August 28, 2005 / Vol. 3, Supplement / CHINESE OPTICS LETTERS **S277**

Studies on all-fiber Raman fiber lasers with domestic Bragg gratings

Geguo Du (杜戈果), Min Zhang (张 敏), Hongwei Li (李宏伟),
Huihui Lu (卢惠辉), Shuangchen Ruan (阮双琛), and Qin Zhu (朱 勤)

Shenzhen Key Laboratory of Laser Engineering, College of Engineering and Technology, Shenzhen University, Shenzhen 518060

Research of the first-order Raman fiber laser pumped by a continuous wave (CW) fiber laser is presented using domestic Bragg gratings with corning SMF-28$^{\mathrm{TM}}$ silica fiber as the gain material. Formation process of Raman laser is studied and output characteristics are measured. Laser output is centered at 1116 nm with 3–dB bandwidth of 0.18 nm. Pump threshold is estimated, which is in good agreement with the experimental value by revising the equation in some references. Techniques for decreasing threshold power and increasing output power are also analyzed.

OCIS codes: 140.3550, 290.5910, 140.3510, 060.0060, 190.4370.

In recent years, Raman amplifiers have attracted great research efforts because of wide amplification bandwidth, flexible center and low noise figure and will play an important role for future large-capacity dense wavelength division multiplexing (DWDM) optical transmission systems and networks. Based on stimulated Raman scattering (SRS) effect, a nonlinear process, a Raman amplifier requires high pump powers. Generally, there are two approaches to design the pump source for a Raman amplifier[1]. The first, sources are achieved through polarization and wavelength multiplexing of several laser diodes, as the optical power of the commercially available pump diodes is limited within 200–300 mW[2]. The second, a more practical way, is to use the Raman process itself to frequency-shift from a high-power fiber laser[3]. This may be accomplished using an Yb-doped double clad fiber laser to pump a cascaded Raman fiber laser[4]. Thus, it is of essential importance to study Raman fiber lasers. However, to our knowledge, in China there are a few reports about this work. A research group in Nankai University has carried out such research because it has imported sets of highly reflective Bragg gratings[5]. We ever did some work with dichroic mirrors[6]. In this paper, results of the first-order Raman fiber laser were presented using domestic fiber Bragg gratings (FBGs).

Raman is a nonlinear optical process in which intense pump light couples to vibrational modes of the glass and is reradiated at a longer wavelength[7]. This process can amplify a signal if the pump is at an appropriately shorter wavelength than the signal. The Raman gain spectrum of conventional silica fibers has maximum gain at a frequency 13 THz lower than the pump frequency[8]. Since the gain spectrum is determined simply by the pump wavelength rather than the fixed energy levels of a dopant, gain can be created at any wavelength with a suitable pump. When intense pump light from a fiber laser is injected into a length of germano-silicate fiber surrounded by sets of highly reflective Bragg gratings, the cascaded Raman converter is formed. The light is contained within the fiber by highly reflective Bragg gratings at each end. Intense light in turn generates Raman gain at the first-Stokes, the second-Stokes, and so forth. The cascade is terminated by a low-reflectivity grating to couple the desired wavelength out of the cavity.

Figure 1 shows the experimental setup. The resonant cavity consists of FBG$_1$, FBG$_2$, FBG$_3$ and corning SMF-28$^{\mathrm{TM}}$ silica fiber. The 1064-nm pump source has its stability $< 4\%$ and nearly diffraction-limited fundamental transverse beam with M^2 of 1.1. The pump light, with 5-W maximum output power, was launched into the 25-km-long corning fiber and FBG$_1$after coupling via a special lens. All the gratings were written in Flexcor fiber after H$_2$ preloading by Shanghai Synetoptics Technology Corporation. The FBG$_1$ has a high reflectivity of $> 99\%$ at 1115.650 nm and the output coupling FBG$_2$ has a reflectivity of 92.23% at 1115.450 nm. Both the FBGs have narrow bandwidth to provide sufficient lasing mode selection and should have same central reflected wavelength but a little difference in practice. A 106-nm FBG$_3$ is also placed at the opposite end to reflect the pump. The mode field diameters (MFDs) in Flexcor fiber and in corning fiber at 1064 nm were different, so, owing to mismatched MFD, when we spliced these fibers optical loss was much great of about 0.3 dB. The characteristics of output power and spectrum of the fiber laser were measured with an optical power meter (FIELDMASTER COHERENT) and an optical spectrum analyzer (OSA) (ADVANTEST Q8384 OPTICAL SPECTRUM ANALYZER, minimum resolution 0.01 nm, operation wavelength range of 0.6–1.7 μm), respectively.

