Simultaneous, multiple wavelength lasing of (Er, Nd):$Y_3Al_5O_{12}$

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(Received 8 June 1987; accepted for publication 18 August 1987)

Simultaneous lasing of both Er^{3+} and Nd^{3+} ions in yttrium aluminum garnet is reported. The crystal was doped with 15% Er^{3+} and 1% Nd^{3+} ions. The Er^{3+} ions lased at 2.94 μm and the Nd^{3+} ions in a broadband from 1.01 to 1.15 μm with a strong peak at 1.064 μm. Significant ion-ion interaction is suggested by the drastically altered fluorescent lifetimes and unusual lasing properties.

The erbium:yttrium aluminum garnet (Er:YAG) laser has been reported as an efficient 2.94-μm source when high concentrations ($\geqslant$10%) of Er^{3+} are used.[1] This lasing involves a transition from the $^4I_{11/2}$ to the $^4I_{13/2}$ state. Since the $^4I_{13/2}$ is a long-lived state compared to the $^4I_{11/2}$, lasing involving such a transition should be self-terminated. However, the $^4I_{13/2}$ state can cross relax in such a manner as to enable efficient lasing.[2] Cross relaxation of the $^4I_{13/2}$ level of Er^{3+} involves the simultaneous decay of one ion from this level to the $^4I_{15/2}$ ground state and excitation of a second ion from the $^4I_{13/2}$ to the $^4I_{9/2}$. Due to the energies associated with these states the total energy stored in the system of two ions is conserved by such a pair of transitions. The ion in the $^4I_{9/2}$ state relaxes rapidly to the $^4I_{11/2}$ state and so the net change in the population difference due to cross relaxation is 3. Such a cross relaxation process actually increases the population difference and enables the phenomenon of quasicontinuous lasing.[3] An approach to improving the 2.94-μm lasing of Er^{3+} was suggested by Kaminskii *et al.*[4] They pointed out that Nd^{3+} ions in the Er:YAG crystal could cross relax the Er^{3+} $^4I_{13/2}$ state and, perhaps, reduce the problem of self-termination. We have followed this suggestion and report, for the first time to our knowledge, on the multiwavelength lasing properties of YAG doped with 15% Er^{3+} and 1% Nd^{3+} ions. Simultaneous lasing was observed at 2.94 μm by the Er^{3+} ions and in a band from 1.01 to 1.15 μm presumably by the Nd^{3+} ions. There is a strong peak at 1.06 μm in the band of emitted laser light.

An examination of the energy levels of Er^{3+} and Nd^{3+} ions in YAG reveals that the Er^{3+} $^4I_{13/2}$ and the Nd^{3+} $^4I_{15/2}$ levels are nearly isoenergetic.[5] This observation led to the suggestion made by Kaminskii *et al.* that the Er^{3+} ions could be cross relaxed by the Nd^{3+} ions.[4] Furthermore, since the Nd^{3+} $^4I_{15/2}$ level is known to relax very rapidly to the $^4I_{9/2}$ ground state this cross relaxation could provide a rapid and efficient means of reducing or eliminating the self-termination of the 2.94-μm Er^{3+} transition. Measurements of various Er^{3+} state lifetimes in 16.7% Er:YAG and in (15% Er, 1% Nd):YAG and of the Nd^{3+} $^4F_{3/2}$ state lifetime in 1% Nd:YAG and (15% Er, 1% Nd):YAG were made and are listed in Table I. It is clear from these results that the introduction of Nd^{3+} strongly affects the Er^{3+} and vice versa.

The entry in Table I for the Nd^{3+} $^4F_{3/2}$ state lifetime in (15% Er, 1% Nd):YAG is obtained from data such as that shown in Fig. 1 in which the log of the observed fluorescence intensity at 1.06 μm is plotted versus time. In such a plot an exponential decay process would appear as a straight line. However, the data are clearly not linear. These data were obtained by exciting the fluorescence with a frequency-doubled, *Q*-switched, Nd:YAG laser and monitoring its decay with a detector with response time < 1 μs. The fluorescence wavelength monitored was selected with a 0.25-m monochromator. The fluorescence signal was captured with a digital processing oscilloscope and 100 signals were averaged and processed with a computer to obtain results such as those shown in Fig. 1. The nonexponential decay indicated is real and not an artifact of the data acquisition and processing equipment. The entry for the lifetime in Table I was obtained from the $1/e$ decay time measured in the early, nearly exponential decay of the fluorescent intensity. As a check on this result we also measured the fluorescence decay at 1.34 μm since this transition also originates on the $^4F_{3/2}$ state of Nd^{3+}. The same nonexponential decay behavior was observed with the same initial $1/e$ decay time. The nonexponential decay behavior of Nd^{3+} in (Er, Nd):YAG is being studied further in continuing work.

