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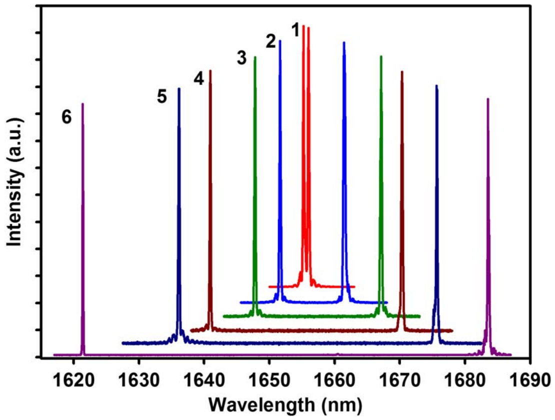

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Novel Raman Fiber Lasers Emitting in the U-Band With Combined Volume Bragg Gratings

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Abstract: Narrow linewidth and widely tunable high-power Raman fiber lasers emitting in the U-band wavelength were demonstrated based on combinations of volume Bragg gratings with different center wavelengths. The narrowed linewidth was 65 pm at a center wavelength of 1657.86 nm with a maximum output power of 8.3 W, corresponding to a slope efficiency of 55.6%. For the tunable Raman fiber laser, continuously tunable dual-wavelength emission was obtained in a wide band (1621.3–1683.5 nm) with a wavelength difference over 60 nm (0.7–62.2 nm). The maximum output power was 11 W, corresponding to a slope efficiency of 76.6%.

Index Terms: Raman fiber laser, volume Bragg gratings, narrow linewidth, dual-wavelength.

1. Introduction

Eye-safe wavelength lasers at ~1.6 μm can be directly applied in lidar, remote sensing, guidance, and free-space optical communication [1], [2], as well as providing an ideal source to generate mid-infrared $(3 \sim 5\ \mu\text{m})$ lasers by optical parametric oscillators [3], [4]. Besides, in many cases, narrow linewidth laser sources are required such as in optical sensor and high resolution spectrum analysis [5]. Therefore, high power, tunable and narrow linewidth laser sources in the 1.6 μm wavelength region have attracted considerable attention in recent years. Directly pumped ion-doped laser mediums and nonlinear frequency conversion are the two main methods to obtain this wavelength band. Active ions used in the direct pumping method include the rear-earth ion Er^{3+} and the transition metal ion Cr^{4+}. For the Er^{3+}-doped lasers, the tuning range covers the C- and L-band in fiber lasers [6]. The U-band in solid state lasers is composed of two discrete parts with center wavelengths at 1634 nm and 1645 nm, respectively [7], [8]. Cr^{4+}-doped materials are usually used to extend the spectral coverage for communication window (1.3–1.7 μm) in amplified spontaneous emission and ultra-short pulse lasers [9], [10]. However, the nonradiative decay, the excited-state absorption and the upconversion in the

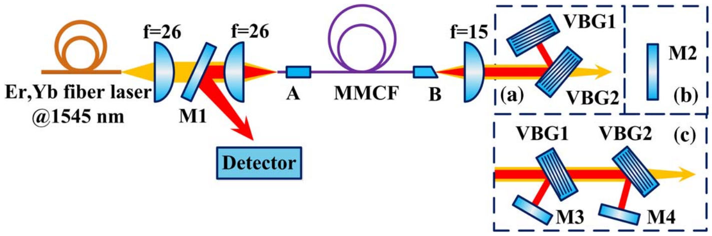

Fig. 1. Experimental setup, including (a) external narrow linewidth resonator, (b) external free-running resonator, and (c) external dual-wavelength resonators based on VBGs.

