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Efficient Dual-Wavelengths Continuous Mode Lasers by End-Pumping of Series $Nd:YVO_4$ and $Nd:GdVO_4$ Crystals and Speckle Reduction Study

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Abstract: In this paper, diode pumped solid state (DPSS) lasers based on end-pumping series $Nd : YVO_4$ and $Nd : GdVO_4$ crystals were studied. Dual-, tri-, and quad-wavelength emissions were achieved. In the dual-wavelength emission operation, an optical-to-optical efficiency (O-O) of 48.9% and the power instability was 0.4% were obtained. These are the most efficient and compact lasers operating in continuous wave mode reported to date with series crystals. Besides this, the effect of changing power ratio between the output laser powers on speckle reduction was investigated for the first time. In addition, tri and quad wavelength emissions were achieved with a reasonable efficiency simply by optimizing the cavity parameters.

Keywords: diode pumped solid state; end-pumping series crystals; Dual-, tri-, and quad-wavelength emissions; Multi emission spectrum; laser speckle reductions; wavelength diversity

1. Introduction

Recently, development of laser sources based on end-pumping of series laser crystals with multiple (dual/tri/quad) emission wavelengths has attracted attention due to their potential applications such as THz generation [1], precise spectroscopy [2], imaging [3], biomedical instrumentation [4], lidar [5], and nonlinear scientific research of optical mixers [6].

Many methods have been reported to achieve multi-wavelength emission such as: inserting optical selective elements (OSE) inside a cavity like etalon [7] or birefringent filter [8], by two inequivalent emitting centers coexisting inside the laser crystal [9], by angle tuning for a laser crystal [10], pumping two distinct crystals separately [11], and pumping two different crystals simultaneously [12]. For single gain medium based multi wavelength emissions their lasing wavelengths generally share the same upper energy level which makes their mode competition serious [13], thus, the approach of end pumping series crystals [12] is considered to be a solution. It uses two separate gain mediums and each crystal has its unique wavelength. They do not share the same upper energy levels which means no mode competition exists, thus, the stability is improved. For example, instability as low as 0.25% (the instability for each wavelength component is 1.93% and 1.23%) has been reported for a free-running dual-wavelength end-pumping series crystal laser [3]. Besides this, the technique can also be used to equate the output intensities for the dual wavelength emission without any custom designed mirrors or inserting any OSEs. The dual-wavelength emissions from two series crystals has been demonstrated using a variety of pairs of laser crystals including $Nd : YVO_4/Nd : GdVO_4$ [14], $Nd : YVO_4/Nd : KGW$ [15], $Nd : YVO_4/Nd : LuVO_4$ [15], $Nd : YAG/Nd : YLF$, and $Nd : YLF/Nd : YLF$ [3]. To date, most of the reported end-pumping series crystal lasers are operated in pulsed mode, and the highest reported O-O efficiency was 33% [15].

In the meantime, end-pumping series crystal lasers have a lower laser speckle effect than general single wavelength diode pumped solid state (DPSS) lasers, since the laser speckle can be reduced when multiple wavelengths are blended together [16]. Laser speckle has a significant impact on several applications mentioned above. However, characteristics of laser speckle of end-pumping series crystal lasers have not been studied. Moreover, laser performance of end-pumping series crystal lasers in the continuous wave (CW) mode, which are important in many practical applications, have not been investigated systematically.

In this paper, compact DPSS lasers based on the end-pumping series $Nd : YVO_4/Nd : GdVO_4$ crystals are investigated in detail. The characteristics of dual-, tri-, and quad-wavelengths emission are studied and discussed. Laser speckle properties of the developed lasers are studied in terms of the power ratio between the emission peaks and the number of emission wavelengths. CW mode compact lasers based on the end-pumping series $Nd : YVO_4/Nd : GdVO_4$ crystals with high O-O efficiency, high stability, and low speckle contrast ratio have been achieved.

