Operation of the High Dopant Density Er:YAG at 2.94 μm

M. Bass[1], *W.Q. Shi*[1], *R. Kurtz*[1], *M. Kokta*[2], *and H. Diegl*[3]

[1]Center for Laser Studies, University of Southern California, Los Angeles, CA 90089, USA
[2]Union Carbide Corporation, Washougal, WA 98671, USA
[3]Allied Corporation, Westlake Village, CA, USA

1. Introduction

Free-running, pulsed, flashlamp-excited operation of 50 and 33% Er doped YAG lasers is reported at 2.94 μm. This laser was described by researchers in the Soviet Union as early as 1975.[1] Since then there have been a number of further reports concerning this material all published by Soviet scientists. This paper represents, to our knowledge, the first publication outside of the Soviet Union about high dopant density Er:YAG laser operation. In addition to confirming some of the performance properties described earlier, this paper presents the unusual temporal waveforms of the Er:YAG, 2.94 μm laser. An outline is given of possible pumping and relaxation processes which may contribute to the laser's operation.

Er:YAG does not lase well at 2.94 μm when the concentration of Er is the usual 1%. However, when larger concentrations are used (generally over 15%) operation at this wavelength can be quite efficient. The relevant spectroscopic data for lasing at this wavelength are given below for 50% Er:YAG:

Upper laser level	$^4I_{11/2}$
Lower laser level	$^4I_{13/2}$
Upper level lifetime	100 μsec
Lower level lifetime	2 msec
Emission cross-section	2.6×10^{-20} cm^2
Pump absorption bands	0.80 μm ($^4I_{15/2}$ - $^4I_{9/2}$)
	0.65 μm ($^4I_{15/2}$ - $^4F_{9/2}$)
	0.54 μm ($^4I_{15/2}$ - $^4S_{3/2}$)
	0.52 μm ($^4I_{15/2}$ - $^2H_{11/2}$)
	0.49 μm ($^4I_{15/2}$ - $^4F_{7/2}$)
	0.45 μm ($^4I_{15/2}$ - $^4F_{5/2}$)
	0.44 μm ($^4I_{15/2}$ - $^4F_{3/2}$)
	0.41 μm ($^4I_{15/2}$ - $^2H_{9/2}$)
	0.38 μm ($^4I_{15/2}$ - $^4G_{11/2}$)

2. Laser Tests

The laser tests were conducted in a water-cooled, double elliptical pump cavity. This cavity had been designed for pumping Alexandrite laser rods and so had the desired silver-backed pyrex reflector. While the laser may work in a gold-plated cavity, the many visible, blue and near uv pump bands suggest better efficiency is possible with a silver pump reflector. The rods reported in this paper were 6.25 mm in diameter and 120 mm long. They were obtained from Union Carbide Corp. and Crystal Optics Research Inc. The flashlamps were 6.5 mm bore diameter, xenon-filled lamps from ILC and, in the pump cavity used, were able to pump 96.5 mm of the rod. Two different pump pulse durations were used; one, called the short pump pulse, was 120 µsec long at full width at half maximum (FWHM) and the other, called the long pump pulse, was 170 µsec FWHM. The resonators mirrors were spaced only 25 cm apart to provide a resonator that was relatively insensitive to thermal lensing in the laser rod. The 100% reflector used was an uncoated, polished copper mirror with a 5 m radius of curvature. Several flat output mirrors were tested but best performance was observed for all rods with a 75% reflector. All tests were conducted with no intracavity apertures and so represent long pulse, multimode lasing in which the whole rod aperture was filled with many oscillating modes.

The performance of the Er:YAG lasers tested is summarized in Figs. 1 and 2. Fig 1 a compares the performance of the 33% doped rod when pumped with the two different pump pulses mentioned above. The

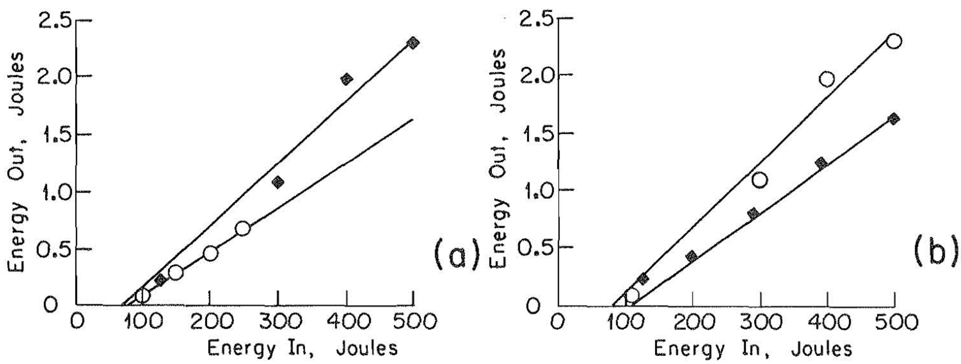

Fig. 1 A. Long pulse laser output energy of 33% doped Er:YAG at 2.94 µm versus input energy. Pump pulse duration =120 µsec for o and 170 µsec for ♦.

