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800 mW/1484 nm highly efficient two-cascaded phosphosilicate Raman fiber laser pumped by Nd:YVO_4 solid-state laser

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Abstract

Using 1064 nm CW Nd:YVO_4 solid-state laser as a pump, 1-km phosphosilicate fiber and cascaded cavities with two pairs of fiber Bragg grating mirrors for 1239 and 1484 nm, we obtained a CW 800 mW/1484 nm Raman fiber laser (RFL) for an actual incident pump power of about 2 W (Nd:YVO_4 power of 6.90 W). The conversion efficiency is as high as 40%. To the best of our knowledge, this is the highest conversion efficiency of RFL pumped by solid-state laser. The output power instability at 1484 nm in half an hour is less than 3%. In addition, the numerical simulations are also performed. Good agreement between the results of numerical simulation and the results of the experiment has been demonstrated.

Keywords: Raman fiber laser; Nd:YVO_4; Highly efficient

1. Introduction

As a vital component in long-distance optical communication, Raman fiber amplifier (RFA) has been attracting more and more attention in recent years. It is due to its inherent advantages, which are characterized by its low noise, ability to provide gain over a wide wavelength range, wavelength flexibility, and temperature stability. Raman fiber laser (RFL) is one of the most attractive pump sources for Raman and for rare earth fiber amplifier. This application has stimulated great interest in RFL.

At present, double-clad fiber lasers (DCFL) have been widely used as the pump source of RFL because of high coupling efficiency with single mode Raman gain fiber, which usually makes the output power of RFL higher [1–6]. In 2004, Xiong et al. developed a 6.66 W/1495 nm cascaded RFL using Yb-doped DCFL at 1070.75 nm as a Raman pump source [1]. In the same year, Sim et al. also obtained high-power cascaded phosphosilicate RFL with the output power 13.2 W/1539 nm, using the same pump source [2]. However, DCFL as a pump usually leads to the higher cost and has the serious thermal effect problem. If we use the solid-state lasers (i.e Nd:YAG, Nd:YVO_4) as a pump, these disadvantages can be avoided. It is more important that the solid-state lasers have been perfectly developed at present. So far CW solid-state laser as a pump source of RFL have rarely been reported. In 1997, Dianov et al. reported the cascaded RFL pumped by Nd:YAG laser with the output power about 1 W/1484 nm for 7 W/1064 nm of pump power [3]. In 2001, Chang et al. developed the dual-wavelength cascaded RFL pumped by CW Nd:YLF laser with the total output power 400 mW at 1480 and 1500 nm for 3.2 W/1313 nm of pump power [7].

In this paper, we report a high-efficient cascaded phosphosilicate RFL pumped by a 1064 nm CW Nd:YVO_4 solid-state laser developed by ourselves. The second-Stokes

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output power of 800 mW/1484 nm is achieved at 6.90 W/1064 nm pump power (about 2 W of actual incident pump power). The conversion efficiency is as high as 40%. As far as we know, this is the highest conversion efficiency of two-cascaded phosphosilicate RFL using solid-state laser as a pump. The good stability of the RFL is presented with the fluctuation of power in half an hour by less than 3%. At last, we compare between the results of experiment and the results of numerical simulations. The good agreement is demonstrated.

2. Experimental setup

Fig. 1 shows the schematic diagram of high-efficient cascaded phosphosilicate RFL. The pump source is a LD end-pumped Nd:YVO_4 solid-state laser with maximum output power 8.4 W at 1064 nm (λ_1). The pump laser is focused by an object lens and then directly injected into the single mode fiber. Object lens's transmission at 1064 nm is about 90%, magnification multiples 10 and a NA of 0.25, which is compatible with that of single mode fiber (0.22).

Raman gain medium is 1-km P-doped fiber fabricated by the Fiber Optic Research Center of Russia, whose characteristic parameters are shown in Table 1. The first-Stokes cavity is formed by a pair of fiber Bragg gratings (FBG1 and FBG4) with reflectivity >99% at 1239 nm (λ_2). The second-Stokes cavity is formed by a pair of the fiber Bragg gratings (FBG2 and FBG3) for 1484 nm (λ_3). The reflectivity of FBG2 is more than 99% and that of FBG3 as the output grating is alterable among 12.5%, 25.7%, 43.6%. Besides, taking into account the residual pump power, a FBG5 at 1064 nm is mounted with its reflectivity more than 99%. Characteristic parameters of FBGs are represented in Table 2. All the FBGs and P-doped fiber (PDF) were fused using the Fujikura 50S fiber fusion splicer.

3. Experimental results

It is very hard to directly couple pump power into single mode fiber, which requires that the pump laser is quite focused by an object lens into the fiber core. We obtain the coupling efficiency of 33% by adjusting carefully.

