Proposal for an Er^{3+}-Doped Chalcogenide Glass Fiber Upconversion Laser Operating at 980 nm and Pumped at 1480 nm

C. C. Ye, M. Hempstead, D. W. Hewak, and D. N. Payne

***Abstract*—We propose a novel fiber upconversion laser operating at 980 nm and pumped at 1480 nm, 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 1480-nm/980-nm upconversion laser. The small-signal gain is analyzed numerically and the lasing possibilities are discussed.**

***Index Terms*—Chalcogenide glasses, erbium materials/devices, optical fiber amplifiers, modeling.**

I. INTRODUCTION

GALLIUM lanthanum sulphide (Ga:La:S) glasses have a very low maximum phonon energy ($\sim$425 cm^{-1}) and high-refractive index (2.36 at 1 μm), 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 fiber is pumped at 1480 nm, 980-nm lasing is possible. A 1480-nm/980-nm upconversion fiber laser could have applications in Er^{3+}-doped amplifiers in cases where it is desirable to combine the remote pumping capability at 1480 nm with the high signal-to-noise-ratio (SNR) amplification obtainable with 980 nm pumping. Similar schemes with other transitions have already been operated in Er^{3+}-doped crystals [4], [5]. Here we show through modeling based on our previous spectroscopic results that such a laser is feasible in Er^{3+}-doped Ga:La:S fiber.

II. LASER MODELING

When heavily doped Er^{3+}:Ga:La:S is pumped at 1480 nm, the upper laser level is populated through cooperative upconversion, an energy-transfer process between two erbium ions at the $^4\mathrm{I}_{13/2}$ level, resulting in one Er^{3+} ion (donor) decaying to the ground state, while another (acceptor) is excited to the $^4\mathrm{I}_{9/2}$ level. Most of the acceptors thus excited will quickly relax to the $^4\mathrm{I}_{11/2}$ level. Since the lifetime of the $^4\mathrm{I}_{11/2}$ level and the 980 nm radiative decay ($^4\mathrm{I}_{11/2} \rightarrow {}^4\mathrm{I}_{15/2}$) rate in Ga:La:S greatly exceed those in other host glasses, population inversion between levels $^4\mathrm{I}_{11/2}$ and $^4\mathrm{I}_{15/2}$ becomes possible, and 980-nm lasing may be realized. The fluorescence spectrum for the $^4\mathrm{I}_{11/2} \rightarrow {}^4\mathrm{I}_{15/2}$ decay is shown in Fig. 1; the intensity at 980 nm is close to the peak value found at slightly longer wavelengths, so that laser action at desired optical amplifier pump wavelengths can be achieved with suitable mirrors.

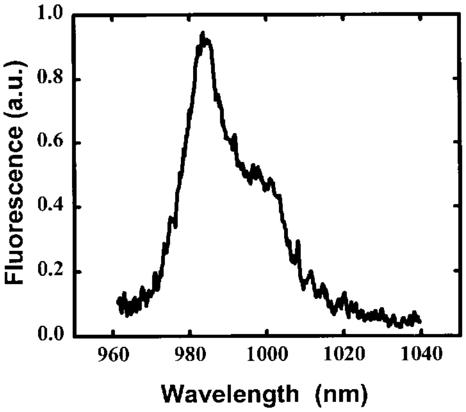

Fig. 1. Spectrum of upconversion fluorescence in the 980-nm region.

In modeling, the gain we consider only uniform cooperative upconversion, and ignore the possibility of nonrandom clustering of the ions. 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 [6]; we neglect possible enhancement in the upconversion (and hence in laser operation) due to Lorentz–Lorenz-type local field effects in the higher index Ga:La:S glass. The possible effects of inverse energy transfer [3] are also considered.

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

The behavior of the Er^{3+}:Ga:La:S fiber laser can be described in terms of rate equations for the population densities

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of the lowest four energy levels. Assuming a uniform dopant and field distribution across the fiber core [7], the rate equations at a given position along the fiber can be written as

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

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

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

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

with

N_i, τ_i	population density and lifetime, respectively, of energy level i (i = 1, 2, 3, 4, refer, respectively, to $^4\mathrm{I}_{15/2}$, $^4\mathrm{I}_{13/2}$, $^4\mathrm{I}_{11/2}$ and $^4\mathrm{I}_{9/2}$ levels);
R_{ij}	transition rate from energy level i to level j;
C, (ξC)	constants for the upconversion and inverse transfer;
β_p, β_{ASE}	ratio of absorption to emission cross sections at pump wavelength and at 1.54 μm;
W_p	pump rate;
W_s, W_{ASE}	stimulated emission rates at 980 nm and at 1.54 μm.

The absorption rate at 980 nm is assumed equal to the emission rate. The population densities and pump and emission rates depend on the longitudinal position along the fiber. The evolution of the pump field, the forward/backward 980-nm lasing field, and forward/backward amplified 1.54-μm spontaneous emission (ASE) can be described by equations similar to those given in [7].

