High peak power first, second, and third order Stokes pulses based on intracavity self-stimulated Raman scattering lasers

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We obtain high peak power pulses in megawatt range of the first (1181 nm), second (1321 nm), and third order (1500 nm) Stokes radiation from self-conversion of the 1067-nm laser radiation based on Nd:KGW laser. The maximum output energy of the first order Stokes laser is 35.3 mJ, which is to our knowledge, the highest reported energy in an intracavity Q-switched laser. The third order Stokes pulse is obtained in an intracavity Q-switched laser.

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In recent years, stimulated Raman scattering (SRS) in crystals has become a promising method for generating new laser spectral lines, which have wide application ranges. Although there are several methods of obtaining frequency conversion by using SRS, intracavity configurations are particularly attractive due to the high intensity inside the laser cavity, low-threshold operation, and high overall conversion efficiencies[1,2]. Neodymium-doped potassium gadolinium tungstate (Nd:KGW) which is a well known Raman-active medium offers efficient Raman operation together with several interesting properties. With Nd:KGW crystal in an intracavity configuration, we can produce a compact, solid-state, multi-wavelength laser for near infrared (IR) and visible spectral regions for various applications[3]. Three Stokes shifted lines corresponding to 901-cm^{-1} frequency shift excited by 1067-nm radiation can be observed. The first order Stokes laser at 1181 nm corresponding to the atmospheric window can be used to study the cloud structure and spatial variations in the atmospheric composition. The second order Stokes laser at 1321 nm has scientific, medical, and dental applications because of the good absorption of water molecules and the good capability of blood hemostasis at this wavelength[4]. An eye-safe laser at the wavelength of the third order Stokes line is required for free-space communication, fiber-optics links, lidar, cleaning of artworks, medicine, and ecology.

In this letter, we report the first, second, and third order Stokes radiation with peak output power of megawatt from an intracavity Q-switched Nd:KGW laser. The maximum pulse energy obtained at the first order (1181 nm) Stokes laser is 35.3 mJ with pulse repetition rate of 10 Hz. To the best of our knowledge, it is the highest value obtained in an intracavity Q-switched laser, and the third order Stokes laser at 1500 nm in eye-safe wavelength range is obtained in an intracavity Q-switched laser for the first time.

The experimental setup is shown in Fig. 1. The b-cut Nd:KGW rod with a 3 at.-% concentration of Nd^{3+} has been proved the best optical quality of output laser[5]. A ϕ3.5×62 (mm) b-cut Nd:KGW rod was used as the laser medium and Raman medium in the experiment. Both end faces of the crystal rod were anti-reflection coated at 1000–1600 nm. The laser rod was side pumped by laser diode (LD) module which contained 32 LD bars. LD bars were manufactured by the Institute of Semiconductor, Chinese Academy of Sciences, and each of them can yield 40-W output power. The end mirror (M_4) with a 1-m concave curvature had a high-reflection coating at 1067 nm. The oscillator was Q-switched with potassium dideuterium phosphate (KD*P) crystal. A polarizer, a quarter-wave plate (M_3), and the electro-optic (E-O) Q-switch constituted the Q-switched system of the cavity. The laser energy was detected by a LPE-1A power-energy meter, manufactured by Beijing Physcience Opto-Electronics Company Ltd. The laser temporal profile was recorded by a Tektronix TDS3052B oscillograph and THORLABS DET210 positive-intrinsic-negative (PIN) photo detector for fundamental laser while THORLABS D400FC fiber photo detector for Stokes laser.

