CW Diode-Pumped Microlaser Operation at 1.5–1.6 μm in Er, Yb : YCOB

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***Abstract*—We report efficient laser operation at 1.5–1.6 μm in an Er, Yb : YCOB laser. The maximum output power of 110 mW was achieved in a hemispherical cavity with a slope efficiency of 20%. We also report 100 mW of output in a flat–flat cavity configuration, and the first report of operation of this type of laser crystal in a true microchip arrangement with $>$10-mW output.**

***Index Terms*—Diode-pumped solid-state laser, microlaser, quasi-three-level laser.**

I. INTRODUCTION

CONTINUOUS-WAVE (CW) lasers operating in the 1.5–1.6-μm wavelength range have many practical applications. The most notable of these is their use in optical telecommunications, but the eye-safe wavelength range also has advantages for applications such as laser range finding and target acquisition, remote sensing, light detecting and ranging, medicine, metrology, and atmospheric phenomena such as measurements of wind shear.

To obtain high beam quality output in this spectral region, solid-state hosts doped with Er^{3+} impurity ions are most commonly employed to take advantage of the quasi-three-level $^4I_{13/2} \rightarrow ^4I_{15/2}$ transition. To improve the pumping efficiency, Yb^{3+} ions are co-doped into the host material to act as a sensitizer for the Er activator ions. The Yb ion has a very efficient absorption line at 975 nm, which corresponds with the emission of efficient InGaAs diode lasers as a pump source. There exists an efficient nonradiative energy-transfer mechanism between the Er^{3+} and Yb^{3+} ions which populates the $^4I_{11/2}$ energy manifold of Er^{3+}. This then decays to the $^4I_{13/2}$ upper-laser level. Suitable host materials for this pumping scheme should be characterized by a large phonon energy to increase the rate of this decay and hence reduce the back-transfer from the Er to Yb ions. Large phonon energies also help to reduce losses due to upconversion and excited-state absorption in the Er ion. Other requirements of the host include a large stark splitting of the Er^{3+} ground state for quasi-four-level operation, and good mechanical and thermal properties.

Laser operation in this range has been obtained in a number of crystalline hosts such as $LiNbO_3$ [1], $Y_3Al_5O_{12}$ (YAG), Y_2SiO_5 [2], and YVO_4 [3], and in glass hosts such as tellurite, phosphate, or fluoride hosts. At present in bulk materials, the glass hosts exhibit the lowest threshold power over the crystalline hosts, but have been severely limited in their output due to poor thermal properties.

The rare earth calcium oxyborate family of crystals $Ca_4REO(BO_3)_3$ has received a great deal of attention in the past few years due to their ease of growth of large crystals via the Czochralski method, nonhygroscopicity, good thermal conductivity, and excellent nonlinear properties [4]–[6]. In addition to these favorable properties, the phonon spectrum is dominated by that of the borate $(BO_3)^-$ anion that has a maximum energy of approximately 1400 cm^{-1} [7]. This then makes it a very attractive host for Er, Yb codoping. In particular, we have concentrated on the $Ca_4YO(BO_3)_3$ (YCOB) crystal, and indeed, laser operation has already been demonstrated in Er, Yb : YCOB with unoptimized dopant concentrations [8]. By studying the energy transfer mechanisms of this material, we have identified the optimum Er concentration for various Yb concentrations theoretically [9] and have grown new crystals accordingly.

In this letter, we investigate the 1.5-μm laser performance of the Er, Yb : YCOB material with improved concentration ratios in a variety of cavity configurations. In particular, we obtained laser operation in a true microchip configuration with mirrors deposited directly onto the laser crystal. We believe this to be extremely promising for further developments of this laser system since the competing glass hosts suffer from a negative value of dn/dT which makes cavity stability issues much more difficult [10].

II. EXPERIMENTAL SETUP

In each case, we used a Y-cut 2-mm-long Er, Yb : YCOB crystal which was doped with 30 at% Yb^{3+} and 1.4 at% Er^{3+} ions. The dopant concentrations have been chosen from studies of the energy transfer mechanisms between the Er and Yb ions [9]. One face of the crystal was coated for high-reflection (HR) ($R > 99.9\%$) between 1.4–1.6 μm and high transmission ($T \approx 92\%$) at 975 nm. The output face was antireflection (AR) coated ($R < 0.5\%$) between 1.4–1.6 μm. The pump source was a 1.6-W fiber-coupled InGaAs diode laser at 975 nm from Mitsui ($M^2 \approx 16$). The output from the pump fiber (50-μm core) was first collimated then focused into the laser crystal. The focused pump spot size was adjusted to find the optimum coupling of the pump mode with the cavity mode for the mirrors we had available. About 90% of the maximum output from the pump fiber was incident on the laser crystal. The absorption coefficient at

