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High Efficiency, Short-pulse 1 198.5 nm $Ba(NO_3)_2$ Raman Laser

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Abstract: A high-efficiency, short-pulse 1 198.5 nm Raman laser was demonstrated by using stimulated Raman Scattering (SRS) in the barium nitrate ($Ba(NO_3)_2$) crystal which was pumped by a 1 064 nm Nd:YAG laser. With an incident pump power of 4.5 W, a maximum of 1.48 W Raman output power at a repetition rate of 30 Hz was obtained, corresponding to an overall optical-to-optical conversion efficiency of 32.9%. The slope efficiency was calculated as 40%. The pulse width of the Raman pulses was reduced to 2.4 ns compared to the pump pulse width of 19.3 ns. The typical Raman pulse had an asymmetric shape, with a very steep positive-going slope and an extended negative-going slope, the mechanism of which was also demonstrated with qualitative analysis. The wavelength of the Raman laser (the first Stokes) was measured to be 1 198.5 nm with FWHM of 1.2 nm.

Key words: Stimulated Raman Scattering (SRS); Raman laser; Short-pulse; $Ba(NO_3)_2$ crystal

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0 Introduction

Stimulated Raman Scattering (SRS) can be used to shift the frequency of lasers over a fixed frequency shift, making access to additional spectral output laser lines[1-3]. In recent years, SRS in crystalline materials has become a promising method to efficiently generate laser radiation at new frequency[4-5]. These materials have high gain, good thermal and mechanical properties, and they are compatible with compact, all-solid-state laser technology. Among various solid-state Raman conversion media, barium nitrate ($Ba(NO_3)_2$) crystal has attracted outstanding attention because of its highest Raman gain of any known crystals and strong mechanical properties [6]. $Ba(NO_3)_2$ crystal has cubic symmetry with wide transparent spectral region from 340 to 1 800 nm, which provides the possibility of Raman conversion in the visible and the infrared ranges[7]. More recently, we have reported a $Ba(NO_3)_2$ Raman laser pumped by a 532 nm Nd:YAG laser, the first Stokes radiation at 563 nm and the second Stokes radiation at 599 nm were obtained[8].

In recent years, more and more research has focused on the solid-state Raman lasers based on $Ba(NO_3)_2$ crystals. However, there are not much reports on the short-pulse 1 198.5 nm $Ba(NO_3)_2$ lasers. Lasers in this spectrum region have a variety of promising applications in the near-infrared spectroscopy and imaging on pharmaceutical inspecting[9]. In this paper, it reports a high efficiency, short-pulse 1 198.5 nm $Ba(NO_3)_2$ Raman laser pumped by a 1 064 nm Nd:YAG laser. With an incident pump power of 4.5 W, a maximum of 1.48 W Raman output power at a repetition rate of 30 Hz was obtained, corresponding to an overall optical-to-optical conversion efficiency of 32.9%. The pulse width of Raman pulses was reduced to 2.4 ns compared to 19.3 ns at the pump wavelength.

1 The experimental setup

The $Ba(NO_3)_2$ Raman crystal was grown by ourselves through the aqua-solution cooling method[10], and cut along the {110} crystallographic axis with the length of 48 mm and the aperture of 10×10 mm^2. The crystal was polished on both faces to reduce the losses of pump and Raman pulses on the crystal surfaces. The highest allowable pump intensity was limited by the optical damage threshold of $Ba(NO_3)_2$ crystal, which was about 10 J/cm^2 at the center of the pump-beam patterns.

The investigations was started with the simple end-pumped Raman resonator shown in Fig. 1. A-attenuator, T- telescope, M_1, M_2- resonator mirrors, $Ba(NO_3)_2$-$Ba(NO_3)_2$ Raman crystal, F-

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filter, E - energy detector. The pump source was a 1 064 nm Nd:YAG laser, with the repetition frequency of 30 Hz and the maximum pulse energy of 433 mJ. The pump beam divergence angle was ~2 mrad with a super-Gaussian pattern in near-field distribution. The average radius of the pump beam was ~7.5 mm. The two lens telescope (T) (5:1) provided 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 meter (E). The stable resonator was composed of two flat dichroic mirrors with a space of 7 cm. With a standard He-Ne laser collimator, the two dichroic mirrors were perfectly paralleled. The crystal was just placed in the middle of the resonator without any cooling device. The input mirror (M_1) was coated for antireflection ($T>90\%$) at the pump wavelength of 1 064 nm and high-reflection (HR, $R>99.5\%$) at the first Stokes wavelength of 1 198 nm. The output mirror (M_2) was coated for high reflection ($R>99.8\%$) at 1 064 nm, optimal transmission ($T=60\%$) at 1198 nm and high transmission (HT, $T>98\%$) at the second Stokes wavelength of 1 370 nm.

