A 1.54 μm Er GLASS LASER PUMPED BY A 1.064 μm Nd:YAG LASER

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Laser oscillation in Er-glass, co-doped with Yb sensitiser, has been achieved by pumping with the 1.064 μm output of a Nd:YAG laser.

1. Introduction

The current interest in optical communication systems operating around 1.5 μm has generated a requirement for coherent sources in this spectral region. Given the variety of measurements and investigations to which such sources would be applied, there is a need for a convenient versatile source, capable of operating cw, pulsed, mode-locked and Q-switched. With such a source in mind, we have looked at the possibilities of an Er glass laser pumped by a Nd:YAG laser. In this paper we report the preliminary results of lasing at 1.54 μm from a commercially available Er glass rod pumped by a pulsed Nd:YAG laser. The performance data indicate that cw lasing using a cw Nd:YAG laser should also be possible, and that a fibre laser based on this same glass should have a very low threshold, compatible with pumping by a diode-pumped miniature Nd:YAG laser.

The possibility of using a Nd laser to pump an Er glass laser, via absorption by Yb sensitisers with subsequent energy transfer to Er (see fig. 1), was first demonstrated by Gapontsev et al. [1]. In that work, and subsequent related work (see Gapontsev et al. [2] for numerous references) the emphasis has been on efficient conversion and high energy operation, using Nd glass lasers (usually phosphate) as the pump. By contrast our emphasis has been to assess the potential for low threshold operation with, for convenience and availability, a Nd:YAG laser as pump. To our knowledge this is the first report of

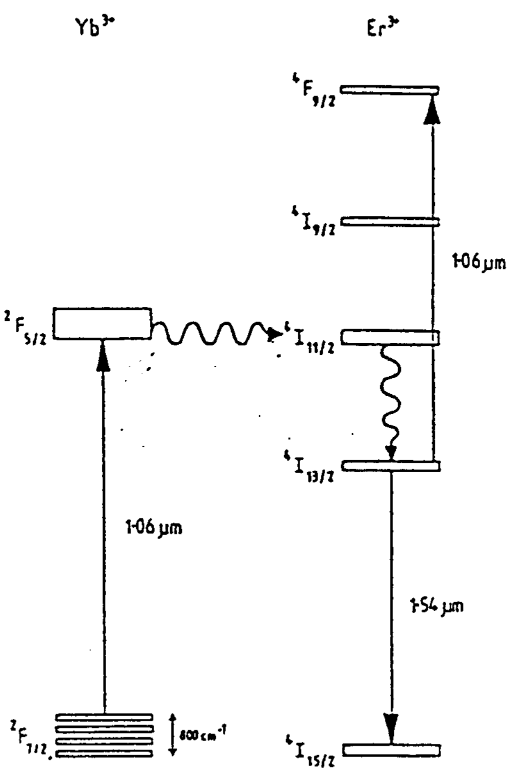

Fig. 1. Pump radiation is absorbed by Yb^{3+} from the highest sublevel of $^2F_{7/2}$. Nonradiative energy transfer occurs from Yb^{3+} ($^2F_{5/2}$) to Er^{3+}($^4I_{11/2}$) and then nonradiative decay to Er^{3+}($^4I_{13/2}$). Lasing at 1.54 μm is from Er^{3+}($^4I_{13/2}$) to the ground level ($^4I_{15/2}$). Excited state absorption of the pump can occur from the metastable level Er^{3+}($^4I_{13/2}$) to Er^{3+}($^4F_{9/2}$).

lasing in Er glass pumped by a Nd:YAG laser. In fact, apart from the convenience and availability of Nd:YAG, the wavelength of 1.064 μm is not ideal since it lies in the steeply falling long-wavelength wing of the Yb $^2F_{7/2} \to {}^2F_{5/2}$ absorption and lies in the short wavelength wing of the unwanted $^4I_{13/2} \to {}^4F_{9/2}$ absorption in Er [2], see fig. 1. On both of these accounts a somewhat shorter pump wavelength is to be preferred, and it is for this reason that with Nd glass laser pumping, phosphate glass ($\lambda \sim 1.055$ μm) has been used in preference to silicate glass [2]. It is therefore likely that replacement of Nd:YAG by, for example, the shorter wavelength Nd:YLF will prove beneficial.