Figure 2 shows the laser emission spectra. When pump power increases to 2.0 W, the first-order Stokes is observed, as shown in Fig. 2(a). With pump power increasing, the residual pump power decreases and the output power of the first-order Stokes line increases, as shown in Figs. 2(b) and (c), respectively. With further increase of pump power, the residual pump power becomes too small to be observed compared to the first-order Stokes line, as shown in Fig. 2(d). Other higher-order Stokes lines are not observed all along. Laser output centered at 1116 nm is observed, its full width at half maximum (FWHM) is about 0.18 nm, as shown in Fig. 3, which is predicted because the FBGs have very narrow bandwidth. Figure 4 shows the measured output power as a function of the launched pump power. Scattered points

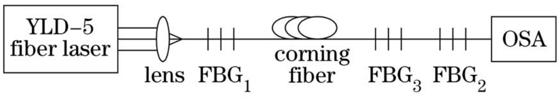

Fig. 1. Schematic configuration of the all fiber Raman laser.

1671-7694/2005/0s0277-03 http://www.col.org.cn

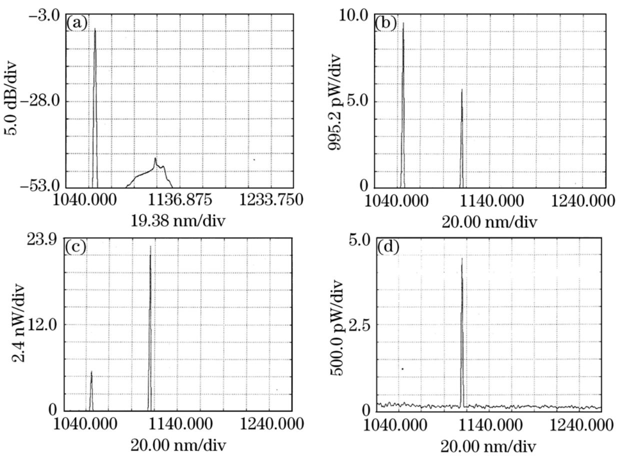

Fig. 2. Spectra of Raman fiber laser with different pump powers: (a) 2.0 W, (b) 2.5 W, (c) 3.0 W, (d) 4.0 W.

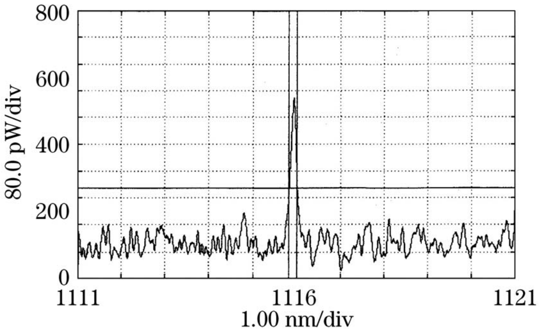

Fig. 3. FWHM of the first-order Stokes line.

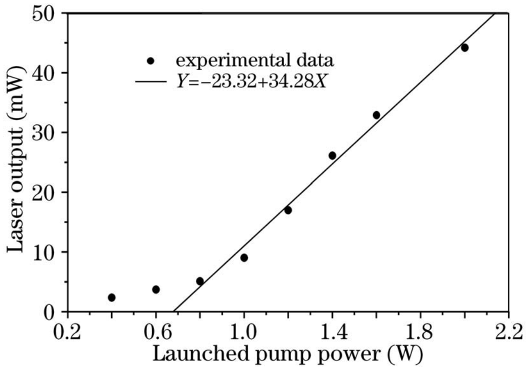

Fig. 4. Output power versus launched pump power.

are experimental data, and the line is a linear fit. The slope efficiency is 3.4% with the launched pump threshold of 680 mW by extrapolating the linear fitting to the X coordinate. A maximum output power of 44.2 mW is measured at the pump power of 5.0 W, thus the corresponding optical-to-optical conversion efficiency is 2.2%, with the couple efficiency of the lens, 40%, considered.

