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Q-Switching of a Diode-Pumped Nd:YVO_4 Laser with a Closely Folded Resonator

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A diode-pumped Nd:YVO_4 laser is developed. The laser has a closely folded resonator. The laser beam in two arms of the folded resonator passes the same acousto-optic modulator. The laser output power and pulsewidth dependence on a Q-switching frequency were measured. It is found that the newly proposed geometry provides an effective means for reducing the pulsewidth while maintaining almost the same output power compared with the usual folded resonator, where the beam in one arm of the resonator passes the acousto-optic modulator.

OCIS codes : 140.3410, 140.4380, 140.3540, 140.5680

I. INTRODUCTION

There has been a lot of study on the diode-pumped solid-state laser for last decades. Diode pumping enabled fabrication of a miniature laser compared with a bulky flash-lamp pumped one. It also gave high efficiency and much reduced thermal load. The many merits of the diode pumped laser lead to rapid expansion of application of the laser to laser display, micro machining, spectroscopy, laser printing etc. The most popular gain medium for diode pumping has been Nd:YAG. Recently uniaxial crystals such as Nd:$GdVO_4$, Nd:YLF, and Nd:YVO_4 are finding application in small power lasers [1, 2]. For laser display application, frequency doubling is used to convert the invisible infrared radiation from Nd^{3+} ion laser transition to visible green light. A frequency doubling crystal such as KTP or $LiNbO_3$ is usually placed in one arm of a folded resonator, and a curved folding mirror focuses the beam for high efficiency [3].

Q-switching of the diode-pumped solid-state laser provides high peak power pulses for a laser pumped by a continuous wave (CW) diode laser. Acousto-optic (AO) Q-switch rather than electro-optic Q-switching has been popular for CW diode pumped lasers as it gives higher Q-switching frequency. For the AO Q- switched laser, the pulse coming out of the resonator has pulsewidth normally longer than several tens or hundreds of ns. In many applications of diode pumped lasers, high peak power is preferred because it leads to high efficiency in frequency doubling and gives efficient removal of material in micro-machining applications. Recently, Gui-qiu Li et al. used GaAs or Cr:YAG saturable absorber in the AO Q-switched resonator to further reduce the pulsewidth by double Q-switching [3, 4]. We are proposing a newly devised- folded resonator geometry to shorten the pulsewidth while using a single AO modulator for Q-switching. In the resonator the laser beam passes two times through the AO modulator. It results in rapid drop of the cavity loss, because the beam undergoes diffraction two times. Compared with the set up using two separated Q-switch modulator in series [5, 6], this method is cheap, simple, and provides an intrinsically synchronized system. The previous setup of the folded resonator usually a had large folding angle near 30° to prevent the beam from hitting the housing of the Q-switching modulator [7]. In this work, the resonator has very small folding angle taking into account the small acceptance angle of the AO modulator. The closely folded resonator offers very small astigmatism, which is beneficial for a circular spatial profile. Astigmatism due to the folding mirror leads to an elliptical beam shape and it has been one of the serious problems in using a folded resonator [8]. To demonstrate the effect of double pass, lasing characteristics of a single-pass resonator are also obtained and compared.

II. EXPERIMENT AND RESULTS

The resonator layout is shown in Fig. 1. The 6-mm long Nd:YVO$_4$ crystal (Onyx) has 0.6 atom% Nd doped and both ends are capped with 3-mm long undoped YVO$_4$ crystal to reduce thermally induced stress and surface deformation [8]. The crystal is enclosed inside a copper housing and it is water cooled by a temperature controlled chiller. The pumping diode laser (Thomson CSF) was delivered through an optical fiber bundle with 600 μm diameter. The maximum output power of diode was 20 W and the beam from the fiber end was expanded with an angle determined by the numerical aperture of the optical fiber (NA=0.22). The expanded beam was collimated by a lens with focal length of 5 cm and it was focused to a spot inside the Nd:YVO$_4$ crystal by a lens with 5-cm focal length. Input coupler with flat surface transmits 95% of the pump beam (808 nm) and has reflectance of 99.5% at 1.064 μm. The crystal housing and input coupler were mounted on a rail for easy adjustment of distance. The folding mirror had 5-m radius of curvature and the folding angle was 1.5°. Several flat output couplers with different reflectivities were tested. The output coupler with 81% reflectivity gave the highest power. The beam measured by a CCD camera showed nearly Gaussian spatial profile close to TEM$_{00}$ mode [9].

