Submitted to IEEE Photonics Technology Letters
1397 Feb. '97

Proposal for an Er^{3+}-doped chalcogenide glass fiber upconversion laser operating at 980nm and pumped at 1480nm

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Abstract: We propose a novel fibre upconversion laser operating at 980nm and pumped at 1480nm, which will allow remote optical pumping of erbium-doped optical amplifiers. From the measured spectroscopy, we show Er^{3+}-doped gallium lanthanum sulphide glass to be a potential host for such a 1480nm/980nm upconversion laser. The small-signal gain is analyzed numerically and the lasing possibilities are discussed.

Introduction: Gallium lanthanum sulphide (Ga:La:S) glasses have a very low maximum phonon energy (~425cm^{-1}) and high refractive index (2.36 at 1μm), as well as high solubility for rare earths [1, 2]. The detailed glass compositions and spectroscopic properties of Er^{3+}:Ga:La:S have recently been measured [3]. As a consequence of these properties, when an Er^{3+}-doped Ga:La:S glass fibre is pumped at 1480nm, 980nm lasing is possible. Such a 1480nm → 980nm upconversion fibre laser could have applications in Er^{3+}-doped amplifiers in cases where it is desirable to combine the remote pumping capability at 1480nm with the high signal-to-noise-ratio amplification obtainable with 980nm pumping. In this letter, we show through numerical modelling based on our previous spectroscopic measurements that such a laser is feasible in Er^{3+}-doped Ga:La:S fibre.

Laser modelling: When Er^{3+}:Ga:La:S is pumped at 1480nm, the upper laser level ($^4I_{11/12}$) is populated through cooperative upconversion, an energy-transfer process between two erbium ions at the $^4I_{11/2}$ level, resulting in one Er^{3+} ion (donor) decaying to the ground state, while another (acceptor) is excited to the $^4I_{9/2}$ level. Most of the acceptors thus excited will quickly relax to the $^4I_{11/2}$ level. Since the lifetime of the $^4I_{11/2}$ level and the 980nm radiative decay ($^4I_{11/2} \rightarrow {}^4I_{15/2}$) rate in Ga:La:S greatly exceed those in other host glasses, population inversion between levels $^4I_{11/2}$ and $^4I_{15/2}$ becomes possible, and 980nm lasing may be realized. The fluorescence spectrum for the $^4I_{11/2} \rightarrow {}^4I_{15/2}$ decay is shown in fig. 1; the intensity at 980nm is close to the peak value found at slightly longer wavelengths.

In modelling the gain, we consider only uniform cooperative upconversion, and ignore the possibility of clustering. As the uniform upconversion constant for this glass has not yet been experimentally determined, a range of values is used in the calculation. These values are comparable to those of silicate glasses [4]; we neglect possible enhancement in the upconversion (and hence in laser operation) due to the higher index of the Ga:La:S glass. The possible effects of inverse energy transfer [3] are also considered.

For Er^{3+}:Ga:La:S fibres, the background loss may not be neglected. A typical value of 10dB/m is assumed. The $^4I_{9/2} \rightarrow {}^4I_{13/2}$ transition rate, R_{42}, is an order of magnitude lower than that of the $^4I_{9/2} \rightarrow {}^4I_{11/2}$ transition rate, R_{43}, and is neglected.

The behaviour of the Er^{3+}:Ga:La:S fibre laser can be described in terms of rate equations for the population densities of the lowest four energy levels. Assuming a uniform dopant and field distribution across the fibre core [5], the rate equations at a given position along the fibre can be written as:

$$\frac{dN_2}{dt} = W_p\left(N_1 - \frac{1}{\beta_p}N_2\right) - W_{ASE}\left(N_2 - \beta_{ASE}N_1\right) + R_{32}N_3 - \frac{N_2}{\tau_2} - 2CN_2^2 + 2\xi CN_1N_4 \qquad (1)$$

$$\frac{dN_3}{dt} = -\frac{N_3}{\tau_3} + R_{43}N_4 - W_s\left(N_3 - N_1\right) \qquad (2)$$

$$\frac{dN_4}{dt} = -\frac{N_4}{\tau_4} + CN_2^2 - \xi CN_1N_4 \qquad (3)$$

$$N_T = N_1 + N_2 + N_3 + N_4 \qquad (4)$$

with N_i, τ_i: are the population density and lifetime respectively of energy level i (i=1, 2, 3, 4, refer respectively to $^4I_{15/2}$, $^4I_{13/2}$, $^4I_{11/2}$ and $^4I_{9/2}$ levels)