The threshold power, P_{th}, defined as the incident power at which the Stokes' gain after a round trip can compensate the loss in the cavity, can be estimated from[9]

$$G = \exp\left(2g_{\mathrm{R}}P_{\mathrm{th}}L_{\mathrm{eff}}/A_{\mathrm{eff}}\right) = \mathrm{Loss}, \quad (1)$$

where g_{R} is the peak value of the Raman gain, A_{eff} is the effective mode across section, often referred to as the effective core area for laser wave, and L_{eff} is the effective interaction length, defined by

$$L_{\mathrm{eff}} = [1 - \exp(-\alpha_{\mathrm{p}}L)]/\alpha_{\mathrm{p}}, \quad (2)$$

where α_{p} represents fiber loss at pump wavelength, which is measured to be 0.8 dB/km in this experiment. The Raman gain coefficient $g_{\mathrm{R}} \approx 1\times10^{-13}$ m/W for silica fibers near 1 μm (pump wave) and scales inversely with the wavelength. For pump wavelength of 1.064 μm, the gain coefficient $g_{\mathrm{R}} \approx 0.94\times10^{-13}$ m/W and is reduced by a factor of two because of mode polarization scrambling. Considering the transmission loss from FBG$_1$ and FBG$_2$ and the excess loss, which includes the splicing loss and the non-resonant loss in the fiber gratings, we have total loss in the cavity of about 2.5 dB. If we use $A_{\mathrm{eff}} \approx 45$ μm^2 as the representative value[10], P_{th} is about 51 mW. This value is much lesser than the practical value. In fact, in this experiment, because of long fiber we cannot neglect the loss at laser wavelength, represented by α_{s}. Based on Laser principles, revising Eq. (1) as

$$G = \exp\left(\frac{2g_{\mathrm{R}}P_{\mathrm{th}}}{A_{\mathrm{eff}}}L_{\mathrm{eff}} - 2\alpha_{\mathrm{s}}L\right) = \mathrm{Loss}. \quad (3)$$

and using $\alpha_{\mathrm{s}} \approx 0.6$ dB/km from the loss curve of the fiber, we got $P_{\mathrm{th}} \approx 670$ mW, which is closely near the experimental value. These results show that Eq. (1) is not suitable here. In order to reduce threshold, we should reduce fiber length to L_{eff} and the cavity loss.

In conclusion, we have fabricated an all-fiber Raman laser based on domestic gratings. The slope efficiency and output power are small. There are several reasons for them. Firstly, Corning fiber is a standard silica fiber with small Raman gain. In order to get efficient conversion, we need long fiber as gain medium, but transmission loss at Raman laser wavelength will enlarge. So optimized fiber length is needed. On the other hand, the fiber with a high Raman gain is expected to get high output power, for example, large Ge doping fiber, in which the large Raman cross-section of GeO$_2$ yields a high Raman gain. Secondly, if the large splicing joint loss can be decreased, a much lower threshold can be achieved. Thirdly, the central wavelength for FBGs should be controlled to laser wavelength accurately because FBGs here are not temperature compensated. Moreover, output reflectivity of the FBG$_2$ is too high, thus optimization is needed for maximum output. After these problems are solved, an efficient and attractive Raman laser will be predicted.

This work was supported by the Shenzhen Science and Technology Bureau Scheme under Grant No. 200207 and Shenzhen Nanshan District Science and Technology Scheme. G. Du's e-mail address is dugeguo@szu.edu.cn.

References

1. G. G. Du, H. X. Su, L. B. Jiang, Q. Zhu, and S. C. Ruan, J. Shenzhen Univ. (Science & Engineering) (in Chinese) **20,** 30 (2003).
2. Y. Emori, K. Tanaka, and S. Namiki, Eletron. Lett. **35,** 1355 (1999).
3. G. Vareille, O. Audouin, and E. Desurire, Electron. Lett. **34,** 675 (1998).
4. V. I. Karpov, E. M. Dianov, V. M. Paramonov, O. I. Medvedkov, M. M. Bubnov, S. L. Semyonov, S. A. Vasiliev, V. N. Protopopov, O. N. Egorova, V. F. Hopin, A. N. Guryanov, M. P. Bachynski, and W. R. L. Clements,

Opt. Lett. **24,** 887 (1999).

5. H. X. Su, K. C. Lü, P. G. Yang, Y. G. Li, F. Y. Lü, and X. Y. Dong, Acta Opt. Sin. (in Chinese) **23,** 53 (2003).
6. G. G. Du, Y. Deng, H. L. Chen, L. B. Jiang, S. C. Ruan, and Q. Zhu, Laser & Infrared (in Chinese) **34,** 169 (2004).
7. A. M. Glass, D. J. DiGiovanni, T. A. Strasser, A. J. Stentz, R. E. Slusher, A. E. White, A. R. Kortan, and B. J. Eggleton, Bell Labs Technical Journal **5,** 168 (2000).
8. R. H. Stolen, and E. P. Ippen, Appl. Phys. Lett. **22,** 276 (1973).
9. G. P. Agrawal, *Nonlinear Finer Optics*(in Chinese) G. J. Hu and C. Huang (translated) (Tianjin University Press, 1992).
10. A. Bertoni, Optical and Quantum Electron. **29,** 1049 (1997).