2. Experiments

2.1. Dual-Wavelength Laser Setup

The configuration of the end-pumping series-crystals cavity is shown in Figure 1a. A plane-plane cavity structure was used in the laser system. A fiber pigtailed laser diode (LD) was used as the pumping light source. The LD had a central-wavelength of 808 nm, and a maximum output power of 7 W. The core diameter was 200 μm with a 0.22 numerical-aperture (NA). The pumping light from the fiber was elliptically polarized, with a power ratio of approximately 2:1 between its maximum power along the vertical (π -polarization) and horizontal (σ -polarization) directions. A graded-index (GRIN) Lens and a plano-convex lens were used to focus the output beam from the LD. The GRIN lens had a 1.8 mm diameter, 0.23 Pitch, 0° Face Angle, and was anti-reflection (AR) coated at 810 nm, while the plano-convex lens had a diameter of 4 mm and a focal length of 2.5 mm. This beam focusing system was used to focus the laser beam into the gain medium with a minimum beam waist (ω_0) of 120 μm .

Figure 1. Experimental setup used in the measurements: (a) diagram for end pumping series crystals laser and (b) schematic diagram for σ - π configurations.

Two crystals, the first laser crystal (LC_1) and second laser crystal (LC_2), were used as the gain mediums. LC_1 was 1-at% doped a-cut $Nd : YVO_4$ and LC_2 was 0.5-at% doped a-cut $Nd : GdVO_4$. The crystals had cross sections of 3 mm $\times$ 3 mm and thicknesses of 2 mm and 4 mm, respectively. The input facet of LC_1 was coated with a high-reflection (HR) coating at 1064 nm and high transmission

coating at 808 nm to be used as the input mirror (M_1), the output facet of LC_1 was AR coated at 1064 nm. Both facets of LC_2 were AR coated at 1064 nm and 808 nm.

The temperatures of LC_1 and LC_2 were controlled by two thermoelectric coolers independently. The output-mirror (M_2) had a reflectivity of 85% at 1064 nm. A filter was used to block the remaining 808 nm pumping light after M_2 , and a polarizing beam splitter (PBS) was employed to separate the π -polarized and σ -polarized components of the output laser beam. The laser output power was measured by a power meter, and output power stability was characterized as well. The output spectrum was captured by an optical spectrum analyzer (OSA) with a resolution of 0.1 nm.

The relative position of the two crystals are shown in Figure 2b. In the experiments, the π -polarization component of the elliptically polarized pumping light was aligned parallel with the c-axis of LC_2 . The distance between the crystals in the σ - π configuration was 0.1 mm. The position of the minimum pump beam waist (z_0) was varied along the optical axis (in z direction) through the cavity, allowing for the control of the gain and pumping absorption efficiency of each crystal [17]. $z_0 = 0$ was defined as the input facet (or M_1) of LC_1 . The pump absorption efficiency of each crystal was also controlled by altering the pumping wavelength (λ_p) which was achieved by changing the temperature of the LD.

Figure 2. Configuration of LC_1 and LC_2 in multi wavelength emission. (a) A 3D configuration with a tilted angle of θ for M_2 , and (b) xy-view of the setup for tri output wavelengths emission with $\theta = 0.7$ mrad and $\phi = 0$ rad (left) and quad wavelengths emission (right) with $\theta = 0.7$ mrad and $\phi = 0.78$ rad.

2.2. Tri/Quad Wavelength Laser Setup

The experimental setup of tri-/quad-wavelengths emission was similar to the one described in the previous section. The tri-/quad-emissions were achieved by rotating LC_1 and tilting M_2 [10,17].

Figure 2 shows the setup of tri-/quad-wavelengths emission. Figure 2a represents a schematic diagram for the series crystals. E_π , E_σ represent the polarization directions of the pump light. θ is the tilting angle of M_2 with respect to y-axis and ϕ is the angle of rotation of LC_1 about the z-axis. The c-axis of the two crystals was parallel to E_π . Figure 2b represents the xy-view for the setup. In Figure 2b, the left subfigure represents the setup of tri-wavelengths emission ($\theta = 0.7$ mrad and $\phi = 0$ rad), and the right subfigure represents the setup of quad wavelengths emission ($\theta = 0.7$ mrad and $\phi = 0.78$ rad). The distance between LC_1 and LC_2 was 0.2 mm. The length of the cavity was 18 mm. The temperature of LC_1 and LC_2 were set at 45 °C and 18 °C, respectively. Tri-/quad- wavelengths started to be seen until input pump power reached 4.2 W and 4.38 W, respectively.

