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Diode-pumped tunable laser with dual Cr:LiSAF rods*

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We propose and demonstrate a simple approach to lower the thermal quenching effect and improve the output power of Cr:LiSAF lasers, which is accomplished by employing two laser rods. The resonator contains two laser rods and is designed by using two "X" folding cavities in cascade. A tunable laser output of ~ 180 mW has been achieved with the pump of single-striped laser diodes. Compared with lasers using single gain rod, the laser with dual rods shows less severe thermal effect and increases the output by more than two times.

Keywords: dual laser rods, combined cavity, tunable laser
PACC: 4260B, 4260D

1. Introduction

All-solid-state Cr:LiSAF lasers have attracted interest since the past few years. Cr:LiSAF has a broad gain linewidth (185nm) and long upper-state lifetime(67μs),[1] which can be used as laser media of tunable and/or femtosecond laser source. More importantly, it can be directly pumped by commercialized laser diodes. Thus diode-pumped Cr:LiSAF lasers have a wide commercial foreground as a replacement for more expensive and voluminous Ti:sapphire lasers, which are usually pumped by Ar-ion or frequency-doubled Nd-doped solid-state lasers.[2−6] However, the output power obtained from standard diode-pumped Cr:LiSAF laser is very limited[7−10] due to the thermal quenching of upper-state lifetime.[11] For temperature higher than 30°C, the upper-state lifetime of Cr:LiSAF almost decreases linearly with temperature.[12] Eventually Cr:LiSAF lasers will not work when the temperature reaches a critical value. Therefore, the pump density in Cr:LiSAF has to be limited. By resorting to the idea of elliptical pumping, higher output power is possible with more pump energy in a larger area.[13−16] It generally adopted a thin Cr:LiSAF slab in which heat efficiently dispersed in a fashion of a one-dimensional heat flow and cylindrical cavity optics which caused elliptical cavity mode to match with the pump spot. Continuous wave (CW) output power of 1.42W was obtained by pumping of high-power diode bar.[15] Providing the cavity mode is highly astigmatic, elliptical pumping approach can sustain high-power pumping without severe thermal quenching.

In this paper we report a diode-pumped laser with a combined cavity containing dual Cr:LiSAF rods. The approach by using dual laser rods reduces the thermal effect, while it offers higher gain. Thus this approach is particularly appropriate for diode pumping. This approach to reduce thermal effect was originally adopted in Nd:YAG lasers.[17] As a result of high gain by employing dual rods, wider wavelength tuning range and higher output power could be obtained as compared with that of the laser with single Cr:LiSAF rod. The resonator with dual laser rods was basically composed of two cavity parts, each was just like a standard "X" folding cavity in which a Cr:LiSAF rod was installed. Each Cr:LiSAF rod was pumped by two single-striped diodes from two ends separately. Using this combined cavity with dual Cr:LiSAF rods, the

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total gain of the laser would be increased by 2 times and the output power would exceed two times as compared with that of the laser with single rod. Thus, it can be expected to generate very high output power for tunable diode-pumped Cr:LiSAF lasers. With total absorbed pump power of 1W, a CW tunable laser of 180 mW was obtained. The laser would be useful as a tunable infrared light source or a tunable blue light source by frequency doubling.

2. Cavity design and analysis

The laser resonator is shown schematically in Fig.1(a). Two Cr:LiSAF laser rods (1.5 at % Cr doping concentration with a size of 3 mm in diameter and 5 mm in length, supplied by VLOC) were used in two "X" folding parts of the combined cavity. Both ends of Cr:LiSAF rod were cut at Brewster's angle for light polarized parallel to the c axis. To efficiently remove the generated heat, Cr:LiSAF rods were wrapped with indium foil and tightly mounted in copper holders. Four AlGaInP laser diodes (supplied by Coherent laser group) serving as pump source emitted maximum 350mW each, from a 50-μm stripe at wavelength of 670 nm. The light emitted from the laser diodes was non-diffraction-limited in the direction parallel to the junction with a beam quality factor of $M^2 = 12$, and was diffraction-limited in the direction perpendicular to the junction. Each pump beam was first corrected for astigmatism by a fibre lens, collimated by an achromatic lens (focal length of 8cm) and then focused through a cavity folding mirror by another achromatic lens (focal length of 8cm) into a Cr:LiSAF rod. All flat mirrors (FM) were high-reflectivity (HR) coated with a film of reflectivity more than 99.7% at wavelength of 850 nm and of a bandwidth more than 100 nm. The four concave mirrors M1, M2, M3 and M4 with a same radius of curvature of 100 mm, were HR-coated (>99.7%) at wavelength of 850 nm and high-transmission (HT)-coated (>90%) at 670 nm on the concave surface and uncoated on the flat surface. The tilted angles of M1, M2, M3 and M4 were all set at a value of about 6° to compensate for the cavity astigmatism. A fused silica prism with Brewster cuts inserted in the cavity was used to tune the wavelength. The arms L1 and L2 were 0.6 m and 0.8 m in length, respectively. The middle arm L between two cavity parts was designed to be 1.4 m long for symmetry.

