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# Erbium-Doped Ion-Exchanged Waveguide Lasers in BK-7 Glass

T. Feuchter, E. K. Mwarania, J. Wang, L. Reekie, and J. S. Wilkinson

*Abstract*—**Ion-exchange in glass is a simple, flexible, technique to realize optical fiber compatible planar waveguide devices. Recently, neodymium-doped waveguide lasers operating at 1060 and 1300 nm have been demonstrated in this technology. Lasers operating at 1540 nm are desirable for telecommunication applications and we report here, for the first time, ion-exchanged waveguide lasers in erbium-doped glass emitting at this wavelength. Lasers in BK-7 glass doped with 0.5 wt% $Er_2O_3$ and pumped at 980 nm exhibited launched pump power thresholds of 150 mW and slope efficiencies of 0.55%. The waveguides operated in a single transverse mode at the lasing wavelength.**

## INTRODUCTION

PLANAR waveguide lasers have been realized in several neodymium-doped host materials, using a broad range of waveguide fabrication techniques [1]. The rapid development of erbium-doped silica fiber amplifiers [2] and lasers [3] has resulted in heightened interest in erbium-doped planar waveguide devices. An erbium-doped silica planar waveguide laser on a silicon substrate, fabricated by flame-hydrolysis-deposition [4], and a waveguide laser in $LiNbO_3$ locally doped with erbium [5], have been demonstrated. Planar waveguide devices have the advantages that modulators may readily be monolithically integrated [6], complex multiple-cavity devices may be defined photolithographically [7], and waveguide geometries may be varied along a device for efficient interfacing to external components and optimization of individual components. In addition, the devices are small, stable, and easy to handle.

Ion-exchanged glass waveguides have the advantages that they are simple, inexpensive, rugged, compatible with optical fibers, and employ a very flexible fabrication process with straightforward control over waveguide parameters [8]. Low-threshold ion-exchanged [9] and diffused [10] waveguide lasers have been demonstrated in neodymium-doped glasses, significantly enhancing the functionality of this technology. Recently, low-loss multimode ion-exchanged waveguides were reported in erbium-doped BK-7 glass [11], but no fluorescence characteristics were given. In this letter, we report the demonstration of a potassium ion-exchanged planar waveguide laser operating at 1540 nm in BK-7 glass doped with 0.5 wt% $Er_2O_3$.

## FABRICATION

The substrate material was prepared by mixing small pieces of BK-7 glass with 0.5 wt% $Er_2O_3$ in a platinum crucible placed in an electric furnace at a temperature which was varied between 850° and 1450°C. The melt was kept well mixed, to maintain an uniform distribution of erbium ions in the host. The glass was removed from the furnace at 1300°C, cast into a stainless steel mould, and annealed at 580°C overnight. The sample was left to cool to room temperature in the annealing furnace.

The glass was sliced to dimensions of approximately $50 \times 20 \times 1$ $mm^3$, and one surface polished to electronic quality. A 250 nm thick aluminum film was deposited on this surface by vacuum evaporation, and standard positive photolithography was used to open straight channels varying in width from 1.5 to 7.5 $\mu m$, in steps of 0.2 $\mu m$, in this aluminum mask. Waveguides were fabricated through these channels by immersing the substrate in molten $KNO_3$ at 395°C for 11 h. These conditions were found to result in several waveguides supporting a single transverse mode at 1540 nm. Those waveguides fabricated through mask openings wider than 5 $\mu m$ were double moded at the pump wavelength, whereas those fabricated through narrower channel openings were single moded. After ion-exchange, the endfaces of the substrate were sawn and polished perpendicular to the waveguides, the resulting waveguide lengths being 36 mm. Dielectric mirrors with reflectivities of 90% at 1540 nm, and transmittance of 90% at the pump wavelength were bonded to the polished endfaces using a UV-curing epoxy.

## RESULTS

The absorption spectrum of the bulk glass, measured using a dual-beam spectrophotometer, is shown in Fig. 1. The spectrum shows an absorption of approximately 0.2 dB/cm at 980 nm, and 1.4 dB/cm at 1540 nm. A maximum gain of approximately 1 dB/cm would be expected from this material under full population inversion [12].