To study the fundamental laser, we used a plane mirror with 35% transmission at 1067 nm as the output coupler. The overall laser cavity length was 30.4 cm. All the data referred in this letter were obtained at 385-μs pump duration to optimize the output energy. The maximum output pulse energy of fundamental laser reached 25 mJ with corresponding pulse width of 8.09 ns when the pump current was 80 A. Besides, we have found a beam with high energy extracted from the end mirror and have recorded the relationship between the beam and the output fundamental laser. It follows from Fig. 2 that the fundamental photon has started to convert into the first order Stokes photon. The transmission of output coupler restricted the output energy of the fundamental laser. Therefore the obtained output energy of fundamental scattering was lower than that of the first

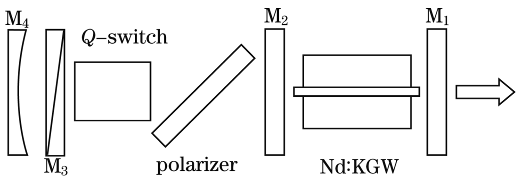

Fig. 1. Schematic of the experimental setup.

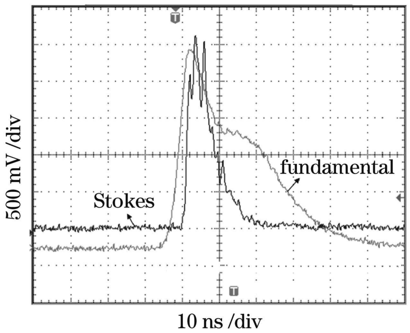

Fig. 2. Oscillogram of temporal profile for fundamental scattering and the beam output from the end of the cavity. The full-width at half-maximum (FWHM) of Stokes and fundamental pulse are 7.042 and 22.38 ns, respectively.

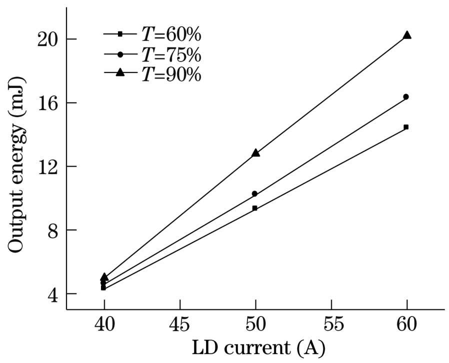

Fig. 3. Output of the first Stokes pulse energy under different transmissions at 1181 nm.

order Stokes radiation.

A plane mirror M_2, which had a high-reflection coating at 1100–1500 nm and an anti-reflection coating ($R < 2\%$) at 1067 nm, was inserted between the crystal rod and the polarizer to generate Stokes laser and shorten the Raman resonator. The length of the Raman resonator became 13.2 cm. This kind of configuration has several advantages in self-SRS laser system. First of all, since high order Raman laser is very sensitive to cavity loss, Raman laser can be locked in the short cavity formed by M_1 and M_2, and avoid passing through the polarizer and the electro-optic (E-O) Q-switch. Thus the loss of the Raman lasers can be greatly reduced and the polarizer and E-O Q-switch will not be exposed to the intense Raman beams. Secondly, M_1 and M_2 can significantly shorten the length of Raman cavity and width of the Raman pulse consequently. Finally, we can achieve different order Stokes laser outputs by changing M_1.

Three sets of plane mirrors with 60%, 75%, and 90% transmission at 1181 nm were used as the output coupler to obtain the first order Stokes scattering respectively. We can see from Fig. 3 that the output pulse energy reaches higher value while a plane mirror with 90% transmission at 1181 nm is used. The temporal profile for the fundamental and the first order Stokes pulse which has been recorded when the mirror with 90% transmission at 1181 nm is used and the pump current reaches 90 A, as can be shown from Fig. 4.

To obtain the first, second, or third order self-SRS laser beams, three sets of plane mirrors with different coatings given in Table 1 were respectively employed as the output coupler. Figure 5 gives the dependences of the output energy of Stokes laser on the pump current at the

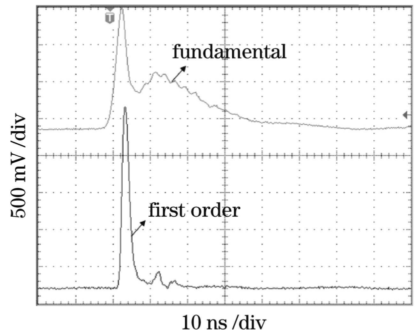

Fig. 4. Oscillogram of temporal profile for fundamental and the first Stokes scattering.

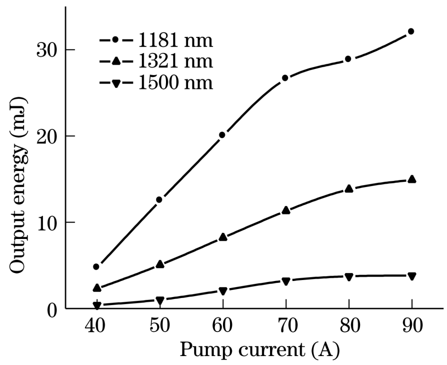

Fig. 5. Energy of Stokes Q-switched laser versus LD pump current.

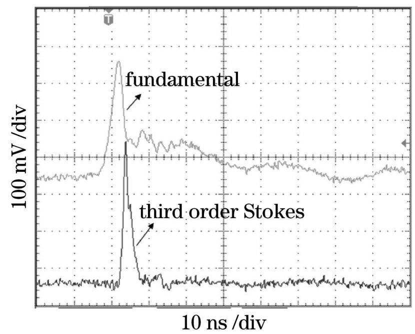

Fig. 6. Oscillogram of temporal profile for fundamental and the third Stokes scattering when the pump current is 90 A.

Table 1. Reflectivity of the Output Couplers at the Wavelengths of the Fundamental and Stokes Beams

Output Coupler	Fundamental (1067 nm)	First-Order Stokes (1181 nm)	Second-Order Stokes (1321 nm)	Third-Order Stokes (1500 nm)
No. 1	$R > 99.8\%$	10%	6%	7%
No. 2	$R > 99.8\%$	$R > 99.7\%$	47%	27%
No. 3	$R > 99.8\%$	$R > 99.7\%$	$R > 99.8\%$	27%

pulse repetition rate of 10 Hz. With 385-μs pump pulse duration and 0.5-J input energy, the obtained maximum output pulse energies of the Stokes components were 35.3, 14.9, and 3.8 mJ, corresponding to the peak powers of 17.83, 5.96, and greater than 2.55 MW, respectively. According to the output energy of the Stokes lasers, the conversion efficiencies of each order Stokes pulse with respect to the input energy reached 7.06%, 2.92%, and 0.74%, respectively. The maximum pulse energy at the first order Stokes pulse was 35.3 mJ. To the best of our knowledge, it is the highest value obtained in an intracavity Q-switched laser, and it is the first time of the third order Stokes pulse obtained in an intracavity Q-switched Nd:KGW laser, as shown in Fig. 6. Because of the deliquescent of E-O Q-switch, the decline in power of the module, and non-optimized lens parameters can lead to the decrease of the conversion efficiency, and the conversion efficiency of eye-safe wavelength laser is low. But the pulse energy can be greatly improved by optimizing the setup. So we can use this configuration to construct a compact solid-state laser which can generate high peak power pulse of third order Stokes laser based on Nd:KGW. This configuration is very simple and attractive because it provides low-threshold operation and high overall conversion efficiency with respect to the output from the system.

In conclusion, we have demonstrated the first, second, and third order Stokes radiation with peak power in megawatt magnitude generated from Raman frequency shift based on the fundamental radiation at 1067 nm. With the pulse repetition rate of 10 Hz, the maximum pulse energy of first order (1181 nm) Stokes laser reaches 35.3 mJ. It is the highest value, to the best of our knowledge, obtained by using an intracavity Q-switched self-SRS laser. Meanwhile, an eye-safe laser which is generated from the third order SRS is obtained based on Nd:KGW laser in an intracavity Q-switched laser.

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