R_{ij} : transition rate from energy level i to level j

C, (ξ C): constants for the upconversion and inverse transfer

β_p, β_{ASE}: ratio of absorption to emission cross sections at pump wavelength and at 1.54μm;

W_p: pump rate;

W_s, W_{ASE}: stimulated emission rates at 980nm and at 1.54μm.

The population densities and pump and emission rates depend on the longitudinal position along the fibre. The evolution of the pump field, the forward/backward 980nm lasing field, and forward/backward amplified 1.54μm spontaneous emission (ASE) can be described by equations similar to those given in [5].

The overlap factors for 1540nm ASE, pump and 980nm signal are taken, respectively, to be 0.82, 0.83 and 0.93 in the fibre of 4μm diameter core, while all overlap factors are assumed to be unity in the fibre of 10μm diameter core. The 1.54μm ASE bandwidth $\Delta\nu$ is assumed to be

2nm. Noting the significant discrepancy between the measured lifetime of the 800nm fluorescence from the $^4I_{9/2}$ level and the calculated lifetime τ_4 [3], the transition rate R_{43} from level 4 to level 3 is assumed to be 1430 s^{-1}. Other optical parameters have been given in [3].

Fig. 2 shows the predicted single-pass small-signal gain versus 1480nm pump power for a fibre of 5cm length doped with $4x10^{20}$ Er^{3+}/cm^3. We can see that the gain is very sensitive to the diameter of the fibre. A small fibre core is essential to realize high pump intensity. For a fibre of 4μm core, and with $C=4x10^{-24}$ m^3/s, the gain is over 5dB when launched pump power is 190mW, increasing to 8dB if $C=8x10^{24}$ m^3/s. The effect of the uncertainty in the inverse energy transfer was examined via a calculation of small-signal gain for a given pump power (300mW). As shown in Fig. 3, when the ratio ξ increases from 0 to 1, the gain decreases by about 1dB.

For a fixed pump power of 300mW, the dependence of small-signal gain on Er^{3+} concentration was calculated for fibres of 8cm and 5cm, as shown in Fig. 4. It is seen that high Er^{3+} concentration is required to obtain a reasonably high gain, reflecting the fact that the upper laser level is populated through Er^{3+} ion-ion energy transfer.

The above numerical results demonstrate that it is indeed feasible to develop an upconversion fibre laser operating at 980nm pumped at 1480nm. The requirement of pump power will be eased as the background loss is decreased.

Laser characteristics: Much experimental effort is currently being devoted to the realisation of single-mode fibres in rare-earth-doped Ga:La:S glass, and a low-loss multimode fibre has recently been demonstrated[6].The calculations above indicate the feasibility of obtaining significant net gain in a tightly confined Er^{3+}:Ga:La:S fibre. In terms of absorbed pump power and ignoring propagation loss, the laser slope efficiency will ultimately be determined by the branching ratio of the $^4I_{9/2} \rightarrow {}^4I_{11/2}$ transition, which is estimated to be around 80%. The dependence of absorbed power on incident power is controlled by fibre length and mirror losses. For the 5cm 5dB fibre example given here, the single-pass power absorption is 1.1dB. Thus we can expect a slope efficiency of 5% for 980nm output power versus 1480nm incident power with most of the pump power passing straight through. With a double-pass pumping configuration, the slope efficiency could be improved. The performance of such a device would be enhanced by filtering of the 1.54μm ASE, which would also help prevent parasitic lasing at this wavelength.

