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Diode end-pumped self-Q-switched and mode-locked Nd,Cr:YAG /KTP green laser*

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We first experimentally demonstrate a laser-diode end-pumped self-Q-switched and mode-locked Nd,Cr:YAG green laser with a KTP crystal as the intra-cavity frequency doubler. The device produces an average output power of 680 mW at 532 nm. The corresponding pulse width of the Q-switched envelope of the green laser is 170 ± 20 ns. The mode-locked pulses have a repetition rate of approximately 183 MHz and the average pulse duration is estimated to be around sub-nanosecond. It is found that the intra-cavity frequency doubling greatly improves the modulation depth and stability of the mode-locked pulses within the Q-switched envelope.

Keywords: frequency doubling, Nd,Cr:YAG crystal, self-Q-switched and mode-locked pulses, green laser

PACC: 4260, 4265K

1. Introduction

The green laser is very useful in many applications, such as under-water communication, projection display, chemistry processing, medicine, and so on.[1−4] However, continuous wave intra-cavity doubled green laser generally suffers from a large noise fluctuation in the output due to the coupling of different longitudinal modes through the sum frequency generation at the frequency doubling crystal.[5] Simultaneous Q-switching and mode-locking is of great interest for the generation of high peak power and short pulses.[6,7] By co-doping the YAG host crystal with Nd^{3+} and Cr^{4+}, the two functions of the gain medium and the saturable absorber can be combined into one and thus a compact self-Q-switched laser can be realized.[8,9] Furthermore, the output laser beam of the Nd,Cr:YAG crystal is linearly polarized without any polarizer in the cavity.[10] Yang *et al* [11,12] showed that the saturation intensity of Nd,Cr:YAG crystal for self-Q-switched and mode-locked operation was much smaller than that of Cr:YAG crystal. In this paper we report, for the first time to our knowledge, the intra-cavity second harmonic generation with KTP crystal in a self-Q-switched and mode-locked Nd,Cr:YAG laser. In our system, self-Q-switched and mode-locked pulses with an almost 100% depth of modulation are realized at 532 nm. In addition, we find that the frequency doubling greatly improves the depth of modulation of the mode-locked pulses within the Q-switched envelope.

2. Experimental setup

Figure 1 shows the experimental setup. A 20 W /400 μm fibre-coupled laser-diode (LD) with a numerical aperture of 0.22 is collimated and focused into a Φ4.5 mm × 14 mm Nd,Cr:YAG crystal by using two plano-convex lenses with 25 mm focal length, which give the coupling efficiency of 90%. The initial transmission of Nd,Cr:YAG crystal is about 80%. One side of the crystal is coated for high reflection at 1064 nm ($R > 99.9\%$) and high transmission at 808 nm ($T > 95\%$), and the other side is coated for antireflection (AR) at 1064 nm. It is wrapped with indium foil and mounted in a water-cooled copper heat sink which is cooled to about 13°C to avoid optical damage of the crystal. A 10-mm long KTP ($KTiOPO_4$) crystal is used for frequency doubling, which is cut for type-II phase matching at 1064 nm and AR-coated for

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1064 and 532 nm on both end faces.

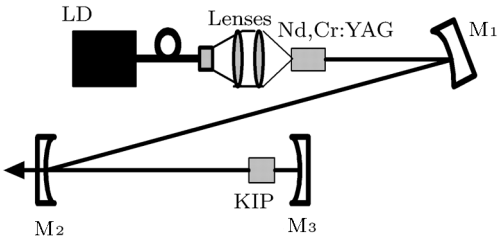


Fig.1. Schematic of self-Q-switched and mode-locked Nd,Cr:YAG /KTP green laser.

In order to obtain good mode matching between the pump beam and the oscillating light, the laser cavity is designed with a z-type resonator. The folded concave mirror M_1 ($r = 30$ cm) is coated for high reflection at 1064 and 532 nm, while M_2 ($r = 22$ cm) is coated for high reflection at 1064 nm and high transmission at 532 nm. The reflection of M_3 ($r = 5$ cm) at 1064 and 532 nm can be changed under different conditions. The distances between M_1 and M_2, M_2 and M_3 are 460 mm and 157 mm respectively. The total length of the cavity is about 820 mm.