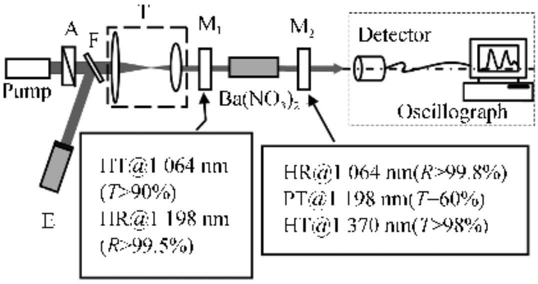

Fig. 1 Experimental setup of $Ba(NO_3)_2$ crystal Raman laser in resonator

2 Results and discussion

SRS can be observed in various configurations: single-pass, multi-pass cells and resonators[11]. In the single-pass cell, varieties of nonlinear processes that often accompanies with the first Stokes pulses. The higher order Stokes components, as well as stimulated Brilluoin scattering and self-focusing can be observed in the single-pass cell, which limit the conversion efficiency of the first Stokes pulses at high pump intensity[11]. For the above reasons, the resonator composed of two dichroic mirrors was adopted in the present experimental setup. To increase the intensity of the first Stokes component and restrain the second Stokes oscillation, the output mirror had an optimal reflectivity for the first Stokes radiation and a high transmission for the second Stokes radiation.

Fig. 2 shows the typical spectrum of the present Raman laser, which was monitored by an Optical Spectrum Analyzer (MS9710C, resolution 0.05 nm). The wavelength of the Raman laser was 1 198.5 nm, with FWHM of 1.2 nm. The frequency shift between Raman and pump lasers is in good agreement with the "breathing" vibration modes of NO_3 molecular group (1 047 cm^{-1})[7]. In some ways, Fig. 2 also indicates that the residual pump lasers and the other nonlinear radiations were successfully filtered and restrained due to the optimized reflectivity of the resonator mirrors.

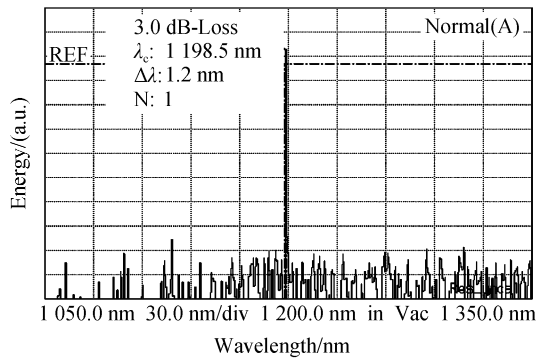

Fig. 2 Spectrum of the Raman laser (the first Stokes)

Fig. 3 depicts the average output power at the Raman wavelength of 1 198 nm as a function of the incident pump power for pulse repetition rate of 30 Hz. The maximum average output power was up to 1.48 W with an incident pump power of 4.5 W, corresponding to an overall optical - to - optical (1 064 nm to 1 198 nm) conversion efficiency of 32.9% with respect to the pump laser input power. The threshold for the Raman laser was 0.8 W at 1 064 nm, and the slope efficiency was calculated to be 40%. The ultimate conversion efficiency is quantum limited for the 1 064→1 198 nm frequency

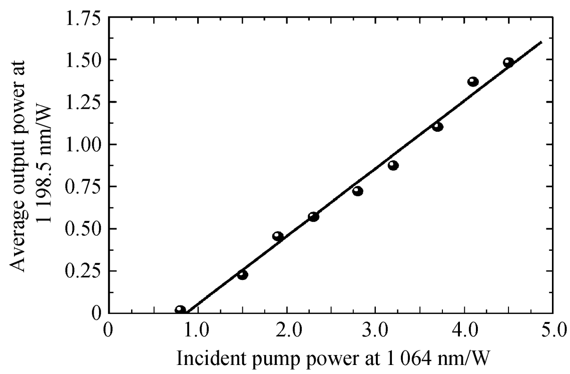

Fig. 3 Average output power of the Raman laser with respect to the incident pump power for pulses repetition rate of 30 Hz

