Diode-pumped cw bulk Er:Yb:glass laser

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Received June 25, 1991

Continuous-wave laser operation of bulk Er:Yb:phosphate glass pumped at 980 nm by an InGaAs index-guided diode laser has been achieved for the first time to our knowledge, with 2 mW of output power obtained at 1.54 μm. To optimize pumping conditions and to investigate the effects of pump wavelength, the Er^{3+}:Yb^{3+} glass disk has also been pumped by a Ti:Al_2O_3 laser at 960 nm and 980 nm, and we obtained high output power (70 mW) and the highest slope efficiency (21% for 980-nm pumping) reported to date for a bulk Er:glass laser

Laser oscillators based on Er^{3+}-doped glasses and fibers have recently become the subject of great interested in particular for their potential use in optical communication systems operating near 1.5 .m and 'n telemetry at an eye-safe wavelength. In this Letter we report what is to our knowledge the first successful cw laser operation of bulk Er^{3+}:Yb^{3+}:Phosphate glass pumped at 980 nm by an InGaAs index-guided strained-layer diode laser. The laser is also pumped at 960 and 980 nm by a Ti:Al_2O_3 laser to show its potential for high power and high efficiency.

Erbium is a three-level laser medium at 1.5 .m and thus requires more population in the excited metastable level than in the fundamental one. This may lead to excited-state absorption of pump light6 that is detrimental to the efficiency of the laser. To avoid this, pumping at both 1.48 gm and 980 nm has been considered a particularly attractive solution. Although 1.48-μm InGaAsP/InP lasers are, because of their advanced technology, the most popular pump sources, newly developed 0.98-μm lasers have advantages over these in terms of low-noise figure, temperature Insensitivity, and higher efficiency of the laser itself.[7] Indeed, new strained-layer ew InGaAs diode lasers emitting at 980 nm with a rated output power of 50 mW have recently become commercially available,[8] and this output power is likely to be increased in the near future. Furthermore the 980-nm wavelength is particularly suitable for the case of codoping with the Yb^{3+} ion, which presents an absorption band at that wavelength and efficiently transfers its excitation energy to the Er^{3+} ion. Continuous-wave laser operation of bulk erbium in glass has so far been demonstrated only by pumping with a cw diode-pumped ND:YAG laser, and the results are impressive.[9] The configuration is, however, somewhat cumbersome because of the small absorption coefficient of the Yb^{3+} ion at the 1064-nm wavelength.

The experimental configuration used for our diode-pumped Er" laser is illustrated in Fig. 1. The active material of the laser consists of a 2.5-mm long by 4-mm-diameter Kigre QE-7 Er^{3+}:phosphate disk codoped with Yb^{3+}. One face of the plano-plano disk is coated for high reflectivity at 1.54 μm (R = 99.9%) and antireflection coated at 960-980 nm (R < 6%). The other face is high-reflectivity coated at 960-980 nm (R = 99.8%) and antireflection coated at 1.54 μm (R = 4%). The resonator design is a standard plano-concave configuration consisting of the high-reflectivity mirror directly coated on one face of the disk and a 5-mm radius-of-

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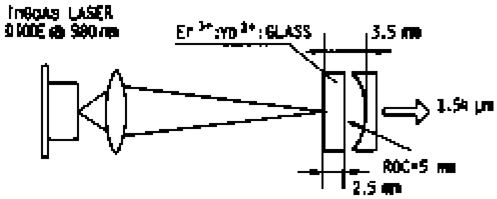

Fig. 1. Schematic of the diode-pumped $Er^{3+}:Yb^{3+}$: phosphate glass laser.