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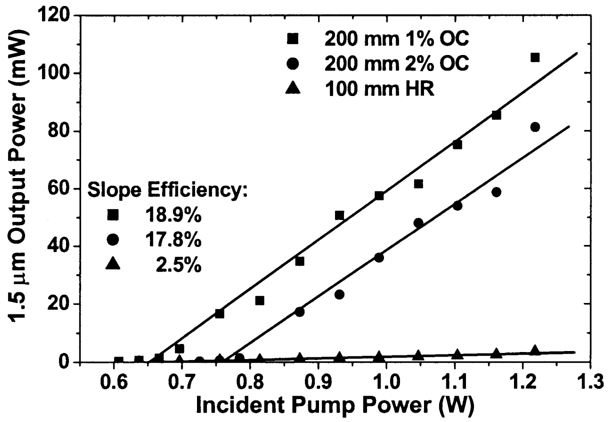

Fig. 1. Output characteristics for the semi-hemispherical cavity.

975 nm due to the Yb ions was $\alpha = 12\,\mathrm{cm}^{-1}$, resulting in ~91% absorption of the pump light in the crystal.

Initially, we investigated the laser in a hemispherical cavity configuration with a variety of output couplers (OC) [an HR mirror of radius of curvature (RoC) 100 mm, and OCs of RoC 200 and 300 mm, each with output couplings of 1% and 2%]. The OC was placed close to the crystal for the best pump-cavity mode overlap.

The laser performance was then explored in a flat–flat cavity arrangement with a view toward microchip operation. The HR coated face of the laser crystal acted as the first mirror, whilst various flat mirrors situated quite close to the AR coated crystal face were used to investigate the optimum output coupling. The total cavity length then, was never much larger than the crystal length itself (2 mm).

Finally, a metallic coating was deposited directly on to the AR coated face of the crystal to realize a true microchip laser. The thickness of this coating was designed so as to give approximately the same amount of output coupling as determined in the previous experiments.

III. LASER PERFORMANCE

A. Semihemispherical Cavity

The optimum pump spot size for the 2-mm crystal was determined to be approximately 110-μm diameter using the Taira condition for pumping three-level lasers with a pump beam with a large M^2 value [11]. This was achieved by an appropriate choice of collimating and focusing lenses for reshaping of the pump beam. Fig. 1 shows the laser output and slope efficiencies for the curved OCs used. The maximum output power observed from the laser was 110 mW which was obtained with a 1% OC with a 200 mm RoC.

The laser output was TEM00 with multiple-longitudinal-modes and varied between 1543 and 1548 nm for the 2% OC and 1543–1555 nm for the 1% OC. Laser oscillation for the 100 mm HR occurred between 1568–1573 nm. This is consistent with the gain cross section of the transition shown in Fig. 2 for the E||Z polarization and appropriate values of the population inversion, β (higher intracavity intensity implies that smaller β required to achieve oscillation).

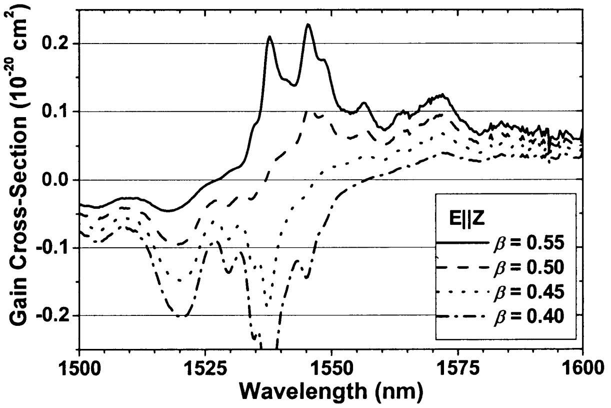

Fig. 2. Gain cross section of the $^4I_{13/2} \rightarrow {}^4I_{15/2}$ transition in Er, Yb : YCOB.

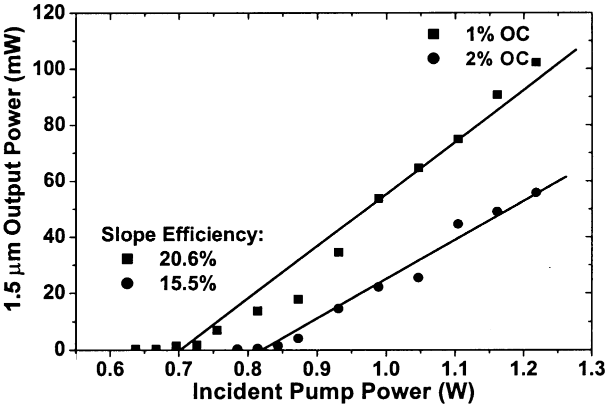

Fig. 3. Output characteristics for the planar–planar cavity.

The pump-cavity mode overlap in each of these cases was not perfect due to the limited availability of mirrors. Better overlap and hence improved laser performance is expected with OCs with a much shorter RoC.