Conclusion: When an Er^{3+}-doped Ga:La:S fibre is pumped at 1480nm, population inversion between levels $^4I_{11/2}$ and $^4I_{15/2}$ can be built up and 980nm lasing can be realized. Based on the measured spectral properties of Er^{3+}-doped Ga:La:S glass, a numerical model was developed to analyze the 980nm light amplification in the fibre. The calculated small-signal gain at 980nm is high enough to construct a fibre laser. The overall slope efficiency of such a laser could be optimized by double-pass pumping configuration, and by filtering the 1.54μm ASE, as well as by optimizing the fibre length and mirror coupling.

Acknowledgements

The Optoelectronics Research Centre is an Interdisciplinary Research Centre partly funded by a grant from the UK EPSRC.

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Figure captions:

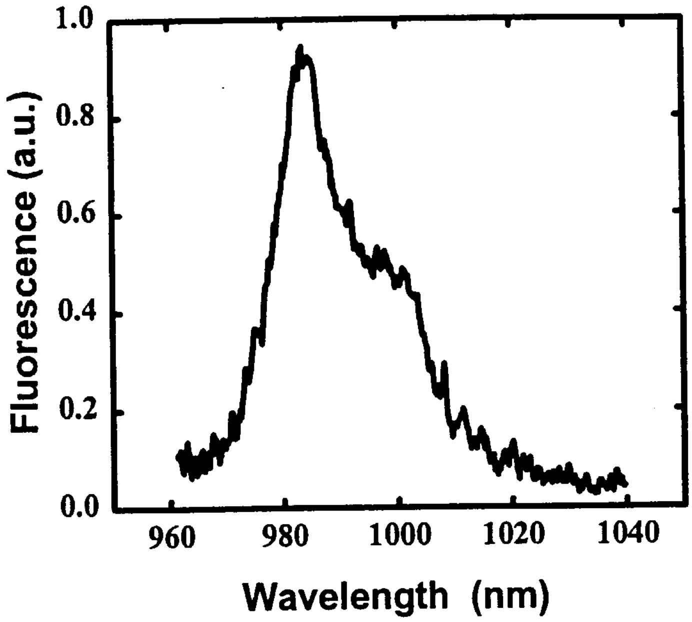
Fig.1 Spectrum of upconversion fluorescence in the 980nm region

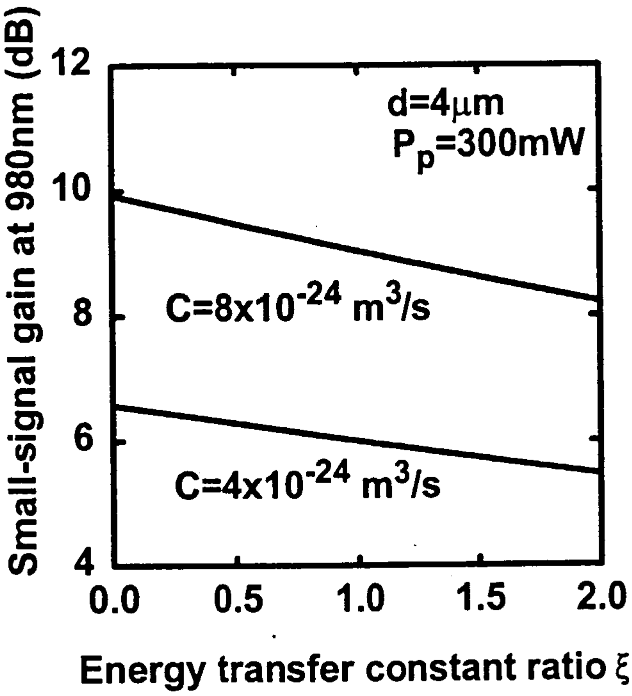
Fig.2 Small-signal gain at 980nm versus pump power when ratio $\xi=0.3$

