The (Holmium,Neodymium):Yttrium Aluminum Garnet Multiple Wavelength Solid State Laser

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Simultaneous laser action was observed at 2.94 and 3.01 μm by the Ho^{3+} ions, and at 1.06 μm by the Nd^{3+} ions. While the 3.01 μm wavelength has been reported in $Ho:YAlO_3$,[1] we believe this is the first report of the 3.01 μm laser emission from YAG. By utilizing mirrors which had nearly equal reflectance at 1.34 and 1.06 μm, simultaneous lasing was observed at both Nd^{3+} wavelengths, a result of the absorptive losses at 1.06 μm due to the high concentration of Ho^{3+}.

Kaminskii et al. suggested that Nd^{3+} could be used to cross-relax the Ho^{3+} $^5I_7$ level and thereby reduce or eliminate the problem of self-termination.[2] The Nd^{3+} $^4I_{13/2}$ level lies ~750 cm^{-1} below the Ho^{3+} $^5I_7$ state in YAG, favoring energy transfer from the holmium to the neodymium ions.[3] This reduces the Ho^{3+} $^5I_7$ lifetime and the bottleneck for 3 μm lasing which normally occurs as a result of this long lifetime.

The measurements summarized in Table I were obtained by exciting fluorescence in the crystals with a frequency-doubled Q-switched Nd:YAG laser. Wavelength selection was accomplished using a 0.25 meter monochromator and the fluorescence was detected with a cooled InSb detector with a response time < 1 usec. The 1.064 μm emission from a Nd:YAG laser was used to calibrate the monochromator, and the bandwidth was found to be ±0.003 μm. A digital processing oscilloscope recorded the fluorescence signals, which were then transferred to an HP9825A computer for storage and manipulation.

The lifetimes of the Ho^{3+} $^5I_7$ and Nd^{3+} $^4F_{3/2}$ levels are dramatically reduced in the doubly-doped materials as a result of strong ion-ion interactions. Furthermore, the Nd^{3+} $^4F_{3/2}$ lifetime has become distinctly non-exponential, determined by monitoring both the 1.06 and 1.34 μm emission from this state.

All lasing tests were conducted in a silver-coated double-elliptical pump cavity with xenon flashlamps. The arc length was 100 mm and the pump pulse duration was 175 μsec full-width at half-maximum. The long pump pulse and short upper level lifetimes of both ions may have resulted in inefficient pumping. A rod 6.35 mm in diameter and 70 mm in length was fabricated from the boule, which was grown using the Czochkralski method. The input energies listed in Table II represent energy input to the lamps, corrected for the mismatch between arc and rod lengths. The rod was prepared with flat, parallel, uncoated faces and all mirrors used in the lasing tests were flat. The results of these lasing tests are summarized in Table II.

With an output coupler designed for 90% reflection at 2.94 μm, simultaneous lasing was observed at 2.940, 3.011, and 1.064 μm (±0.003 μm). During lasing there is a temporal shift from the initial 2.94 μm lasing to the 3.01 μm transition. When an output coupler with a reflectivity of 90% at 1.34 um and 88% at 1.06 μm was used, simultaneous lasing occurred at 1.064 and 1.339 μm. The temporal behavior of this lasing is illustrated in Fig.1. The 1.34 μm transition has a lower threshold than the 1.06 μm lasing [see Figs. 1(a) and (b)]. As the input energy is increased the 1.06 μm output rapidly becomes more intense, and 1.34 μm lasing only occurs at the leading and trailing edges of the 1.06 μm lasing. When the reflector was changed to one which had a maximum reflectivity at 1.34 μm-and R < 40% at 1.06 μm, only 1.34 μm lasing was observed in an uninterrupted pulse.

Simultaneous lasing by Ho^{3+} and Nd^{3+} ions was observed in (Ho,Nd):YAG. The fluorescent lifetimes of both the Nd^{3+} $^4F_{3/2}$ and Ho^{3+} $^5I_7$ were dramatically reduced in the doubly-doped material when compared to singly-doped crystals. These changes indicate strong ion-ion interactions in this crystal, which lead to more efficient 3 μm laser operation. With appropriate mirrors, it is believed that simultaneous operation would occur on all four of the reported lasing wavelengths.

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[1]A.A. Kaminskii, V.A. Fedorov, and I.V. Mochalov, Sov. Phys. Dokl. 25, 744 (1980).

[2]A.A. Kaminskii, T.I. Butaeva, A.O. Ivanov, I.V. Mochalov, A.G. Petrosyan, G.I. Rogov, and V.A. Fedorov, Sov. Tech. Phys. Lett. 2, 308, (1976).

[3]A.A. Kaminskii, Laser Crystals (Springer-Verlag, Berlin, 1981).