B. Microchip Lasers

The *La*COB family of crystals are particularly suited to microchip lasers since large crystals of good optical quality can be grown quite quickly, and they are able to accommodate quite a large proportion of impurity dopant ions, e.g., up to 45 at% Yb can be doped into the YCOB host [4].

To investigate microchip operation in our Er, Yb : YCOB crystals we substituted a flat OC for the curved OC used previously. Fig. 3 shows the result (recall that the input face of the crystal has a HR coating creating a flat input coupler). The OC was positioned as close as possible to the output face of the crystal. Again we find that the optimum output coupling is 1%, for which we obtain ~100 mW of output at 1550 nm.

This result was extremely promising, so we evaporated a metallic coating over the top of the existing AR coating on the output face of the crystal to investigate true microchip performance. This is a preliminary step which was used to evaluate the feasibility of further work in this area. The coating had a reflectivity of ~97.5% and a transmission of ~0.7% at the laser wavelength. Hence, it also had ~1.8% absorption as well which acted as an intracavity loss. Fig. 4 shows the output characteristics of the laser. Approximately 11 mW of polarized

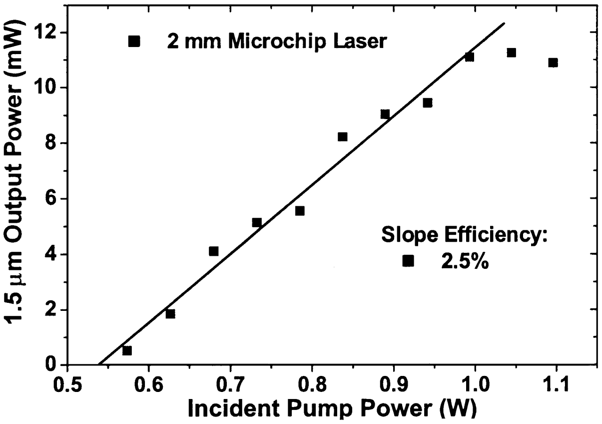

Fig. 4. Output produced by the microchip laser.

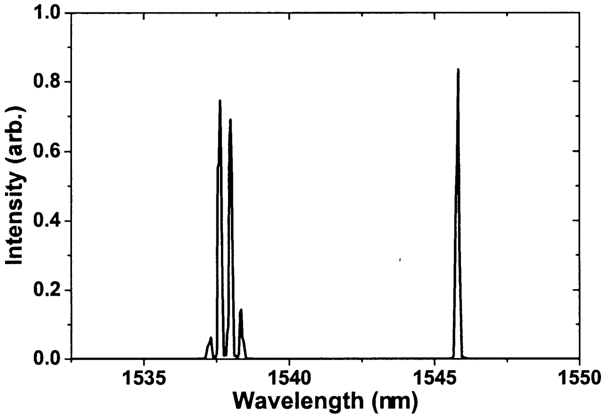

Fig. 5. Output spectrum of the microchip laser.

output was obtained for the incident pump power of ~1.2 W. The jumps in the output power at 0.8-W and 0.95-W input power are due to the appearance of additional longitudinal modes in the output.

Whilst the results are not as good as for the planar–planar cavity, the threshold (~0.5 W) is 300 mW lower than that seen with a 2% output coupler. With an appropriate dielectric output coupler deposited directly onto the crystal, we expect to see at least equivalent slope efficiencies which will result in output powers of the order of 150 mW.

Fig. 5 shows the typical output spectrum at maximum pump power. It can be seen that the output consists of two mode groups at 1537 and 1546 nm with a modulation due to the longitudinal mode spacing of the cavity length. These mode groups correspond to the two peaks observed in Fig. 2 for a high value of β that is consistent with a high inversion threshold due to the intracavity loss introduced by the metallic coating.

IV. CONCLUSION

Efficient laser operation has been demonstrated for the first time in the Er, Yb : YCOB crystalline host. Over 100 mW of output in the range 1043–1073 nm in both hemispherical and planar–planar cavity configurations was obtained, equivalent to that obtained in the YVO_4 host [3], however, with a much higher slope efficiency with respect to incident pump power. The Er dopant concentration (1.4 at%) is still not quite optimum and further improvements are expected in the gain and output with slightly lower concentration. The output wavelength observed in the different configurations can be explained in terms of the gain cross section of the Er $^4I_{13/2} \rightarrow ^4I_{15/2}$ transition.

The first realization of true microchip operation in Er, Yb : YCOB has also been demonstrated with >11 mW of output at 1537 and 1546 nm observed. Much better performance is expected with the application of low-loss dielectric coatings in place of the lossy metallic coating used and we expect this work to generate a renewed interest in this material for efficient monolithic eyesafe devices based on the YCOB host.

Note Added in Proof: Recent results have shown ~250 mW of 1.5-μm output power in the hemispherical cavity with 1% output coupler and 2 W of pump. Similar laser threshold and slope efficiency were obtained.

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