High-power and highly efficient operation of wavelength-tunable Raman fiber lasers based on volume Bragg gratings

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Abstract: Highly efficient and high-power operation of Raman fiber lasers in fixed-wavelength and wavelength-tunable cavity configurations based on a graded-index multimode fiber is reported. Fixed-wavelength and wavelength tunable operating regimes are achieved using volume Bragg gratings (VBGs) with center wavelengths of 1658 nm and 1750 nm, respectively. The fixed-wavelength laser yielded a maximum output power of 10.5 W at 1658.3 nm with a FWHM linewidth of ~0.1 nm for the launched pump power of 23.4 W, corresponding to a slope efficiency of 82.7% with respect to the launched pump power. The measured beam quality in the form of M^2 factor is ~1.35, corresponding to the fundamental mode of the fiber. For the wavelength-tunable Raman fiber laser, a wavelength tuning range of 37 nm from 1638.5 to 1675.1 nm is obtained with a maximum output power of 3.6 W at 1658.5 nm for the launched pump power of 13.0 W.

OCIS codes: (140.0140) Lasers and laser optics; (140.3510) Lasers, fiber; (140.3550) Lasers, Raman; (190.4370) Nonlinear optics, fibers.

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#205737 - $15.00 USD Received 29 Jan 2014; revised 19 Feb 2014; accepted 23 Feb 2014; published 13 Mar 2014

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1. Introduction

Raman fiber lasers, based on the third-order nonlinear effect of stimulated Raman scattering (SRS), have attracted considerable attention in recent years due to their unique wavelength agility, low quantum defect and high output power [1–5]. Benefiting from the broad Raman gain spectrum, considerable flexibility in the operating wavelength selection is allowed through the choice of pump source and Raman gain fiber, especially in the eye-safe wavelength regime around 1.6-1.7 μm that cannot be covered by traditional rare-earth-doped fiber lasers. Particularly, laser sources at 1658 nm could be an efficient pump source of mid-infrared optical parametric oscillators (OPOs) for generating a signal wavelength at 2.7 μm and an idler wavelength at 4.3 μm precisely and simultaneously [6]. These dual mid-IR wavelengths are of great interest in surgical operation, CO2 sensing and mid-IR countermeasure applications [7,8].

Typical Raman fiber lasers consist of a pump source and a gain fiber terminated with a set of fiber Bragg gratings (FBGs) as cavity mirrors on both ends. Traditionally, single-mode fibers would be a favorable Raman gain medium for the intensity-dependent SRS effect in Raman fiber lasers. However, the use of single-mode Raman gain fibers greatly reduces the pump power coupling efficiency for multimode pump source, and thus limits the further output power scaling. Recently, many groups have demonstrated efficient Raman fiber laser sources based on multi-mode Raman gain fibers [9,10]. In ref [10], a maximum output power of 5.8 W ($M^2 = 3.5$) was obtained in a Raman fiber laser based on a graded-index multimode fiber with an optical conversion efficiency of 56%. In addition, for many applications in the eye-safe wavelength range around 1.6-1.7 μm, narrow spectral linewidth with flexible operating wavelength is also required while maintaining the high output power and good beam quality. Nevertheless, conventional architectures of Raman fiber lasers using FBG-pair as the lasing feedback components typically have output spectrum bandwidth larger than ~1 nm for output power of several watts level [9,10] due to the strong nonlinear effects such as four-wave mixing resulting from the high intensity in the fiber core [11] and the greatly reduced effectiveness of wavelength-selection and spectrum narrowing for FBGs in slightly multimode fibers [12]. Alternatively, volume Bragg gratings (VBGs), recorded in photo-thermal refractive (PTR) glass, have now been widely used as an effective wavelength selection and spectrum narrowing component in high power fiber lasers due to its high diffraction efficiency, narrow spectral selectivity, low insertion losses and good thermal stability [12,13]. Furthermore, VBGs benefit from a comparatively efficient mode-selective property due to their angle selectivity [14], which means that higher order modes in fibers suffer from a higher cavity loss and thus only lower order modes are favorable in the laser resonator.