3. Experimental results and discussion

First, we investigate the characters of the self-Q-switched and mode-locked laser operating at 1064 nm. Here M_3 ($r = 5$ cm) acts as the output coupler (OC) mirror. In order to optimize the laser, various OC mirrors with transmission (T) of 2.5%, 6% and 15% at 1064nm are used in the experiment. The average output power of the self-Q-switched and mode-locked laser as a function of incident pump power is presented in Fig.2. The slope efficiency of the laser increases with the increase of the transmission of OC mirror. With the OC mirror of $T = 2.5\%$, an average output power of 658 mW is obtained at the incident pump power of 17 W. When the incident pump power is further increased, the output power falls off, which is believed to be the result of the thermal lens effect of the Nd,Cr:YAG crystal. With the OC mirror of $T = 15\%$, a maximum average output power of 2.29 W is obtained at an incident pump power of 19 W. The corresponding slope efficiency is calculated to be 15.3%. Measuring the polarized direction of self-Q-switched and mode-locked laser of the fundamental, we find that almost 80% of the laser beam is horizontal polarized without any polarizer in the cavity. A digital oscilloscope (Tektronix 3052B 500 MHz 5×10^{-4} T/s) records the pulse temporal behaviour through a fast photodiode with a rise time less than 1 ns. Typical oscilloscope traces of the self-Q-switched pulses of the fundamental are presented in Fig.3. Figure 3(a) shows the pulse train at an incident pump power of 6.29 W. Multiple pulsing amplitudes are observed with the increase of the pump power, as is clearly shown in Fig.3(b). This phenomenon is due to the effect of spatial hole burning which is most pronounced when the gain region is at one end of the laser cavity.[13]

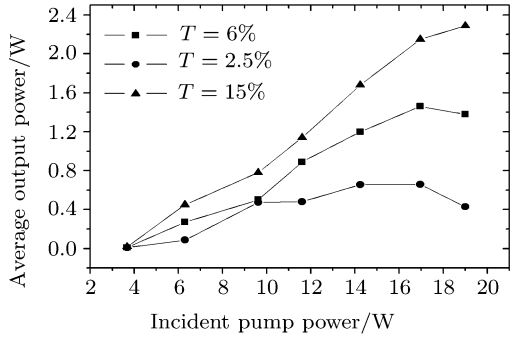


Fig.2. The relationship between the average output power of the fundamental and the incident pump power corresponding to different output coupling transmission.

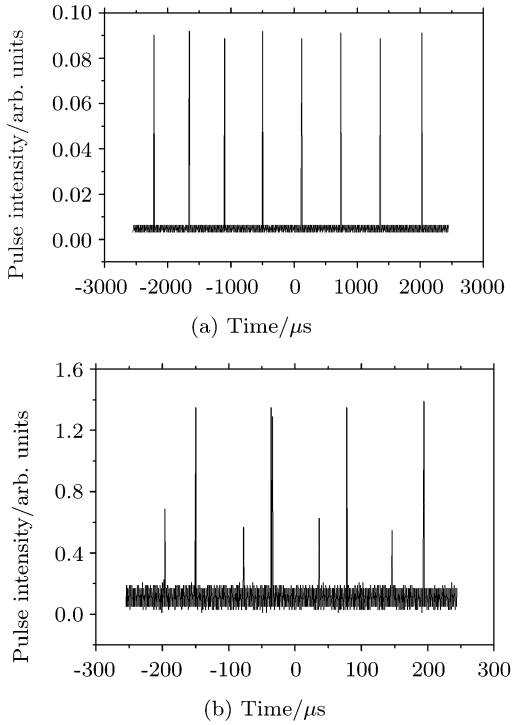
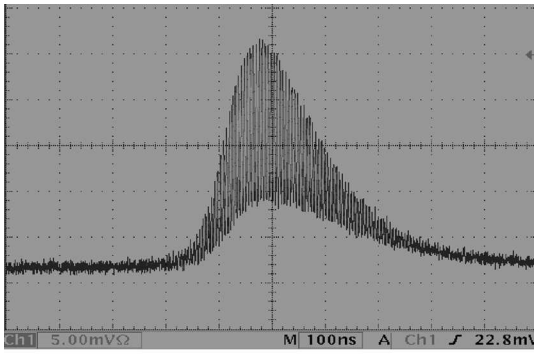


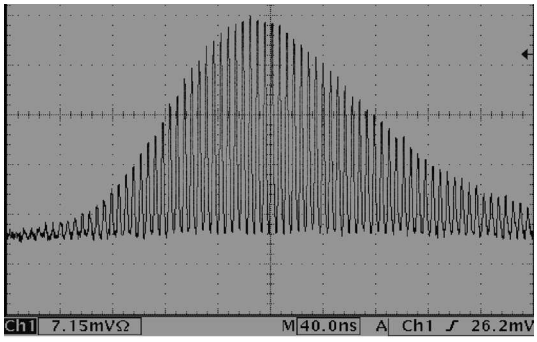
Fig.3. Oscilloscope traces of trains of Q-switched pulse of the fundamental at incident pump power of (a) $P_{\rm in}$= 6.29 W and (b) $P_{\rm in}$= 16.96 W.

The lifetime of the second excited state of the Cr^{4+}:YAG crystal is very short, so the saturation of the excited state absorption (ESA) is responsible

for the mode-locking.[14] The temporal behaviour of mode-locked pulses of the fundamental is shown in Fig.4(a). The pulse interval of mode-locked pulses within the Q-switched envelope is 5.45 ns, which is matching exactly with the cavity round trip transit time. It can be found that the mode-locked modulation depth in Fig.4(a) is about 70%. Although the mode-locked modulation depth of the fundamental is not very well, the mode-locked modulation depth of green laser is almost 100%, as shown in Fig.4(b). From Figs.4(a) and 4(b) we obtain the result that the frequency doubling crystal greatly improves the modulation depth of mode-locked pulses of the fundamental, due to the nonlinear conversion processes. Mukhopadhyay *et al* also found the similar phenomenon.[3,15]



(a)



(b)

Fig.4. Oscilloscope trace of the pulse envelope. (a) Self-mode-locked pulses of the fundamental light. (b) Self-mode-locked pulses of the green laser.