Cr^{4+}-doped mediums will impede the laser performance and make it not suitable to work in continuous wave lasers [11]. Besides, it is difficult to grow Cr^{4+}-doped materials with high concentration [12]. Optical parametric amplifier is one method to generate the laser at ~1.6 μm [13]. However, in this configuration, a pump source with high peak power is typically required. Compared with the above technologies, Stimulated Raman scattering (SRS) based on the third order nonlinear effect is an efficient technology to extend the spectral coverage due to the wide Raman gain spectrum. In silica fibers, the typical frequency shift is ~13.2 THz, therefore, Stokes spectrum locates in the 1.6–1.7 μm band with pump source of Er^{3+}-doped fiber lasers. Typically, for the tunable Raman fiber lasers, their tunability can be realized by changing the period of the inserted fiber Bragg gratings (FBGs). However, limited by the narrow bandwidth, poor thermal and mechanical strain capacity properties of the FBG (e.g., the thermal tunability is 10.5 pm/°C [14] and the dynamic range is ~50 nm by compression or bending method [15]), the tuning range is not broad enough to meet the need of more applications. Moreover, it is hard to select specific wavelength repeatedly with FBGs [16]. In large mode area fibers, the FBGs are not suitable for narrow linewidth selection. Volume Bragg grating (VBG) recorded in photosensitive silicate glass is attractive for high power and stable wavelength selection management because of its broadband wavelength selective ability and high damage threshold. For a single VBG, the wavelength tuning span can be over 110 nm [6], and for combined VBGs, narrowed spectral linewidth can be 2.2 pm in Tm-doped fiber laser [17] and 38 pm in Er, Yb fiber laser [18]. For the U-band wavelength, as far as we know, there is no report on high power, narrow linewidth and continuously tunable multi-wavelength lasers based on VBGs.

In this letter, we employed two combined VBGs to construct external resonators in Raman fiber lasers using a multimode communication fiber. With serial-aligned VBGs, further narrowed laser spectrum at 1657.86 nm was achieved with linewidth (full-width half-maximum, FWHM) of 65 pm, and the maximum output power was 8.3 W. With parallel-aligned VBGs, a maximum total output power of 11 W was obtained in a wide tuning range (1621.3–1683.5 nm) covering the whole U-band, stable dual-wavelength emission was achieved simultaneously with wavelength difference from 0.7 nm to 62.2 nm. The frequency difference was tunable in a wide band (0.08–6.85 THz).

2. Experimental Setup

The experimental setup is illustrated in Fig. 1. The pump source was an in-house made cladding-pumped Er, Yb-codoped fiber laser with center wavelength of 1545 nm and spectral linewidth of ~0.3 nm. The spectral linewidth was broad enough to suppress the generation of the stimulated Brillouin scattering (SBS). The core diameter of the Er, Yb fiber is 30 μm (0.2 NA). The output of the pump source was free-space coupled into the core of the Raman gain fiber by two lenses with the same focal length of 26 mm. The Raman gain fiber used in our scheme was an ordinary graded-index multiple mode communication fiber (MMCF) (Corning Corporation) with core diameter of 50 μm (0.21 NA) and cladding diameter of 125 μm. About 70% of the pump power was coupled into the core of the Raman gain fiber, and the maximum launched pump power was 21.5 W. Facet B was angle polished at ~8° to suppress the broadband reflection. M1

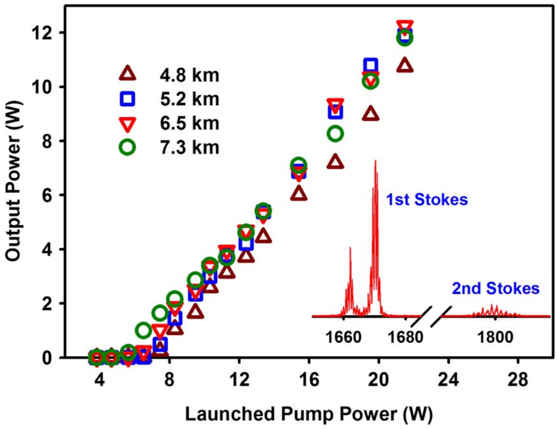

Fig. 2. Output powers as functions of launched pump power for different fiber lengths. (Inset) Laser spectrum of the 6.5 km Raman fiber.