In Nd:YAG, the lifetime of the $^4F_{3/2}$ state is nearly 240 μs and the decay process is governed by a single exponential mechanism. Clearly the presence of the Er^{3+} ions signifi-

TABLE I. Lifetimes of the states of Er and Nd in (Er, Nd:YAG) and Er in Er:YAG and Nd in Nd:YAG.

State	Material	Lifetime (ms)
$^4I_{11/2}$ of Er^{3+}	15% Er, 1% Nd:YAG	0.053 ± 0.004
$^4I_{11/2}$ of Er^{3+}	16.7% Er:YAG	0.107 ± 0.008
$^4I_{13/2}$ of Er^{3+}	15% Er, 1% Nd:YAG	0.081 ± 0.007
$^4I_{13/2}$ of Er^{3+}	16.7% Er:YAG	5.00 ± 0.1[a]
$^4F_{3/2}$ of Nd^{3+}	15% Er, 1% Nd:YAG	0.008 ± 0.0005[a]
$^4F_{3/2}$ of Nd^{3+}	1% Nd:YAG	0.237 ± 0.005

[a]These entries are the initial $1/e$ decay time of a process which does not appear to have a single exponential decay rate.

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cantly alters the decay processes of the Nd^{3+} ions. Similarly the Nd^{3+} ions affect the Er^{3+} ions. The desired reduction of the Er^{3+} $^4I_{13/2}$ state lifetime has been achieved, although it is still longer than that of the $^4I_{11/2}$. One result of this is that the contribution of cross relaxation to the Er^{3+} $^4I_{11/2}$-$^4I_{13/2}$ inversion is considerably reduced with respect to that in Er:YAG. This can be understood since the cross relaxation rate is proportional to the square of the $^4I_{13/2}$ state population and this population does not grow as large as it would in Er:YAG. As seen in the lasing waveforms in Fig. 2, the phenomenon of quasicontinuous lasing is not observed for the 2.94-μm emission from (Er, Nd):YAG.

The lasing tests were performed with xenon flashlamp pumping in a silver-coated double-elliptical pump cavity. The pump pulse duration was 175 μs (full width at half-maximum) and the lamp arc length was 100 mm. Crystals of (15% Er, 1% Nd):YAG were grown by the Czochralski technique. Rods of 6.25 mm in diameter and 80 mm long were prepared. The tests reported in this letter were conducted with flat, parallel, and uncoated rod ends and 72 mm exposed to the pump light. The mirrors used were obtained from two different sources but had not been designed specifically for multiwavelength operation.[6] These were flat mirrors and they were spaced by 41 cm. In all cases the total reflector had measured reflectance of 99.7% at 2.94 μm and $>98.5\%$ in the 1-μm region.

When mirrors designed for reflection $\geqslant 80\%$ at 2.94 μm were used, simultaneous lasing at 2.94 μm and in a band between 1.01 and 1.15 μm with a peak at 1.064 μm was detected. The lasing waveforms shown in Fig. 2 were obtained with a mirror designed for 90% reflection at 2.94 μm. The transmission of this mirror was 47% at 1.06 μm. Both waveforms were obtained with 550 J of pump energy into the lamps. This energy has been corrected to account for the difference in the arc and exposed rod lengths. This input corresponds to 5.1 × threshold for the 1.06-μm lasing and 4.5 × threshold for the 2.94-μm lasing. The only experimental difference between the two oscillographs is the setting of the 0.25-m monochromator used to distinguish between the lasing wavelengths. The waveforms were obtained with detectors having submicrosecond response times.

