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Passive mode-locking performance of mixed Nd:La$_{0.11}$Y$_{0.89}$VO$_4$ crystal

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Abstract: Passive mode locking of a diode pumped Nd:La$_{0.11}$Y$_{0.89}$VO$_4$ mixed crystal laser with a semiconductor saturable absorber mirror (SESAM) was experimentally investigated for the first time to our knowledge. Stable CW mode-locking has been achieved on both $a$-cut and $c$-cut mixed crystals. In case of the $a$-cut crystal, when a 2% output coupler (OC) was used, the shortest pulse obtained was 4.5 ps and the highest output power was 0.94 W, while when a 6% OC was used, the shortest pulse obtained was 6.8 ps and the highest output power was 5.16 W. In the latter case the optical conversion efficiency is 38% and the slope efficiency is 40.3%, respectively; with the $c$-cut crystal the shortest pulse achieved was 5.5 ps. Moreover, simultaneous mode locking at two close wavelengths of 1064.3 nm and 1066.2 nm was observed on the $c$-cut crystal. The mode locked pulse beating generated temporal interference fringe of 0.5 THz repetition rate.

OCIS codes: (140.3480) Lasers, diode-pumped; (140.4050) Mode-locked lasers.

References and links
Q-switching performance with mixed Nd:Lu\textsubscript{0.11}Gd\textsubscript{0.89}VO\textsubscript{4} laser crystals,” Opt. Lett. 32(15), 2152–2154 (2007).


1. Introduction

Ultrashort pulse lasers have wide-spread applications in industry, military and scientific researches. They have been intensively investigated in the past [1–6]. Passive mode locking of lasers has the advantages of compact laser design, low cost, and ultrashort pulse generation. Depending on the gain medium bandwidth and the saturable absorbers used, mode locked pulses ranging from picoseconds to femtoseconds had been demonstrated with the technique. The passive mode locking performance of Nd\textsuperscript{3+} doped vanadate crystals has also been extensively studied. Stable mode locked pulses with pulse widths of ~20 ps and 2.1 ps for the Nd:YVO\textsubscript{4} [3, 4], 9.2 ps and 8 ps for the Nd:GdVO\textsubscript{4} [6], 8.6 ps for the Nd:LuVO\textsubscript{4} [7] have been demonstrated.

A goal of mode locked laser research is to generate narrow pulses with high average power. It is well-known that lasers with broader gain bandwidth can generate narrower mode locked pulses. Hence, in order to generate shorter pulses a series of the Nd\textsuperscript{3+}-doped mixed crystals were developed. Previous experiments with Nd\textsuperscript{3+}-doped vanadate mixed crystals have demonstrated ~3.8 ps mode locked pulses on the Nd:Gd\textsubscript{0.5}Y\textsubscript{0.5}VO\textsubscript{4} [5], 5.5 ps on the Nd:Gd\textsubscript{0.5}Lu\textsubscript{0.5}VO\textsubscript{4} [8], and 5.1 ps on the Nd:Lu\textsubscript{0.15}Y\textsubscript{0.85}VO\textsubscript{4} [9], respectively. Mixed crystals can be doped to have broader gain spectrum than single crystals. As a result, they often produce narrower bandwidth limited pulses. However, a drawback of the mixed crystals is that their thermal conductivity also decreases as compared to that of the single crystals. Thermal conductivity is one of the important parameters of laser gain media. Decreased thermal conductivity of a laser gain medium results in thermal management issues that can be difficult to resolve and often limit the highest achievable pulse energy and/or average power. Therefore, it is highly desirable to find a mixed crystal gain medium that has not only broader gain bandwidth but also large thermal conductivity.

A recently developed new mixed crystal, Nd:La\textsubscript{0.11}Y\textsubscript{0.89}VO\textsubscript{4} is such a candidate. A study on the thermal property of the crystal has shown that it has a thermal conductivity of 5.84 W m\textsuperscript{-1}K\textsuperscript{-1}, which is almost the same as that of the Nd:YVO\textsubscript{4} (5.23 W m\textsuperscript{-1}K\textsuperscript{-1}). In a previous paper we have experimentally investigated the CW operation performance of the mixed crystal [10]. Experimental results show that it is promising as a high power gain medium. In this paper we further report on the CW passive mode-locking performance of the mixed crystal. A diode pumped Nd:La\textsubscript{0.11}Y\textsubscript{0.89}VO\textsubscript{4} laser passively mode locked with a SESAM was constructed. In our experiments both the \textit{a}-cut and \textit{c}-cutNd:La\textsubscript{0.11}Y\textsubscript{0.89}VO\textsubscript{4} mixed crystals were used as the gain medium. It was found that different cuts of the mixed crystal have different passive mode locking performance.