was used to export the Raman laser to the detector. In order to reduce the risk of damage in fiber, two fiber end sections were both mounted in water-cooled aluminum-made V-groove heat sinks which were kept at around 17 °C. Center wavelengths of VBG1 and VBG2 (OptiGrate Corporation) locate at 1658 nm and 1750 nm, respectively. The dimensions of VBG1 and VBG2 are 5 mm × 5 mm × 9 mm and 8 mm × 6 mm × 3.7 mm, respectively. The radius of the collimated beam following the lens $(f = 15\ \text{mm})$ was $\sim$3 mm. Both VBG1 and VBG2 are designed with the spectral selectivities (FWHM) of < 1.6 nm and diffraction efficiencies of $> 98\%$. The two VBGs were mounted in copper blocks. Dichroic mirrors M2 and M1 are high reflectivity $(R > 99\%)$ at 1650–1800 nm and high transmission $(T > 96.9\%)$ at 1530–1590 nm. Plane mirrors M3 and M4 with high reflectivity $(R > 99\%)$ at 1500–1700 nm were placed behind the two VBGs to compose resonators with VBG1 and VBG2, respectively. The feed-back to comprise a laser cavity is provided by the 4% Fresnel reflection at the perpendicularly cleaved fiber facet A in one end, and by the VBG pairs (serial-aligned, section a) or a single high reflective M2 (working in free-running condition, section b) or two pairs of plane mirror and VBG (parallel-aligned, section c) in the opposite end.

3. Experimental Results and Discussions

For the maximum launched power of 21.5 W, an optimal fiber length is necessary for the laser performance. Based on the classic cascaded Raman equations in Ref. [19], optimum total Raman fiber length was simulated to locate at $\sim$7 km. Then, four fibers with different lengths were employed in experiment and worked in the free-running regimes. Stokes output powers as functions of launched pump power based on different fiber lengths are shown in Fig. 2. A maximum output power of 12.3 W was generated for a launched power of 21.5 W when the fiber length was 6.5 km. The laser threshold was reduced with increasing the Raman gain fiber length. An optical spectrum analyzer (AQ6375, Yokogawa) with a spectral resolution of 0.05 nm was used to monitor the laser spectrum. The spectrum for the 6.5 km Raman fiber at the launched pump power of 17.5 W is inserted in Fig. 2 in linear scale. The laser spectrum distributes in a wide range due to the wide Raman gain spectrum. The two peaks in the 1st order Stokes spectrum correspond to Raman frequency shifts of 13.2 THz and 14.7 THz, respectively. At this pump level, the 2nd order Stokes signal was still low enough. It is possible to further improve the laser performance and suppress the second-order Stokes if the reflection range of the coatings of mirror M2 can be controlled in a narrower band.

The 6.5 km Raman gain fiber was chosen to be applied in the resonator in the next experiments. In the free-running condition, the center wavelength of the laser spectrum was measured to be 1670.4 nm with spectral linewidth of 2.5 nm. In order to restrict the spectral linewidth in a narrow band, the VBGs were employed in the resonator. The wavelength-selection

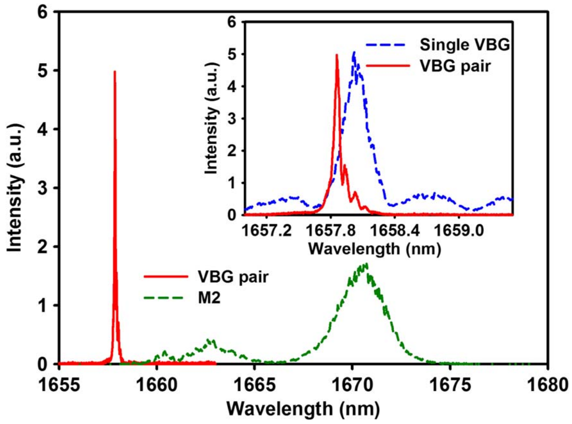

Fig. 3. VBG pair narrowed laser spectrum and free-running laser spectrum. (Inset) Spectrum selected by single VBG and VBG pair at ~1658 nm.

