Z-scan Measurement of Upconversion in Er:YAG

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Introduction

Cooperative, or energy-transfer, upconversion reduces the population of the $^4I_{13/2}$ manifold in Er:YAG, increasing the laser threshold, but not, in theory, the slope efficiency [1]. We have measured the cooperative upconversion parameter in Er:YAG using the z-scan technique as a function of Er concentration (0.5% to 5%) with the sample at room temperature (298 K) and 80 K. The value we obtain at room temperature is 2-3 times larger than previously reported [2,3]. The value we obtain at 80 K is approximately eight times larger than the value at room temperature.

An Er:YAG laser operating at cryogenic temperatures has recently produced 400 W at 1645 nm [4]. Knowledge of the low-temperature upconversion coefficient will allow further improvements in the design. It may also help explain the interesting temperature-dependent output power which peaks at ~160 K [5].

A previous measurement of upconversion relied on a short-pulse laser [2]. One advantage of the z-scan technique is that the measurement can be carried out with the same quasi-cw diode laser that will pump the Er:YAG laser being developed.

Model

A model including the lowest four manifolds of Er^{3+} was used to fit the data. Included in the model is a rate equation for the population of each manifold, e.g.

$$\frac{dN_1}{dt} = +\frac{I\sigma}{h\nu}\left(f_e N_2 - f_a N_1\right) + N_2 W_{21} + N_3 W_{31} + N_4 W_{41} + C_{up} N_2^2. \tag{1}$$

Here, N_1 (N_2) is the population of the $^4I_{15/2}$ ($^4I_{13/2}$) manifold, I is the laser intensity, σ is the absolute cross section, f_a (f_e) is the probability that an ion in the $^4I_{15/2}$ ($^4I_{13/2}$) manifold is in a sublevel that can absorb (emit) a laser photon, W_{ij} is the relaxation rate from level i to level j, and C_{up} is the upconversion coefficient. Also included in the model is a propagation equation for the laser beam:

$$\frac{dI}{dz} = I\sigma\left(f_e N_2 - f_a N_1\right) = -\alpha I. \tag{2}$$

To account for the Gaussian intensity profile, the power is divided into eight equal portions associated with the peak intensity: I_p, $(7/8)I_p$, etc. The transmitted powers are then calculated separately as though at a uniform intensity, and then summed. The difference between eight slices and sixteen was negligible, so we used the former to speed the calculation.

Experiment

A DFB laser operating continuously at 1532 nm was amplified in a single mode fiber up to 3 W to provide the illumination. The duty cycle was reduced to 10% with a shutter operating at 1 Hz, to avoid heating the samples. An InGaAs photodiode and lock-in amplifier were used to detect the beam transmitted through the sample. The samples were 10 mm in diameter, 1 mm thick, and anti-reflection coated. The sample was placed in a cryostat for the 80 K measurements (Fig. 1).

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The standard z-scan geometry was used [6], with a 20 cm focal length lens. The intensity profile was measured by translating a razor blade across the beam and fitting to the error function to determine the waist (Fig. 2a).
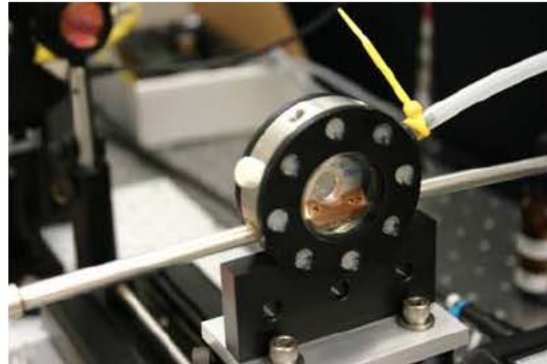

Fig. 1 10-mm diameter Er:YAG sample in the liquid nitrogen flow cryostat.