When we use the reflectivity of FBG3 (R_{out}) 12.5%, the P-doped fiber length of 1-km and Nd:YVO_4 laser at 6.90 W (actual incident pump power about 2 W $= 6.90 \times 90\% \times 33\%$), we obtain the total output power of 800 mW measured by the LPE-1B optical power meter. The inset of

Table 1
Characteristic parameters of PDF

Dopant concentration of P_2O_5	13 mol%	Raman gain coefficient (G_R/A_{eff})	1.31×10^{-3} W^{-1} m^{-1}@1064 nm, 0.95×10^{-3} W^{-1} m^{-1}@1240 nm
Cut-off wavelength	1000 nm	Loss (dB/km)	1.8@1064 nm
Length	1000 m		1.1@1240 nm
Δn	<0.011		1.0@1480 nm

Table 2
Characteristic parameters of FBG

FBG	Wavelength (nm)	Bandwidth (nm)	Reflectivity (%)	Fiber length (m)
FBG1	1239.070	1.078	99.6	1.5
FBG2	1484.070	1.100	99.9	1.5
FBG3	1484.144	1.008	12.5	1.5
FBG4	1239.126	1.036	99.8	1.5
FBG5	1064.420	1.100	99.7	1.5
Alterable FBG3	1484.430	1.100	25.7	1.5
Alterable FBG3	1483.620	0.930	43.6	1.5

Fig. 2 shows the output spectrum of the RFL at 800 mW measured by the ADVANTEST optical spectrum analyzer, which is attenuated by 40 dB. It can be seen that the intensity of second-Stokes laser is overwhelmingly stronger than that of pump laser and first-Stokes laser by more than

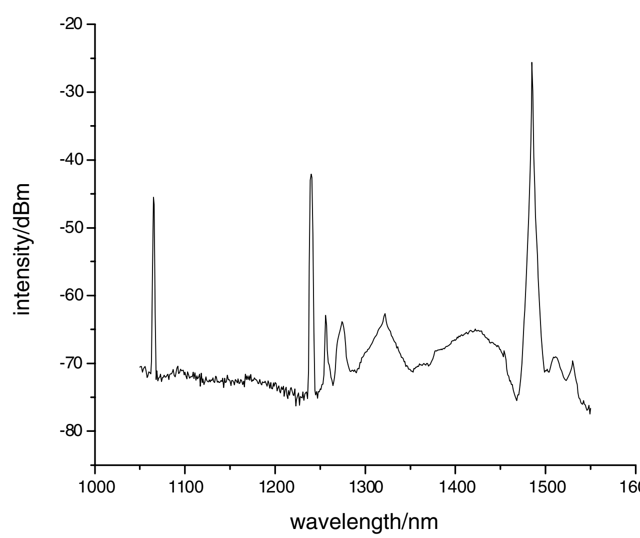

Fig. 2. Raman fiber laser output spectra at 800 mW.

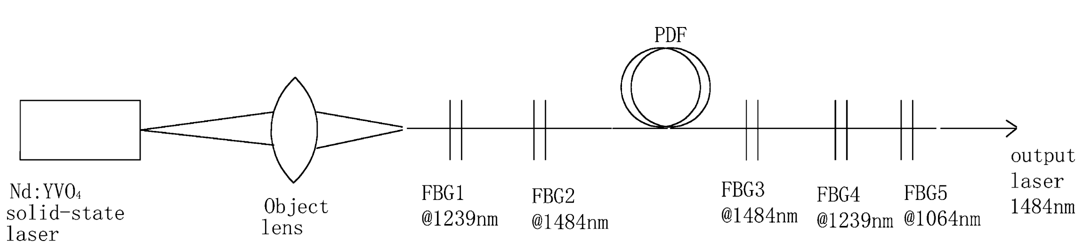

Fig. 1. Experimental setup of cascaded phosphosilicate Raman fiber laser.

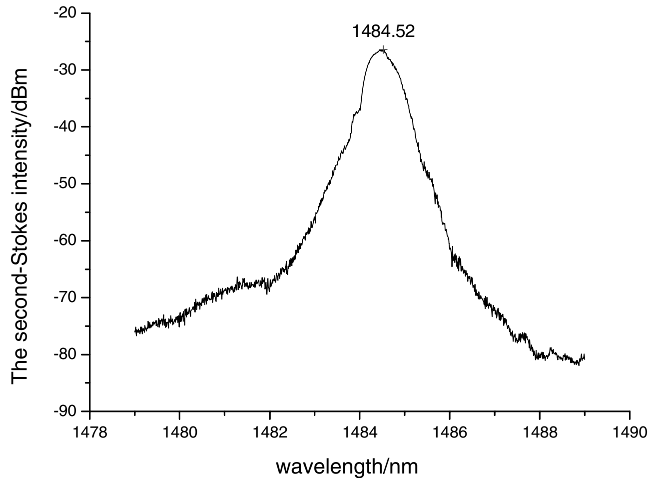

Fig. 3. The second-Stokes laser output spectra at 800 mW.