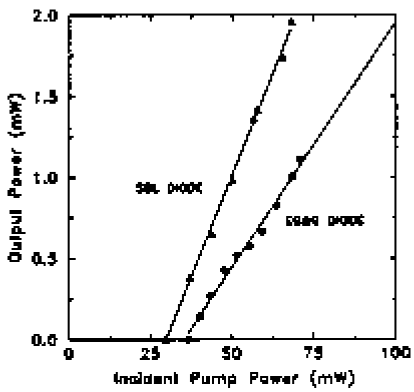

Fig. 2. Output power from the diode-pumped $Er^{3+}:Yb^{3+}$: phosphate glass laser as a function of the input power incident upon the rear face of the laser disk with the SDL 6300 InGaAs diode laser and the EG&G InGaAs diode laser.

curvature (ROC) output spherical mirror. With a resonator length of 3.5 mm the waist, which occurs at the end face of the disk, has a spot size (half-width $1/e^2$ of intensity) of 35 μm, and the mode spot size is almost constant inside the disk. The $Er^{3+}:Yb^{3+}$ laser is end pumped by an InGaAs strained semiconductor laser. The light emitted by the diode is collected and focused by a high numerical-aperture triplet lens (N.A. = 0.6) with a focal length of 6.5 mm. Two different InGaAs diode lasers from Spectra Diode Laboratories (SDL) and EG&G have been used as pump sources. The SDL Model 6300 index-guided diode laser provided as much as 68 mW of input power on the active material centered at a wavelength of 979 nm in a near-diffraction-limited beam with divergences of 30 and 10 deg (FWHM). The dimensions of the emitting area are 1 μm x 3 μm. The EG&G laser diode provided a slightly higher- pump power (as much as 75 mW) but with higher divergence angles of 40 and 16 deg (FWHM). The emitting area is 0.5 μm x 3.5 μm. In both cases, the pump beam is focused to an average spot size of ~30 μm inside the active material, so that the corresponding Rayleigh range is approximately equal to the disk thickness. It must be noted that an optimum length of the active material that depends on the input pump power must exist in our case. As the length is increased, in fact, the amount of absorbed pump light obviously increases, but the gain along the pumping direction decreases and eventually changes into net loss. Using simple rate-equation calculations, and taking into account the presence of Yb^{3+} codoping, we find that the pump intensity I_p, for a zero-loss condition (i.e., when the metastable and ground-state populations of Er^{3+} ions are equal, assuming that there are no other losses in the glass) and for an infinitely thin material is given by $I_p = N_E h\nu_p/\alpha_Y T_E$, where N_E is the total Er^{3+}-ion concentration, T_E is the lifetime of the ${}^4I_{13/2}$ laser level, ν_p is the pump frequency, and α_y is the absorption coefficient of the Yb^{3+} ion at the Pump wavelength. Assuming that $N_E=1.2 \times 10^{19}$ ions/cm^3, $\mathbf{T_E}$ = 8 ms, and $\alpha_y=6\ cm^{-1}$,[10] we obtain I_p = 50 W/cm^2 (i.e., approximately 5 mW for a 10^4 -μm^2 pump area). It should be noted that direct pumping of Er^{3+} ions has been neglected in the calculation because of the much lower concentration of Er^{3+} ions ($1.2 \times 10^{19}\ cm^{-3}$) compared with that of the Yb^{3+} ions ($1 \times 10^{21}\ cm^{-3}$).[11] It should also be noted that the pump beam is not a circular Gaussian and may be better described by an elliptic Gaussian beam. Therefore the pump area inside the active material is not circular, and the average value of the spot size should be considered. In our case, the ratio between the mode and the average pump spot size must have an Optimum value that is slightly larger than unity. A diameter of the pumping, beam appreciably smaller than the mode spot size would in fact create uninverted regions in the tail of the mode, which would introduce unwanted losses. On the other hand, a pump-beam diameter appreciably larger than the spot size would not ensure TEM_{00}-mode operation, since higher-order transverse modes could oscillate.

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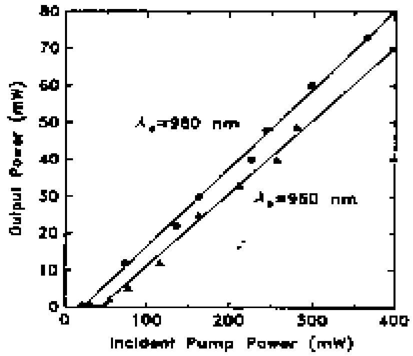

Fig. 3. Output power from the $Er^{3+}:Yb^{3+}$:phosphate glass laser pumped by a $Ti:Al_2O_3$ laser as a function of the input power incident upon the rear face of the laser disk for a pump-light wavelength λ_p of 980 and 960 nm.