B. Long pulse laser output energy versus input energy for two different Er dopant densities in YAG. o = 33% and ♦ = 50%.

improvement in efficiency as the pump pulse duration is increased agrees with observations reported previously[2] and suggests that the reported 3-5% efficiencies are realizable. Fig. 1b shows the relative performance of the 33 and 50% doped rods. when pumped with the long pump pulse. The difference observed may be specific to the pump pulse waveform and pump cavity used in this work. The performance differences may depend on these parameters and so this data should not be taken as a firm preference for the 33% rod over the 50% rod. More research is necessary with excitation conditions properly tailored to the rod to be used. Both rods showed excellent optical quality when observed through crossed polarizers and no significant scattering of a HeNe beam could be detected. It should be noted that the 0.63 μm HeNe beam is attenuated in Er:YAG but the orange HeNe line is transmitted and should be used.

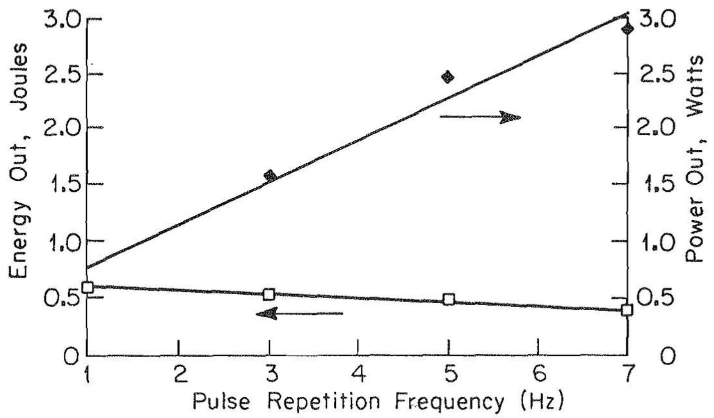

Fig. 2 Energy and power output of the 33% Er:YAG versus pump repetition rate using the 120 μsec duration pump pulse.

Fig. 2 shows the average power obtained using the 33% rod and the short pump pulse. These tests were limited by power supply considerations and it is clear that much higher average powers are possible. When the long pump pulse was used the maximum power supply repetition frequency was 3 Hz. At this prf over 5 W of average power was observed. The drop-off in energy per pulse indicates the onset of thermal lensing in the medium. Since no corrective measures were taken other than using a short resonator this problem can benefit from further laser engineering.

A major design consideration in developing this laser is preparing reliable, damage-resistant optical coatings. The major coating consideration is that the material not contain any water when it is set down and that it not adsorb water from the atmosphere afterwards. The absorption of water at 2.94 μm is maximum and so any water in a coating causes unacceptably high losses and low damage threshold. High reflection coatings were reliably produced by coaters who had experience in making coatings for HF and DF lasers. On the other hand, only one manufacturer made reliable AR coatings for the laser rods. These coatings performed reliably at pulse energies of over 1.7 J. AR coatings supplied by another manufacturer damaged at outputs of less than 250 mJ. In fact, the data given in Figs. 1 and 2 were taken with uncoated rods to avoid the issue of coating properties.

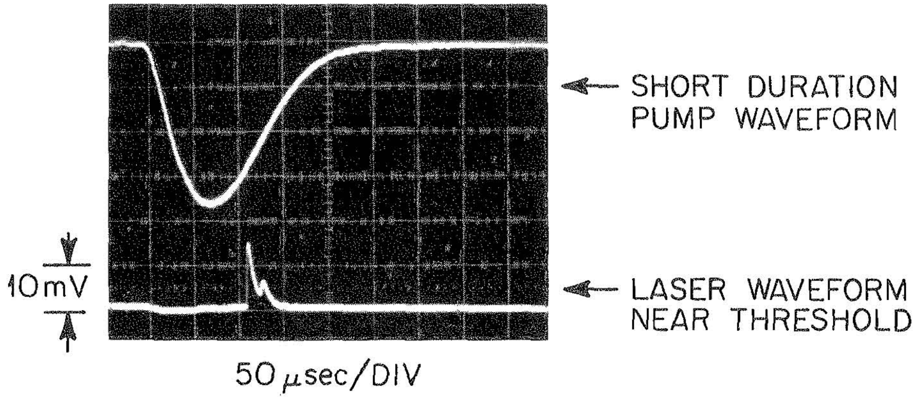

Fig. 3 Er:YAG laser waveform near threshold.

