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Diode-side-pumped Nd:YAG/$BaWO_4$ dual-wavelength Raman laser emitting at 1502 and 1527 nm

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ABSTRACT

A diode-side-pumped, actively *Q*-switched eye-safe dual-wavelength laser employing crystal Nd:YAG as gain medium and $BaWO_4$ as Raman medium is demonstrated for the first time to the best of our knowledge. The dual-wavelength Raman laser emission at 1502 and 1527 nm is based on the stimulated Raman scattering action of the dual-wavelength fundamental laser emission at 1319 and 1338 nm. With the pump power of 125 W and pulse repetition frequency of 5 kHz, the maximum dual-wavelength output power of 2.3 W was obtained, comprising a 1.4 W, 1505 nm laser component and a 0.9 W, 1527 nm laser component. The simultaneous *Q*-switching and mode locking of the dual-wavelength Stokes laser without mode locking component was obtained at the pump power of about 50–90 W and the pulse repetition frequency of 1 kHz. The mode-locked pulse width was less than 75 ps at the pump power of 90 W.

1. Introduction

Since water absorption in eye tissue and the intraocular fluid prevents light in the spectral range of 1.4–1.8 μm from reaching the retina, there is a considerable interest in compact laser sources with wavelengths in this eye-safe regime. Moreover, there is an excellent atmospheric transparency at the wavelength range of 1.5–1.7 μm. Therefore, lasers operating in the eye-safe region around 1.5 μm have found increasing demand in laser range finder and lidar applications [1]. Specially, the dual-wavelength laser near 1.5 μm with a small wavelength separation has important applications in the eye-safe differential lidar [2,3]. The methods of generating eye-safe laser include Er^{3+}, Cr^{4+}, and Yb^{3+} doped solid-state laser [4–6], optical parametric oscillators (OPO) [7–9], and stimulated Raman scattering (SRS) [10–14]. In particular, SRS is a very efficient method and one of the most important nonlinear frequency conversion processes to produce the eye-safe laser lines. Compared with the fundamental lasers without SRS process, the Raman lasers provide pulse duration shortening and beam quality improvement through Raman beam cleanup [15,16]. Compared with the OPOs, Raman lasers are freedom from phase matching constraints. Up to now, lasers output in the 1.5 μm eye-safe region have be obtained with the Raman crystals either in the first Stokes line pumped by 1.3-μm Nd-doped lasers [12,17–19] or in the third Stokes line pumped by 1.06-μm Nd-doped lasers [10,20–22]. However, all the researches focused on the single wavelength laser near 1.5 μm in the previous studies. Recently, our group demonstrated an efficient dual-wavelength laser emitting near 1.5 μm region based on the first Stokes lines pumped by the dual-wavelength fundamental lasers emitting at 1319 and 1338 nm [23]. This presents a potential and noteworthy method using both the SRS and the dual-wavelength fundamental laser to achieve dual-wavelength operation laser near 1.5 μm with a small wavelength separation, which is very attractive for the eye-safe differential lidar. In Ref. [23] of our previous work, the ceramic Nd:YAG was employed as laser medium and $BaWO_4$ crystal was employed as Raman medium based on the diode-end-pumped laser scheme. The maximum dual-wavelength output power of 0.82 W was obtained, comprising a 0.37 W, 1505 nm laser component and a 0.45 W, 1527 nm laser component. The reason of the low output power is that the diode-end-pump scheme was adopted. Firstly,

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though the diode-end-pumped scheme has a higher overlapping efficiency of pump beam and intracavity laser beam that leads to a higher conversion efficiency compared with the diode-side-pumped laser scheme, the small gain medium volume limits the population conversion available which is unfavorable to increase the output power; secondly, the thermal effect of laser medium was much more serious due to high quantum defect and the nonuniform pumping of the diode-end-pump scheme. Compared with the diode-end-pump scheme, the diode-side-pumped scheme could provide much higher diode power and would lead to much higher output power [24,25].

In this paper, for the first time to the best of our knowledge, we reported our results on a diode-side-pumped actively *Q*-switched eye-safe dual-wavelength Raman laser, in which a diode-side-pumped Nd:YAG module is used as the fundamental laser source and a $BaWO_4$ crystal is used as the Raman active medium. The maximum dual-wavelength output power of 2.3 W was obtained, comprising a 1.4 W, 1505 nm laser component and a 0.9 W, 1527 nm laser component, which is much higher than our previous results [23]. In addition, it is noted that the phenomenon of simultaneously *Q*-switched and mode-locked (QML) of the dual-wavelength Raman laser was observed although there is no any other mode locking component in the cavity in our experiment for the first time. The mode-locked pulse width was less than 75 ps at the pump power of 90 W and a pulse repetition frequency (PRF) of 1 kHz.