The fluorescence emission spectrum of the bulk glass, measured by pumping a sample at a wavelength of 980 nm using a Ti:sapphire laser and observing the resultant output spectrum using an optical spectrum analyzer, is shown in Fig. 2. This spectrum compares well with emission from

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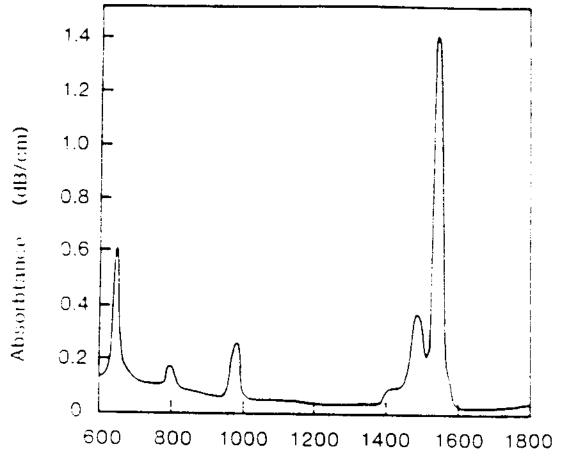

Fig. 1. Absorption spectrum for bulk BK-7 glass doped with 0.5 wt% $Er_2O_3$.

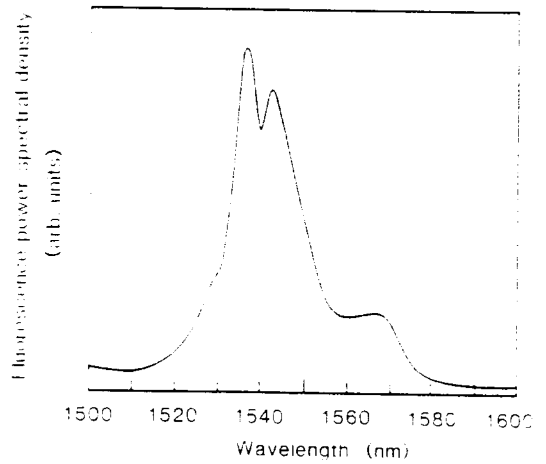

Fig. 2. Fluorescence spectrum for bulk BK-7 glass doped with 0.5 wt% $Er_2O_3$.

other erbium-doped multicomponent-glasses [13], with peaks at 1538 and 1544 nm. The longer wavelength peak in erbium-doped silica occurs at 1555 nm: thus the gain available in erbium-doped BK-7 at longer wavelengths is reduced when compared with silica [13]. The lifetime of the upper lasing level was measured in the bulk sample by mechanically chopping the pump light, and measuring the near-exponential decay of the fluorescence with time. The lifetime was found to be 10 ms.

The waveguide lasers were pumped at a wavelength of 980 nm using a tunable Ti:sapphire laser. The laser emission and the transmitted pump power from the waveguides were measured using an optical power meter. The launched pump power was calculated from the transmitted pump power and the typical waveguide losses of 0.5 dB/cm, assuming negligible absorption from the erbium-ions due to the very high population inversion. The majority of the waveguides made through mask openings greater than 3.5 $\mu$m were found to lase, exhibiting estimated launched pump power thresholds between 150 and 300 mW. The wider waveguides were found to exhibit lower thresholds. Those smaller than 3.5 $\mu$m did not lase. Absence of lasing in waveguides made through channel openings less than 3.5 $\mu$m is attributed to imperfections in the fabrication process, which increased the waveguide losses, and to the loss of waveguiding for very narrow channel openings. A laser characteristic, showing total laser output power (the sum of that emitted through the 10% transmitting mirrors at both ends) against estimated launched pump power, for the waveguide fabricated by diffusion through a 7.3 $\mu$m channel opening, is shown in Fig. 3. This represents the waveguide laser with the lowest threshold. The threshold is approximately 150 mW, and the slope efficiency approximately 0.55%, with respect to the launched pump power. The maximum output power measured was 0.40 mW when the launched pump power was 270 mW.

The lasing spectrum shown in Fig. 4 was measured using an optical spectrum analyzer, when the launched pump power was approximately 250 mW. The spectrum shows a single peak at 1538 nm and a double peak at 1544 nm: these wavelengths correspond to the maxima in the fluorescence spectrum. At pump powers just above threshold, only the double peak at 1544 nm has sufficient gain to oscillate. Lasing at around 1600 nm has been reported in erbium-doped silica waveguide lasers [4]. In the device reported here, insufficient gain was available at 1600 nm to allow lasing [3], [13], causing oscillation at the peaks of the fluorescence spectrum around 1540 nm.

