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Spectral characteristics of 2 μm microchip $Tm:YVO_4$ and Tm,Ho:YLF lasers

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Abstract

In this paper, we present experimental results concerning the spectral emission obtained with two microchip lasers emitting in the 2 μm range. We show that high efficiency is achieved in both cases at room temperature. Nevertheless, while $Tm:YVO_4$ oscillates always on longitudinal modes and may easily be single frequency with high power, Tm:Ho:YLF is always emitting several transverse modes for any pumping conditions with temperatures between 13°C and 35°C. This result is interpreted considering the gain of these two amplifier media and the mode guiding resulting from the thermal properties of the two host materials. © 1998 Elsevier Science B.V. All rights reserved.

1. Introduction

Extensive research is being devoted to the development of solid state lasers emitting in the eye safe spectral range with the possibility of efficient diode-pumped sources. There is a promising range of applications foreseen for such devices including LIDAR [1], metrology [2] and medical applications. The microchip concept, where the mirrors are coated directly on the crystal faces, results in very compact sources with high spatial quality beams. Resulting from the compactness of the cavity, these lasers are very frequency stable and it would be advantageous to set up a single frequency source for some applications like local oscillators for heterodyne detection, master oscillators for MOPA driving and oscillators for metrologic apparatus. We present the frequency characteristics obtained for both $Tm:YVO_4$ and Tm,Ho:HLF microchip lasers.

2. Experimental apparatus

With the goal to control efficiently the crystal temperature and to optimize the pump light absorption, an active mirror configuration has been chosen [3]. In this configuration, the rear face of the crystal, which is coated for high reflection of both the laser and the pump wavelengths, is bonded on a heat sink. The front face is coated for high transmitivity for the pump and proper reflectivity for the laser wavelength. The pump is injected from the front face through a dichroic beam splitter which reflects the pump

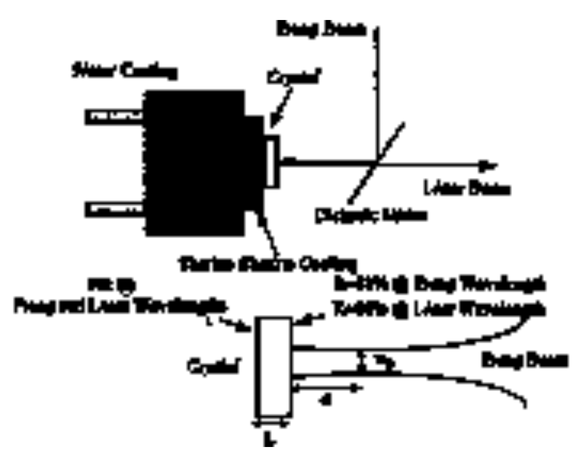

Fig. 1. Experimental apparatus for pumping and cooling.

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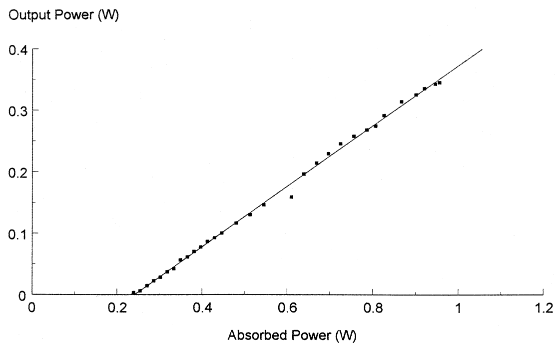

Fig. 2. Output power versus absorbed pump power for the YVO_4 0.5 mm thick crystal pumped by a 26 μm waist size.

light and transmits the laser light. The polarization of the pump is parallel to the *c*-axis of the crystal in both cases. The crystal is then cooled uniformly by the rear face and the pump travels back and forth allowing better pump power deposition. This configuration is shown in Fig. 1. In addition, since the front face is not totally transparent for the pump light ($R_p = 18\%$), a Fabry-Perot cavity is established for the pump allowing for the capability to store the launched pump power resulting in a higher efficiency. Theoretical investigations and experimental results concerning such a configuration has been published [4]. For our experiment, the crystal is pumped by a Ti:sapphire laser capable of supplying up to 2 W on the fundamental mode.