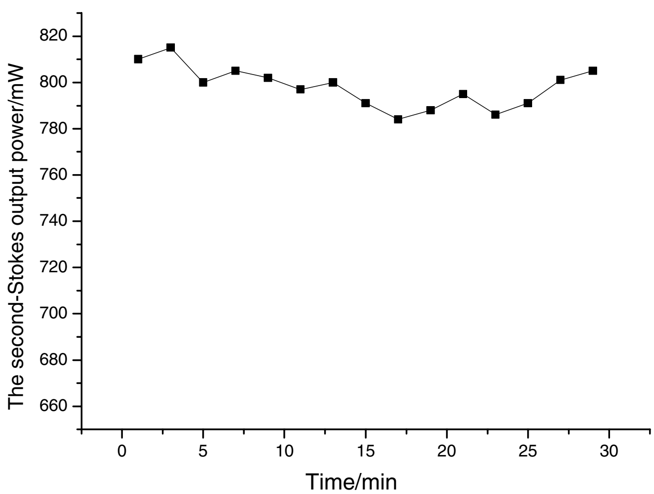

Fig. 4. The stability testing of Raman fiber laser at output power level of 800 mW.

20 dB. As a result, we think the total output power 800 mW is almost the second-Stokes laser. The central wavelength of the second-Stokes is 1484.52 nm and its linewidth is approximately of 0.60 nm (see Fig. 3).

We carry out the stability testing of the Raman fiber laser by monitoring the output power with the optical power meter. At the output power level of 800 mW, the output power of Raman fiber laser is stable and its fluctuation of power is less than 3% in half an hour shown in Fig. 4.

4. Numerical simulations

Taking into account coupling both copropagating and counterpropagating Stokes waves, we use the non-linear differential equations (see [8,9] for more detail) to describe the spatial evolution of optical powers in the Raman fiber at stationary state. From the set of equations, one can easily demonstrate that $c_i = P_i^+ \cdot P_i^-$ is a constant ($i = 1, 2, 3$). If we define $u_i = \ln(P_i^+/\sqrt{c_i})$, the coupling equations can be written as the following Eqs. (1) [9]. Consequently, we only need to solve an initial value problem

$$\begin{aligned}
\frac{du_1}{dz} &= -\alpha_1 - g_1\frac{\lambda_2}{\lambda_1}\sqrt{c_2}(e^{u_2} + e^{-u_2}) \\
\frac{du_2}{dz} &= -\alpha_2 + g_1\sqrt{c_1}(e^{u_1} + e^{-u_1}) \\
&\quad - g_2\frac{\lambda_3}{\lambda_2}\sqrt{c_3}(e^{u_3} + e^{-u_3}) \\
\frac{du_3}{dz} &= -\alpha_3 - g_2\sqrt{c_2}(e^{u_2} + e^{-u_2})
\end{aligned} \tag{1}$$

The boundary conditions become:

$$u_1(0) = \ln\left(\frac{P_0}{\sqrt{c_1}}\right) \quad \text{and} \quad u_i(0) = \frac{1}{2}\ln(R_i^0) \quad \text{for } i = 2, 3$$

$$u_i(L) = -\frac{1}{2}\ln(R_i^L) \quad \text{for } i = 1, 2, 3$$

Here, L is the cavity length of the RFL and P_0 is the actual incident pump power. λ_1, λ_2 and λ_3 are, respectively, the wavelength of the pump laser, first- and second-Stokes wave. α_1, α_2 and α_3 are their corresponding loss coefficients. The pump-to-first- and first-to-second order Raman gain constants are g_1 and g_2. Considering the sum of one-path splicing loss and background loss of Bragg grating (0.2 dB), R_i^0, R_i^L represent the mean reflectivity of FBGs at left and right end, respectively. The parameters involved in our simulation except those declared elsewhere are listed in Tables 1 and 2.

In this paper, the numerical simulations are performed using the ODE solver in MATLAB 7.0. For a RFL operation at $P_0 = 2$ W, Fig. 5 shows the conversion efficiency η (defined as P_{out}/P_0) as a function of the cavity length L ($R_{out} = 12.5\%$). It can be seen that the optimal cavity length is 350 m with the highest conversion efficiency 46%. Even if the cavity length is 1000 m, the conversion efficiency is as high as about 40%. The conversion efficiency is higher than the optimization conversion efficiency of