The waveform of the laser emission of Er:YAG at 2.94 μm is somewhat like that of any conventional optically pumped solid-state laser near threshold. Fig 3 shows the observed waveform at threshold using the short pump pulse. The important point is that there are relaxation oscillation (RO) spikes and that lasing begins after the peak of the pump pulse. When this laser is pumped well above threshold with either the long or the short pump pulse the output waveform is as shown in Fig. 4. The Er:YAG laser waveforms shown in Figs. 3 and 4 were obtained with a Judson Infrared J-10 InSb detector, cooled to 77 °K, with a specified response time of 500 nsec. These waveforms were subsequently verified with a 50 nsec response time Judson Infrared Model J-12-18C-R250U InAs room temperature detector.

In the case of Fig. 4 lasing begins before the peak of the pump and ends when the pump is nearly over. In between it operates nearly

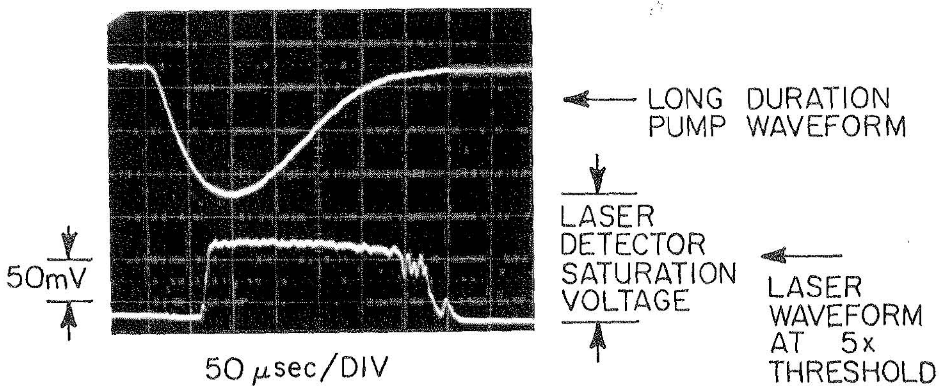

Fig. 4 Er:YAG laser waveform at 5 times threshold.

continuously without RO spikes typical of optically pumped solid state lasers. This type of RO spike does not appear until the pump has fallen well below threshold. It is expected that the improved performance reported for longer pump pulses is related to this mode of lasing in which some process operates to alter and extend the population inversion.

3. Discussion

The long pulse performance of the Er:YAG laser in terms of both energy per pulse and average power has been shown to be comparable to other optically pumped solid-state lasers. Higher outputs and efficiencies can be expected using longer duration pump pulses.[3]

The unusual waveforms observed at high output energies are the result of a combination of processes. These include contributions to the inversion due to:

1, the usual "four-level" pumping process involving excitation from the $^4I_{15/2}$ ground state,

2, "three-level" pumping from the long-lived lower laser level, the $^4I_{13/2}$ state, and

3, cross-relaxation between nearby Er^{3+} ions. The cross-relaxation process is one in which an ion in the $^4I_{13/2}$ state relaxes to the $^4I_{15/2}$ state while, simultaneously, a neighboring ion in the $^4I_{13/2}$ jumps to the $^4I_{9/2}$ state.

When in the $^4I_{9/2}$ state the ion rapidly relaxes into the upper laser level. The process of cross-relaxation is particularly important in high concentration material and is discussed in detail by Bagdasarov et al.[4] An analysis is in progress of the relative importance of the several processes of excitation and relaxation as they contribute to the observed quasi-continuous lasing. This work will be reported at a later date.

The 2.94 μm operation of the Er:YAG laser is sufficiently interesting to warrant further study. It is a material which can be grown easily and lases well. It has potential application in surgery and as a source to drive a variety of infrared sources at important wavelengths. Since it is compatible with existing Nd:YAG laser systems exploration of its potential is straightforward. As has been pointed out in the present work and in the work of the Soviet scientists, optimum efficiency requires longer duration pump sources and so conversion of Nd:Glass or ruby lasers may lead to better performance. Reliable optical coatings for 2.94 μm requires that they be specified to contain and adsorb no water. As a result of this work it is clear that the Er:YAG laser is available to anyone who wishes to use it.

Acknowledgment

The work at U.S.C. was supported by AFOSR Contract No. AFOSR-84-0378.

References

[1]E. V. Zharikov, V. I. Zhekov, L. A. Kulevskii, T. M. Murina, V. V. Osiko, A. M. Prokhorov, A. D. Savel'ev, V. V. Smirnov, B. P. Starikov, and M. I. Timoshenko, Sov. J. of Quantum Electronics 4, 1039 (1975)

[2] V. I. Zhekov, V. A. Lobachev, T. M. Murina and A. M. Prokhorov, Sov. J. Quantum Electron. 13, 1235 (1984)

[3]I. A. Scherbakov, General Physics Institute, Moscow, USSR, seminar presented at U.S.C., June 1986

[4] Kh. S. Bagdasarov, V. I. Zhekov, V. A. Lobachev, A. A. Manenkov, T. M. Murina and A. M. Prokhorov, Izvestiya Akademii Nauk SSSR, 48, 1765, (1984)