2. Experimental details

The Nd:La\textsubscript{0.11}Y\textsubscript{0.89}VO\textsubscript{4} crystal is a mixture of Nd:LaVO\textsubscript{4} and Nd:YVO\textsubscript{4}. It possesses the same ZrSiO\textsubscript{4} structure with a tetragonal space group as Nd:YVO\textsubscript{4}, but not the monoclinic space group as Nd:LaVO\textsubscript{4}. Figure 1 shows the polarized fluorescence spectra of the crystal measured with a UV-VIS-NIR spectrophotometer (V-570 Jasco Corporation) at room temperature. The \(\pi\) polarized fluorescence is much stronger than the \(\sigma\) polarized fluorescence. The fluorescence peak at 1.06 \(\mu\)m has a FWHM bandwidth of 5.1 nm and 2.2 nm for the \(\sigma\) and \(\pi\) polarized spectrum, respectively. The broad fluorescence bandwidth of the Nd\textsuperscript{3+} in the...
mixed crystal is due to that the Nd:LaVO₄ and Nd:YVO₄ are two difference crystal systems, and the La³⁺ and Y³⁺ ions have big difference in ion radius and masses. Therefore, there are bigger local crystal-field variations in the mixed crystal, which causes bigger inhomogeneous gain broadening than that of the Nd:Lu₀.₅Gd₀.₅VO₄ and Nd:Y₀.₅Gd₀.₅VO₄ mixed crystals [11,12] under the same mixture degree. In addition, the small La doping concentration guarantees that Nd:La₀.₁₁Y₀.₈₉VO₄ could still maintain the thermal conductivity of the Nd:YVO₄ to the full extent. The broad fluorescence spectrum and excellent thermal property of the mixed crystal favor the generation of high power mode-locking.

![Polarized fluorescence spectrum of Nd:La₀.₁₁Y₀.₈₉VO₄ at room temperature.](image)

The Nd:La₀.₁₁Y₀.₈₉VO₄ is a uniaxial crystal. Along different crystal axes it has different gain properties. As shown in Fig. 1, the mixed crystal has different fluorescence strength for the $\pi$ and $\sigma$ polarizations. If the crystal is $a$-cut, both the $\pi$ polarization and $\sigma$ polarization gain coefficients could play a role on the laser oscillation, while for the $c$-cut crystals, which is cut along the optical axis, only the $\sigma$ polarization gain coefficient involves in the laser oscillation. Because the strength of the $\pi$ polarization gain is much stronger than that of the $\sigma$ polarization gain, as a result of the gain competition, an $a$-cut crystal would oscillate at the $\pi$ polarization under the CW operation [13, 14]. It was expected that the different cuts of the mixed crystal would influence the mode-locking performance of the crystal.

We designed a diode pumped Nd:La₀.₁₁Y₀.₈₉VO₄ mixed crystal laser with a three-mirror folded cavity. A schematic of the laser configuration is shown in Fig. 2. The pumped source was a 35 W fiber coupled laser diode (LD) array with a central wavelength at 808 nm. The fiber had a core size of 100 $\mu$m in radius and a numerical aperture (NA) of 0.22. The crystals had a Nd³⁺ doping concentration of 0.3 at.% and were either $a$-cut with dimensions of 3 mm × 3 mm × 6 mm or $c$-cut with dimensions of 3 mm × 3 mm × 4 mm. Both light passing facets of the crystals were anti-reflection (AR) coated at the lasing wavelength of 1064 nm and the pumping wavelength of 808 nm (R<0.2%). The input mirror M1 was a plane mirror AR coated at 808 nm and high-reflection (HR) coated at 1.06 $\mu$m. M2 is a concave mirror with a radius of curvature of 500 mm. Mirrors with transmission of either 2% or 6% at 1.06 $\mu$m was used in the experiments. The length of branches L1 and L2 was 480 mm and 509 mm, respectively. Taking into account the measured thermal lens effect in the laser crystal, the mode radius of the laser beam in the gain medium and on the SESAM were calculated to be about 120 $\mu$m and 130 $\mu$m, respectively. The SESAM used was a commercial product (BATOP Optoelectronics, Germany). It had an absorbance (A) of 3% at 1.06 $\mu$m, a modulation depth of 1.6%, and a saturation fluence of 70 $\mu$J/cm².
3. Results and discussion

