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Ion-Exchanged Waveguide Amplifier in Erbium-Doped Glass for Broad-band Communications

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We discuss the fabrication, characterisation and modelling of planar erbium-doped amplifiers realised as ion-exchanged waveguides in glass.

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Introduction

Integrated optical circuits have the potential to be inexpensive devices suitable for mass manufacture, with complex functionality and reproducible properties. In optical networks such as those envisioned for digital telephony in Germany and for CATV services, optical power is exhausted at the curb, and the signal from an optical channel termination must be carried electrically to a number of end users. The EU RACE project R2109 LIASON has proposed a "lossless splitter," combining an upstream amplifier section and a downstream splitter to extend the optical network into customer premises [1]. The combination of stringent fabrication tolerances and a large potential market makes an integrated optical circuit an ideal solution. In the LIASON project this circuit will be realised using ion-exchanged waveguides in a dual glass substrate, one portion - the amplifier section - doped with erbium and the other undoped. The most stringent requirements arise from the 1x16 CATV lossless splitter [1], which demands a gain of about 13 dB and a noise figure of better than 5.4 dB for a coupled 980 nm pump power of 70 mW. We describe here the status of our development of the amplifying portion of this device.

Design considerations

Compared to fiber devices, planar waveguides have high propagation losses, so that an erbium amplifier must be relatively highly doped and short in order to perform well. Given this requirement for high doping levels, we need a glass host that minimises the well-known problems of clustering and uniform upconversion.

The erbium-doped amplifier employs a quasi-3-level energy level structure, so that the use of a bulk host incurs reabsorption losses which reduce the net gain and increase the noise figure. For this reason, most planar erbium-doped devices reported to date [2,3] utilize the etching of thin doped films to define waveguides in which the erbium ions are confined to the core. However, the effect of reabsorption may be greatly mitigated by using very tightly confined waveguide modes. Moreover, with the ion-exchange technique we have fabricated waveguides with propagation losses below 0.05 dB cm^{-1} in undoped waveguides. This is significantly lower than for etched guides with inherently higher roughness.

Amplifier Fabrication and Waveguide Characterization

We used as substrates polished borosilicate glass wafers doped with 0.5 wt% Er_2O_3 (3.95×10^{19} Er^{3+} cm^{-3}). We have studied a number of candidate host materials; this glass has been selected because it showed no tendency to clustering or phase separation, and the uniform upconversion coefficient is expected to be low [4].

The waveguides were fabricated by a 2-step diffusion process in molten salt baths. In the first step, Tl^{+} indiffusion through a mask produced waveguide structures, which were then buried by a second field-assisted and maskless exchange to improve the propagation loss and mode profile. The maximum refractive index difference is approximately 1.5%, which permits a waveguide bend radius as low as 10 mm without significant additional losses.

Waveguides of length 23 cm, with the layout shown in fig. 1, and 45 cm were made. The 23 cm guide had a cutoff at 1240 nm, and an insertion loss of 4.3 dB (including coupling losses) as measured at 1310 nm with standard monomode SMF28 fibers. The 45 cm guide had an insertion loss of 8.2 dB at the same wavelength. This indicates propagation losses of about 0.18 dB cm^{-1} and coupling losses of the order of 0.3 dB.

The erbium aborption spectrum in the 1450-1570 nm range was determined by two methods; from the absorption of the emission from a tunable laser diode and from the transmission spectrum of white light as measured with a monochromator. The two methods were in good agreement, and the peak absorption at about 1537 nm was 23.5 dB in the 23 cm guide.

The mode profiles of the waveguides were measured by imaging the near-field; at 1550 nm (980 nm), the diameter at $1/e^2$ intensity was 8.5 μm (7 μm) in the direction parallel to the surface, and 6 μm (5μm) in the depth direction.

Amplifier performance

We have measured the gain of the 23 cm device at 1537 nm for pump wavelengths of 980 nm and 1480 nm. Fig. 2 shows the internal gain (ratio of signal intensity with and without pump minus signal absorption without pump) versus transmitted 980 nm pump power (for 40 mW of transmitted power the incident power was 230 mW). We obtained a maximum internal gain of about 10 dB, corresponding to about 6 dB net gain. Pumping with 50 mW incident power at 1480 nm, we observed approximately 5 dB internal gain, for a negligible net gain.

Modelling the amplifier performance

We have developed a comprehensive numerical model for the amplifier, which includes the effects of uniform upconversion and clustering, as well as forward and backward ASE and pump and signal saturation. It accounts for the mode profiles, assuming Gaussian intensity distributions. Uniform upconversion is incorporated as a quadratic term in the rate equations.

As inputs to this model, we have determined the appropriate absorption and emission spectra, and estimated the uniform upconversion coefficient σ_{UC} from spectroscopic measurements [4]. In the context of the pair-induced-quenching model [5], we have an upper limit for the clustering fraction f_c of less than 0.1 (i.e. <10% of ions are in clusters).