3. Tm:YVO_4 microchip laser

In a first step, we tested two Tm:YVO_4 crystals supplied by Casix (China). Doping concentration is 5% atom Tm. The crystals are 3×3 mm^2 in transverse size and 1 mm or 0.5 mm thick. The faces are perpendicular to the *a*-axis. The rear face coating reflects 99.5% for both the pump and lasing wavelengths and the front face coating is 98% for the laser wavelength at 2 μm and 18% for the pump at 798 nm. From the Fabry-Perot effect for the pump light, less than 10% of the pump light is reflected when the laser is above threshold for the 1 mm thick crystal and 27% for the 0.5 mm thick crystal. This reflectivity does not depend upon the launched pump power as demonstrated in Ref. [4]. Fig. 2 shows the laser power versus the absorbed pump power for a pump beam waist size equal to 26 μm and crystal thickness of 0.5 mm. The corresponding laser beam waist size decreases from 50 μm at threshold to 30 μm for highest pump power [5]. With this configuration, the output power versus pump power does not depend on the temperature between 15°C and 35°C. For both crystal lengths, the emitted mode is perfectly Gaussian for any pump power up to 2 W available from our Ti:sapphire laser. In Fig. 3 both the experimental near field mode profiles and the best Gaussian fits for two directions parallel and perpendicular to the crystal *c*-axis are plotted. By plotting the mode profiles in various planes perpendicular to the light propagation direction, we determine an M^2 quality factor higher than 1.3.

Fig. 4 shows the emission spectrum for various pump powers for the 1 mm crystal with a pump waist size equal to 17 μm. For emitted power up to 62 mW, the laser oscillates on a single longitudinal mode centred at about 1.92 μm. For higher pump power, new longitudinal modes appear. When emitting 625 mW, the spectrum consists of 11 longitudinal modes separated by the cavity free spectral range of 0.9 nm. The same experiments have been conducted with the 0.5 mm thick crystal. Fig. 5 shows the

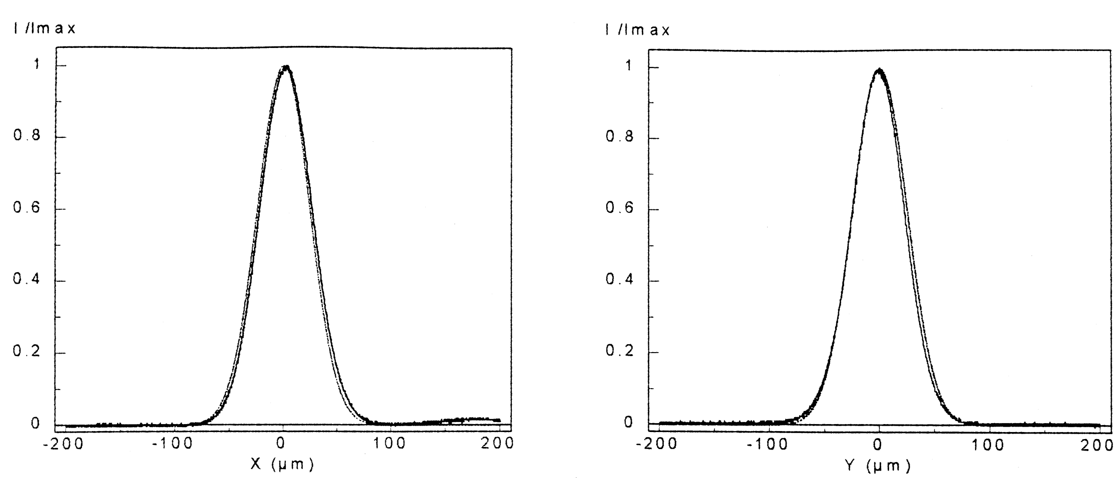

Fig. 3. Mode shape following two perpendicular directions for the 0.5 mm thick YVO_4 crystal pumped by a 26 μm waist size.