3.1 The performance of a-cut crystals

Figure 3 shows the mode locking performance of the laser when an output mirror with an OC = 2% was used, while Fig. 4 shows that when an output mirror with an OC = 6% was used. When an output mirror with an OC = 2% was used, the self-started mode-locking had a threshold of 2.87 W. A maximum average output power of 0.94 W was obtained under an incident pump power of 5.67 W. It gives an optical conversion efficiency of 16.8%, and a slope efficiency of 29.5%. Because the output coupling of the laser was small, the energy density of light inside the cavity was high. The laser crystal and the SESAM could easily be damaged. Therefore, with the output coupling we didn’t increase the pump power above 5.67 W. When an output mirror with an OC = 6% was used, the threshold of the self-started mode locking changed to about 2.66 W. A maximum average output power as high as 5.16 W was achieved under an incident pump power of 13.59 W, corresponding to an optical conversion efficiency of 38% and a slope efficiency of 40.3%. Even at the pumped power of 13.59 W, no crystal damage and the laser output saturation were observed. Further increase on the pump power would damage the SESAM used. We note that the mode locking threshold with OC = 2% was even higher than that with OC = 6%, which looks abnormal. We suspect that it could be due to some technical artifacts e.g. the non-uniform quality of the SESAM used, or dirt on the output mirror etc.

Fig. 3. (a): Variation of the average output power versus the incident pump power with OC = 2%. (b): Measured autocorrelation trace of the mode-locked pulses. Insert: Optical spectrum of the mode-locked pulses.
Figure 5 shows a typical mode-locked pulse train measured with a 10 ns/div time scale. In the inset of the figure the pulse train measured with a time scale of 10 μs/div was also shown. The repetition period of the pulses was 6.78 ns, which corresponds to the cavity roundtrip time and gives the pulse repetition rate of 148 MHz. Based on the measured average output power and the pulse repetition rate, we estimated that the maximum pulse energy was about 35 nJ.

The pulse duration of the mode-locked pulses was measured with a commercial autocorrelator (Pulse Checker 50). The measured autocorrelation traces are shown in Figs. 3(b) and 4(b). In the case of OC = 2%, the autocorrelation trace has a pulse duration of 7.0 ps. If a sech² pulse profile is assumed, the mode locked pulses have a FWHM pulse width of 4.5 ps. The mode-locked pulse spectrum was measured with an optical spectrum analyzer with a resolution of 0.05 nm. The mode locked pulse spectrum shown in Fig. 3(b) insert has a FWHM line width of 0.4 nm. Thus the time-bandwidth product of the mode locked pulses was about 0.47, indicating that the pulses were slightly chirped. In the case of OC = 6%, the mode locked pulses had a FWHM width of 6.8 ps and a FWHM spectral bandwidth of 0.24 nm. The time-bandwidth product of the pulses is 0.43.

Compared with results obtained on the Nd:Y₀.⁵Gd₀.⁵VO₄ mixed crystal, the mode-locked pulses have a comparable pulse width. However, the average output power obtained on the Nd:La₀.₁¹Y₀.₈₉VO₄ mixed crystal is much larger than that (3.9 W) obtained on the Nd:Y₀.₅Gd₀.₅VO₄ mixed crystal. Moreover, both the slope efficiency and the optical conversion efficiency are higher than those achieved on the Nd:Y₀.₅Gd₀.₅VO₄ mixed crystal.
Comparing with another mixed crystal \( \text{Nd:Lu}_{0.5}\text{Gd}_{0.5}\text{VO}_{4} \), the obtained maximum average output power is comparable, but the slope efficiency and optical conversion efficiency are higher. Our experimental result shows that the \( \alpha \)-cut \( \text{Nd:La}_{0.11}\text{Y}_{0.89}\text{VO}_{4} \) is a good laser gain medium for the high power laser mode-locking.