conversion to 88.8%. On the other hand, saturation of the Raman gain was not observed at the present pump power levels thus far, so higher efficiencies are anticipated for higher pump powers. 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 pulse's temporal behaviors were recorded by a 1.5 GHz LeCroy9362 digital oscilloscope with a 1 GHz DET210 fast photodiode. When the maximum Raman output was achieved, the Raman output pulse width was reduced to ~2.4 ns (FWHM) compared to the pump pulse width of 19.3 ns. Fig. 4 shows the typical time shapes for the pump and Raman pulses. The slower rise time curve is 1 064 nm pump pulse, and the rapidly rising curve is the Raman pulse at 1 198 nm. The Raman pulses had an asymmetric shape, with a very steep positive-going slope and an extended negative-going slope. The shape of such Raman pulses is similar to the result of our previous SRS experiment conducted in gas cell[12], which can be explained by the following chain reaction. When the pump laser energy exceeds the threshold of Raman pulse energy, the Raman energy will ascend quickly, leading to the reduction of residual pump laser energy, for more and more pump laser energy is converted to Raman pulses. With the reduction of the residual pump laser energy, the Raman energy also decreases, making the pump laser obtain energy compensation over again. So following the raise of pump laser energy, the Raman energy ascends again. Such cycle will continue until the pump laser energy is consumed to the threshold level of Raman pulses. Consequently, the Raman pulses are shaped and compressed through the above mechanism, with a very steep positive-going slope and an extended negative-going slope.

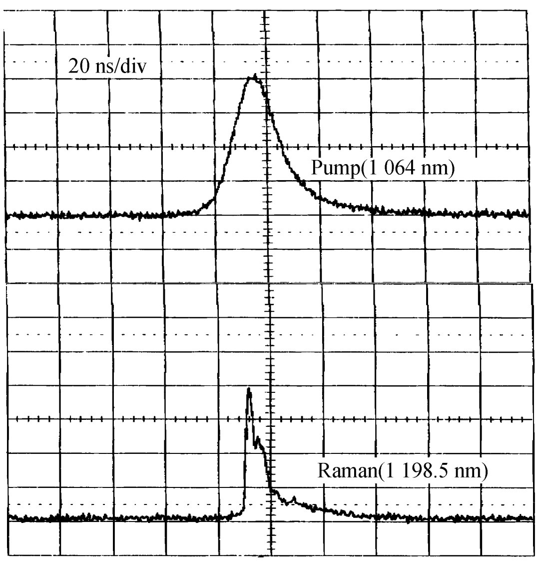

Fig. 4 Typical oscilloscope traces for the pump and Raman pulses

3 Conclusions

In summary, a high efficiency, short-pulse 1 198.5 nm Raman laser was obtained, with a $Ba(NO_3)_2$ crystal in resonator pumped by a 1 064 nm Nd:YAG laser. The output wavelength of the Raman laser was at 1 198.5 nm with FWHM of 1.2 nm. When the pump laser operated at power of 4.5 W, a maximum of 1.48 W Raman output power at a repetition rate of 30 Hz was obtained, corresponding to an overall optical-to-optical (1 064 nm to 1 198 nm) conversion efficiency of 32.9%. The slope efficiency was calculated to be 40%. The pulse width of the Raman pulses was reduced to 2.4 ns compared to the pump pulse width of 19.3 ns. The compact size and high efficiency of the present Raman laser make it an attractive source for practical applications.

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高效率,窄脉冲 1 198.5 nm $Ba(NO_3)_2$ 喇曼激光器

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摘 要:利用 1 064 nm的Nd:YAG激光抽运振荡腔内的硝酸钡晶体,获得高效率、窄脉冲的喇曼激光输出.硝酸钡晶体由水溶液降温法生长,长度为 48 mm.喇曼振荡腔由对抽运光、一阶、二阶斯托克斯光有不同反射率的双色平面镜构成.当抽运光功率达到 4.5 W 时,获得最高的一阶斯托克斯喇曼激光功率为 1.48 W,相应的转换效率为 32.9%,并测得斜率效率为 40%.由于受激喇曼散射的作用,喇曼脉冲光由抽运脉冲光的 19.8 ns 压缩为 2.4 ns,获得的喇曼激光脉冲波形具有的"上升沿陡峭、下降沿缓慢"的特性,对其形成过程作了定性分析.测得喇曼激光的波长为 1 198.5 nm,半峰全宽(FWHM)为 1.2 nm.

关键词:受激喇曼散射;喇曼激光器;窄脉冲;硝酸钡晶体

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