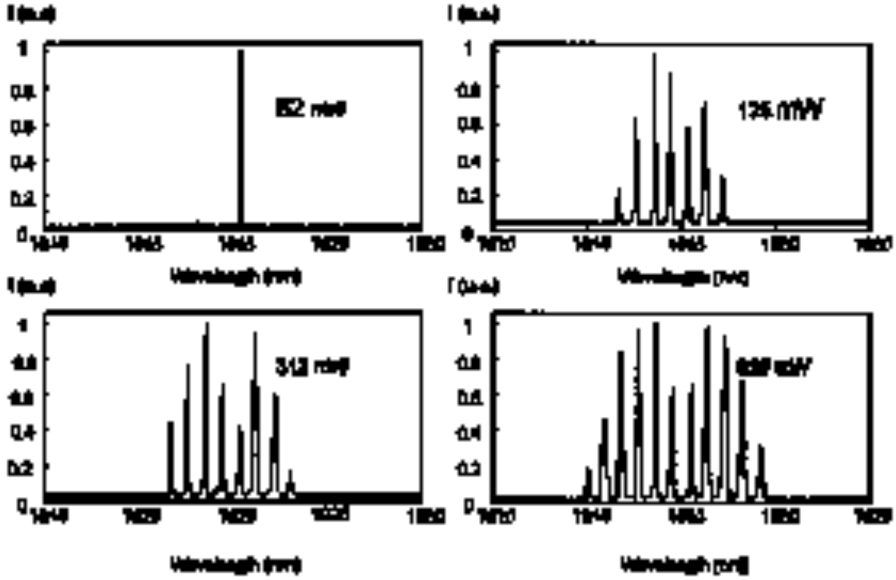

Fig. 4. Emitted spectrum for the 1 mm thick YVO_4 crystal for various emitted powers.

emitted spectrum for four values of the pump power. For low pump power, the emission is centred around 1920 nm. Increasing the pump power, the intensity emitted at 1920 nm stabilizes while a new emitted line at 1860 nm grows up. We also observe that the spectrum is made of longitudinal modes equally separated by the free spectral range, now 1.8 nm. Fig. 6 shows the relative intensity emitted at 1920 nm and 1860 nm respectively. This is the result of the reabsorption of the laser light inside the crystal accordingly with Ref. [6]. Though surprising, single longitudinal mode oscillation has never been observed with this crystal length by changing either the pump power near threshold, the pump beam size or the focus point location with respect to the crystal. This unexpected result has yet to be interpreted clearly.

4. Tm,Ho:YLF microchip laser

While the 1.9 μm wavelength is strongly absorbed by water vapour, Tm,Ho:YLF emission at 2.064 μm seems to be more attractive. However, this laser is very sensitive to

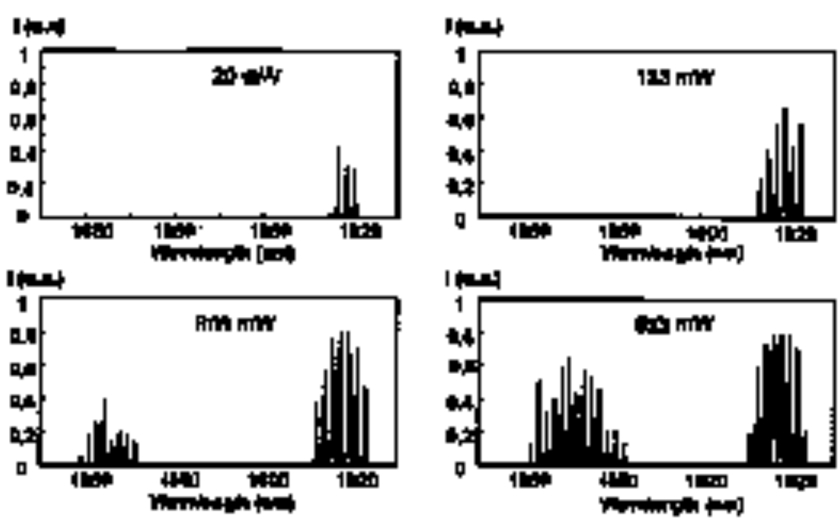

Fig. 5. Emitted spectrum for the 0.5 mm thick YVO_4 crystal for various emitted powers.

