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Passive mode locking of a Nd:YAG laser with co-doped Nd, Cr:YAG as saturable absorber*

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We demonstrate the characteristics of relatively low saturation intensity using co-doped Nd, Cr:YAG as saturable absorber for passively mode locking the Nd:YAG laser. The difference of the saturation intensity between Q-switched and mode-locked operation in co-doped Nd, Cr:YAG was only one to two orders of magnitude, while Cr:YAG was generally reported at a difference of five orders of magnitude. More than 80% mode locking modulation depth was achieved at an incident pump power of 4.4W, corresponding to an intracavity intensity of 6×10^4W/cm^2, using a 68cm long plano-concave cavity.

Keywords: Nd, Cr:YAG crystal, passive mode locking, saturable absorber
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1. Introduction

All-solid-state passively Q-switched lasers have attracted much attention for scientific and industrial applications. They are used in micromachining, ranging, remote sensing, laser communication and nonlinear optics. Passively Q-switched lasers have advantages such as compactness, low cost, high efficiency. They are simple to fabricate and require no high-voltage or rf drivers. Cr^{4+}:YAG and Semiconductor saturable absorber are often used to perform passive Q-switching and passive mode locking.[1,2] Cr:YAG crystal is preferable for its excellent optical properties, good photochemical and thermal stability, low saturation intensity and high damage threshold, which makes it attractive as Nd-doped lasers.[2] The relaxation time of the first excited state is about 4.2μs.[3] This slow process prevents it from mode locking operation. However, the excited state absorption (ESA) is significant and the relaxation time of the upper state is in the subnanosecond region, which makes it suitable for mode locking.[4,5] Recently, the Q-switched and mode locked operation of Nd:YAG/Nd:YVO_4 laser with Cr:YAG as saturable absorber has been reported, including both lamp and diode pumping.[6,7]

The operation principle of a Cr:YAG passively Q-switched laser is that the intracavity average inversion density reaches a critical threshold. The onset of lasing, at that point produces a high intracavity intensity to bleach the saturable absorber and increase the cavity gain, then gives rise to a Q-switched output pulse.[8] It was generally known that the excitation phenomenon has taken place between the ground state and the first excited state at lower pump level and the ESA is too weak. So the Cr:YAG acts only as a passive Q-switch. But the higher intracavity intensity makes it a possibility to saturate the excited state and realize the passive mode locking because of its shorter relaxation time.[9] The cross section and the relaxation time of the ESA used were σ_e=2.2–8$\times10^{-19}$cm^2 and τ_e=100ps, respectively.[10] With these values, we obtained I_S=2.4–8.6GW/cm^2. That is to say, the intracavity intensity must reach the order of gigawatt per square centimetre. It is very difficult to obtain such high intensity for a simple plane-concave cavity. The folded cavity has been adopted in order to obtain higher intensity inside Cr:YAG.[6] This makes the whole system more complicated. In this paper,

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we report the characteristic of ultra low saturation intensity using Nd, Cr:YAG as saturable absorber for passive mode locking. The difference of the saturation intensity for the Q-switched and mode locked operation in co-doped Nd, Cr:YAG was only one to two orders of magnitude. Cr:YAG was generally reported by a difference of five orders of magnitude. More than 80% mode locking modulation depth was achieved at an intracavity intensity of 6×10^4W/cm^2.

2. Experimental set-up

The 12W/800μm fibre coupled diode was used to directly pump a 8mm long Nd:YAG crystal as shown in Fig.1 (a). The side facing the pump diode was coated for high reflectivity at 1.06μm and high transmission for 808nm. Two different output couplers were used in our experiment: one used a radius of curvature of 25cm with a reflectivity of 97% at 1.06μm for short cavity experiment (L < 20cm); the other used a radius of curvature of 2m with a high reflection of 99.8% at 1.06μm for longer cavity experiment (L > 50cm). An uncoated co-doped 1mm thick Nd, Cr:YAG or an uncoated 1mm thick Cr:YAG was placed into the cavity as the saturable absorber. The Nd:YAG crystal was wrapped in indium foil for reliable heat transfer and mounted inside a water-cooled copper cell. The 1% Nd^{3+} and 1% Cr^{4+} co-doped crystals were obtained from the North China Research Institute of Electro-Optics in Beijing, made by the standard Czochralski method. The initial transmission of Nd, Cr:YAG crystal and Cr:YAG crystal at 1.06μm were both 80%. Fig.1 (b) shows a V cavity structure with a cavity length greater than 1m used in the experiment. The mirror in bow place was a plane mirror with high reflectivity coating at 1.06μm.