The output power from the Er^{3+} laser was measured by a radiometer (UDT Model S380) with a calibrated germanium sensor head (UDT Model S2575Ge). Figure 2 shows curves of the output versus input power of the erbium laser pumped with each of the InGaAs diode lasers. The output coupling is 1% in both cases. It is apparent that the best results (29.6-mW threshold, 5% slope efficiency) were obtained with the SDL diode. The maximum output power in this case is 2 mW at 68 mW of pump power. The EG&G diode resulted in higher threshold (36.5 mW) and lower slode efficiency (3%). This may be ascribed to the different ellipticity of the beams. We recall that the emitting area of the EG&G diode laser is slightly wider (3.5 μm versus 3 μm) and much narrower (0.5 μm versus 1 μm) than in the SDL device. In both cases, much better results are anticipated by a careful reshaping of the pump beams by means of astigmatic optics, such as an anamorphic prism pair with a suitable expansion ratio. We note that the measured values of threshold pump power are substantially higher than the previously estimated power for zero-loss condition. We believe that this result may be due to at least three circumstances: (i) The pump power needed to reach oscillation may substantially exceed that just needed to equalize the populations, owing to the low gain and relatively high losses of the laser (re-absorption losses, because it is a three-level laser). (ii) The pump intensity reaching the end face of the disk is substantially lower than that of the input beam, because of the strong attenuation of the pump beam through the laser disk. (iii) The beam ellipticity certainly also helps to increase the laser threshold. As a final note, however, it is worthwhile to point out that the threshold achieved in the best case (26 mW) is substantially lower than the extrapolated value (70 mW) given in Ref. 3 for diode laser pumping.

In order to clarify the importance of the beam shape and to test the effects of the pump wavelength and of the coupling efficiency, the $Er^{3+}:Yb^{3+}$ laser was also pumped by a Ti:sapphire laser beam oscillating at either 980 or 960 nm. In this case the pump beam was focused by a 25-mm focusing optic, which gives a spot size inside the active material of approximately 40 μm. The best results were obtained using a plano-concave resonator with a spherical mirror of 10-mm ROC, which provides a 50-μm mode beam waist. Three different values of reflectivity (0.95, 0.98, and 0.99) were tested. Figure 3 shows plots of output power versus input power for both 960- and 980-nm pumping. Both curves are obtained with the 98% output coupler, which gives the best performance. The slope efficiency (21% for 980 nm and 20% for 960 nm) substantially exceeds the results discussed above for diode pumping. This efficiency is also comparable with that (28%) reported for multi-mode erbium fiber lasers,[4] although it is still appreciably smaller than that reported (50%) with single-mode erbium fiber lasers.[2,12] It should be pointed out, however, that no particular attempts have been made so far to optimize the efficiency in our laser. On the other hand, it is important to note that output power and slope efficiency are approximately equal for the cases of 980- and 960-nm pumping. This implies

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that the emission wavelength of diode lasers is not particularly critical for the pumping process and can be changed throughout a relatively large range.

In conclusion, we have demonstrated cw operation of an Er^{3+}:Yb^{3+}:phosphate glass laser pumped by an InGaAs laser diode at 980 nm. In preliminary experiments, 2 mW of output power with approximately 70 mW of pump power has been obtained. High output power (70 mW) and efficiency (21%) have been demonstrated by using a TEM_{00} focused beam from a Ti:sapphire laser as a pump source. Thus with an optimized diode-pumped configuration, an all-solid-state, compact, high-efficiency, high-power, single-transverse-mode cw source at 1.54 µ,m should soon be obtainable. This source has great potential for both optical fiber communications and other applications in which an eye-safe wavelength is required.

This research has been partially supported by the National Research Council (C.N.R.) of Italy under the Progetto Finalizzato on Electro-Optical Technologies. The EG&G InGaAs diode laser was kindly supplied to us by Pirelli Cavi S.P.A., Italy.

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