Diode-pumped actively Q-switched Tm:YAP/BaWO$_4$ intracavity Raman laser

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Abstract: We report an intracavity Raman laser based on BaWO$_4$ Raman conversion in a diode-pumped actively Q-switched Tm:YAP laser for the first time. With an incident diode power of 17.5 W and a pulse repetition rate of 1 kHz, the maximum average output powers of 880 mW and 306 mW for the fundamental laser at 1.94 $\mu$m and the first Stokes laser at 2.36 $\mu$m were obtained, respectively. The pulse width and pulse energy of the first Stokes laser were 14.1 ns and 0.31 mJ, respectively. The Raman gain coefficient of the BaWO$_4$ crystal was estimated to be 1.1 cm/GW at 1.94 $\mu$m.

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References and links
Stokes component of Raman self-frequency conversion at 2365 nm for a Tm:KY(WO4)2 wavelength were seldom reported in the last ten years. In 2002, Batay et al. observed the first... and playing a more and more important role in generating new laser lines [7,8]. The output Raman material is a potential method to extend the spectral coverage of the present lasers, generate the IR laser source. In addition, stimulated Raman scattering (SRS) in solid-state molecules exhibit strong absorption lines around the infrared (IR) spectrum, such as CH4 (2.35 μm), C2H4 (2.9 μm), NH3 (2.1 μm), HF (2.5 μm), CO (2.3 μm) and H2O (around 2.5 μm). Several technologies have been developed to obtain laser sources in the 2-3 μm region. GaSb-based diode lasers emitting at wavelengths above 2 μm have been reported [1,2]. Crystalline and fiber rare-earth doped lasers have been utilized for generating the tunable emission in the 2-3 μm region [3,4]. Nonlinear optical processes can also produce the IR radiation. For instance, optical parametric oscillators based on MgO-doped periodically poled LiNbO3 [5] and difference frequency generators based on GaAs [6] are efficient devices to generate the IR laser source. In addition, stimulated Raman scattering (SRS) in solid-state Raman material is a potential method to extend the spectral coverage of the present lasers, and playing a more and more important role in generating new laser lines [7,8]. The output wavelength of a Raman laser depends on Raman spectrum of the Raman crystal and the wavelength of the fundamental laser. The commonly known Raman crystals include Ba(NO3)2 [9,10], YVO4 [11,12], GdVO4 [13], diamond [14,15], and variety of tungstate crystals [16–22].

For Raman lasers based on tungstate crystals, Nd-doped lasers are primarily used as fundamental lasers. The Raman lasers based on tungstate crystals with more than 2 μm output wavelength were seldom reported in the last ten years. In 2002, Batay et al. observed the first Stokes component of Raman self-frequency conversion at 2365 nm for a Tm:KY(WO4)2 sample [23]. In 2013, we reported a diode-pumped actively Q-switched Tm,Ho:GdVO4/BaWO4 intracavity Raman laser at 2.53 μm [24]. As the fundamental laser, the Tm,Ho:GdVO4 laser operated at liquid Nitrogen temperature. With an incident pump power of 2.8 W, an average output power of 186 mW for the first Stokes laser of 2.53 μm was obtained at a pulse repetition rate (PRR) of 1 kHz.

In this paper, we report an intracavity Raman laser based on BaWO4 Raman conversion of a Q-switched Tm:YAP laser at room temperature. To the best of our knowledge, this is the first time BaWO4 Raman conversion in a diode-pumped actively Q-switched Tm:YAP laser has been demonstrated. With a pump power of 17.5 W, the maximum average output powers of 880 mW for the fundamental laser of 1.94 μm and 306 mW for the first Stokes laser of 2.36 μm were obtained at a PRR of 1 kHz, respectively. The total optical-to-optical conversion efficiency was 6.8%. The pulse width and single pulse energy of the first Stokes...
laser at 2.36 μm were approximately 14.1 ns and 0.31 mJ, respectively. The Raman gain coefficient of the BaWO₄ crystal was also estimated to be 1.1 cm/GW at 1.94 μm.