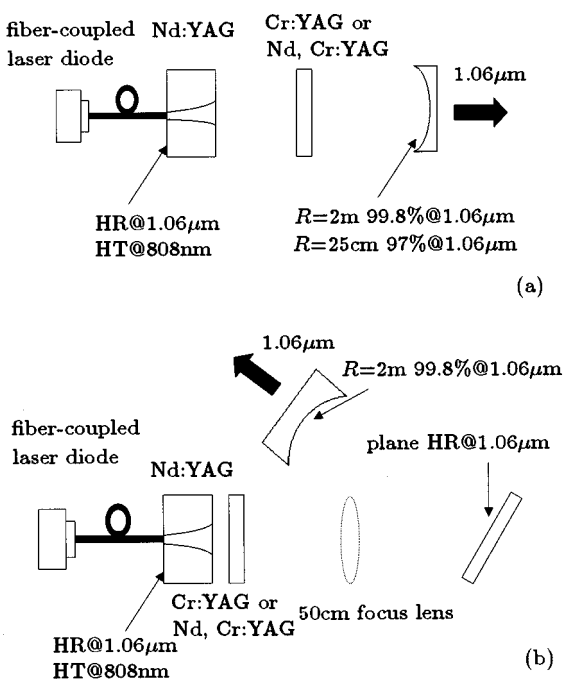


Fig.1. Experimental set-up of Nd, Cr:YAG or Cr:YAG saturable absorber passive mode locking laser. (a) Experimental set-up for cavity length shorter than 1m. (b) Experimental set-up for cavity length longer than 1m. HR, high reflection; HT, high transmission.

3. Experimental results

In short cavity experiments, the Cr:YAG was firstly used as a saturable absorber. The cavity length (L) was 19cm. The distance (d) between the laser gain medium and the saturable absorber was 8mm. The lasing threshold was reached at an input power of 5.2W. A digital oscilloscope (Tektronix 620) recorded the pulse temporal behaviour through a fast photo diode with a rise time of 20ps. Quite stable Q-Switched pulses were obtained and the pulse modulation phenomenon was not observed even for pump power higher than 6.8W. A maximum average output power of 129mW was measured at an input pump power of 6.8W at a repetition rate of ~2.5kHz and a pulse width of 100ns. Fig.2 gives a plot of the average output power against the pump power. In order to compare with the different characteristics with the Cr:YAG, the Nd, Cr:YAG has been operated in the same configuration. It reached the threshold at an incident pump power of 0.88W. The Q-switched pulse was stable at low pump level and the stable mode locking phenomenon occurred when the pump power was higher to 2.3W. Fig.3 shows the stable Q-switched and mode locked pulse envelope. An output power of 142mW was obtained at a pulse repetition of ~7.5kHz and a pulse width of 350ns. The average output power

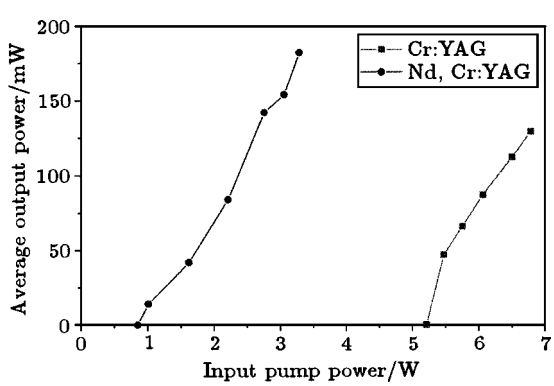


Fig.2. Average output power as a function of input pump power when using Cr:YAG or Nd, Cr:YAG as a saturable absorber.

is also presented in Fig.2. The mode locked modulation depth reached 80%. In this case, the intracavity intensity was about 2.0MW/cm^2.