The laser output characteristics of the AO Q-switched laser were compared for two cases, single-pass and double-pass geometry. When we tested single-pass geometry of the beam, the AO modulator for the Q-switch was positioned at a place marked by the solid line in the Fig. 1. In this setup one arm of the beam in the resonator crosses the AO modulator. When we tested double-pass geometry of the beam, the AO modulator was moved to a place indicated by a dotted line. In double-pass geometry, the laser beam in both arms crosses the AO modulator. The distance from input coupler and folding mirror is 37 cm and the distance from folding mirror to output coupler is 18.5 cm. When the diode pump laser power incident on the Nd:YVO$_4$ crystal was higher than 11 W, the laser became unstable due to thermal lens and the lasing ceased. From ABCD matrix calculation of the resonator, the focal length of the thermal lens at this pump power is estimated as about 54 cm. As the resonator folding angle is very small, the calculated beam sizes in sagittal and tangential planes had difference less than 0.1%. The calculated beam waist of TEM$_{00}$ mode at the output coupler surface is the smallest and it is 340 μm, while the beam waist at the crystal is 477 μm. The measured radius of diode pump laser spot at focus is 274 μm. The pump beam waist at entrance surface of the crystal is 490 μm, which is close to TEM$_{00}$ mode waist.

The temporal profiles of pulses from the Q-switched Nd:YVO$_4$ laser for single-pass and double-pass geometry are shown in Fig. 2 when the Q-switching rate is 10 kHz. The peak heights of temporal profiles are reshaped for comparison. The pulsewidth for double-pass geometry is about half of single-pass case and its shape is the more asymmetrical indicating fast growing of the pulse [10]. The dependences of pulsewidth on the diode pump power for both geometries are shown in Fig. 3. The figure shows that the double-pass geometry reduces the pulsewidth to less than half of the single-pass case over the most range of the diode pump power. To see the effect of the Q-switching rate on pulsewidth reduction ratio for the single-pass and double-pass geometry cases, the Q-switching rate was changed to 10, 15, and 20 kHz respectively. The temporal profile showed reduced pulsewidth over the whole range of Q-switching rate variation.

For a laser with Q-switch turn-off time much shorter than pulse buildup time, the pulsewidth t_p of repetitively Q-switched laser is given from rate equations as follows

$$t_p = \frac{r_i - r_f}{r_i - \ln r_i - 1}\tau_c \ , \qquad (1)$$

where $r_i = n_i/n_{th}$, $r_f = n_f/n_{th}$, and τ_c is the photon lifetime

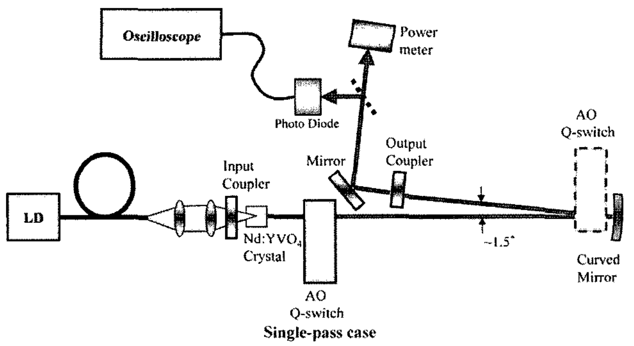

FIG. 1. The layout of diode-pumped, folded Nd:YVO$_4$ laser resonator.

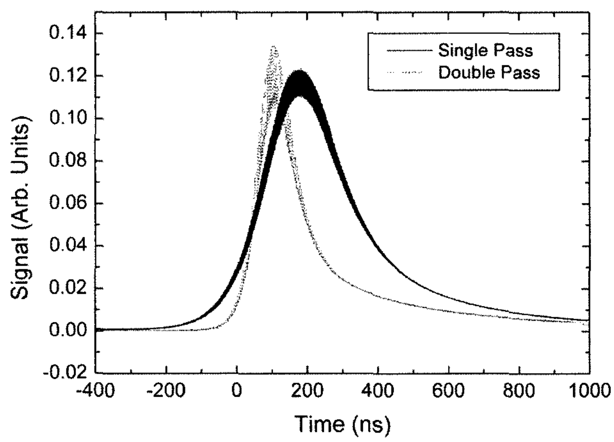

FIG. 2. The temporal profiles of Nd:YVO$_4$ laser with single-pass and double-pass geometry.