The overlap factors [7] for 1540 nm ASE, pump and 980-nm signal are taken, respectively, to be 0.82, 0.83, and 0.93 in the fiber of 4-μm diameter core, while all overlap factors are assumed to be unity in the fiber of 10-μm diameter core. The 1.54-μm ASE bandwidth is assumed to be 2 nm. Noting the significant discrepancy between the measured lifetime of the 800-nm fluorescence from the $^4\mathrm{I}_{9/2}$ level and the calculated lifetime τ_4 [3], the transition rate R_{43} from level 4 to level 3 is assumed to be the average measured value of 1430 s^{-1}. Other optical parameters have been given in [3].

Fig. 2 shows the predicted single-pass small-signal gain versus 1480-nm pump power for a fiber of 5-cm length doped with 4 × 10^{20} Er^{3+}/cm^3. We can see that the gain is very sensitive to the diameter of the fiber. A small fiber core is essential to realize high pump intensity. For a fiber of 4-μm core, and with $C = 4 \times 10^{-24}$ m^3/s, the gain is over 5 dB when launched pump power is 190 mW, increasing to 8 dB if $C = 8 \times 10^{24}$ 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 (300 mW). As shown in Fig. 3, when the ratio ξ increases from 0 to 1, the gain decreases by about 1 dB.

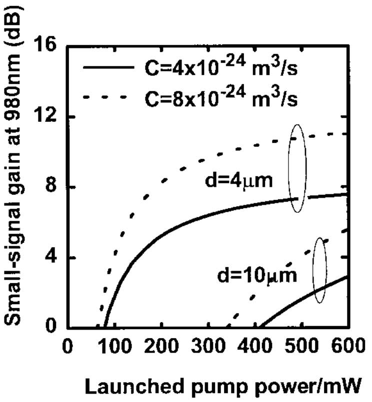

Fig. 2. Small-signal gain at 980 nm versus pump power when ratio ξ = 0.3.

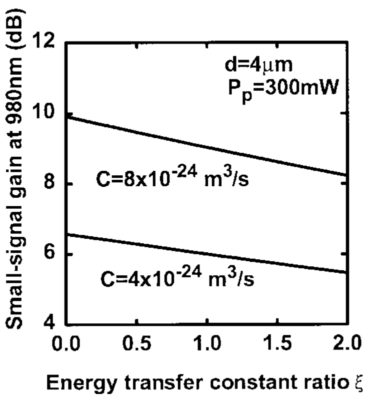

Fig. 3. Small-signal gain versus ratio ξ when pump power P_p = 300 mW.

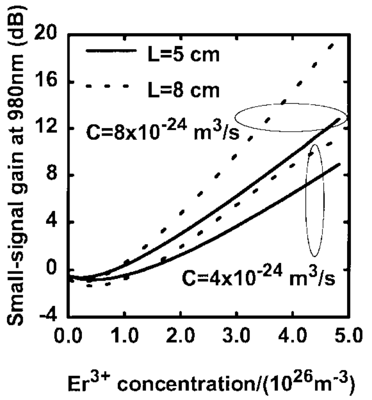

Fig. 4. Small-signal gain at 980 nm versus Er^{3+} concentration. Fiber core diameter d = 4 m, ξ = 0.3, launched pump power P_p = 300 mW.

For a fixed pump power of 300 mW, the dependence of small-signal gain on Er^{3+} concentration was calculated for fibers of 8 cm and 5 cm, as shown in Fig. 4. It is seen that high Er^{3+} concentration favors high gain, because 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 fiber laser operating at 980 nm pumped at 1480 nm. The requirement of pump power will be eased as the background loss is decreased, although the gain/unit length is sufficiently high that the losses are not a dominant factor.

III. LASER CHARACTERISTICS

Much experimental effort is currently being devoted to the realization of single-mode fibers in rare-earth-doped Ga:La:S glass, and a low-loss multimode fiber has recently been demonstrated [8].The calculations above indicate the feasibility of obtaining significant net gain in a tightly confined Er^{3+}:Ga:La:S fiber. 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 fiber length and mirror losses. For the 5-cm/5-dB fiber example given here, the single-pass power absorption is 1.1 dB. Thus we can expect a slope efficiency of 5% for 980-nm output power versus 1480-nm 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 1.54-μm ASE, which would also help prevent parasitic lasing at this wavelength. The maximum power output of the laser will be limited by "bottlenecking" in the upconversion and the $^4I_{9/2} \rightarrow {}^4I_{11/2}$ transitions, which have maximum rates of CN_T and R_{43}, respectively. Thus, a fiber of 0.1-m length, 10-μm-core diameter, and $N_T = 2.5 \times 10^{26}\text{m}^{-3}$ has an output power limit of about 500 mW.

IV. CONCLUSION

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

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