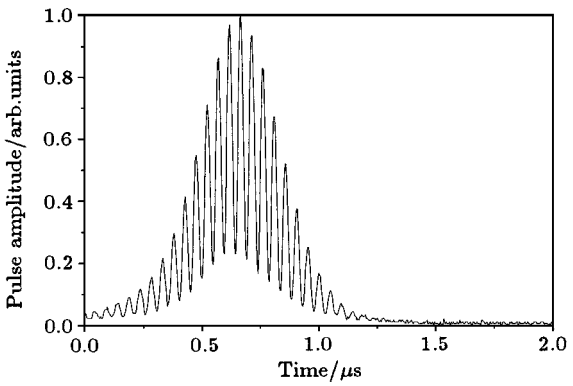


Fig.3. Oscilloscope trace of a Q-switched and mode locked pulse envelope when Nd, Cr:YAG was used as a saturable absorber with a cavity length of 20cm.

In longer cavity experiments, the co-doped Nd, Cr:YAG was inserted into the cavity with L=68cm and d=63cm. It reached the lasing threshold at an incident pump power of 4.1W. The stable Q-switched pulse was achieved at low pump power and the mode locking phenomenon appeared more and more obviously at increasing pump power from 4.4W to 5.2W. More than 80% mode locking modulation depth was achieved at an input pump power of 4.8W, corresponding to an average output power of 9.6mW at a pulse repetition rate of ~6kHz and a pulse width of 800ns. The relatively stable oscilloscope trace of the modulation pulse envelope is shown in Fig.4. The mode-locking pulse width was measured to be about 800ps with a pulse interval of 4.7ns. In this case, the intracavity intensity was only 6×10^4W/cm^2.

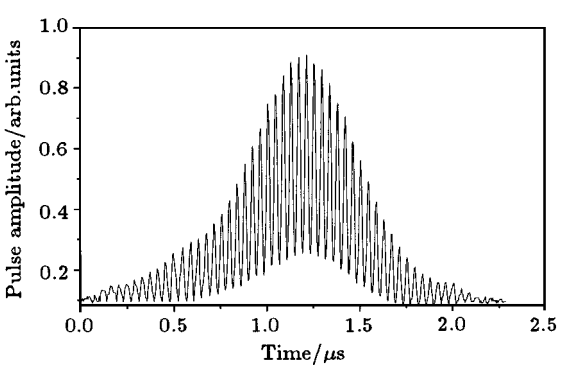


Fig.4. Oscilloscope trace of a Q-switched and mode locked pulse envelope when Nd, Cr:YAG was used as a saturable absorber with a cavity length of 68cm.

Experiment has also been performed using a V cavity of longer cavity length. With a high reflection plane mirror in bow place, the Nd, Cr:YAG crystal was placed close to the gain medium so that there was no focusing effect on the Nd, Cr:YAG crystal. At a cavity length of 1.9m, in order to make the cavity easier to adjust, a focusing lens of 50cm curvature was placed in the middle of the cavity. The lasing threshold was reduced to 2.8W. At an input pump power of 3.5W, quite stable mode locking pulses were obtained, as shown in Fig.5. The measured mode locking pulse width was about 350ps with a pulse interval of 12.7ns, corresponding to a pulse envelope width of 7.5μs. It was worthwhile noting that the low output efficiency is due to the high reflection of the output couplers used.

In the same situations of the above two cases, after changing co-doped Nd, Cr:YAG to Cr:YAG, there was no emission even at pump power higher than 7.5W. The reason is attributed to the intracavity intensity that was too low to bleach the Cr:YAG saturable absorber.