Fig.3 Small-signal gain versus ratio ξ when pump power $P_p=300mW$

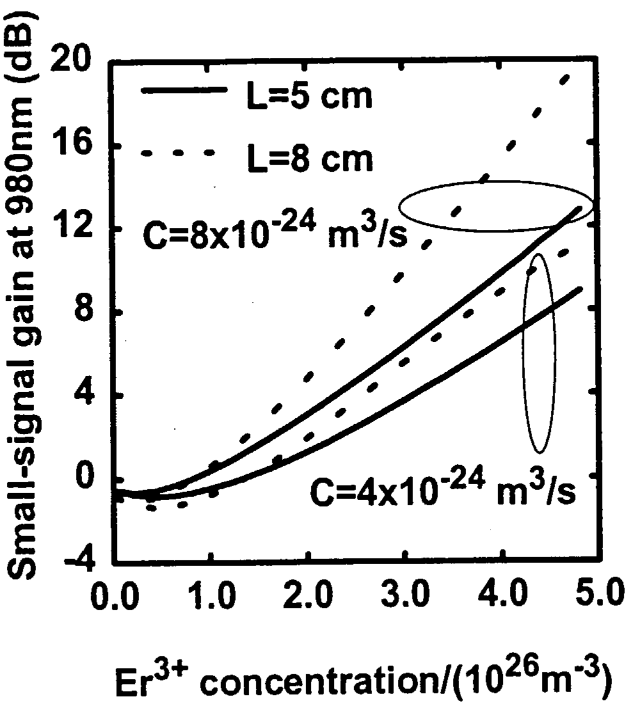
Fig.4 Small-signal gain at 980nm versus Er^{3+} concentration

Fibre core diameter d=4μm, $\xi=0.3$, launched pump power $P_p=300mW$

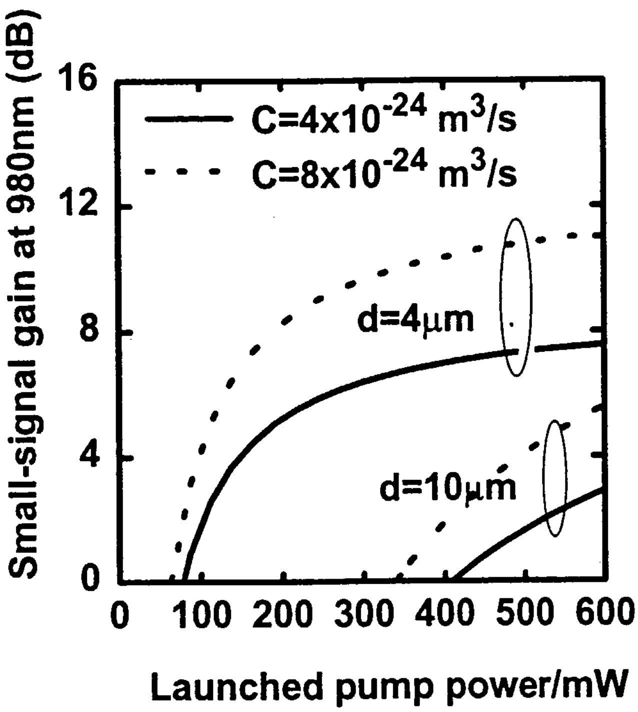

1.0
0.8
0.6
0.4
0.2
0.0
Fluorescence (a.u.)
960
980
1000
1020
1040
Wavelength (nm)



d=4μm
Pp=300mW
C=8x10-24 m3/s
C=4x10-24 m3/s
Small-signal gain at 980nm (dB)
12
10
8
6
4
0.0
0.5
1.0
1.5
2.0
Energy transfer constant ratio ξ



Small-signal gain at 980nm (dB)
20
16
12
8
4
0
-4
L=5 cm
L=8 cm
C=8x10^{-24} m^3/s
C=4x10^{-24} m^3/s
0.0
1.0
2.0
3.0
4.0
5.0
Er^{3+} concentration/(10^{26}m^{-3})



Small-signal gain at 980nm (dB)
16
12
8
4
0
C=4x10^-24 m^3/s
C=8x10^-24 m^3/s
d=4μm
d=10μm
0
100
200
300
400
500
600
Launched pump power/mW