In this paper, we report on high-power operation of fixed-wavelength and wavelength-tunable Raman fiber lasers based on a graded-index multimode fiber. Using a VBG with the center wavelength of 1658 nm, we have obtained a maximum output power of 10.5 W at the fixed-wavelength of 1658.3 nm with a FWHM linewidth of ~0.1 nm, corresponding to a slope efficiency of 82.7% with respect to the launched pump power. To the best of our knowledge, this is the highest output power and narrowest spectral width achieved in Raman fiber lasers based on a multimode fiber. In the wavelength-tunable regime, another VBG with a longer

#205737 - $15.00 USD Received 29 Jan 2014; revised 19 Feb 2014; accepted 23 Feb 2014; published 13 Mar 2014

center wavelength of 1750 nm was employed and the operating wavelength was tuned from 1638.5 to 1675.1 nm with a maximum output power of 3.6 W at 1658.5 nm for the launched pump power of 13.0 W, covering a tuning range of 37 nm.

2. Experiments and results

The schematic diagram of the experimental setup is depicted in Fig. 1. The pump source was an in-house constructed high power continuous wave Er,Yb co-doped fiber laser at 1545 nm. A maximum output power in excess of 36 W was obtained from the pump source. The output beam propagation factor (M^2) at the maximum power was measured to be ~3.2. More details can be found in Ref [15].The output laser beam from the pump source was collimated and then focused through a set of lenses into the core of the Raman gain fiber. The Raman gain fiber employed in the experiment was a standard graded-index multimode telecom fiber. The fiber core was germanium doped with a diameter of ~50 μm and numerical aperture (NA) of ~0.2. The coupling efficiency into the core of the gain fiber was measured to be ~70% with respect to the incident pump power onto the fiber. Both end sections of the fiber were carefully mounted in water-cooled V-groove heat sinks to prevent possible thermal damage to the fiber coating. A dichroic mirror with high transmission at the pump wavelength and high reflectivity over the 1.6-1.8 μm band were positioned at a small angle tilt between the coupling lenses to allow efficient extraction of the laser output.

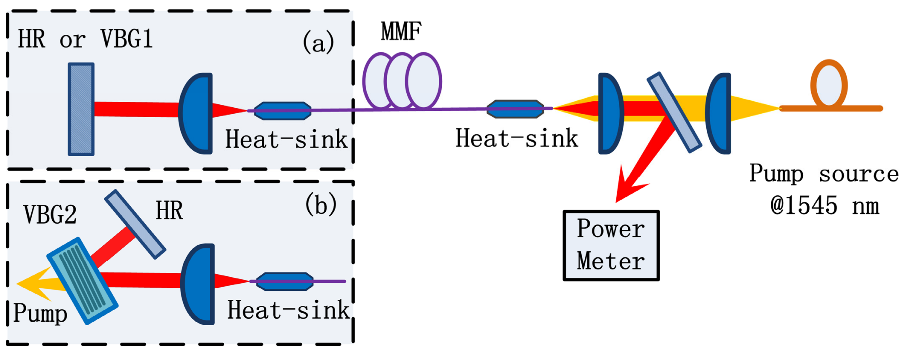

Fig. 1. Schematic diagram of Raman fiber lasers based on a graded-index multimode fiber, (a) free-running or fixed-wavelength operation; (b) external cavity for wavelength-tunable operation.

Lasing characteristics of the free-running Raman fiber lasers (i.e., without wavelength selection) for different gain fiber lengths were first evaluated. Lasing feedback for the free-running operation regime was provided by the 3.6% Fresnel reflection from a perpendicularly-cleaved fiber end facet (also acting as the output coupler) and, at the opposite end, by a simple external cavity comprising an antireflection-coated collimating lens and a high-reflection (HR) plane mirror over the band from 1500 to 1700 nm. Stokes output powers' dependence on the launched pump power for different Raman fiber lengths is shown in Fig. 2. The 2.5 km Raman fiber laser had the best performance in terms of output power and slope efficiency. A maximum output power of 12.3 W at ~1658 nm with a slope efficiency of 86.3% was obtained for the launched pump power of 23.4 W. The calculated output power as a function of gain fiber length (see Fig. 3.) indicates that optimized gain fiber length is also located at around ~2.5 km for the given pump power. Besides, a Raman fiber lasers with longer effective fiber length tends to have lower pump threshold, which also agrees well with our simulated results (see Fig. 4). It is worth noting that the theoretical Stokes output powers are higher than the experimental results, which is due to the assumed uniform Raman gain across the fiber. Actually, the effective area between the pump and Stokes laser grows increasingly with the pump depletion and thus the Raman gain reduced across the fiber. The output powers were all linearly dependent on the launched pump power,