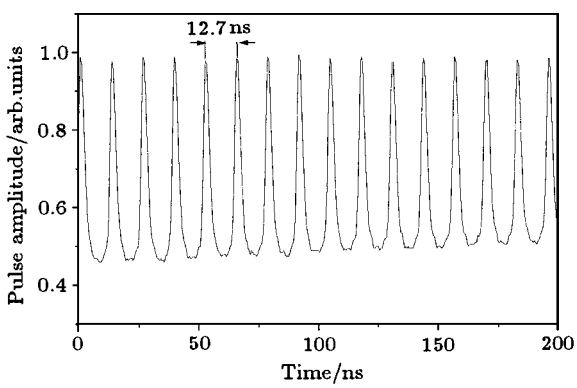


Fig.5. Oscilloscope trace of the stable mode locked pulses when Nd, Cr:YAG was used as a saturable absorber with a cavity length of 1.9m.

4. Discussion

The lasing threshold of Cr:YAG as saturable absorber was five times higher than that of Nd, Cr:YAG in a short cavity as shown in Fig.1. In other words, the Nd, Cr:YAG was easier to bleach and the saturation intensity for the Q-switched operation was lower than that of Cr:YAG. Furthermore, the 80% mode locking modulation depth was observed at an input pump power of 2.3W. This value was less than half that of other reports.[6] The cavity length was shorter than 20cm. To the best of our knowledge, we firstly report the passive mode locking operation in such a short cavity using a Cr-doped saturable absorber. After increasing the cavity length to longer than 50cm, there was no emission when using the Cr:YAG. The

lower cavity intensity led to this result comparing with the shorter cavity in our configuration. Although the threshold increased several times, the mode locking was achieved at a low pump power of 4.8W that was much lower than other reports.[6,7] Moreover, it was of utmost importance that the intracavity intensity was only about 6×10^4W/cm^2, which was dramatically lower than the gigawatts per square centimetre for Cr:YAG passive mode locking operation. The above data of our experiments confirmed that the characteristics of the Nd, Cr:YAG and Cr:YAG for passive mode locking was distinctly different in that the ESA saturation intensity of Cr:YAG is five order higher than the ground state saturation intensity for the different absorption cross-section and relaxation time. But for the Nd, Cr:YAG, it was quite obvious that the mode locking phenomenon appeared when increasing the pump power a little after Q-switched operation in our experiments. That is to say, the difference of the saturation intensity between the Q-switched and mode locked operations was only one to two orders of magnitude. Further investigations such as the fluorescence spectral analysis of this crystal, the measurement of the absorption cross section and the relaxation time are currently underway.

The limitation of modulation depth resulted from two key influencing factors. Firstly, the initial transmission (parameter T_0) is a key factor for the Cr:YAG passive mode locking characteristics. Lower T_0 leads to deeper modulation depth.[6] Secondly, adequately higher intracavity intensity might improve the performance of the modulation depth using a longer cavity length. Our experimental result suggests that, using a relatively compact folded cavity structure or intracavity lens to slightly improve the intensity on the Nd, Cr:YAG crystal with a proper initial absorber transmission, 100% mode locking modulation depth may possibly be achieved in a foreseeable future. Moreover, other broadband host materials might provide an elegant way to realize more efficient passive mode locking.[11] Its ultra low saturable power intensity has attractive application prospect. Hence a low pump diode laser in combination with a compact plano-concave cavity could realize the efficient mode locking to obtain subnanosecond pulses.

5. Conclusion

We report the characteristic of relatively low saturation intensity using Nd, Cr:YAG as saturable absorber for passive mode locking. The difference of the saturation intensities for the Q-switched and mode locked operation in co-doped Nd, Cr:YAG was only one to two orders of magnitude, while for Cr:YAG it was generally reported at a difference of five orders of magnitude. More than 80% mode locking modulation depth was achieved at an incident pump power of 4.4W corresponding to an intracavity intensity of 6×10^4W/cm^2 using a 68cm long plano-concave cavity. Using several different cavity lengths, the mode locking depth from 60% to 80% was achieved.

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