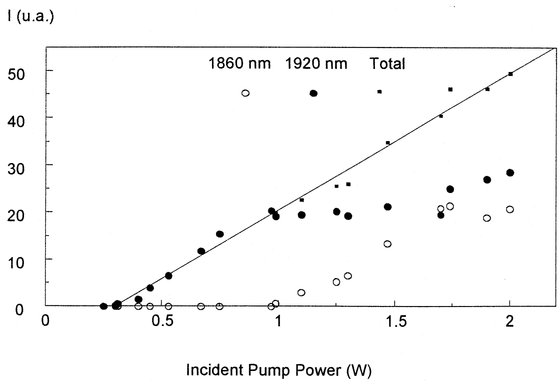

Fig. 6. Relative intensities emitted at 1920 nm and 1860 nm by the 0.5 mm thick YVO_4 crystal versus launched pump power.

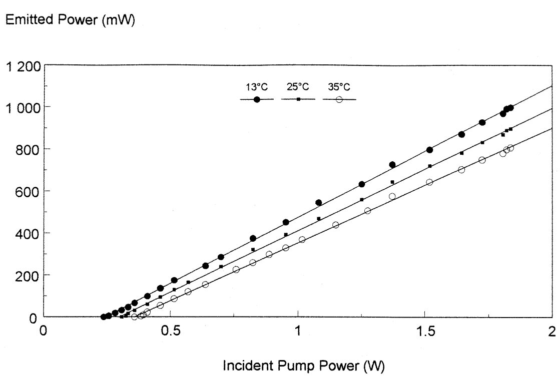

Fig. 7. Output power supplied by the 2.5 mm thick YLF crystal versus pump power for various crystal temperatures.

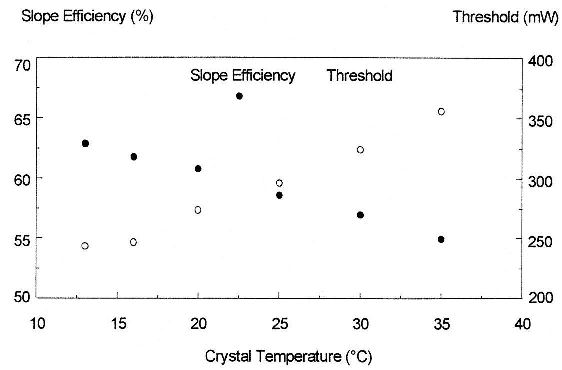

Fig. 8. Slope efficiency (left scale, full circles) and threshold (right scale, open circles) versus crystal temperature for 1.8 W pump power.

thermal loading and, with the conventional end pumped configuration, where the crystal is peripherally cooled, good efficiency requires very low temperature. Single frequency operation has already been obtained with 5.3% overall efficiency at -10°C [7].

The crystal we used has 2.5 mm length, the doping concentration is 6% Tm, 0.6% Ho, and the reflectivities of the faces are identical to the former case. Resulting from the Fabry-Perot effect for the pump light, the reflected pump power is negligible in this case. With the active mirror configuration, overall efficiencies as high as 54% at 13°C and 43% at 35°C have been obtained for 1.8 W pumping as shown in Fig. 7. The corresponding pump efficiencies are 1.415 and 1.12 respectively. These results can be compared to the pump efficiency equal to 1.17 obtained with a diode-pumped 2.18 mm crystal at 0°C [11]. We also observe in Fig. 8 that neither the pump threshold

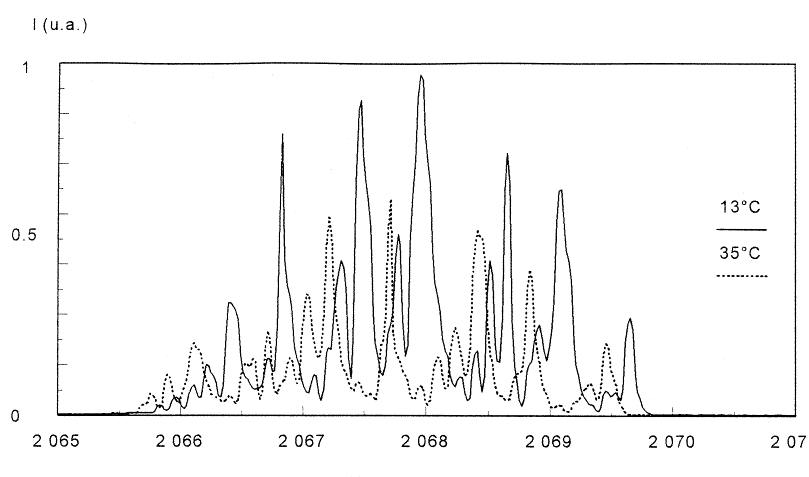

Fig. 9. Emitted spectrum for the YLF crystal at 13°C (solid line) and 35° (dashed line).