2.3. The Speckle Contrast Imaging Configuration

Figure 3 shows the setup used for measuring the speckle contrast ratio (SCR). The SCR of the proposed laser systems was measured by projecting the output beam via a projection lens onto a white print paper, then using a CCD camera (C2400 from Hamamatsu/ spectral response: 400–1800 nm) to capture the speckle-pattern. The focal length of camera lens is 50 mm with f/16. Both the distances from projection lens to screen and screen to camera were set to be 50 cm.

Figure 3. Experimental setup for speckle test.

3. Results and Discussions

3.1. Dual Output Wavelengths

Figure 4a shows the single 1063.7 nm laser spectrum. Figure 4b shows spectrum at $z_0 = z_{BPP}$, at which an equal output power is achieved for the two wavelengths. As mentioned in Section 2.1, the lasing wavelength from LC_1 is 1063.7 nm in σ polarization (σ pol.) and 1062.4 nm from LC_2 in π polarization (π pol.).

Figure 4. (a) and (b) are the single (1063.7 nm) and dual-wavelength normalized emission spectrum respectively.

Figure 5 shows the change in output power of the 1062.4 nm emissions from $Nd : GdVO_4$ (blue line with triangles) and 1063.7 nm emissions from $Nd : YVO_4$ (red line with dots) versus the change of z_0 . In the experiments, the maximum pump power was set to 6.5 W and z_0 was adjusted to change the power ratio between two different wavelengths. In the σ - π configuration, the pumping wavelength was set at 805 nm. Figure 5 is separated into Region I and Region II by the balance point position (z_{BPP}),

which is defined as the position of beam waist of the pumping beam where an equal output power was achieved for the two wavelengths. The z_{BPP} was found to be 2.6 mm as shown in Figure 5. The total power at z_{BPP} is 3.18 W. It is worth noting that the balanced power ratio at z_{BPP} point is important for speckle reduction, which will be further illustrated in the following sections.

Figure 5. The measured output powers of 1062.4 nm (triangle up) and 1063.7 nm (dots) for σ - π configuration.

The absorption of LC_1 controlled the amount of leaked pump power to LC_2 . So, the pumping wavelength is shifted to be 805 nm (via controlling the LD temperature) because the change in pump wavelength (<808 nm) will decrease the absorption of LC_1 , resulting in a decrease of the gain in LC_1 . The same effect will happen to LC_2 as well, so that the overall O-O efficiency of such series crystal end-pumping is lowered.

The change in power ratio is related to the change of the pump beam waist position (z_0) [18]. With the increase of z_0 , one can observe that 1063.7 nm laser power decreased, and 1062.4 nm laser power increased, until they become equal at $z_0 = z_{BPP}$.

In Figure 5, when $z_0 = 0$, the output power of 1063.7 nm laser is higher than 1062.4 nm laser, because the minimum pump beam waist (ω_0) is on the input facet of LC_1 , so the overlapping ratio between pump light size and laser mode size in LC_1 is large, making the gain of LC_1 higher. In addition, only a small fraction of pump power leaked from LC_1 so that the output power of 1062.4 nm laser is smaller than the power of 1063.7 nm. By continuing to increase z_0 , the pump power absorbed by LC_1 decreases; this leads to a decrease in the power of the 1063.7 nm laser and an increase in the power of the 1062.4 nm laser. This is because the change in the overlapping ratio will be larger with respect to the mode size of LC_1 and vice versa to LC_2 . In region II, when z_0 is close to z_{BPP} , ω_0 will be much closer to the 1st edge of LC_2 , thus the power of 1062.4 nm laser increased while the power of 1063.7 nm laser decreased.

The output power of dual wavelengths emissions (when z_0 was fixed at z_{BPP}) are shown in Figure 6. Based on the total power presented in Figure 6, the maximum O-O efficiency was 48.9% (51.7% after compensating infra-red (IR) filter and PBS losses) and, the slope-efficiency was 61% for the linear best fit (dotted blue line) which is shown in Figure 7. To the best of our knowledge, this is the highest efficiency achieved by dual wavelength laser for σ - π configuration.