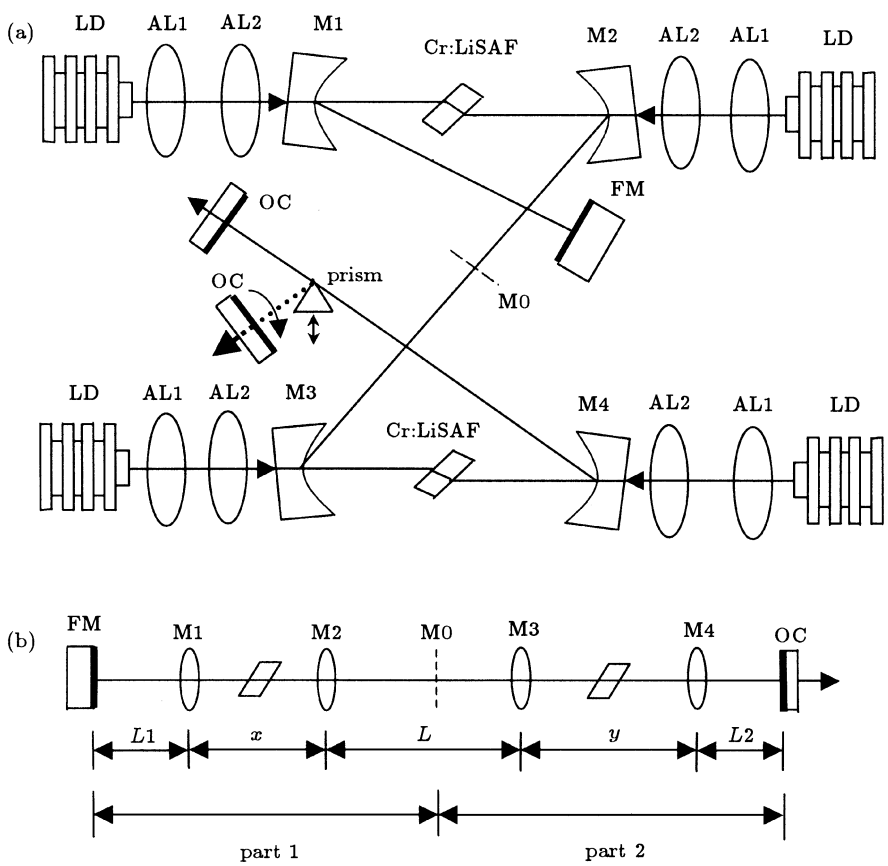


Fig.1. (a) Resonator configuration: folding mirrors M1, M2, M3 and M4 have the same radius of curvature R=100mm and tilted angle $\theta/2 \sim 6^0$. The length of Cr:LiSAF rods is 5mm. (b) Schematic of the resonator parameters.

To obtain optimum mode matching and cavity stability, we numerically simulated the cavity mode of this novel resonator based on mode-image theory and transform-circle theory.[18,19] The relationship of beam waist radius in the Cr:LiSAF rod of cavity part 1 and the folding distance x between M1 and M2 is shown in Fig.2. By taking into account the astigmatism of Brewster's cut Cr:LiSAF rods and tilted folding mirrors in simulations, the beam waist at the centre of stability regions is an elliptical shape with a long radius and short radius of about 35μm and 25μm respectively, which match well with the elliptical pump spot of about 70μm and 20μm in radii, within the Cr:LiSAF rod. Similar to a single "X" folding cavity, the combined cavity has two symmetric stability regions in terms of x, and the width of every stability region is $\sim$4 mm. As a combined cavity, the laser mode is determined by cavity parts 1 and 2 together. We investigated the influence of the mode size in one rod by the other cavity part. Figure 3 shows the dependence of the beam waist radius in Cr:LiSAF rod of part 1 on folding distance y of part 2. In the right branch of the curve (used in the experiment since it has a suitable spot size for mode matching), the waist radius of part 1 varies gently as the folding distance y of part 2 changes (the parameter of x is optimized).