2. Pump energy requirement

The advantages of using a laser to longitudinally pump another laser are well known: the small pumped volume minimises the pump power requirement and this in turn minimises the thermal input to the medium. For a glass host medium with its relatively low thermal conductivity the reduced thermal load is particularly important and especially so for high repetition rate or cw operation.

To make a rough estimate of the pump energy requirements to reach threshold we calculate the number of pump photons that must be absorbed in order to pump half of the Er ground state population to the $^4I_{13/2}$ level. The laser medium we have used is a 7.5 cm long cylindrical rod of Kigre QE-7 Er phosphate glass, with an estimated Er concentration $N_0 \sim 1 \times 10^{25}$ m^{-3}. This estimate is based on the measured unpumped absorption coefficient of ~7 m^{-1} at 1.54 μm and an assumed value of 7×10^{-25} m^2 for the stimulated emission cross section [2]. With the pump beam focussed to a waist spot size w_p, so as to have a confocal parameter equal to the rod length l ($2\pi w_p^2 n/\lambda_p = l$, where n is the refractive index), the pumped volume is $\sim \lambda_p l^2/n$, thus indicating a minimum possible pump energy of $\lambda_p l^2 N_0 h\nu_p/2n$. Inserting the relevant parameter values yields a predicted pump energy of ~4 mJ. However, the pump light is only weakly absorbed (~18% of the 1.064 μm pump being absorbed in a rod 7.5 cm in length at room temperature) leading to an increased predicted threshold of ~20 mJ incident on the rod.

This estimate assumes 100% transfer efficiency from Yb to the upper laser level in Er. While measurements of fluorescence lifetime shortening for Yb indicate near 100% transfer from Yb to Er [1], it has been pointed out [3] that this transfer is not necessarily all to the $^4I_{13/2}$ upper laser level. In fact absorption of pump light from the $^4I_{13/2}$ level is one process which reduces net transfer efficiency to $^4I_{13/2}$. Estimates by Gapontsev [3] indicate a net transfer efficiency to $^4I_{13/2}$ of somewhat less than 50%, but this figure may be lower in the case where Nd:YAG is used as the pump since the longer pump wavelength leads to stronger absorption from the $^4I_{13/2}$ level [2].

In practice we have measured a threshold of ~300 mJ incident pulse energy (at room temperature) suggesting a significantly lower transfer efficiency. At elevated temperatures a threshold of ~150 mJ has been achieved, indicating that a cw threshold of ~20 W is to be expected.

3. Experimental arrangement

Given the predicted pumping requirements indicated above we chose to carry out an initial investigation using a long pulse Nd:YAG laser as the pump source, having a pulse duration of 5 ms, comparable to the ~8 ms lifetime of the Er $^4I_{13/2}$ level. This provided significantly higher power than usually available from a cw Nd:YAG laser, but on the other hand allowed operation at lower intensity and hence with lower damage risk than for typical non-Q-switched Nd:YAG lasers of 100–200 μs pulse duration.