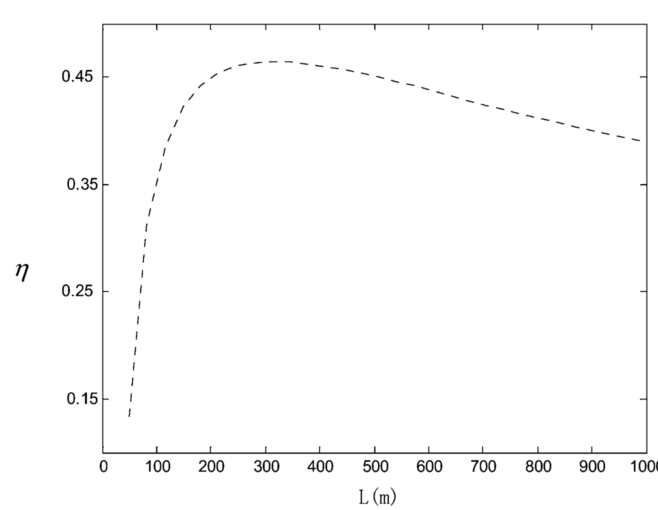

Fig. 5. Variation of the conversion efficiency versus the length of fiber.

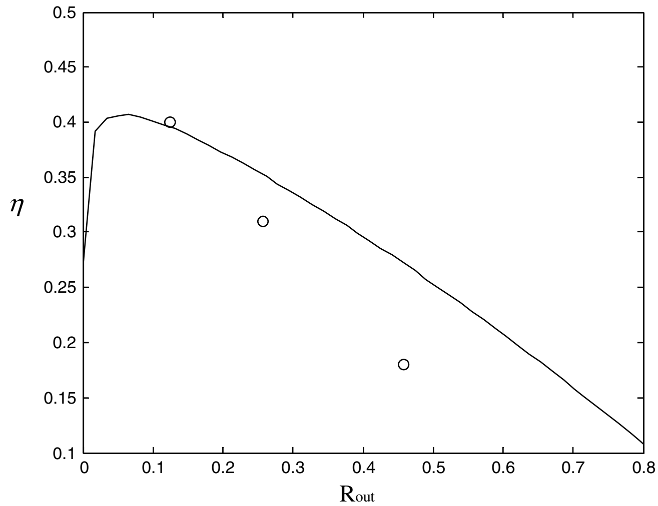

Fig. 6. Variation of the conversion efficiency versus the reflectivity of FBG3 (full line, theoretical results; circles, experimental results).

34% for 2 W pump power demonstrated by Kurukitkoson et al. [10]. It is mainly attributed to the fact that the sum of one-path splicing loss and background loss of Bragg grating (0.2 dB) is less than that (0.36 dB) in Ref. [10]. Besides this, the Raman gain coefficients and the reflectivities of FBGs except for the output FBG3 is slightly higher than those in Ref. [10].

Fig. 6 shows the conversion efficiency η as a function of R_{out} ($L = 1000$ m) by the full line. The optimal reflectivity of FBG3 is approximate 10%. However, the conversion efficiency only degraded by less than 1% for $R_{\text{out}} = 12.5\%$. As a result, it is tolerable to choose the cavity length $L = 1000$ m and the reflectivity of output grating $R_{\text{out}} = 12.5\%$. Of course, we believe that the conversion efficiency will increase with the optimal cavity length $L = 350$ m and the optimal reflectivity of FBG3 $R_{\text{out}} = 10\%$. This will be our following work.

5. Comparison with the experimental results

In our experiment, for the cavity length $L = 1000$ m, we choose the different reflectivity of FBG3 among 12.5%, 25.7%, 43.6%. Their corresponding output powers are 800, 620, 360 mW with the actual incident pump power of 2 W. As shown in Fig. 6 by the circles, their conversion efficiencies are 40%, 31%, 18%, respectively. It can be seen that the agreement between theory and experiment is good. The larger discrepancy at the reflectivity 43.6% should be attributed to the fact that the output laser line 1484.52 nm has exceeded the bandwidth range of this FBG.

6. Conclusion

We develop a CW 800 mW/1484 nm phosphosilicate Raman fiber laser using two cascaded cavities for 1239 and 1484 nm wavelengths, which is pumped by 6.90 W Nd:YVO_4 solid-state laser(the actual incident pump power about 2 W). The output power instability at 1484 nm in half an hour is less than 3%. The conversion efficiency is as high as 40%. As far as we know, this is the highest conversion efficiency that RFL pumped by solid-state laser has achieved. In addition, the numerical simulations are performed. It is demonstrated that the conversion efficiency is close to the highest conversion efficiency with $L = 1000$ m and $R_{\text{out}} = 12.5\%$ as we choose. At last, we compare between the theoretical results of the conversion efficiency as a function of R_{out} and the experimental results. The agreement is good.

In addition, it should be indicated that we have obtained the higher output power of 1.5 W for about 3 W pump power recently. However, some detail works do not perfectly perform now.

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