Table I. Lifetimes of the states of Ho^{3+} and Nd^{3+} in (Ho,Nd):YAG, Ho^{3+} in Ho:YAG, and Nd^{3+} in Nd:YAG)

State	Material	Lifetime(μsec)
$^5I_6$ of Ho^{3+}	(10% Ho,1% Nd):YAG	41 ± 3
$^5I_6$ of Ho^{3+}	15% Ho:YAG	47 ± 3
$^5I_7$ of Ho^{3+}	(10% Ho,1% Nd):YAG	170 ± 10
$^5I_7$ of Ho^{3+}	15% Ho:YAG	5500 ± 500*
$^4F_{3/2}$ of Nd^{3+}	(10% Ho,1% Nd):YAG	8.5 ± 0.8*
$^4F_{3/2}$ of Nd^{3+}	1% Nd:YAG	237 ± 10

* Value is initial 1/e decay time of a non-exponential process

Table II. Lasing output energies from (10% Ho,1% Nd):YAG

Energy In	Energy Out (mJ) ± 10%			
(Joules)	1.06 μm	2.94+3.01μm	1.06 + 1.34μm	1.34μm
99	21	3	29	61
148	47	13	61	132
207	81	24	108	178
342	137	41	192	261
Mirrors: Output Coupler	R=90%, 2.94 μm T=3%, 1.06 μm R<10%, 1.34 μm		R=88%, 1.06 μm R=90%, 1.34 μm	R=88%, 1.06 μm R=90%, 1.34 μm
High Reflector	Enhanced Silver		Enhanced Silver	Max R, 1.34 μm

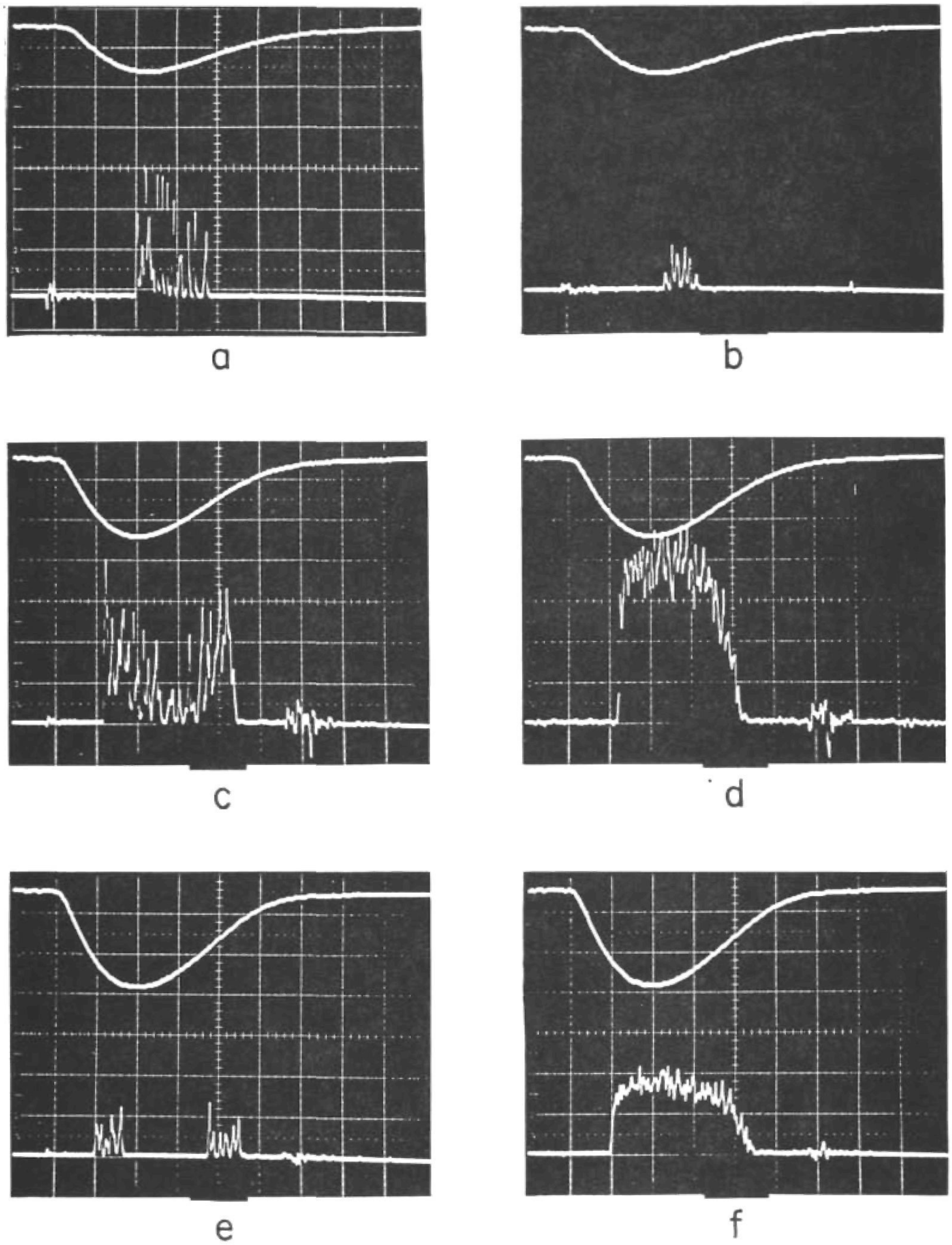

Fig. 1. Laser waveforms for the Nd^{3+} 1.34 and 1.06 μm signals from (10% Ho, 1% Nd):YAG. The upper trace monitors the current pulse to the flashlamps. The horizontal scale is 50 μs/div in all oscillographs. Waveforms at 1.34 (a) and 1.06 μm (b) with 69 joules (corrected) input. Vertical scale is 10 mV/div. Waveforms at 1.34 (c) and 1.06 μm (d) with 148 joules (corrected) input. Vertical scale is 20 mV/div. Waveforms at 1.34 (e) and 1.06 μm (f) with 207 joules (corrected) input. Vertical scale is 50 mV/div.