To maximise the available TEM$_{00}$ power from the Nd:YAG laser, a telescopic resonator was used [4,5]. With a plane 80% reflectivity output coupler, ×3 telescope, and 6 mm×75 mm Nd:YAG rod, this laser gave 5 ms pulses of up to 90 W, in a linearly polarised TEM$_{00}$ mode, at a repetition rate of 5 Hz. The linear polarisation produced by means of two Brewster angle plates in the resonator, was necessary to enable efficient isolation of the Nd:YAG laser from the Er laser using a polariser and quarter wave plate (fig. 2). With the generous power available from the pump laser the pump focussing condition in the Er rod could be relaxed somewhat from the confocal condition ($2\pi w_0^2 n/\lambda_p = l$, implying a waist size $w_0 = 90$ μm) and a waist size of 170 μm was actually used, achieved with a lens of focal length 20 cm. The

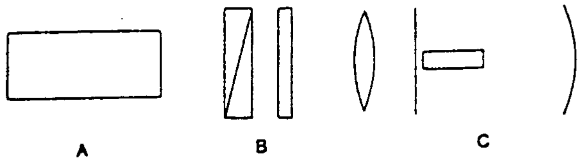

Fig. 2. Arrangement of telescopic resonator Nd:YAG pump laser (A) and Er glass laser resonator (C), with isolation (B) provided by a polariser and quarter wave plate.

erbium laser resonator, fig. 3, consisted of a plane mirror (pump input mirror) and a concave mirror, 20 cm radius, spaced by 22 cm, with the laser rod adjacent to the plane mirror. This resonator was chosen to give a calculated TEM_{00} spot size, at 1.54 μm, of 130 μm at the plane mirror, and hence comparable to the pump spot size in the rod. The plane mirror had ~99% reflectivity at 1.54 μm and ~90% transmission at 1.064 μm. The concave mirror had >99% reflectivity at 1.54 μm. To investigate the optimum output mirror transmission (for maximum power) an inclined plate was placed in the resonator, providing a known loss as a function of tilt angle.

With the arrangement described above, threshold for 1.54 μm oscillation with the glass rod at room temperature corresponded to ~64 W incident on the input mirror, and hence ~10 W of absorbed pump power. A significant increase in absorption, and corresponding decrease in threshold was obtained by heating the rod, thus increasing the thermal population in the upper levels of the Yb $^2F_{7/2}$ manifold. Most of the results have therefore been taken at a temperature of ~90°C, where the absorption of pump radiation was ~30% over the rod length. The threshold power incident on the input mirror was thereby reduced to ~32 W. Further increase in temperature, while producing stronger absorption, did not lead to further significant threshold reduction.

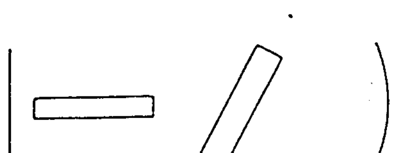

Fig. 3. Er glass laser resonator, with plane pump input mirror (A), Er rod (B), concave mirror (D), and inclined plate (C) to provide a calibrated output coupling.

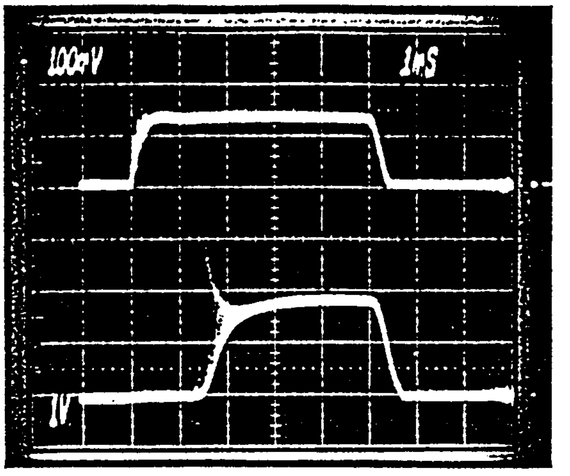

Fig. 4. Upper trace shows the 1.064 μm pump pulse, lower trace the 1.54 μm Er laser output. The Er rod was at 90°C and the input pump power of 90 W was ~3× the threshold value.