## DISCUSSION

The realization of erbium-doped waveguides in glass permits fabrication of integrated laser sources operating at wavelengths around 1540 nm. These devices are attractive for application in the field of telecommunications, as 1540 nm is the wavelength of minimum attenuation in single mode silica fibers for transmission. The lasers described in this letter were designed to operate around this wavelength.

The threshold with respect to launched power is somewhat high because

a) in a three-level laser system such as Er glass operating at 1540 nm, population inversion between the ground state and the upper laser level must reach 50% before any gain to overcome the cavity losses can be achieved;
b) the pump absorption is low (< 8% of launched power, assuming 50% population inversion), and
c) the waveguide and mirror-butting losses are not optimized.

As cavity losses are of the order of the available gain, the population inversion of the erbium-ions must be high, reducing the amount of pump power absorbed by erbium-ions in the ground state. Assuming 5% pump absorption, the threshold with respect to absorbed pump power may be estimated as 7.5 mW and slope efficiency as 11%, which compares well with other work [4], [5]. The launched pump power threshold and slope efficiency may be further optimized with respect to the erbium concentration. However, significant cooperative upconversion will occur when the amount of erbium exceeds a certain concentration [14]. Erbium-doped BK-7 glass has not yet been characterized with respect to this effect, and new host-glass compositions may exhibit im-

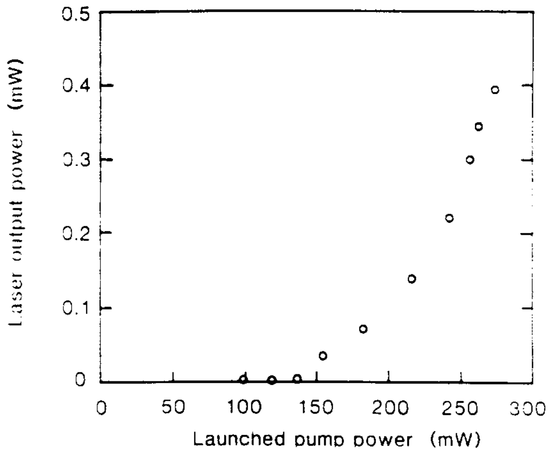

Fig. 3. Lasing characteristics of waveguide laser fabricated through a 7.3 μm channel opening.

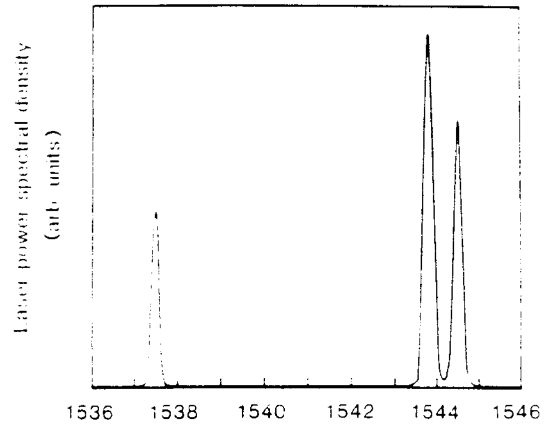

Fig. 4. Lasing spectrum at a pump power of 270 mW.

proved properties. Other approaches to improving performance include reflecting the pump back into the cavity from the output mirror to increase the absorbed power [5] and optimization of device parameters with respect to channel opening, diffusion depth, waveguide length, and mirror reflectivity/transmittivity.

## CONCLUSION

We have demonstrated erbium-doped ion-exchanged glass waveguide lasers for the first time. The substrate material was BK-7 glass doped with 0.5 wt% $Er_2O_3$, and the laser exhibited a threshold of approximately 150 mW, and a slope efficiency of 0.55%, with respect to launched pump power. Improvements in performance may be expected with reduced waveguide and mirror losses, optimized parameters, suitably modified host material, and improved launched pump power absorption within the cavity. The excellent noise performance inherent in the Er/glass laser system leads us to believe that this technology will yield very narrow linewidth fiber-compatible sources for long distance telecommunication systems.

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