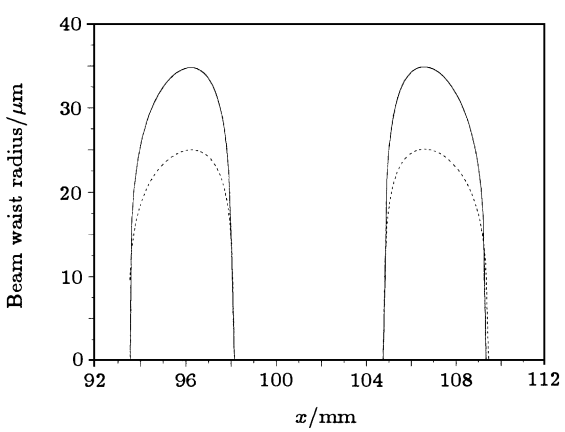


Fig.2. Beam waist radius of cavity mode in Cr:LiSAF rod of part 1 as a function of the folding distance x between M1 and M2. The solid curve and the dashed curve indicate the beam waist in the tangential plane (xz plane) and in the sagittal plane (yz plane) respectively. In the course of calculation, the optimum parameters of y=106.5mm and the folding angle $\theta/2 = 6.12°$ are used.

Similarly, when the parameter of y is optimized, the waist radius of part 2 is nearly invariable as the folding distance x of part 1 varies (not plotted). Thus, when x and y are taken their optimum values, the beam waists of part 1 and 2 are insensitive to each other and hence the stability of the laser resonator is relatively optimum. By further calculations under the condition of x and y varying near their optimum values, we find that the position of the beam waist in the middle arm L is almost invariable and is at the location of 0.6 m away from the folding mirror M2. Thus the combined cavity is simultaneously divided into two 0.6 m–0.6 m and 0.8 m–0.8 m symmetric sub-cavities, in a sense that the laser mode in each part of the combined cavity is exactly identical to that of the resonator formed by the same cavity part. The size of beam waist and the width of stability region in parts 1 and 2 correspond to those of 0.6m–0.6m and 0.8m–0.8m symmetric "X" folding cavities respectively. This can be understood easily and is also verified by various calculations. The combined resonator becomes more stable by dividing itself into two symmetric sub-cavities.

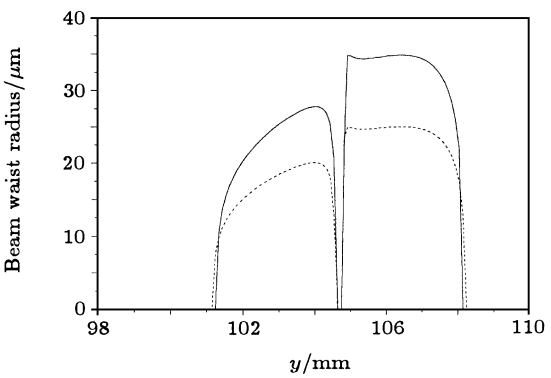


Fig.3. Beam waist radius of cavity mode in Cr:LiSAF rod of part 1 as a function of the folding distance y between M3 and M4. The solid curve and the dashed curve indicate the beam waist in the tangential plane (xz plane) and in the sagittal plane (yz plane) respectively. In the course of calculation, the optimum parameters of x=106.5mm and the folding angle $\theta/2 = 6.12°$ are used.

3. Experiment

In the experiment, we first mounted a coupler at the position M0 that was 0.6 m away from the folding mirror M2 (Fig.1(a)). With an appropriate alignment of cavity part 1 to form an oscillator, we obtained 100 mW CW laser output at 872 nm with 2% coupler under absorbed pump power of 0.5 W (the prism not inserted). This laser was optimized for a better output power by varying the arm length of the cavity and carefully adjusting the cavity mirrors. Resorting to the output laser of this oscillator (cavity part 1) as a guiding light, we adjusted cavity part 2 and made cavity part 1 and 2 to form a perfect resonator. Then the

coupler at M0 was taken away and an oscillator was formed by cavity part 1 and 2. By using 4 pumping diodes, the CW laser output was obtained from this combined resonator. We used various couplers of 1%, 2% and 5% to maximize the output power, and found that the 2% coupler was the optimum. CW laser output of 230 mW was achieved under a total available absorbed pump power of 1 W. This output power exceeded 2 times that of the oscillator formed by cavity part 1 (100mW), and the laser showed a higher gain. The output laser beam was a round TEM_{00} mode.