We have indicated on fig. 2 the modelled gain when pumping at 980 nm, under different assumptions about the uniform upconversion coefficient and the level of clustering. These differing assumptions reflect our uncertainty about these quantities, but it must be noted that some of the other parameters, such as waveguide losses at 980 nm and the exact modal profiles, also have non-negligible uncertainty. Given these uncertainties, we conclude that the model is in reasonable agreement with the data, although its predictions are reliable only to within about ±2 dB at the highest pump powers used.

Conclusion

For the first time in an ion-exchanged waveguide format, we have fabricated long, low-loss guides which show appreciable net gain when pumped at 980 nm. This performance is comparable with 10 dB for 280 mW of pump power in sputtered guides [2] but inferior to the 27 dB for 264 mW of pump achieved in flame-hydrolysis deposited guides [3].

Although promising, the performance as yet falls far short of that required for the intended CATV application. We are currently working to make substantial improvements by exploiting the high index change - up to 0.1 - possible with Tl^+ ion exchange to make much more tightly confined modes. We also anticipate that detailed study of the fabrication conditions, combined with the use of an overlay, will enable us to reduce the signal propagation losses towards the values we have achieved in undoped guides, of less than 0.05 dB cm^{-1}.

Acknowledgements

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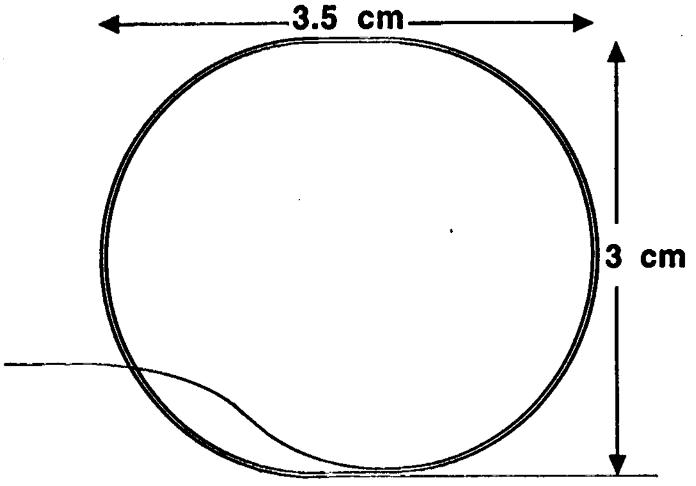

Fig. 1: Scheme of 23 cm waveguide layout

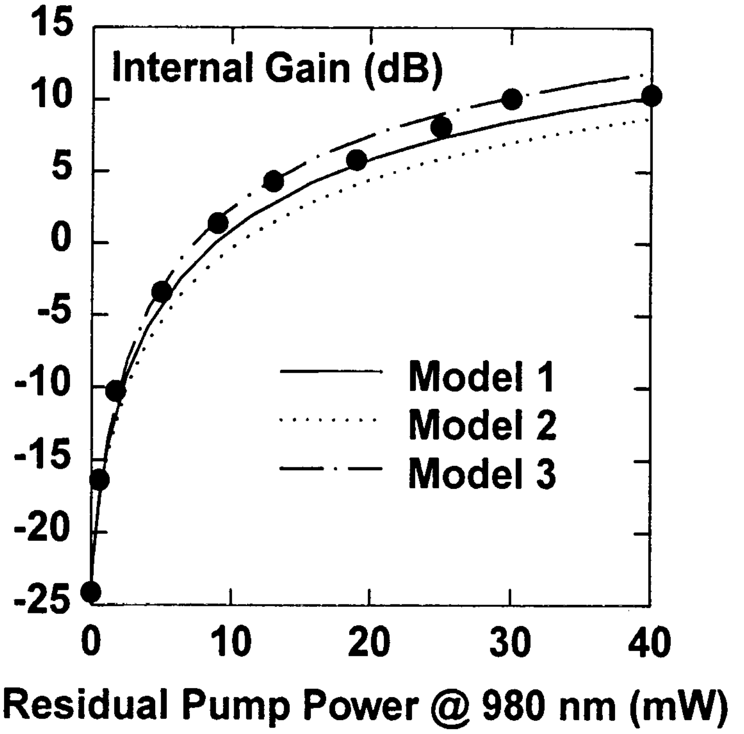

Fig. 2: Internal gain. Model parameters:

1: f_c= 0.05, σ_{UC}=2x10^{-18} cm^3 s^{-1}

2: f_c= 0.1, σ_{UC}=3x10^{-18} cm^3 s^{-1}

3: f_c= 0.0, σ_{UC}=1x10^{-18} cm^3 s^{-1}