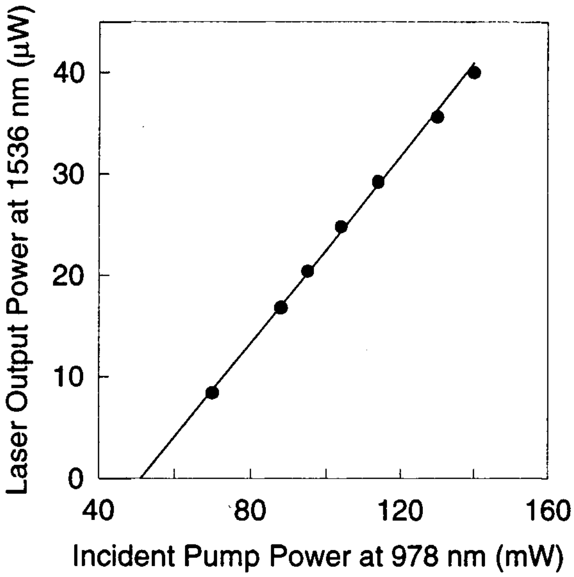

Figure 3. Laser characteristics.

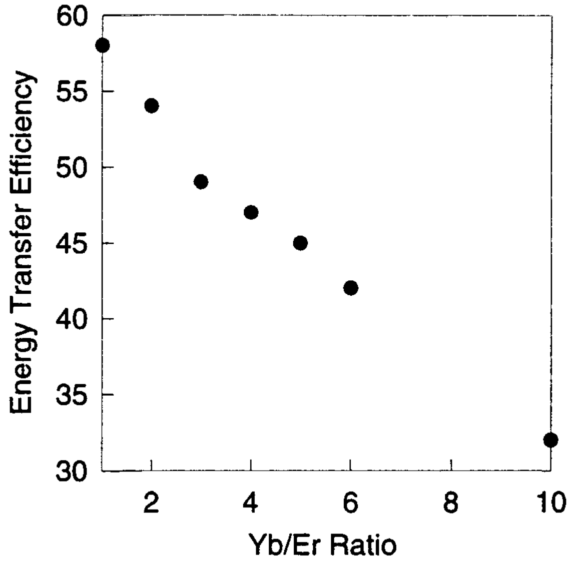

Figure 4. Energy transfer measurements.

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