3.2 The performance of \( \alpha \)-cut crystals

We have also investigated the mode locking performance of the \( \alpha \)-cut crystal with the same laser configuration as shown in Fig. 2. The result is shown in Fig. 6(a) when an output mirror with an \( \text{OC} = 6\% \) was used. The self-started mode-locking of the laser had a threshold of 3.9 W. Under an incident pump power of 9.01 W, the maximum average output power obtained was 2.06 W, which gives an optical conversion efficiency of 23\%, a slope efficiency of 27\%. Interestingly, when the pump power was below 1.96 W, the laser oscillated only at 1064.3 nm, when the pump power became larger than 1.96 W, the laser oscillated at the 1064.3 nm and 1066.2 nm simultaneously.

Fig. 6. (a): Variation of the average output power versus the incident pump power. (b): Measured autocorrelation trace of the mode-locked pulses. Upper left insert: the fine structure of autocorrelation trace. Upper right Insert: Optical spectrum of the mode-locked pulses.

The autocorrelation trace and the corresponding optical spectrum of the mode locked pulses were shown in Fig. 6(b). If a sech\(^2\) pulse profile is assumed, the mode locked pulses have a FWHM pulse width of 5.5 ps. The autocorrelation trace exhibits strong amplitude modulation. A similar result was reported before [15, 16] and was shown to be a result of temporal interference of two phase-locked pulses with different carrier frequencies. The measured optical spectrum clearly confirmed the dual-wavelength oscillation of the laser. In particular, the two oscillating wavelengths are 1064.3 nm and 1066.2 nm, respectively. Based on the measured fine structure of the autocorrelation trace, as shown in the left insert of Fig. 6(b), the interference pattern has a time period of 2.02 ps, which corresponds to a repetition rate of 0.5 THz. The repetition rate exactly equals to the beat frequency of the two oscillating wavelengths. In experiments we had also measured the pulse train simultaneously. There was only one mode-locked pulse train observable on the oscilloscope trace, indicating that the two mode-locked pulses are synchronized and temporally overlapped.

To understand the observed mode locking result, we note that for the \( \alpha \)-cut crystal there is only the \( \sigma \) polarized gain component. As shown in Fig. 1, there are two peaks locating at 1064 nm and 1066 nm respectively in the spectrum. As they have comparable gain coefficient, they were mode locked simultaneously by the SESAM. Due to the fact that the center frequencies of the mode locked pulses were close, under the effect of the SESAM, the phases of the pulses were also locked. Consequently, the measured autocorrelation trace of the laser displayed an interference pattern. We note that the intensity modulation depth of the interference pattern is bigger than that observed in Nd:CNGG and Nd:LYSO lasers [15,16]. The modulation depth is determined by the intensity ratio of the two beating pulses. Based on
the measured laser emission spectrum, the spectral intensity of the two different wavelength pulses is comparable, which is in consistent with the numerical result reported by Cong et al [16].

4. Conclusion

In conclusion, the passive mode-locking performance of a diode pumped Nd:La$_{0.11}$Y$_{0.89}$VO$_4$ mixed crystal laser with a SESAM was experimentally investigated for the first time. In case of the $a$-cut crystal, when a 2% OC is used, the shortest pulse width obtained is 4.5 ps and the highest output power is 0.94 W. And when a 6% OC is used, the shortest pulse width is 6.8 ps and the highest output power is 5.16 W. The results show that the mixed crystal could be a promising gain medium for the high power mode locked lasers. In case of the $c$-cut crystal, dual-wavelength mode locking was observed. The shortest pulses of 5.5 ps are obtained at the highest output power of 2.06 W with a 6% OC in the case. The temporal beating of the mode-locked pulses with different center wavelengths has generated a subset pulse train with 0.5 THz repetition rate. We believe that the dual-wavelength mode locking is a unique feature of the mixed crystal and it is associated with the gain line splitting of the Nd$^{3+}$ ions in the mixed crystal.

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