Figure 6. The measured output power versus pump power for σ - π configuration, where the total output power, output power for 1062.4 nm, and 1063.7 nm are represented by black dots, red triangle up, and blue square, respectively.

Figure 7. The measured total output power versus input pump power for σ - π configuration.

In addition, the O-O efficiency for π - π configuration has been studied. In that configuration, the c-axis of LC_1 is parallel to the c-axis of LC_2 . Because the absorption coefficient of LC_1 in π polarization is 4 times higher than σ polarization, the input pumping wavelength was further shifted to 804 nm to further decrease the pump power absorption of LC_1 (pump power was 7.7 W). The temperature of LC_1 and LC_2 was 45 °C and 18 °C, respectively; 2.72 W total output power was achieved at $z_{BPP} = 2.5$ mm. The O-O efficiency was 35% (37% after compensating IR filter losses).

The output power stability of dual-wavelength emission at the balance power point (BPP) was also studied (Figure 8). A power meter was used to record the power fluctuations over 1200 s in 1 s intervals. The power fluctuations of the total power and each polarization component were

recorded and analyzed. According to the method presented in ref. [1], the power instabilities for both wavelengths blended together is 0.4%, while it is 1.9% for 1063.7 nm components and 1.1% for 1062.4 nm. The low power instability is mainly due to the fact that the two output wavelengths are from different crystals, and the mode competition is negligible in this type of laser [15]. The laser beam quality was measured by the knife edge method in case of dual emission; the M^2 was factor < 1.2 for 1062.4 nm and 1063.7 nm.

Figure 8. The measured (a) total power for σ - π configuration, (b) power of 1063.7 nm in σ -polarization, (c) power of 1062.4 nm in π -polarization.

As mentioned in the introduction, when multiple wavelengths are emitted from the same laser, the overall speckle produced by this laser is lower compared to the conventional single wavelength lasers. This can greatly improve the light source quality for multiple applications described earlier. Thus, the speckle level of this laser was studied as well. The captured images of speckle patterns are shown in Figure 9, according to the measurement method reported in [19], the SCR from the single- and dual-wavelength laser were 70% and 53.9%, respectively. Figure 9a, b shows the measured speckle images for 1063.7 nm and dual wavelength emissions at z_{BPP} , respectively. The setup described in Section 2.3 was used to capture the images.

The SCR dependence with different power ratio of two wavelengths was studied as well. Figure 10 shows the SCR variation under different power ratios between 1062.4 nm and 1063.7 nm. The power ratio of the two wavelengths was changed by tuning z_0 as described in the previous sections. In Figure 10, the X-axis represents power at 1063.7 nm over the total-output-power at the two wavelengths (P_{λ_1} and P_{λ_2} are the power of 1063.7 nm and 1062.4 nm lasers, respectively), where 1.0 means that the output emission wavelength is purely 1063.7 nm, and 0.5 (at BPP) means the output power is the same at each output wavelength. The minimum SCR of ~53.9% is achieved when the power ratio of 1063.7 nm and 1062.4 nm was approximately 1:1.

The experimental results matched the simulations based on the reported theoretical model [19]. In the simulations, the following parameters were used: $\lambda_1 = 1062.4$ nm, $\lambda_2 = 1063.7$ nm, $\Delta\lambda_1 = 0.3$ nm, $\Delta\lambda_2 = 0.4$ nm, $\sigma_h = 200$ μ m, $\theta_i = \theta_r = 45^\circ$, $P_{\lambda_1} = P_{\lambda_2} = 1.5$ W. Where, $\Delta\lambda_1$ and $\Delta\lambda_2$ are the linewidths for 1062.4 nm and 1063.7 nm, respectively, σ_h is the standard derivation of surface roughness fluctuation of the screen, θ_i is the incident angle of the laser beam, and θ_r is the receiving angle of camera used in the measurements. Ideally, SCR can be reduced by $1/\sqrt{N}$ where N is the number of incoherent laser wavelengths with equal output power and sufficient wavelength difference [20]. In the dual

wavelength emission with 1:1 power ratio, the expected reduction is $1/\sqrt{2}$. This agrees well with the measured results at 1:1 power ratio point.