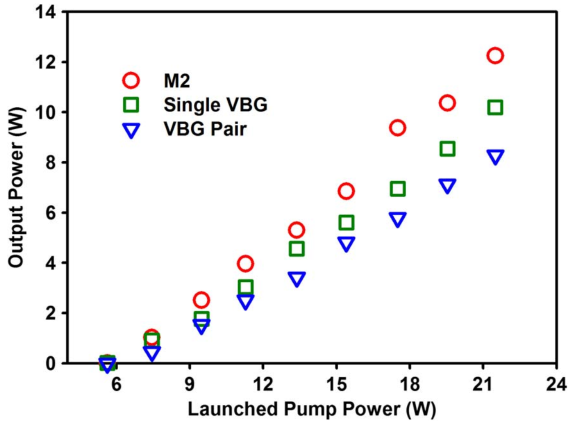

Fig. 4. Output power as functions of the launched pump power for M2, single VBG, and VBG pair.

characteristic of the VBG can be expressed by $\lambda_B = \lambda_0 \cos\theta$ [20], where λ_0 represents the normal incidence wavelength and θ is the incident angle of the laser onto the VBG. Wavelength tuning can be performed simply by adjusting the deflection angles of the VBGs. When we made the VBG1 work in the normal incidence condition (take the place of M2), the laser spectral linewidth was 0.26 nm at 1658.02 nm. In some applications, such as optical sensors, a narrower spectral linewidth is needed. To further narrow the laser spectrum, VBG1 and VBG2 were serial-aligned in the resonator [see Fig. 1(a)]. VBG2 worked in a large incident angle $(\sim 18.7^\circ)$ for ~1658 nm; then, VBG1 worked in normal incidence acting as a feedback mirror to compose a complete resonator. In addition, during the operation, the VBG pair was carefully adjusted to keep high reflectivity to reduce the cavity loss. The mechanism that we can obtain further narrowed laser spectrum is due to the fact that, the pass bands of the filters will achieve an overlap if they are well combined, contributing to a significant reduction in reflective bandwidth of the VBGs, as simulated in [17]. Another optical spectrum analyzer (AQ6370C, Yokogawa) with a spectral resolution of 0.02 nm was used to measure the narrowed laser spectrum, and the result is shown in Fig. 3. As a comparison, the spectrum selected by single VBG1 working in the normal incidence condition was inserted in Fig. 3 in dotted line. At the launched pump power of 15.4 W, the further narrowed spectral linewidth was measured to be 65 pm with center wavelength at 1657.86 nm.

The output powers as functions of the launched pump power of the 6.5 km Raman fiber using M2, single VBG and VBG pair are shown in Fig. 4 for comparison. With M2, the slope efficiency

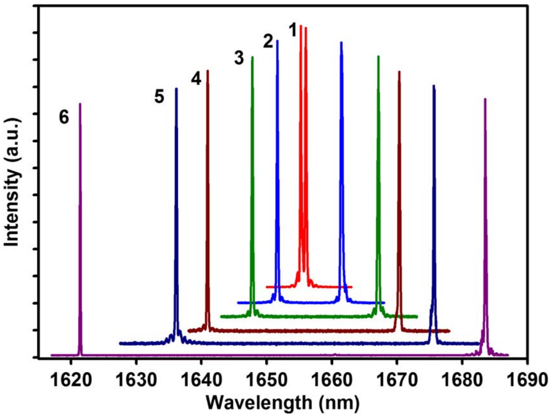

Fig. 5. Laser spectrum of the tunable dual-wavelength pair.

was measured to be 80.1% with respect to the launched pump power. However, due to the lower reflectivity and relatively higher insertion loss of VBG1 than M2, the maximum output power with VBG1 was 10.2 W, corresponding to a slope efficiency of 63.4%. VBGs working in large deflection angle will lead to a reduction in the effective reflectivity and hence a drop in output power, as we have simulated in earlier work [21]. Hence, with VBG pair, the maximum output power was measured to be only 8.3 W, corresponding to a slope efficiency of 55.6%. As there is no sign of saturation for the highest pump power, the output power still can be further improved simply by increasing the pump power. With VBG pair, when the output power was 5.2 W, the beam quality factor M^2 was measured to be $\sim$1.5 by a beam profiler (Nanoscan, Photo).