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suggesting that there is considerable scope to scale up the output power by simply increasing the pump power.

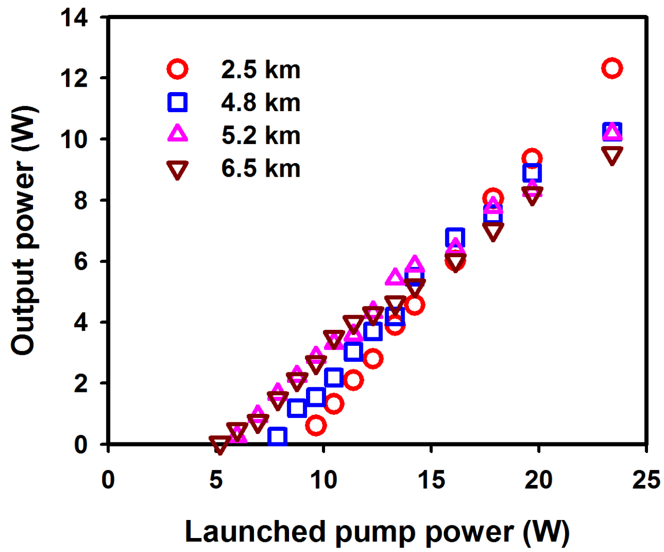

Fig. 2. Output power characteristics as a function of launched pump power for different Raman fiber lengths under the free-running operating regime.

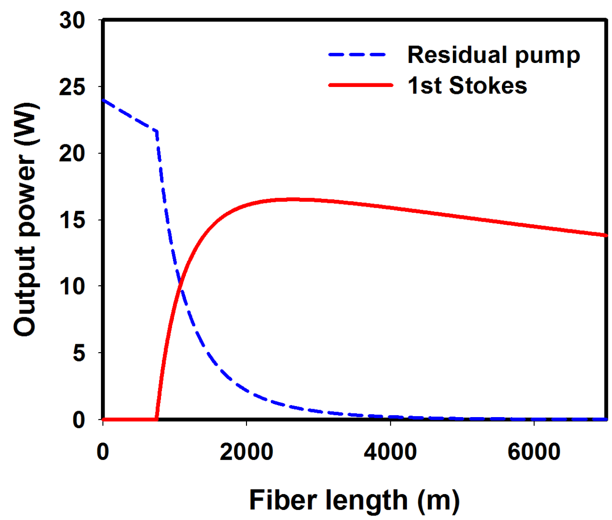

Fig. 3. Simulated output power characteristic as a function of gain fiber length under the free-running operating regime.

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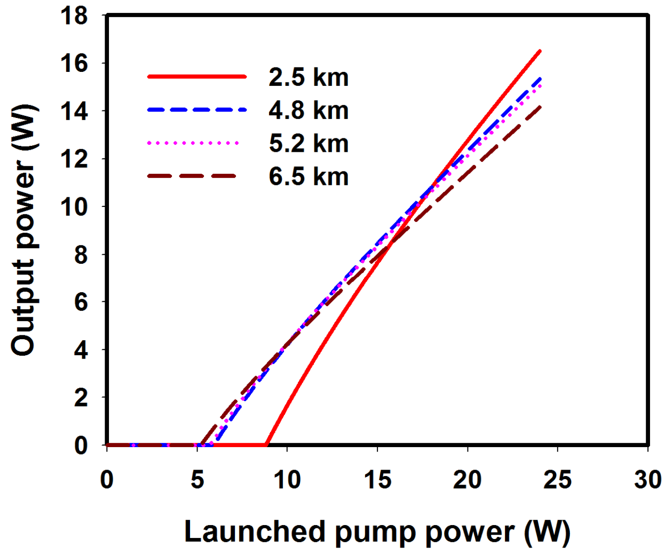

Fig. 4. Simulated Stokes output power characteristics as a function of launched pump power for different Raman fiber lengths under the free-running operating regime.