2. Experimental setup

Figure 1 shows the experimental configuration of the intracavity Raman laser based on BaWO₄ Raman conversion. The pump source is a 20 W fiber-coupled continuous-wave 794 nm diode laser with a 400 μm fiber core diameter and a numerical aperture of 0.22. A focus lens system with a pair of plane-convex lenses was used to focus the pump beam into the laser crystal. The pump spot diameter in the laser crystal was approximately 560 μm. The coupling efficiency of the focus lens system is 95%. The laser gain medium was an a-cut 3.0 at.% Tm:YAP crystal with dimensions of 3 mm × 3 mm × 10 mm. Both end faces of the laser crystal were antireflection coated for the fundamental laser wavelength at 1.94 μm and the pump wavelength at 794 nm. The laser crystal was wrapped in indium foil and held in a copper heat sink which was maintained at a temperature of 18 °C. The a-cut 4 mm × 4 mm × 20 mm BaWO₄ crystal was used as Raman gain medium. Both end faces of the BaWO₄ crystal were antireflection coated in the range of 1800–2550 nm (R<3%). The Raman laser was wrapped with indium foil and mounted on a water-cooled copper heat sink maintained at 19 °C. A water-cooled Brewster-cut acousto-optic modulator was used for Q-switched operation, and was driven at 27 MHz with 50 W RF power.

The Raman laser comprised a fundamental laser cavity and a Raman laser cavity. For the fundamental laser, we used an L-shaped cavity composed of three mirrors (M1, M2 and M4). As the output coupler of the fundamental laser, the mirror M1 with a curvature radius of 300 mm was partial transmission at 1.94 μm (T = 4%). The 45° dichroic flat mirror M2 was antireflection coated at 794 nm (R<1%), and high reflectivity at 1.94 μm (R>99.8%). The curved mirror M4 with a curvature radius of 500 mm, shared by the Raman cavity as the output coupler of the Raman laser, was coated for high reflectivity at 1.94 μm (R>99.5%), and partial transmission at 2.36 μm (T = 10%). One surface of the flat intracavity mirror M3 was antireflection coated at 1.94 μm (R<1%), the other surface was antireflection coated at 1.94 μm (R<1%) and high reflectivity at 2.36 μm (R>99.5%). Mirrors M3 and M4 constituted the Raman laser cavity. The physical cavity lengths of the fundamental laser and the Raman laser were about 148 mm and 33 mm, respectively.

3. Experimental results and discussion

The spectral information of the Raman laser in Q-switched operation was monitored by a Zolix spectrograph (Omni-λ 300, resolution of the spectrum is 0.1 nm). The fundamental and Raman laser output powers were measured by a power meter (Coherent, PM30). The pulse temporal behaviors of the fundamental and Raman lasers were recorded by a 300 MHz bandwidth digital phosphor oscilloscope (Tektronix,TDS3032B) with a >100 MHz bandwidth IR detector (Vigo, PVM-10.6).

The operation of the Raman laser was investigated at a PRR of 1 kHz. The fundamental laser was measured to be linearly polarized, and its polarization was parallel to the c-axis of
the BaWO₄ crystal. Figure 2 shows the spectral information of the Raman laser, which was recorded at an incident pump power of 15.2 W. It can be seen that the fundamental laser emission was at 1.94 μm and the first Stokes component was at 2.36 μm. We can see that the frequency shift of the fundamental laser and the first Stokes component was 924 cm⁻¹, which was in agreement with the Raman frequency shift of the α-cut BaWO₄ crystal reported in [22,25]. In this experiment, the second Stokes component was not observed at the maximum Raman output power.

Figure 3 shows the average output powers of the fundamental laser at 1.94 μm and the first Stokes laser at 2.36 μm as function of the incident pump power at 794 nm. As shown in Fig. 3, the fundamental and Raman output powers increased almost linearly with the incident pump power from 9.1 W to 17.5 W. The maximum average output powers of 880 mW at 1.94 μm and 306 mW at 2.36 μm were obtained at a pump power of 17.5 W, respectively. At the highest output power level, the power stabilities of the fundamental laser and the first Stokes laser were less than 1.2% and 1.6% in 30 minutes, respectively. With incident pump power further increasing, the coating of the cavity mirror M3 was damaged, which resulted in a sudden decrease of the output powers of the fundamental laser and the first Stokes laser. If quality of the mirror coating could be improved, the average output power of Raman laser would continue to grow.

