High-efficiency 1598.5-nm third Stokes Raman laser based on barium nitrate crystal

Huiting Chen (陈慧挺)[1,2], Qihong Lou (楼祺洪)[1], Jingxing Dong (董景星)[1], and Wanchun Chen (陈万春)[3]

[1]*Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800*

[2]*Graduate School of the Chinese Academy of Sciences, Beijing 100039*

[3]*Institute of Physics, Chinese Academy of Sciences, Beijing 100080*

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A high-efficiency eye-safe Raman laser was demonstrated by use of the third Stokes radiation in a $Ba(NO_3)_2$ crystal pumped by a 1064-nm Nd:YAG laser. The output wavelength of the Raman laser was 1598.5 nm with a full-width at half-maximum (FWHM) of 1.5 nm. With an incident pump energy of 140 mJ, a maximum of 18-mJ Raman output energy was generated at a repetition rate of 30 Hz, corresponding to an optical-to-optical conversion efficiency of 12.9%. The Raman pulse duration was shortened to 2.9 ns compared with that of the pump pulse of 19.3 ns. The eye-safe solid-state Raman laser is expected to have wide applications in range-finding, telemetry, laser radar, and other aspects.

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In recent years, stimulated Raman scattering (SRS) in solid-state materials has become a promising method to efficiently generate laser radiations at new wavelengths[1−3]. Among various solid-state Raman conversion media, barium nitrate ($Ba(NO_3)_2$) crystal has attracted much attention because of its highest Raman gain of any known crystals and strong mechanical properties[4]. However, most of the recent research on $Ba(NO_3)_2$ lasers has focused on the radiations in the visible and near-infrared regions[5−7]. Few reports are available for the eye-safe Raman lasers with a spectrum near 1.5—1.6 μm. Laser operating in the eye-safe region has found increasing demand in range-finding, telemetry, laser radar applications[8].

More recently, Murray *et al.* have reported an eye-safe $Ba(NO_3)_2$ Raman laser operating at the first Stokes radiation (1.535—1.556 μm) pumped by a 1.3-μm Nd:YAG laser[9]. However, eye-safe $Ba(NO_3)_2$ Raman lasers operating at the third Stokes radiation (1.598 μm) have not been reported to our knowledge.

In this letter, we present a high efficient, 1598-nm third Stokes $Ba(NO_3)_2$ Raman laser pumped by a 1064-nm Nd:YAG laser. At an incident pump energy of 140 mJ, a maximum of 18 mJ Raman output energy at a repetition rate of 30 Hz is obtained, corresponding to an overall optical-to-optical conversion efficiency of 12.9%.

The $Ba(NO_3)_2$ Raman crystal is grown by ourselves through the aqua-solution cooling method[10]. It is cut along the {110} crystallographic axis with the length of 48 mm and the aperture of 10 × 10 (mm). The transmission spectrum of $Ba(NO_3)_2$ crystal, as shown in Fig. 1, shows the wide transparent spectral region from 0.34 to 1.8 μm. It is very suitable for the Raman conversion pumped by 1064-nm Nd:YAG lasers.

The experimental configuration for the third Stokes Raman laser is a simple end-pumped Raman resonator with the $Ba(NO_3)_2$ crystal as depicted in Fig. 2. The stable resonator is composed of two flat mirrors. They have a special dichroic coating for efficient conversion at the third Stokes component in a resonator Raman configuration. The input mirror (M1) has an antireflection coating at 1064 nm on the entrance surface ($T > 90\%$) and a high-reflection (HR) coating at the first, second, and third Stokes wavelengths (1197, 1369, and 1598 nm, respectively) on the other surface ($R > 99.5\%$). The output mirror (M2) has a high-reflection coating at 1064, 1197, and 1369 nm ($R > 98\%$) and a partial-reflection (PR) coating at 1598 nm ($R = 25\%$). Note that the output mirror's reflectivity is not optimized and it is limited in availability. With a standard He-Ne laser collimator, the two resonator mirrors are perfectly paralleled.

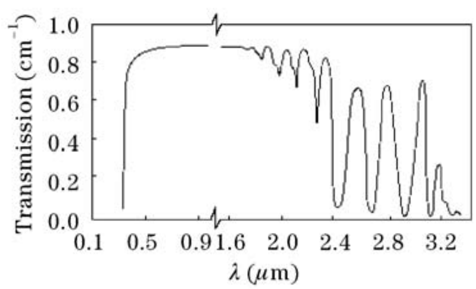

Fig. 1. Transmission spectrum of $Ba(NO_3)_2$ crystal.