Based on the experimental and the simulation results mentioned above, the 2.5 km Raman fiber was employed as the gain fiber to scale up the output power at a fixed wavelength. Since the 1545 nm pump beam generated Raman gain with a peak at ~1658 nm in a germano-silicate Raman fiber, a reflective VBG (VBG1) with a center wavelength of 1658 nm and spectral selectivity of 0.33 nm was selected to lock the operating wavelength. VBG1 (Optigrate corp.) had a thickness of 9 mm with its clear aperture of 5 × 5 mm^2 and was mounted in a copper heat sink with a layer of indium foil (0.1 mm in thickness) to ensure good heat dissipation. In the fixed-wavelength Raman fiber laser, the external cavity was modified to include VBG1 as the wavelength-locking component and one cavity reflector in place of the previous HR plane mirror. The collimating lens of 15 mm focal length was chosen to obtain a comparable laser spot with the clear aperture of the VBG, making full use of the VBG aperture. In addition, the fiber end adjacent to the external cavity was angle cleaved at ~8° to suppress the broadband feedback and 2nd Stokes generation from the two uncoated fiber facets.

Laser output power of the fixed-wavelength Raman fiber laser as a function of launched pump power is shown with squares in the Fig. 5. Output power up to 10.5 W at 1658.3 nm was generated for the launched pump power of 23.4 W, corresponding to a slope efficiency of 82.7% with respect to the launched pump power. The relatively higher output power and slope efficiency achieved in the free-running Raman fiber laser for the same launched pump power is attributed to the higher pump intensity in the fiber core resulting from the residual pump being retro-reflected back into the cavity by the HR mirror after a single pass. The maximum output power fluctuations remained below ~2%. This instability is mainly due to the external disturbance such as vibration, varying the pump launching conditions. To scale further up to several tens watts of output power, an isolator should be used between the pump source and Raman laser to suppress the reflections from the Raman fiber laser. The output laser beams for the fixed-wavelength and free-running Raman fiber lasers at the maximum output power were near-diffraction-limited with the beam propagation factor (M^2) measured by a beam profiler (Nanoscan, Photo Inc) to be ~1.35 and ~1.46, respectively. These were comparable with the theoretical value of ~1.3 for the LP01 mode in a graded index multimode fiber according to Ref [16]. The single-mode laser operation in a multimode fiber core benefited from the beam cleanup effect of SRS in a graded-index multimode fiber [17,18]. In addition, it is worth noting that the beam quality of the fixed-wavelength Raman fiber laser was somewhat better than that of the free-running configuration, which is attributed to the mode-selective characteristic of VBG1 in a situation where higher order modes in fibers with larger divergence cannot be reflected into the fiber effectively and thus a lasing feedback for these modes cannot be formed. Characterization in terms of laser brightness B, determined as in $B = P/(M^2)^2\lambda$, was also performed. In the equation of brightness definition, P is the power and λ is the wavelength. The generated Stokes signal at the fixed wavelength of 1658 nm was more than 2.7 times brighter than the pump beam. Significant brightness enhancement indeed occurred due to the beam cleanup effect.

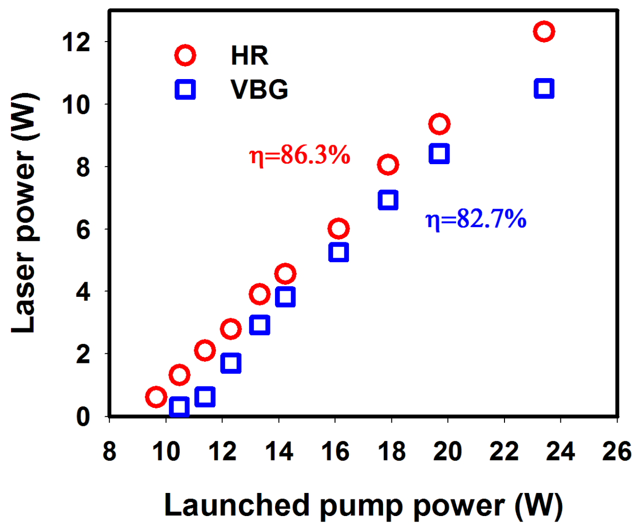

Fig. 5. Laser output powers as a function of launched pump power under the free-running and VBG1-locked fixed-wavelength operating regimes.