To generate the terahertz wave by difference signal generation method, a stable dual-wavelength laser is necessary for an optical beat source [22]. To obtain the dual-wavelength emission, the two VBGs were parallel-aligned [see Fig. 1(c)] to generate two wavelengths oscillation simultaneously. The intensity of the two wavelengths can be balanced by adjusting the feedback from the high reflective mirrors M3 and M4. The spectrum (measured by AQ6375, resolution of 0.05 nm) of the tunable dual-wavelength pair for the launched pump power of 17.5 W is shown in Fig. 5. During the operation, the two wavelengths of each wavelength pair were tuned symmetrically to $\sim$1658 nm to achieve roughly equal Raman gain coefficient. The linewidth of each individual wavelength was measured to be $<$ 0.35 nm. The intensity of the two wavelengths was then balanced and the wavelength difference $(\Delta\lambda)$ was tuned from 0.7 nm to 62.2 nm. This corresponds to a possible tunable terahertz frequency range continuously varied from 0.08 THz to 6.85 THz with the center wavelength of 1650 nm. The wavelength tuning range was from 1621.3 nm to 1683.5 nm covering the whole U-band, corresponding to Raman frequency shift varied from 9.15 THz to 16 THz, which was much narrower than the Raman gain band (40 THz) of Ge-doped silica fibers. This is attributed to the fact that, with the decreased Raman gain coefficient, the laser threshold became high obviously for wavelength away from 1658 nm, resulting in a narrow tunable wavelength range under current pump level. For the wavelength away from this range, the corresponding laser output power would drop dramatically.

Fig. 6 shows the corresponding total output power for different dual-wavelength pairs. Due to the decrease of the Raman gain coefficient, the total output power of the dual-wavelength decreased gradually when the corresponding wavelengths were tuned away from 1658 nm. At the wavelengths of 1655.2 nm and 1655.9 nm, the maximum total output power of 11 W was obtained, corresponding to a slope efficiency of 76.6% with respect to the launched pump power. The maximum power value was lower than that obtained in the free-running laser operation. This is due to the fact that VBG2 worked in the incident angle of $\sim 18.9^\circ$ for 1655.9 nm, leading to a reduction in the effective reflectivity. Similarly, because of the large deflection angle and low Raman gain coefficient, the maximum output power was only 3.3 W at the wavelength difference of 62.2 nm. At the wavelength difference of 0.7 nm, the beam propagation factor M^2 was

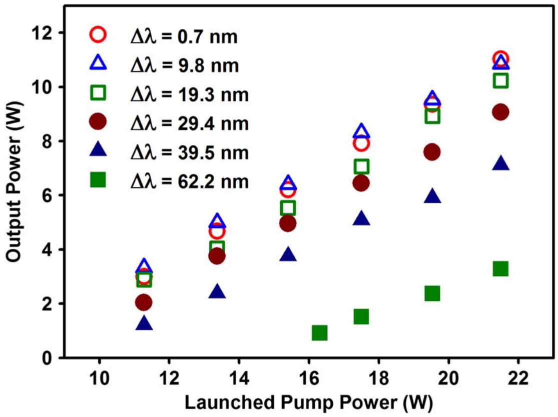

Fig. 6. Output power as functions of the launched pump power for different dual-wavelength pairs.

measured to be ~2.2 for the output power of 3 W. Unbalance intensities of the two wavelengths in short time could be controlled by slightly adjusting their respective feedback, whereas the total output power for the same launched pump power almost remained unchanged. Taking the wavelength difference of 9.8 nm for example, the intensity difference of the two wavelengths could be controlled below 0.6 dB effectively in 5 minutes at the launched pump power of 17.5 W.

4. Concussion

In conclusion, we have demonstrated a narrow linewidth and a widely tunable dual-wavelength Raman fiber lasers in the first-order Stokes range with two combined VBGs. For the narrow linewidth Raman laser, the further narrowed linewidth was 65 pm with center wavelength of 1657.86 nm. For the dual-wavelength Raman laser, the wavelength difference was tunable continuously from 0.7 nm to 62.2 nm. The corresponding tuning range of the laser wavelength covers the whole U-band. With launched pump power of 21.5 W, the maximum output powers were 8.3 W and 11 W, respectively, corresponding to slope efficiencies of 55.6% and 76.6%. The novel lasers have the possibility to be applied in high resolution optical sensors and generating tunable terahertz wave beyond 6.85 THz.

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