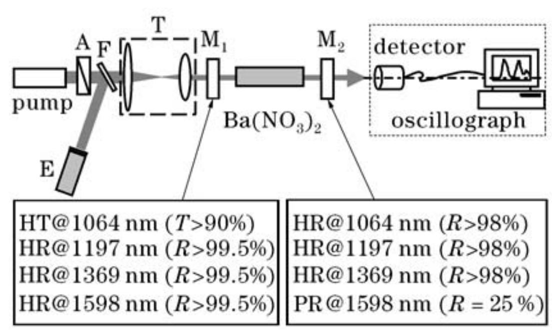

Fig. 2. Schematic of a 1598-nm third Stokes Raman laser based on $Ba(NO_3)_2$ crystal. F: filter.

The pump source was a 1064-nm Nd:YAG laser, with a repetition frequency of 30 Hz, a maximum pulse energy of 433 mJ, and a divergence angle of 2 mrad. The average radius of the pump beam was ∼ 7.5 mm with a super-Gaussian pattern in the near-field. A telescope system (T) composed of two lenses (50- and 10-mm focal lengths, respectively) was used to provide a collimated pump beam with the radius of 1.5 mm at the input mirror. The variable attenuator (A) was used for fine adjustment of the pump pulses energy, which was monitored by a calibrated energy detector (E). Both sides of the crystal were polished to reduce the Fresnel losses on the crystal surfaces. The overall length of the Raman resonator was approximately 7 cm, with the crystal in the middle of the resonator.

First we studied the single-pass SRS of $Ba(NO_3)_2$ crystal without the Raman resonator. The strong Stokes Raman radiations were generated, which had spatial cone structures by Raman four-wave mixing (FWM). The spectrum on the single-pass SRS output was measured by an optical spectrum analyzer (MS9710C), which is a diffraction-grating spectrum analyzer with a resolution of 0.05 nm. Figure 3 depicts the optical spectrum for the single-pass SRS of $Ba(NO_3)_2$ pumped by the 1064-nm Nd:YAG laser. It can be seen that the frequency shift between Stokes and pump laser lines agrees very well with the "breathing" vibration modes of the nitrate moiety (1047 cm^{-1}).

When the Raman resonator was used, the pump, first and second Stokes radiations were successfully filtered and restrained. Figure 4 displays the experimental results for the optical spectrum of the Raman laser in the resonator. The output wavelength of the third Stokes Raman laser was 1598.5 nm, with a narrow full-width at half-maximum (FWHM) of 1.5 nm. Figure 5 shows the output energy for the third Stokes Raman laser as a function of the incident pump energy at a pulse repetition rate of 30 Hz. The pump threshold for the third Stokes Raman laser was approximately 40 mJ. With an incident pump energy of 140 mJ, the maximum output energy was up to 18 mJ, corresponding to an overall optical-to-optical (1064—1598 nm) conversion efficiency of 12.9%. Moreover, the saturation phenomenon of Raman gain was not observed at the present pump energy levels thus far, so higher efficiencies are anticipated for higher pump energies. On the other hand, the highest allowable pump energy was limited by the optical damage threshold of $Ba(NO_3)_2$ crystal, which was measured as 10 J/cm^2 at the center of the pump-beam patterns in our previous experiment. Apparently, for even higher efficiency of SRS conversion, reduction of losses is required, e.g. placing the $Ba(NO_3)_2$ crystal in a moisture-free box with Brewster windows. The ultimate conversion efficiency is quantum limited for the 1064 → 1598 nm frequency conversion to 66.5%.

The pulse's temporal behaviors were recorded by a digital oscilloscope (LeCroy 9362, 10 Gsamples/s, 1.5 GHz bandwidth) with a fast photodiode (DET210, 1 GHz bandwidth). The typical time shapes for the pump and Raman pulses are shown in Fig. 6. When the maximum

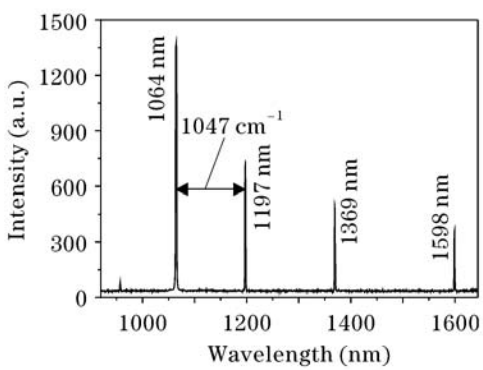

Fig. 3. Spectrum for SRS of $Ba(NO_3)_2$ crystal in single-pass experiment pumped by 1064-nm laser.