Spectrum of the laser output was recorded using an optical spectrum analyzer (AQ6375, Yokogawa). The measured fixed-wavelength and free-running laser output spectra at the maximum output power are shown in Fig. 6. The free-running Raman fiber laser had two discrete broadband spectra with primary peaks at 1658 nm and 1671 nm, corresponding to the two Raman gain peaks of germano-silicate fibers, while the VBG1-locked output spectrum was much narrower with a FWHM bandwidth of ~0.1 nm recorded at a resolution of 0.05 nm. In addition, the free-running output spectrum in logarithmic scale is also shown in the inset of Fig. 6. We can see that there appears a signal of 2nd order Stokes at ~1790 nm. Despite this, the magnitude of 2nd order Stokes signal still remained >26 dB lower than the 1st order Stokes signal at ~1658 nm.

For the wavelength-tunable operating regime under a launched pump power of 13.0 W, the 5.2 km Raman fiber was chosen as the gain fiber to obtain good performance based on the experimental and simulation results. To achieve a broad wavelength tuning range, another reflective VBG (VBG2) with a longer center wavelength was employed to substitute for VBG1 and was aligned at an angle tilt. VBG2 (Optigrate cop.) was designed to have a center wavelength of 1750 nm with peak reflectivity of 99.9% and spectral selectivity of 0.8 nm. An additional HR plane mirror was included in the modified external cavity as the terminal cavity reflector. Wavelength tuning was realized by adjusting the angles of both VBG2 and the followed HR plane mirror. Figure 7 shows the laser output power characteristics against the tuned operating wavelength for the launched pump power of 13.0 W. A tuning range of 37 nm from 1638.5 to 1675.1 nm was obtained with a maximum output power of 3.6 W at 1658.5 nm. It can be seen that there is a significant decrease in output power over the both two ends of the tuning range, where lasing became relatively difficult due to the large lasing threshold. This is attributed to the reduced gain at these operating wavelengths. Wavelength tuning

#205737 - $15.00 USD Received 29 Jan 2014; revised 19 Feb 2014; accepted 23 Feb 2014; published 13 Mar 2014

range can be extended to longer or shorter operating wavelength side by simply changing the pump wavelength accordingly.

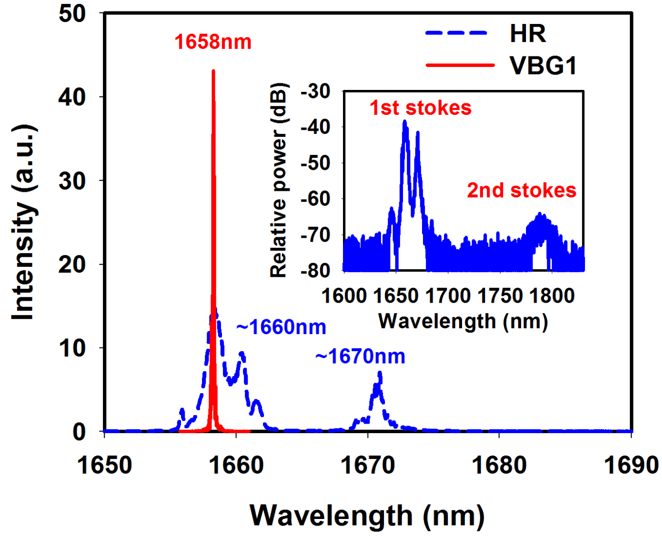

Fig. 6. Laser output spectra of Raman fiber lasers under the free-running and VBG2 wavelength-locked modes of operation. Inset: the free-running output spectrum in logarithmic scale recorded at the launched pump power of 21.8 W.