The dependence of laser output power of the combined cavity on absorbed pump power is shown in Fig.4. The laser pump threshold is only 250mW that is much less than the total absorbed pump power of 1.0W, thus the laser will be efficient. The slope efficiency of the laser output is $\sim 30\%$ for 2% output coupler. The laser output power increases slowly during the pumping regime of rod 2 (pump power of 0.5–1 W), which suggests that the pump system of cavity 2 may not be aligned to the cavity mode perfectly. Nevertheless, the output power almost increases linearly as the pump power increases, and no indications of thermal quenching or limitations have been observed throughout the tested pump power range. As a control experiment for testing the thermal effect, we have applied all the 4 diodes to a single rod, and the output power can be seen to start to decrease from the absorbed pump power over 0.7 W. Based on our approach with dual laser rods, we can predict that a higher output power is possible if a higher pump power is available.

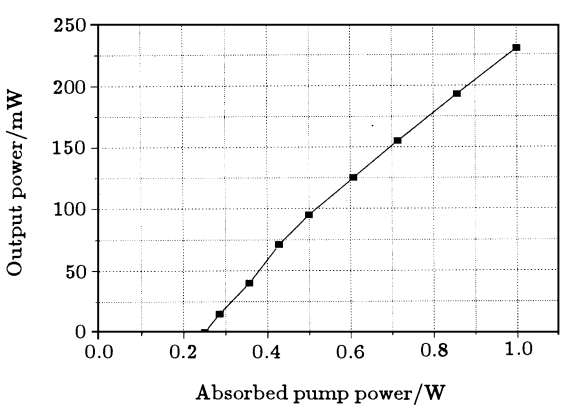


Fig.4. Output power of the combined cavity with dual Cr:LiSAF rods as a function of absorbed pump power.

By simply using a Brewster angle cut prism to serve as a wavelength tunable element in the laser cavity (Fig.1), we obtained tuning output of the laser. The comparison of tuning curve of the combined cavity with dual rods and that of the cavity with single rod is shown in Fig.5. Because the combined cavity provides a higher gain, it offers a much wider wavelength tuning range than the cavity with single rod, as clearly shown in Fig.5. Limited by the resolution of prism, the typical linewidth of the tunable laser is around 2 nm. The maximum output power of the combined cavity reduces to 180mW due to the inserting loss of the prism. The measured peak wavelength of the combined cavity output is around 872 nm, which agrees well with the peak emission of Cr:LiSAF.

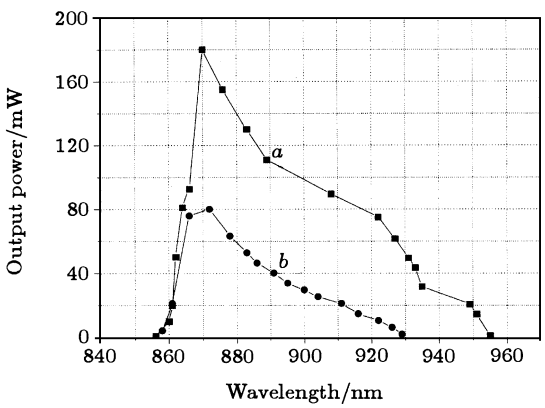


Fig.5. Tuning curves of the different cavities. *a* the combined cavity with dual Cr:LiSAF rods and *b* the cavity with single rod.

4. Conclusion

In summary, we have demonstrated a diode-pumped tunable laser with dual Cr:LiSAF rods. This simple approach can efficiently reduce the thermal effect and linearly scale up the output power with increasing pump power. By use of a prism inserted in the combined cavity, a tunable CW laser has been achieved. Under the absorbed pump power of 1 W, the tunable laser with a power of 180 mW has been obtained. In the course of experiment, there are no indications of thermal quenching or limitations. Finally, we predict that with a higher pump power available from diodes, the laser output power can be improved greatly.

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