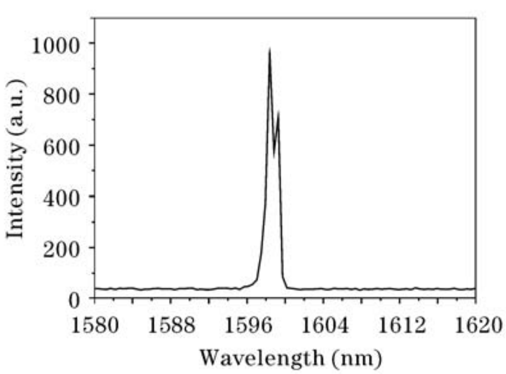

Fig. 4. Spectrum for the third Stokes Raman laser in the Raman resonator.

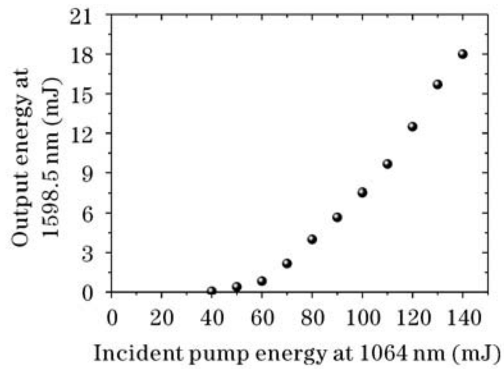

Fig. 5. Output energy of the third Stokes Raman laser with respect to the incident pump energy.

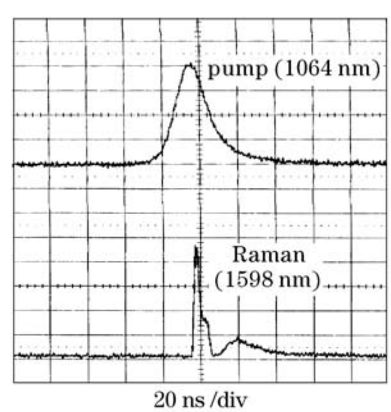

Fig. 6. Typical oscilloscope traces for the pump and the third Stokes Raman pulses.

Raman output was achieved, the Raman output pulse duration was reduced to $\sim$ 2.9 ns (FWHM) compared with the pump pulse of 19.3 ns. As a consequence, the peak power was higher than 6.2 MW.

In summary, a high efficiency eye-safe Raman laser has been obtained by use of the third Stokes radiation in a $Ba(NO_3)_2$ crystal pumped by a 1064-nm Nd:YAG laser. The wavelength of Raman laser was 1598.5 nm with a FWHM of 1.5 nm. The Raman pulse duration was shortened to 2.9 ns compared with the pump pulse of 19.3 ns. When the pump laser operated at energy of 140-mJ, a maximum of 18-mJ Raman output energy was generated at a repetition rate of 30 Hz, corresponding to an overall optical-to-optical conversion efficiency of 12.9%. The compact size and high efficiency of the present Raman laser make it be an attractive source for practical applications.

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H. Chen's e-mail address is htchen4@yahoo.com.cn.

References

1. T. T. Basiev, A. A. Sobol, P. G. Zverev, V. V. Osiko, and R. C. Powell, Appl. Opt. **38,** 594 (1999).
2. Z. Ye, Q. Lou, J. Dong, Y. Wei, and L. Ling, Chin. Opt. Lett. **1,** 406 (2003).
3. R. P. Mildren, M. Convery, H. M. Pask, J. A. Piper, and T. Mckay, Opt. Express **12,** 785 (2004).
4. P. G. Zverev, W. Jia, H. Liu, and T. T. Basiev, Opt. Lett. **20,** 2378 (1995).
5. H. M. Pask, S. Myers, J. A. Piper, J. Richards, and T. McKay, Opt. Lett. **28,** 435 (2003).
6. J. Simons, H. Pask, P. Dekker, and J. Piper, Opt. Commun. **229,** 305 (2004).
7. A. S. Grabtchikov, V. A. Lisinetskii, V. A. Orlovich, M. Schmitt, R. Maksimenka, and W. Kiefer, Opt. Lett. **29,** 2524 (2004).
8. L. R. Marshall, J. Kasinski, and R. Burnham, Opt. Lett. **16,** 1680 (1991).
9. J. T. Murray, R. C. Powell, N. Peyghambarian, D. Smith, W. Austin, and R. A. Stolzenberger, Opt. Lett. **20,** 1017 (1995).
10. W. Chen, D. Liu, C. Zhang, L. Wu, and A. Xie, Mater. Res. Bull. **39,** 309 (2004).