Here M_3 mirror is replaced by one of mirrors with the same radius and high reflection at 1064 and 532 nm ($R > 99.9\%$) and the M_2 ($r = 22$ cm) mirror is used as the OC mirror at 532nm.

When the frequency-doubling crystal of KTP is put at a tight focusing position in the cavity, the output power characteristic of the green laser is obtained, as shown in Fig.5. At an incident pump power of 19 W, an average output power of 680 mW is achieved. In fact, just 80% of the fundamental is used for the generation of the green laser beam, due to the polarized direction of the fundamental light. Furthermore, Fig.5 does not show a sign of saturation, indicating that higher average output power can be obtained at higher incident pumping power. The pulse-to-pulse intensity fluctuation of the self-Q-switched pulse of the green laser is presented in Fig.6, which is recorded at the incident pump power of 5.6 W; this value is found to be less than ± 4%.

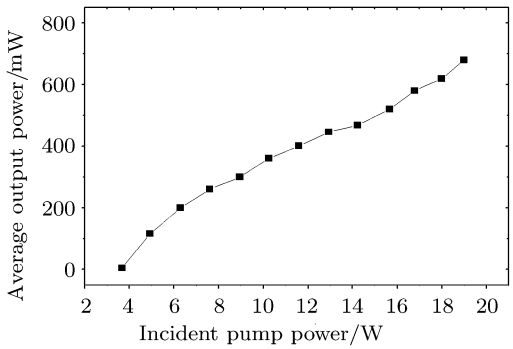


Fig.5. The average output power of the green laser as a function of the incident pump power.

However, the pulse-to-pulse amplitude fluctuation is more apparent with the increase of the incident pump power. This instability is actually the intrinsic vulnerability of all passively Q-switched and mode-locked lasers.

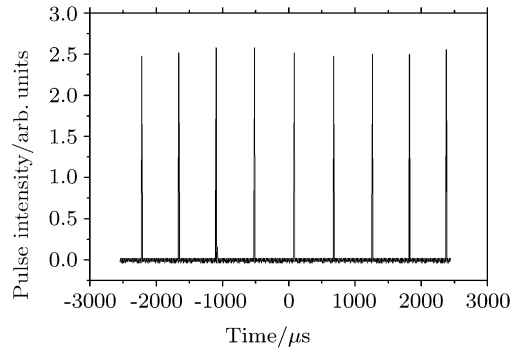


Fig.6. Oscilloscope traces of trains of Q-switched pulse of the green laser at incident pump power of 5.6W.

Figure 7 clearly exhibits the Q-switched pulse repetition rate of the green laser envelope as a function of the incident pump power. The repetition rate of the green laser increases almost linearly with increasing incident pump power. The highest self-Q-switched pulse repetition rate is 29.6 kHz at an incident pump power of 19 W. The mode-locked pulse width of the green laser is measured to be less than 2 ns using the oscilloscope (Tektronix 3052B, 500 MHz bandwidth 5×10^{-4} T/s) and a fast photodiode with rising time of about 0.1 ns. The measured mode-locked pulse width is limited by the resolution of the detection devices used in the

experiment. We believe that the actual pulse width is in the sub-nanosecond region, as could be deduced from the relaxation time of the ESA of Cr^{4+}:YAG. [16]

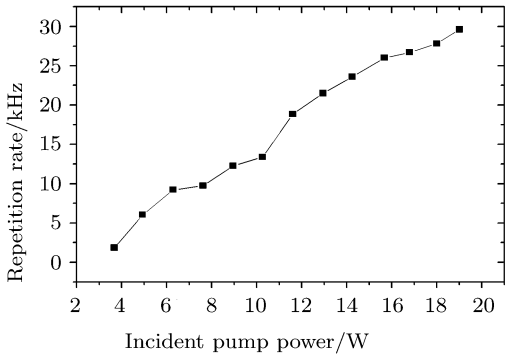


Fig.7. The repetition rate of Q-switched envelope of the green laser as a function of the incident pump power.

4. Conclusion

In conclusion, we have investigated an LD end-pumped self-Q-switched and mode-locked Nd,Cr:YAG green laser by intra-cavity frequency doubling with KTP crystal. At an incident pump power of 19 W, 680 mW of average output power of the green laser with 29.6 kHz repetition rate of the self-Q-switched envelope has been achieved. Almost 100% mode-locked modulation depth with sub-nanosecond pulse width of the mode-locked pulses is obtained. We also find that the frequency-doubling crystal greatly improves modulation depth of the mode-locked pulse within the self-Q-switched envelope.

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