Figure 9. (a) Single-wavelength speckle image, (b) dual-wavelength speckle image.

Figure 10. The speckle contrast ratio (SCR) as a function of normalized power ($P_{\lambda 2}/(P_{\lambda 1}+P_{\lambda 2})$).

3.2. Tri and Quad Output Wavelengths Emission

By tilting the cavity output mirror, tri-wavelength emission can be achieved, and quad-wavelength emission can be achieved by further rotating the LC_1 [17,21]. As shown in Figure 2b in Section 2.2, the left subfigure represents the setup of tri-wavelength emission ($\theta = 0.7$ mrad and $\phi = 0$ rad), and the right subfigure represents the setup of quad-wavelength emission ($\theta = 0.7$ mrad and $\phi = 0.78$ rad). The distance between LC_1 and LC_2 was 0.2 mm. The length of the cavity was 18 mm. The temperature of LC_1 and LC_2 were 45 °C and 18 °C, respectively. Figure 11a,b shows the output spectra of tri- and quad-wavelength emission. In tri-wavelength emission, the peak wavelengths were at 1062.4 nm (π pol.), 1063.6 nm (π pol.), and 1064.6 nm (π pol.). The total output power was 1 W with an O-O efficiency of 23.8%. In quad-wavelength emission, the peak wavelengths were 1062.3 nm (π pol.), 1063.6 nm (π pol.), 1064.5 nm (π pol.), and 1066.1 nm (σ pol.). The output power was 1.55 W with an O-O efficiency of 35.4%. The M^2 factor was measured to be <2 ; it was obvious that the quality of the total output lasers from each case became worse.

Figure 11. The measured output spectrum of (a) tri-wavelength emission at 1062.4 nm, 1063.6 nm, and 1064.6 nm, and (b) quad-wavelength emission at 1062.3 nm, 1063.6 nm, 1064.5 nm, and 1066.1 nm.

As indicated in Figure 11a,b, the line emissions are very close to each other and some of them have the same polarization, so it was very hard to use IR filters or even PBS to isolate each individual line emission to do further investigation and measurement.

The SCR under tri- and quad-wavelength emission were measured to be 59.5% and 57.5%, respectively, which are lower than the SCR of single wavelength emission (i.e., 70%). One can notice that these values do not follow the $1/\sqrt{N}$ relationship as described above, which can be understood as follows. First, the power levels at different emission wavelengths were not equal. According to [22], the unequal power results in a limited speckle reduction effect. Second, the wavelength differences between adjacent wavelengths are not large enough; this causes co-related speckle patterns to be generated at the different wavelengths, and further limits the speckle reduction effect [19].

4. Conclusions

In this paper, the end pumping lasers for series crystals have been studied and optimized in the CW mode. Dual output wavelengths were achieved with O-O efficiency of 48.9% in σ - π configuration. This is the highest efficiency reported in literature for this type of laser.

The output power instability was measured for dual wavelengths emission, 0.4% for both 1062.4 nm and 1063.7 nm blended together, 1.1% for 1062.4 nm and 1.9% for 1063.7 nm, the power fluctuation was in between the results in [1,3]. On the other hand, it was expected that the power instability and the spatial beam quality will be deteriorated in case of tri- and quad- emission modes due to the mode hopping and mode competition between the output line emissions.

The generation of tri- and quad-output wavelengths has been performed without adding any optical elements. The maximum power and O-O efficiency was 1W/23.8% and 1.55W/35.4% for tri- and quad-output wavelength emission, respectively.

SCR has been studied for this type of laser as well. It has been shown that the SCR depends on the power ratio of the two wavelengths, and a minimum SCR can be achieved when powers at each emission wavelength are equal, which agrees with the theoretical simulations.

It is worth noting that the present work (in dual emission mode) provides a dynamic way to change SCR of a laser, simply by changing the position of the beam waist of the pumping beam. It is considered that lasers based on the end pumping for series crystals could be very useful to the applications that need low laser speckle, high efficiency, and high power. As a future work, the quality of the output beam should be further investigated and improved.

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