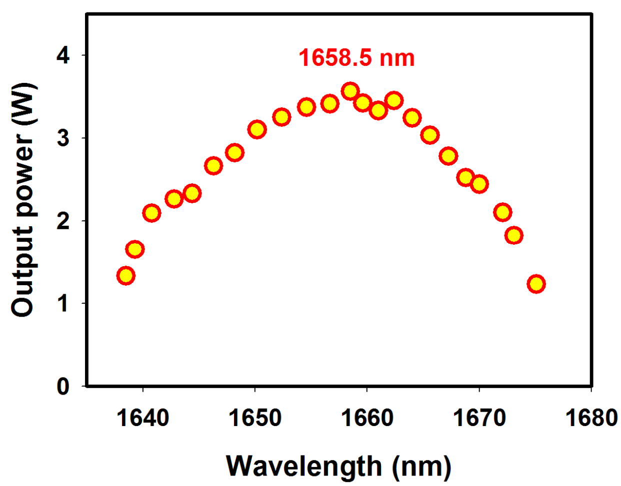

Fig. 7. Laser output power versus tuned operating wavelength under the wavelength-tunable mode of operation.

The measured laser output spectra at different tuned operating wavelength are shown in Fig. 8. The spectra were recorded at the maximum output powers with a resolution of 0.5 nm. We can see that there is no pronounced noise or side-peak signal detected over the whole tuning process. In addition, the spectral linewidth of the tunable Raman fiber laser remained approximately constant over the whole tuning range at less than ~0.3 nm (FWHM).

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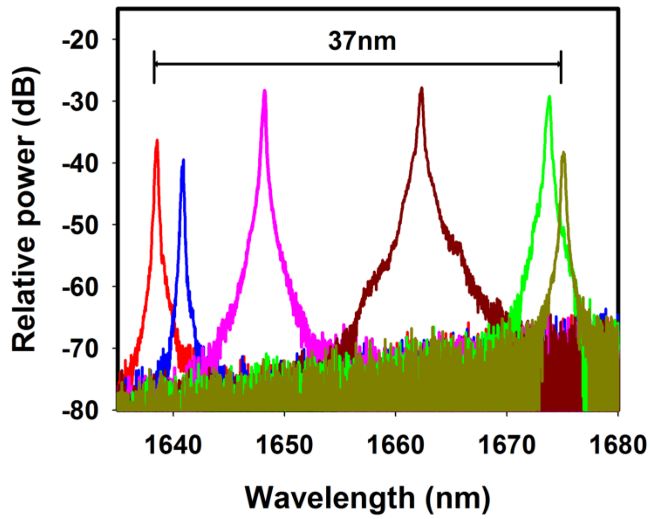

Fig. 8. Laser output spectra at different tuning wavelengths in logarithmic scale.

3. Conclusion

In conclusion, we have demonstrated highly efficient high-power operation of fixed-wavelength and wavelength-tunable Raman fiber lasers based on a graded-index multimode fiber. A reflective VBG with peak reflectivity at 1658 nm arranged at normal incidence was employed to generate a maximum output power of 10.5 W at fixed-wavelength of 1658.3 nm with a FWHM linewidth of ~0.1 nm, corresponding to a slope efficiency of 82.7% with respect to the launched pump power. For comparison, the free-running Raman fiber laser was also constructed to yield a maximum output power of 12.3 W for the same launched pump power. Further output power scaling up should be possible by simply increasing the pump power with an isolator inserted between the pump source and Raman laser. Near-diffraction-limited output laser beams from the fixed-wavelength and free-running configurations were obtained arising from the beam cleanup effect of SRS in a graded-index multimode fiber and the mode-selective property of VBGs. For the wavelength-tunable operating regime, wavelength was tuned from 1638.5 to 1675.1 nm, covering a whole tuning range of 37 nm. Further extension of the wavelength tuning range can be easily achieved by altering the pump wavelength.

Acknowledgments

This work is supported by the National Natural Science Foundation of China (NSFC 61078035, 61177045), the Research Fund for the Doctoral Program of Higher Education of China (RFDP: 20110071110016) and the Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD).