Highly efficient cascaded P-doped Raman fiber laser pumped by Nd:YVO_4 solid-state laser

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A highly efficient cascaded P-doped Raman fiber laser (RFL) pumped by a 1064-nm continuous wave (CW) Nd:YVO_4 solid-state laser is reported. 1.15-W CW output power at 1484 nm is obtained while the input pump power is 4 W, corresponding to the power conversion efficiency of 28.8%. The threshold pump power for the second-order Stokes radiation is 1.13 W. The slope efficiency is as high as 42.6%. The experimental results are in good agreement with theoretical ones. Furthermore, the power instability of the P-doped RFL at 1484 nm in an hour is observed to be less than 5%.

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Recently Raman fiber lasers (RFLs) based on P-doped fibers have been widely investigated theoretically[1,2] and experimentally[3−6] due to their attractive applications in optical communication and sensors. The Stokes shift ($\sim$ 1330 cm^{-1}) for P-doped fibers is larger than germanosilicate fibers ($\sim$ 440 cm^{-1}). Hence, a smaller number of cascades are demanded for the P-doped RFLs to generate the same laser radiation while using the same pump wavelength. For instance, only one cascade for 1.24 μm and two cascades for 1.48 μm are required with 1-μm laser as a pump. Furthermore, almost any wavelength of the telecommunication range can be generated by combining the P_2O_5 Stokes shift with the SiO_2 Stokes shifts in the P-doped fibers[7,8]. It is also possible to realize multi-wavelength lasers simultaneously using cascaded or composite cavities[9,10]. These advanced sources can be widely used as pump sources for discrete and distributed Raman amplifications and Er^{3+}-doped fiber amplifiers in long-haul telecommunication systems.

High power Yb- or Nd-doped dual-cladding fiber lasers (DCFL) have been widely used as pump source for the RFLs[5,6,11]. However, DCFL as a pump usually leads to a high cost and a serious thermal effect problem. Alternatively, solid-state lasers, sophisticated in technique and lower in cost in comparison with DCFL, are also used as a pump. Dianov *et al.*[4] reported a cascaded P-doped RFL with about 1-W output power at 1484 nm pumped by 8 W/1064 nm Nd:YAG laser in 1997, the power conversion efficiency was about 12.5%. In 2001, Chang *et al.* developed a 400-mW dual-wavelength cascaded RFL at 1480 and 1500 nm using 3.2 W/1313 nm continuous wave (CW) Nd:YLF laser as a pump[12]. Zhang *et al.* reported 300 mW/14xx nm RFLs pumped by 1342-nm Nd:YVO_4 laser in 2005[13]. We developed a highly efficient 800 mW/1484 nm RFL using LD-pumped 1064-nm Nd:YVO_4 laser in 2006[14]. In this letter, 1.15-W output power at 1484 nm is reported in the modified laser system. To our knowledge, it is maximum output power for Nd:YVO_4-laser-pumped P-doped RFL. Furthermore, the experimental results are compared with the theoretical prediction developed in Ref. [2].

Figure 1 shows the configuration of linear cascaded cavity P-doped RFL used in our experiments. The Fabry-Perot resonant cavities for the first-order and second-order Stokes radiations consist of fiber Bragg gratings FBG1 and FBG4, FBG2 and FBG3, respectively. FBG1 and FBG4 are highly reflective (> 99%) at 1239 nm, and FBG3 at 1484 nm. The reflectivity of FBG2 is 12.5% at 1484 nm, which allows to couple a part of the second-order Stokes radiation out of the cavity. The use of highly reflective FBG0 with a Bragg wavelength at the pump wavelength yields a double-pass pumping scheme. Raman gain medium is 1-km P-doped fiber fabricated by Fiber Optic Research Center of Russia. The Raman fiber has loss coefficients of 1.8 dB/km at 1060 nm, 1.16 dB/km at 1240 nm, 1.0 dB/km at 1480 nm and Raman gain coefficients of 1.31×10^{-3} $W^{-1}\cdot m^{-1}$ for 1064-nm pump and 0.95×10^{-3} $W^{-1}\cdot m^{-1}$ for 1240-nm pump. The splicing losses in all splicing points are less than 0.02 dB.

A laser diode (LD) single-end-pumped Nd:YVO_4 CW solid-state laser with the maximum output power of 12.5 W at 1064 nm was used as the pump. The pump beam was coupled to Raman cavity using an objective lens with magnification of 10 and numerical aperture (NA) of 0.25. A 99:1 coupler was used to monitor the incident pump power. By adjusting carefully, about 4-W pump power was injected into Raman cavity with the maximum output power of Nd:YVO_4 laser, which corresponded to a coupling efficiency of 36% while considering extra losses introduced by the objective lens and coupler. Total laser

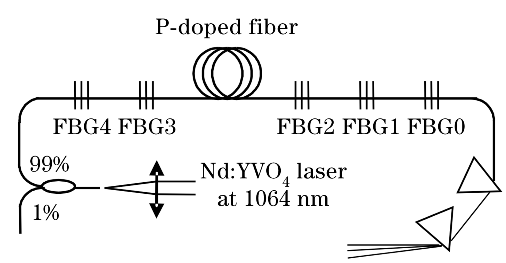

Fig. 1. Schematic of the cascaded P-doped RFL.

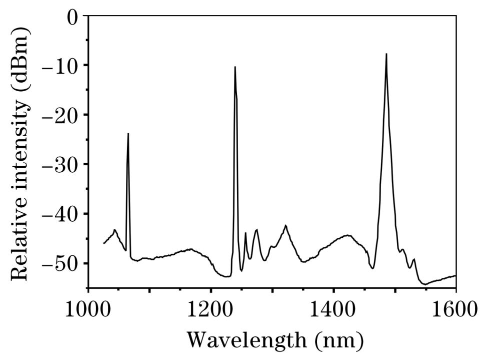

Fig. 2. Output spectrum of the RFL.

output power was measured to be 1.5 W. Figure 2 shows the output spectrum of the RFL measured by the ADVANTEST Q8384 optical spectrum analyzer. As shown in Fig. 2, the output laser beam comprises the pump, first- and second-order Stokes radiations. In order to distinguish these radiations, two prisms were used at laser output end. The maximum output power of the second Stokes wave was 1.15 W, corresponding to power conversion efficiency of 28.8%. The higher conversion efficiency compared with that in Ref. [4] is mainly attributed to the following facts. Firstly, the P-doped fiber in our experiments has lower loss and higher Raman gain. Secondly, the reflectivity for output coupler (FBG2) has been optimized according to the theoretical model in Ref. [2]. In addition, the reflectivity (> 99%) of our FBGs is higher than those (∼ 90%) in Ref. [4]. Stability of the laser was also measured by monitoring the output power at 1484 nm. At the output power level of 1.15 W, the power fluctuation is less than 5% in an hour.

As a result of using FBG0, output residual pump power is very small. But output power of the first Stokes wave is still large although FBG1 is highly reflective, because the spectral broadening of the first Stokes radiation causes a part of light to leak from the cavity. As shown in Fig. 3, a deep pit with about 1-nm bandwidth occurs in the output spectrum of the first-order Stokes radiation for the bandwidth of the first-order Stokes radiation inside cavity is greater than reflective bandwidth of FBG1. Except for the spectral broadening of the first Stokes wave, the output spectra of the second Stokes wave broaden with increasing the pump power as shown in Fig. 4. Figure 5 shows 3-dB bandwidth and peak wavelength

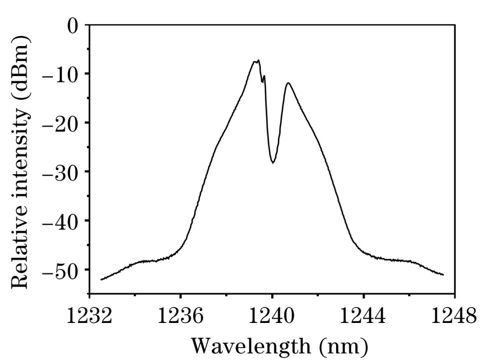

Fig. 3. Output spectrum of the first-order Stokes wave.

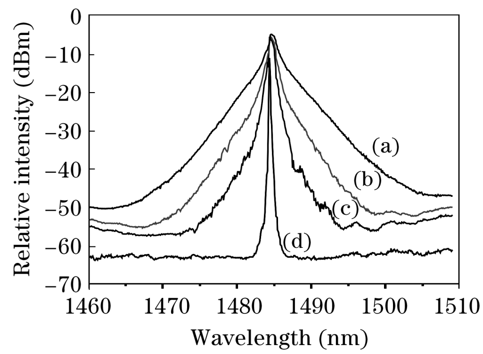

Fig. 4. Output spectra of the second-order Stokes radiation with the pump powers of (a) 4, (b) 2.3, (c) 1.6, and (d) 1.2 W.

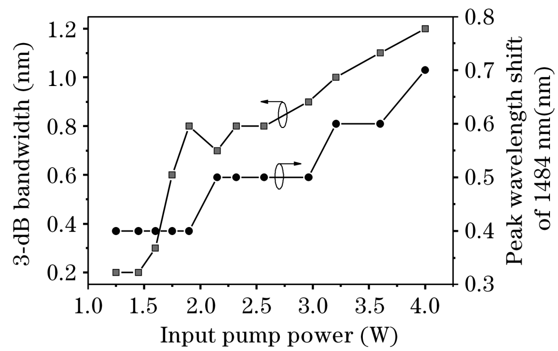

Fig. 5. 3-dB bandwidth and peak wavelength shift of the second-order Stokes radiation versus input pump power.

shift of 1484 nm at different input powers. The spectral broadening from 0.2 to 1.2 nm and slight red-shift for peak wavelength occur with increasing the pump power. The spectral broadening effects for Stokes radiations, attributed to four-wave-mixing interactions between longitude modes[15,16], have an impact on power conversion efficiency. The effective reflectivity of FBG, which is always lower than the reflectivity at central wavelength, can be introduced[15].

Figure 6 shows the output power of the second-order Stokes radiation versus input pump power. In Ref. [2], we have developed an analytical model for the P-doped cascaded RFL. The threshold pump power, slope efficiency, and power conversion efficiency can be expressed as

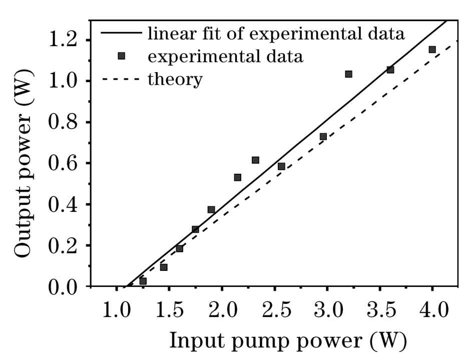

Fig. 6. Output power of the second-order Stokes radiation versus input pump power.

$$P_{\mathrm{th2}} = \frac{\delta_1}{2g_{01}L_0^{\mathrm{eff}}}\mathrm{e}^{\Delta_0}, \quad (1)$$

$$\eta_{\mathrm{s}} = \frac{t_2}{\sqrt{R_2^L}}\frac{g_{01}}{g_{12}}\frac{\lambda_1}{\lambda_2}\frac{L_0^{\mathrm{eff}}}{L_2^{\mathrm{eff}}}\mathrm{e}^{-\Delta_0}, \quad (2)$$

$$\eta_{\mathrm{t}} = \eta_{\mathrm{s}}(1 - \frac{P_{\mathrm{th2}}}{P_{\mathrm{in}}}), \quad (3)$$

where $\Delta_0 = \delta_0 + \frac{g_{01}\lambda_1}{g_{12}\lambda_0}\delta_2$. g_{01} and g_{12} represent Raman gain coefficients from the pump to the first-order Stokes and from the first-order Stokes to the second-order Stokes, respectively. δ_0, δ_1, and δ_2 are respectively single-pass loss factors for the pump, first-order, and second-order Stokes radiations due to loss of Raman fiber, transmitted loss of FBGs, and extra loss. t_2 denotes effective output transmissivity including extra loss and spectral broadening effects. L_0^{eff} and L_2^{eff}, defined as the effective length of Raman fiber at the pump and the second-order Stokes wavelengths, can be solved approximately as

$$L_0^{\mathrm{eff}} = L\frac{\sinh(\frac{1}{2}\ln\frac{1}{R_0^L}) - \sinh(\Delta_0)}{\frac{1}{2}\ln\frac{1}{R_0^L} - \Delta_0}, \quad (4)$$

$$L_2^{\mathrm{eff}} = L\frac{\sinh(\frac{1}{2}\ln\frac{1}{R_2^L}) + \sinh(\frac{1}{2}\ln\frac{1}{R_2^0})}{\frac{1}{2}\ln\frac{1}{R_2^L} + \frac{1}{2}\ln\frac{1}{R_2^0}}, \quad (5)$$

where R_0^L, R_2^0, and R_2^L are the effective reflectivities of FBG0, FBG3, and FBG2 including extra losses and spectral broadening effects, respectively.

The threshold pump power, slope efficiency, and power conversion efficiency calculated using experimental data and theoretical formulas are also listed in Table 1. The results indicate that the experimental results are in good agreement with theoretical ones.

In summary, a highly efficient P-doped RFL with CW output power of 1.15 W at 1484 nm pumped by 12.5 W/1064 nm Nd:YVO_4 solid-state laser (about 4 W is injected into Raman cavity) is developed. The threshold pump power for the second-order Stokes radiation is measured to be 1.15 W. The conversion efficiency and slope efficiency are as high as 28.8% and 42.6%, respectively. The experimental results, including threshold pump power, slope efficiency and conversion efficiency, are in good agreement with theoretical ones. The power instability of the P-doped RFL at 1484 nm in an hour is observed to be less than 5%.

Table 1. Comparison between the Experimental and Theoretical Results

	Experimental Value	Theoretical Value
Threshold Pump Power	1.13 W	1.11 W
Slope Efficiency	42.6%	38.3%
Conversion Efficiency	28.8%	27.6%

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