The laser and waveform detection system described in the preceding paragraph was used to detect lasing at 2.94 and 1.06 μm. In addition, clear evidence for laser emission from the (15% Er, 1% Nd):YAG (waveforms made up of relaxation spikes) was seen in a continuous band from 1.01 to 1.15 μm. The broadband was detected with mirrors designed for reflection at 2.94 μm as well as with mirrors designed for use at 1.06 μm. A Nd:YAG rod was inserted in the pump cavity and lased with the 65% R at 1.06 μm output mirror. This rod produced only the common 1.064-μm laser emission and no detectable broadband as seen with a doubly

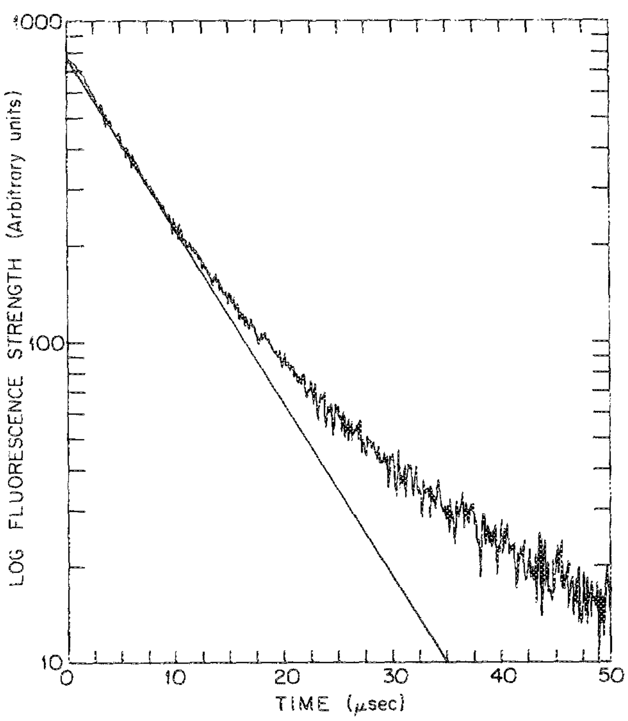

FIG. 1. Log of fluorescence signal decay vs time for the 1.06-μm emission from Nd^{3+} ions in (15% Er, 1% Nd):YAG.