2. Experimental setup

Fig. 1 shows the experimental setup for the diode-side-pumped, actively *Q*-switched eye-safe dual-wavelength Nd:YAG/$BaWO_4$ Raman laser. The plane–plane configuration resonator was employed in our experiment. The plane–plane cavity can accommodate more serious thermal load than the concave-plane cavity. In other words, using a plane–plane cavity to partially offset the thermal lens should improve the resonator stability and hence power extraction. Especially for higher pump power, the plane–plane cavity is operating in a dynamically more stable regime than the concave–plane one [26]. The rear mirror (RM) and output coupler (OC) are designed for the first-Stokes generation at 1.5 μm. The RM was high-reflection (HR) coated at 1319–1338 nm ($R>99.996\%$) and 1502–1527 nm ($R>99.998\%$) on the other face. The OC was HR coated at 1319–1338 nm ($R>99.9\%$) and partial-reflection (PR) coated at 1502 ($T=14\%$), 1527 nm ($T=11\%$). The fundamental emission at 1319 and 1338 nm corresponds the stimulated emission cross sections being 8.7×10^{-20} and 9.2×10^{-20} cm^2, respectively [27]. Although the stimulated emission cross section of the 1338 nm emission is slightly larger than that of the 1319 nm emission, if the cavity losses for both wavelengths are comparable, the dual-wavelength emission of the two wavelengths could occur. However, under strong pumping, it was found that the intensity of the 1319 nm emission is much higher than that of the 1338 nm emission in Nd:YAG crystal

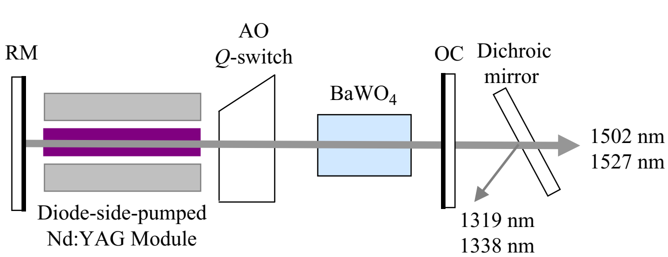

Fig. 1. Schematic diagram of the diode-side-pumped dual-wavelength Nd:YAG/$BaWO_4$ Raman laser.

lasers [28,29]. Using the method described in Ref. [30], in our experiment, with the OC transmissions at 1319 nm ($T=0.09\%$) slightly higher than that at 1338 nm ($T=0.03\%$), the fundamental dual-wavelength generation could be effectively balanced. Both mirrors had a transmission of $>90\%$ at 1064 nm to suppress the 1.06 μm laser line. The diode-side-pumped Nd:YAG module (Northrop Grumman, USA) was consisted of a Nd:YAG crystal rod (1.0 at%, ∅3 mm × 65 mm), a cooling sleeve, a diffusive optical pump cavity and three diode array modules operating at 808 nm. It was used as the fundamental laser source. The total pump power for Nd:YAG module was 200 W. The 46-mm-long acousto-optic (AO) *Q*-switch (Gooch and Housego) had anti-reflection (AR) coatings on both faces at 1319–1338 nm and 1502–1527 nm ($T>99.8\%$) and was driven at 27.12 MHz center frequency with the rf power of 50 W. The Raman active medium was an *a*-cut $BaWO_4$ crystal with the size of $5\times5\times47$ mm^3. Both ends of the Nd:YAG and $BaWO_4$ crystals were AR coated at 1319–1338 nm and 1502–1527 nm ($R<0.2\%$). The Nd:YAG laser module and the *Q*-switch were water cooled to be 19 °C. The $BaWO_4$ crystal was wrapped with indium foil and mounted in water-cooled copper blocks. And the water temperature was maintained at 19 °C. The overall cavity length was about 19 cm.

The average output power was measured by a power meter (Molectron PM30) connected to Molectron EPM2000 (Coherent Inc.).

3. Experimental results and discussion

Before using the Raman output coupler to generate the Raman output, we first studied the performance of this laser operating at the fundamental wavelength. One plane output coupler with 2.8% and 2% transmission at 1319 and 1338 nm was employed instead of the Raman output coupler. Fig. 2 depicts the average output power with respect to the incident pump power at a PRF of 5 kHz and continuous wave (CW) mode. The maximum CW output power of 15.3 W was obtained at an incident pump power of 125 W, corresponding to a slope efficiency of 12.2%. The present CW output power (15.3 W) with the diode-side-pumped scheme is much greater than the result (5.9 W) obtained by the diode-end-pumped scheme in the work of Guo et al. [30] and the result (3.4 W) in our previous work with diode-end-pumped scheme [23]. According to Fig. 2, with a low PRF of 5 kHz, the lower of the average output power of 8.8 W was obtained. And the output power goes saturated at higher pump power under the PRF of 5 kHz. The main reason for this problem may be self-focusing, which was discussed by Chen et al. [31]. Under the PRF of 5 kHz,

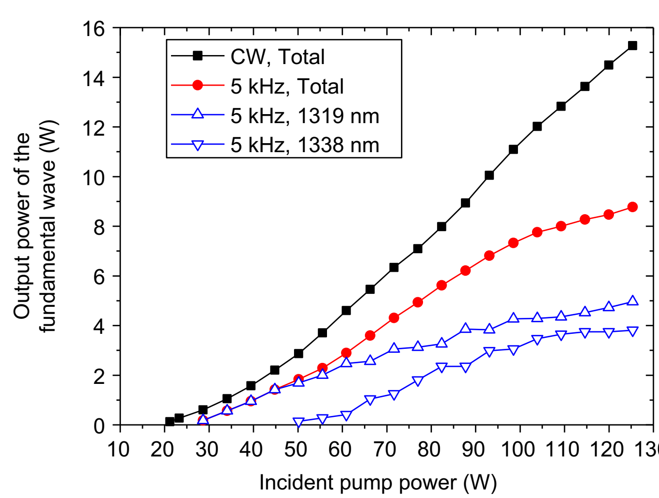

Fig. 2. Output power of the fundamental laser versus the incident pump power.