![Fig. 2. Optical spectrum for the Raman laser based on intracavity BaWO₄ Raman conversion.](image)

![Fig. 3. Average output power at 1.94 and 2.36 μm as a function of incident pump power at a PRR of 1 kHz.](image)

The threshold powers of the fundamental laser and the Raman laser at a PRR of 1 kHz were 7.0 W and 9.1 W (see Fig. 3), respectively. Figure 4(a) shows the typical pulse shape of
the fundamental laser at an incident pump power of 9 W. We can see that the pulse shape of
the fundamental laser was almost symmetrical under the Raman threshold pump power.
Figure 4(b) shows the typical pulse shapes for the Raman and fundamental lasers, which were
recorded at an incident pump power of 15.2 W. Once the Raman laser pulse arose, the
envelope of the fundamental laser pulse would change. The depletion of the fundamental laser
pulse resulted in building up of the Raman laser pulse.

For efficient Raman conversion, the fundamental radiation intensity inside the Raman
cavity must exceed certain threshold level. When the Raman medium is placed in a Raman
cavity, the SRS threshold condition can be expressed as \[ g I_{th} L = 25 / N_{\text{eff}}, \] \[ (1) \]
Where \( g \) is the Raman gain coefficient of the medium; \( I_{th} \) is the threshold intensity of the
fundamental radiation in the Raman medium; \( L \) is the length of the Raman medium; \( N_{\text{eff}} \) is the
effective number of passes of Raman radiation through the Raman cavity, which can be
expressed as
\[
N_{\text{eff}} = \left( \frac{L}{\tau_0 c} + \frac{1}{25} \ln \frac{1}{\sqrt{R}} \right)^{-1},
\]
\[ (2) \]
Where \( L \) is the optical length of the Raman cavity; \( \tau_0 \) is the fundamental pulse duration; \( c \) is
velocity of light; \( R \) is the product of the reflectivities of the Raman cavity mirrors for the
Raman radiation.

When the fundamental output coupler M1 is used, the threshold intensity of the
fundamental radiation for the generation of the first Stokes component in the BaWO_4 crystal
can be estimated. According to Eqs. (1) and (2), the Raman gain of the BaWO_4 crystal at 1.94
\( \mu \)m could be estimated. For this experiment, the average fundamental output power was 240
mW for the threshold pump power of the Raman laser. The corresponding fundamental pulse
duration \( \tau_0 \) was approximately 170 ns. By using ABCD matrix, the average diameter of the
fundamental laser beam in the BaWO_4 crystal was calculated to be approximately 260 \( \mu \)m. The
fundamental intensity \( I_{th} \) was estimated to be 33 MW/cm^2. The output coupler reflectance
\( R \) for the first Stokes component was 2.36 \( \mu \)m was 90%. The optical length of the Raman cavity
\( L \) was approximately 4.8 cm. The effective number of passes was calculated to be \( N_{\text{eff}} = 330 \).
Therefore, the Raman gain coefficient of the BaWO_4 crystal was approximately 1.1 cm/GW
at 1.94 \( \mu \)m.

Figure 5 shows a stretched single pulse shape and a typical oscilloscope trace of the
Raman laser pulse train at a pump power of 17.5 W, indicating the pulse duration of the first
Stokes laser was approximately 14.1 ns. The corresponding single pulse energy and peak
power were calculated to be 0.31 mJ and 22 kW, respectively. The Raman output beam
profile was measured with a commercial beam analyzer (Electrophysics, MicronViewer 7290A). As shown in Fig. 6, the output beam was close to fundamental transverse electromagnetic mode (TEM\(_{00}\)).

Fig. 5. Oscilloscope trace of the Raman laser at an incident pump power of 17.5 W and a PRR of 1 kHz: (a) the stretched single pulse shape; (b) the Raman laser pulse train.

Fig. 6. The Raman laser output beam spatial profiles measured with a beam analyzer: (a) two dimensional distributions; (b) three dimensional distributions.

4. Conclusions

In conclusion, the characteristics of the intracavity Raman laser based on BaWO\(_4\) Raman conversion in the diode-pumped actively Q-switched Tm:YAP laser has been demonstrated. With an incident pump power of 17.5 W, an average output power of 306 mW at the first Stokes wavelength of 2.36 \(\mu\)m was obtained at a PRR of 1 kHz, 880 mW at the fundamental wavelength of 1.94 \(\mu\)m was obtained at the same time. The pulse width and pulse energy of the first Stokes laser were approximately 14.1 ns and 0.31 mJ, respectively. It presents the potential for increasing the average output power of the Raman laser by optimizing cavity design and employing high-quality mirrors. The Raman gain coefficient of the \(a\)-cut BaWO\(_4\) crystal was estimated to be 1.1 cm/GW at 1.94 \(\mu\)m.

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