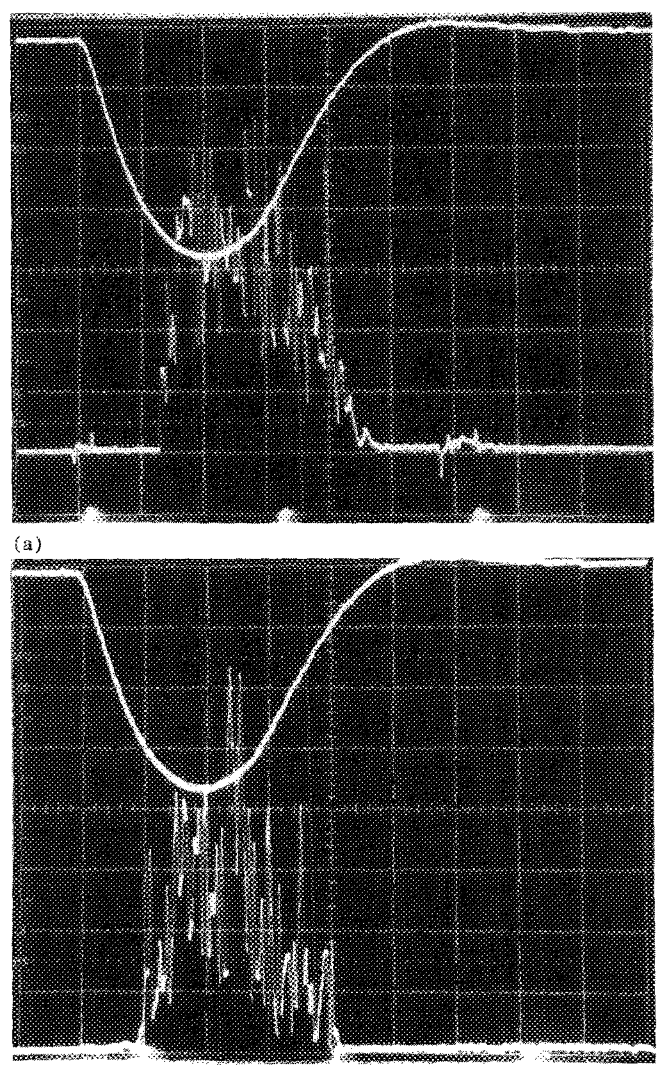

FIG. 2. Laser waveforms for the (a) 2.94 and (b) 1.06 μm signals from (15% Er, 1% Nd):YAG. These were obtained with 550 J to the flashlamps and are at 4.5 × and 5.1 × threshold, respectively. The horizontal scale for both waveforms is 50 μs/div.

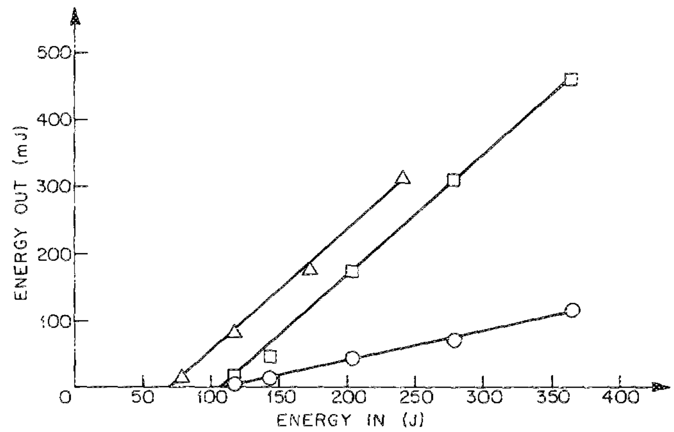

FIG. 3. Long pulse energy out vs energy in for (15% Er, 1% Nd):YAG. The input energy plotted is the total input to the flashlamps multiplied by 0.72 to account for the difference in arc and exposed rod length. (△) Data for 1 μm band lasing with the 65% R 1.06-μm mirror. (□) The 1-μm band output energy observed with a mirror designed for 90% R at 2.94 μm and which has 47% T at 1.06 μm. (○) Data for the 2.94-μm output using this mirror.

doped rod. This enabled calibration of the monochromator and demonstration that the instrumental bandwidth was $\pm$ 3 nm. If individual Nd^{3+} lines[7] were lasing to make up the band, the equipment would have resolved them into separate lines. The broadband of lasing contained a strong peak at 1.06 μm. Data are not yet available to resolve the energy distribution between the 1.06-μm line and the broadband and to determine the dependence of each on the mirror design. The broadband emission is another new feature of Nd^{3+} lasing observed in doubly doped (Er, Nd):YAG.

The long pulse output versus input energy of the (Er, Nd):YAG laser is plotted in Fig. 3. The abscissa is the total energy input to the flashlamps multiplied by 0.72 to account for the difference between the arc and exposed rod lengths. Data are shown for the case of the 90% R mirror described above and a standard 1.06-μm 65% R mirror. A calibrated filter which rejected light at 1 μm was used to enable measurement of the energy at 2.94 μm when both wavelengths were lasing. The 1-μm light energy shown in Fig. 3 is the difference between the measured 2.94-μm energy and the total energy measured with a calibrated joulemeter.

Simultaneous lasing by Er^{3+} and Nd^{3+} ions in doubly doped (Er, Nd):YAG was observed for the first time. Measurements of the state lifetimes of the ions in the doubly doped material indicate strong ion-ion interactions. These interactions result in unusual lasing properties such as the broadband of laser light detected in the 1.01–1.15 μm region. Work is in progress to more fully understand the interactions and to improve the lasing properties. This includes work with improved material, laser mirrors, and rod coatings, and attempts to tune the broadband emission. Other host and dopant combinations are being considered as possible members of this new class of multiple wavelength lasers.

This work was supported by the Air Force Office of Scientific Research under contract No. AFOSR-84-0378. Cooper Laser Sonics provided a gift to support this work. C. Enderby of Cooper Laser Sonics provided impetus to this work by suggesting that dual wavelength operation might occur and would be desirable for medical applications.

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