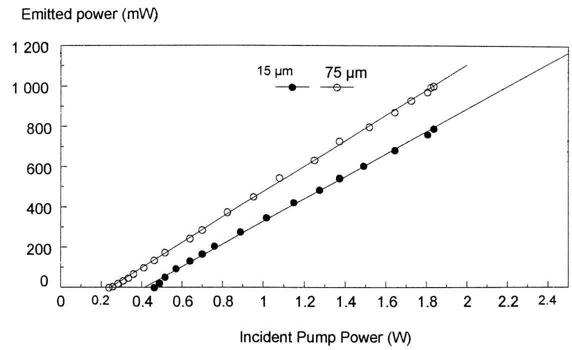

Fig. 10. Output power versus pump power for the YLF crystal for pump beam sizes equal to 15 μm and 75 μm.

nor the slope efficiency strongly depend on the temperature due to the more uniform cooling in the active mirror configuration.

Fig. 9 shows the emitted spectrum around 2.0635 μm for 13°C and 35°C with a pump beam waist size of 75 μm, corresponding to optimal power extraction computed from Ref. [5]. The spectrum always exhibits higher order transverse modes. In order to minimize transverse mode oscillations, we reduced the pump beam waist to 15 μm. Indeed, the laser modes spread out into the unpumped region when the pump beam waist size decreases (see Ref. [4] for thermal guiding and Ref. [8] for gain guiding). This resulted in a reduced efficiency as shown in Fig. 10 which shows the emitted power against pump power for both 15 μm and 75 μm pump waist sizes at 13°C. The corresponding emitted spectrum for 50 mW emitted power is shown in Fig. 11, demonstrating that single frequency emission was not possible with this configuration. With this crystal, the laser beam waist size poorly depends upon either the pump power decreasing from 150 μm at threshold to 125 μm for 1.8 W pump power, or the pump beam size inhibiting only a 10% variation between 15 μm and 75 μm.

5. Discussion

Several parameters must be taken into account for mode formation in microchip lasers. The main effect for setting up the mode seems to be thermal guiding [9]. If one considers the radial temperature distribution induced by a Gaussian pump beam, which waist size is w_p, the waist size of the guided mode w_g will be given by [9]:

$$w_g^2 = \lambda w_p \left(\frac{LK}{Q\pi n_0 \mathrm{d}n/\mathrm{d}T} \right)^{1/2},$$

where λ is the wavelength, L is the crystal length, Q the rate of heat generation, K is the thermal conductivity, n_0 the refractive index and $\mathrm{d}n/\mathrm{d}T$ is the linear change of refractive index with temperature. For YVO_4, $\mathrm{d}n/\mathrm{d}T$ is positive and a stable Gaussian mode exists. On the contrary, $\mathrm{d}n/\mathrm{d}T$ is negative for YLF and the mode is made of a spherical wave similar to those of unstable resonators. However, since the crystal is not uniformly heated along the laser propagation axis and uniformly cooled on the rear face, this model no longer holds and we must take into account the curvature of the front face by the radial temperature distribution which may compensate the divergence of the guided mode.