Results

The transmission of each sample as a function of position shows a peak where the beam intensity is highest, due to saturation of the absorption (Fig. 2b). The effect of upconversion is to lower the peak, because upconversion depletes the $^4I_{13/2}$ manifold, shifting the onset of saturation to higher intensities.
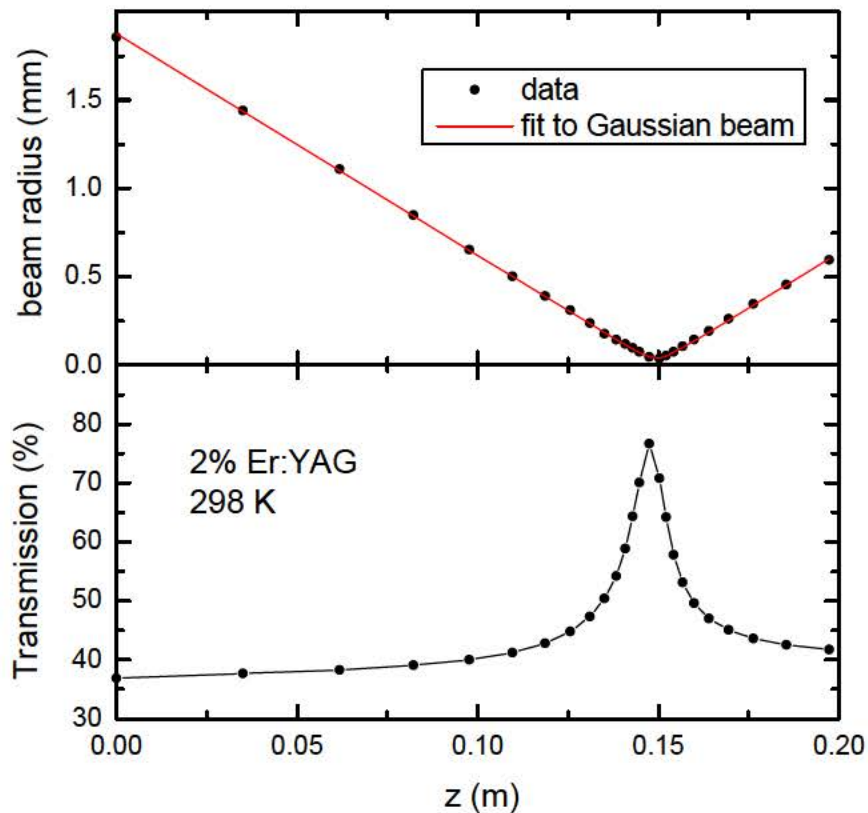

Fig. 2 (a) beam radius as a function of position,
(b) transmission of a 2% Er:YAG sample at 298 K.

The shift can be clearly seen in a plot of effective absorption coefficient vs peak intensity (Fig. 3). α_{eff} is calculated from experimental data (symbols), and plotted, along with the simulation curves for $C_{up} = 0$ (dashed line) and for $C_{up} = 1.5 \times 10^{-17}$ cm^3/s (solid line). The different symbols correspond to runs at different power levels. We estimate the accuracy to be approximately a factor of two in C_{up}.
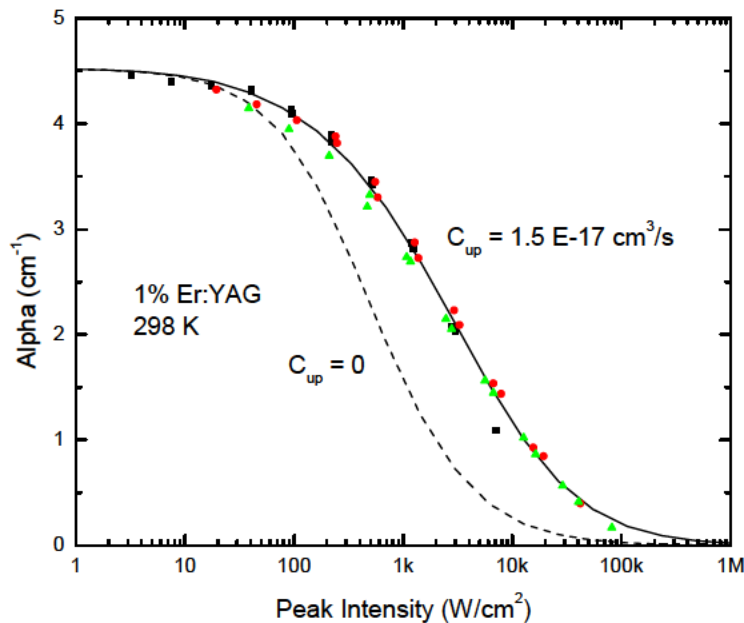

Fig. 3 Effective absorption coefficient vs peak Intensity, for 1% Er:YAG at 298 K.

For a 1% sample at 80 K, our data indicate a value of $C_{up} = 8 \times 10^{-17}$ cm^3/s (Fig. 4). These are the first reported measurements of Er:YAG upconversion at cryogenic temperatures.