Fig. 4 shows a typical output pulse from the Er laser, with initial ringing behaviour, settling to steady state output in ~1 ms. Fig. 5 shows in more detail the trailing edge of the Er output and the pump pulse. It is interesting to note that lasing continues after the pump pulse has terminated and ringing can be produced on the trailing edge of the Er laser pulse. The output from the inclined plate was monitored by a Ge photodetector and the reflected power from one surface of the inclined plate, measured with an average power meter, was used to calculate the total output power. By varying the plate angle, and hence the output coupling, we found a maximum average output power of ~45 mW for a total output coupling of ~8%, corresponding to a total peak output power of ~2.2 W. Under these optimum coupling conditions the photon conversion efficiency, from absorbed pump photons to emitted 1.54 μm photons is ~10%, a result which suggests a rather low transfer efficiency from Yb to the $^4I_{13/2}$ level of Er.

4. Conclusion

We have shown that, despite its rather weak absorption at 1.064 μm, Yb:Er phosphate glass can be pumped sufficiently hard by a Nd:YAG laser to achieve lasing with reasonable gain and efficiency. Clearly a number of improvements in the perform-

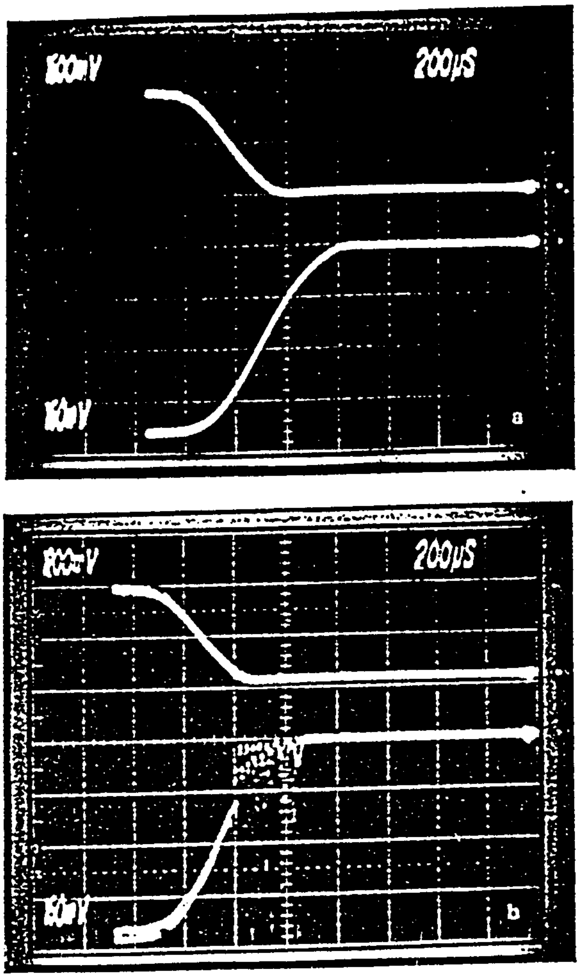

Fig. 5. Detail of the trailing edge of the Er laser output (lower trace inverted): (a) shows lasing continuing after the pump pulse has finished; (b) shows the ringing which can be produced by the transient effect of the falling pump pulse.

ance reported here can be made with an optimised arrangement. The low degree of observed (and estimated [6]) thermal lensing and birefringence and the low threshold indicate that pumping with a cw Nd:YAG laser should be possible. Improved utilisation of the available pump power could be achieved by placing the Er rod in the Nd laser resonator [2].

The long fluorescence lifetime makes the Er laser well suited to energy storage and Q-switching. Using a mechanical chopper we have readily produced a pulse of ~400 ns duration. The long pumping pulse used for this laser is also suitable for the development of steady state actively mode-locked operation and experiments are planned to test such performance. Combined mode-locking and Q-switching should readily produce multikilowatt peak powers.

Very low threshold operation as seen in Er doped fibres [7] should ultimately be possible by fabricating the Yb:Er glass in the form of a monomode fibre. This would offer the opportunity of pumping by means of a diode pumped Nd:YAG or Nd:YLF laser. These various possibilities suggest that laser-pumped Er glass lasers could provide a convenient and versatile source of radiation in the 1.5 μm region.

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