A complete study of the mode formation in such a configuration is presented in Ref. [4] taking into account the active mirror configuration and the Fabry-Perot effect for the pump light. Using these theoretical results, the generalized radius of curvature of the laser wave on the output mirror reads:

$$\frac{1}{q} = \frac{\alpha_e}{2KL} B + \frac{\mathrm{i}}{L} \sqrt{\frac{n_0(\alpha_e + \mathrm{d}n_c/\mathrm{d}T)}{2K} B},$$

where α_e is the thermal expansion coefficient and B is a factor depending upon the characteristics of the laser and the pump and laser intensities normalized to the corre-

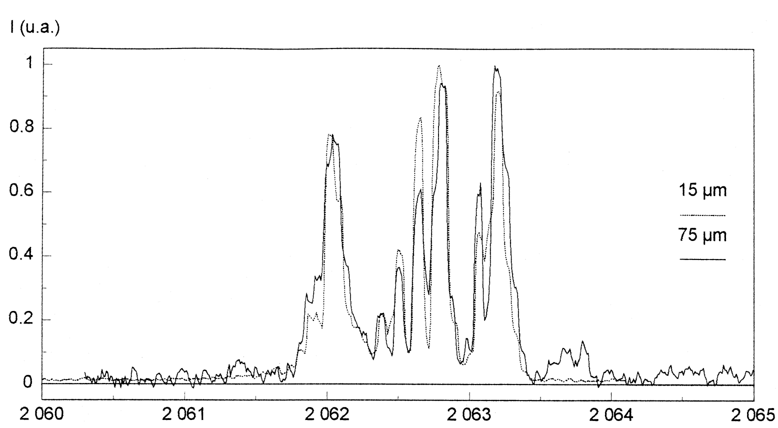

Fig. 11. Emitted spectrum for the YLF crystal at 13°C for the two pump beam sizes 15 μm (dashed line) and 75 μm (solid line) and a constant output power equal to 50 mW.

sponding saturation intensities travelling inside the crystal and participating in the heat exchange [4]. B is always positive. For YLF, $dn_c/dT = -4.3 \times 10^{-6}/°C$ and $\alpha_e = 13.3 \times 10^{-6}/°C$ showing that the cavity remains stable in spite of the sign of the thermal dispersion for YLF.

We now consider an equivalent cavity made of a spherical output mirror and a plane rear mirror which is a good approximation as shown in Ref. [12]. Computed from the experimental waist size measurements, the Rayleigh range near threshold on the output mirror is 47.5 mm for the YLF laser with 2.5 mm length and 9.1 mm for the YVO_4 laser with 0.5 mm length. Then, by computing the Rayleigh range in the waist plane assumed to be set on the rear mirror, we can compute the equivalent $g = 1 - L/R$ parameter for both cavities. The results are 0.99723 and 0.99698 for the YLF and the YVO_4 crystal respectively. We then conclude that the two laser cavities are equivalent to quasi plano–plano cavities capable of the same transverse mode discrimination.

The last parameter implicated for promoting transverse mode oscillation is the gain. Indeed, the stimulated emission cross section is 15×10^{-20} cm^2 for Tm:Ho:YLF [10] against 6.7×10^{-22} cm^2 for Tm:YVO_4 [6]. The doping concentrations are equal to 5.59×10^{19} cm^{-3} and 6.0×10^{20} cm^{-3} respectively. Then, the product σNx which is proportional to the gain when the crystal is pumped is 21 times larger for the first crystal than for the second one. In addition, the gain length is 2.5 times larger. As a result of the efficiency of the rear face cooling, the laser beam is not reabsorbed during propagation in the amplifier medium. Thus, in comparable cavities, the Tm,Ho:YLF microchip laser operates high above threshold allowing oscillation of several high order transverse modes.

6. Conclusion

We have presented experimental results concerning frequency characteristics obtained for both Tm:YVO_4 and Tm,Ho:YLF microchip lasers in active mirror configurations and we have shown that this configuration is capable of realizing high efficiency in both cases. Nevertheless, the conditions required for achieving single mode operation are not clear. Indeed, with a 1 mm long Tm:YVO_4 crystal, single frequency oscillation has been achieved with a pump beam waist size corresponding to the maximal power extraction. On the other hand, with a 0.5 mm crystal with the same characteristics in material and face reflectivity for which a better longitudinal mode discrimination is expected, no single mode operation can be achieved whatever the pumping conditions. For a 2.5 mm long Tm:Ho:YLF crystal, transverse mode oscillation is always observed. This behaviour has been imputed to the high small signal gain of such an amplifier medium when properly cooled. We assume that single frequency operation should be obtained by using a shorter crystal and/or a higher output coupling.

Acknowledgements

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