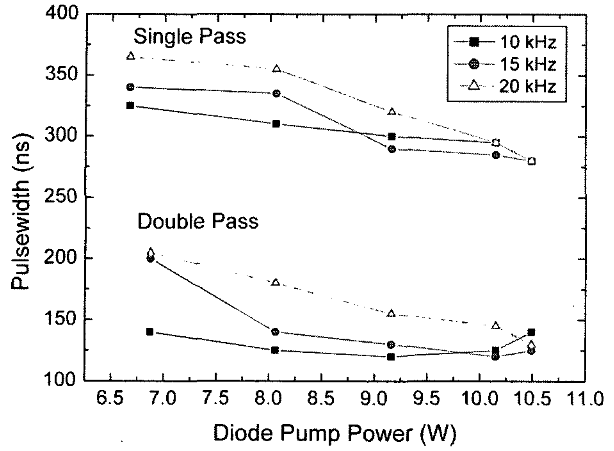

FIG. 3. The measured pulsewidth of Nd:YVO_4 laser as a function of diode pump power. Results from single-pass and double-pass geometries are shown.

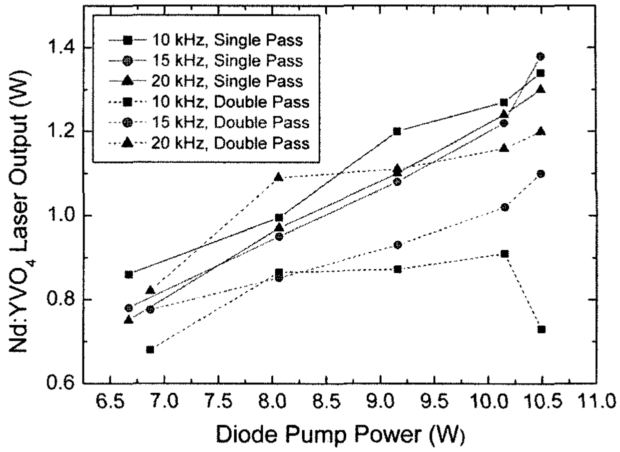

Fig. 4. The measured power of Nd:YVO_4 laser as a function of diode pump power and Q-switching rate. Solid line represents single-pass and dotted line corresponds to double-pass cases respectively.

of the laser resonator [10, 11]. The parameter n_i, n_f, and n_{th} represent the initial population inversion density, the residual inversion density, and the threshold inversion density respectively. The Eq (1) shows that the pulsewidth depends on the inversion density and photon lifetime. The pulsewidth becomes lengthened with increase of Q-switching rate because it leads to low initial inversion density.

As the Q-switching time of an acousto-optic (AO) modulator is dominated by transit time of the sound wave across the beam diameter, Q-switching time of the AO modulator is generally slower than for the electro-optic Q-switch, where switching time is decided by the electronic switching time [10]. Thus the pulsewidth of the AO Q-switched pulse is usually longer than the electro-optically Q-switched one. As can be seen in Eq. (1), shorter pulsewidth can be made by reducing the laser cavity length or by intensely pumping the laser. However, for the cw pumped laser, inversion is usually small and pulse buildup time is long. In this case, fast switching of the beam can be an effective method for pulsewidth reduction. Increased loss results in fast gating of the beam. For an intensely pumped laser, usually two AO modulators have been used in series to increase hold off [3]. The method also contributes to pulsewidth reduction as the loss in the AO modulator is doubled. Double pass has an effect of two AO modulators in the resonator with one AO modulator.

Fig. 4 shows the Nd:YVO_4 laser power for single and double-pass cases. Solid lines represent single-pass cases and broken lines represent double-pass cases respectively. When the Q-switching rate is 10 kHz, the output power in double-pass case drops to about 81% of the single-pass case. However the ratio becomes nearly 100% when the Q-switching rate becomes 20 kHz. The result indicates that the additional loss of the beam by introduction of double pass has almost no influence on the conversion efficiency of the laser. Therefore, it provides an effective means for pulsewidth reduction.

III. CONCLUSIONS

A diode-pumped laser with closely folded resonator was fabricated. By reducing the folding angle to 1.5°, beams in both arms of the folded resonator could pass through the AO modulator for Q-switching. To see the effect of the double-pass geometry, lasing characteristics of single-pass geometry were measured and compared with those of double-pass case. The pulse from double-pass geometry had much reduced pulsewidth while maintaining almost the same power at 20 kHz Q-switching rate. When a nonlinear crystal is placed in the folded arm for frequency doubling, negligibly small astigmatism provides for a circular beam shape. A much shorter resonator can be made when smaller size AO modulator is used. The pump power can be increased in that case and it will give higher efficiency as well as shorter pulsewidth.

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