We find that C_{up} is approximately proportional to [Er] at both temperatures (Fig. 5). A linear fit to the four samples at room temperature would indicate a C_{up} value of 1.0×10^{-17} cm^3/s for the 1% sample. A value of 5×10^{-18} cm^3/s was previously obtained with a time-dependent method based on the non-exponential decay of luminescence from the $^4I_{13/2}$ level [2]. A value of 3.5×10^{-18} cm^3/s was obtained with a steady-state method based on the upconversion-induced change in lasing threshold [3].
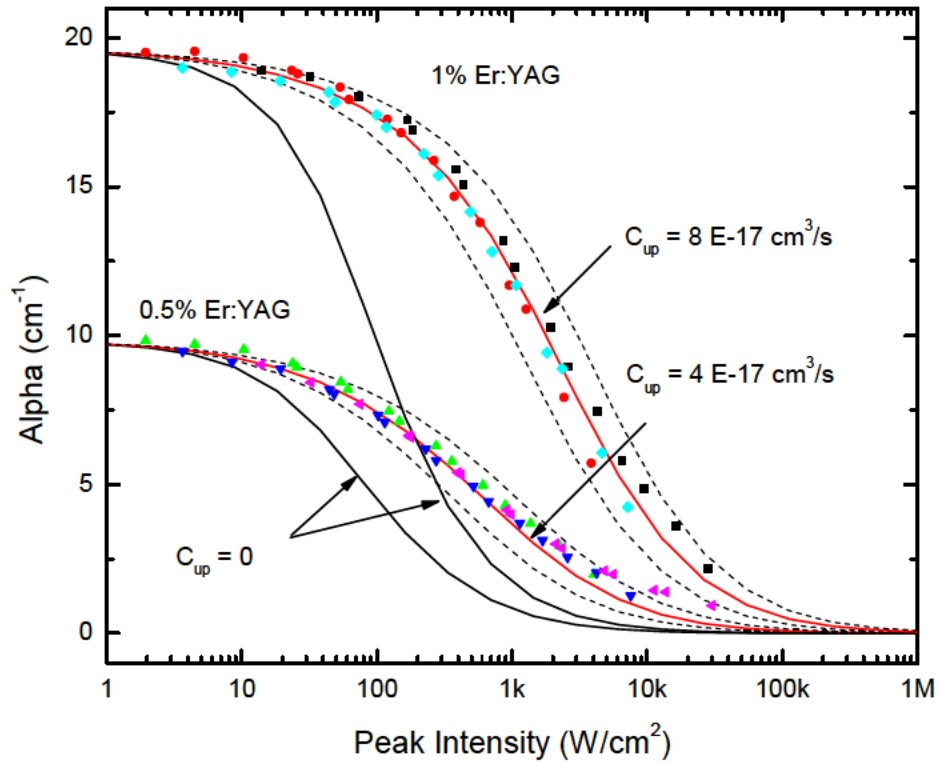
Fig. 4 Er:YAG z-scan experimental data obtained at 80 K, for 1532 nm (symbols). The curves are simulations for different values of C_{up}. The dashed lines represent values of C_{up} that differ from the red lines by a factor of two.
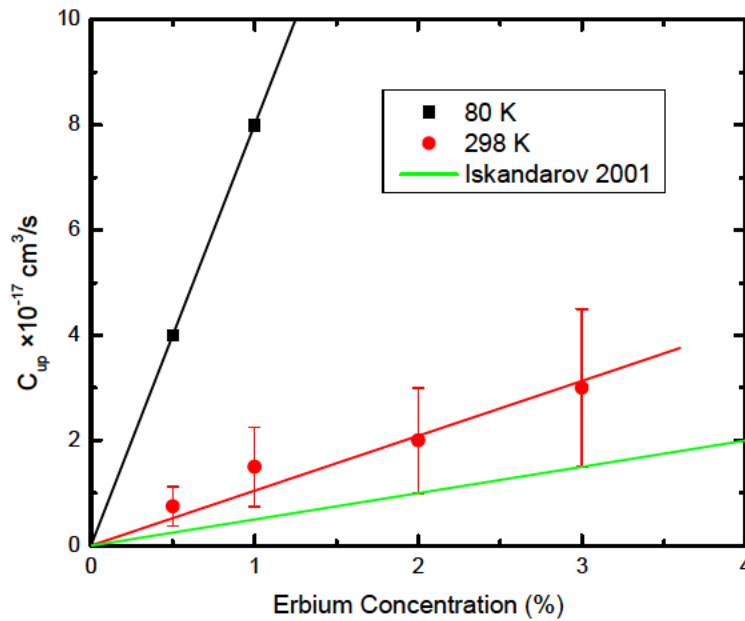

Fig. 5 Measured upconversion coefficient as a function of [Er] for 80 K and 298 K, along with a linear fit. The green line is a linear fit to the low concentration results from Ref. 2.

Conclusion

Z-scan measurements on Er:YAG have been made at room temperature and 80 K. The data have been interpreted with a steady-state model including rate equations for the (intensity-dependent) populations of the lowest four manifolds, and an equation for the (population-dependent) propagation of the light. Our room temperature results for C_{up} are approximately twice the values previously obtained with other techniques. Our values for C_{up} at 80 K are the first obtained at a cryogenic temperature, and are approximately eight times larger than at room temperature.

High power Er-doped lasers for eye-safer applications are currently being designed to operate at cryogenic temperatures because the optical, thermal, and mechanical properties of Er:YAG, for example, improve as the temperature is lowered, depending on the particular transitions involved. Knowledge of the low-temperature C_{up}, and its dependence on Er concentration will allow the effect of upconversion to be minimized by choosing the optimum doping level. An advantage of the z-scan technique for measuring upconversion is that it can be carried out with the same quasi-cw diode laser that will pump the solid-state laser being designed.

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