Multiwavelength Raman fiber laser with a continuously-tunable spacing

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Abstract: A spacing-tunable multiwavelength Raman fiber laser with an independently-adjustable channel number is proposed and demonstrated. It uses a novel free-spectral-range (FSR)-tunable comb filter based on a superimposed chirped-fiber Bragg grating (CFBG) and a linear cavity formed by a bandwidth-tunable CFBG reflector, a pumped highly-nonlinear fiber for Raman gain, and an optical circulator based loop mirror. Multiwavelength laser operations with spacing tuning from 0.3 to 0.6 nm and channel number adjustment from 2 to 10 have been achieved.

OCIS codes: (140.3510) lasers, fiber; (140.3550) lasers, Raman; (140.3600) lasers, tunable (230.1480) Bragg reflectors

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1. Introduction

Multiwavelength fiber laser sources have attracted a lot of research interests due to their potential applications in wavelength-division-multiplexing (WDM) optical fiber communication, sensing and testing systems. Several gain mechanisms such as erbium-doped fiber, semiconductor optical amplifier and stimulated Raman scattering, have been employed in these lasers [1-9]. Among them, multiwavelength Raman fiber laser has been regarded as a potential and prosperous solution with several important advantages such as the stable multiwavelength operation at room temperature and the extremely broad workable wavelength band nearly without limitation, given pump lasers at the corresponding wavelengths are available [5-7]. For all multiwavelength fiber lasers, the channel spacing should preferably be tunable in order to provide design flexibility and functionality. Because the current WDM systems have different channel spacings based on their specific applications, spacing-tunable multiwavelength lasers may have flexible applications in these systems with various channel spacings. However, most of the multiwavelength fiber lasers reported to date are not tunable or are only discretely tunable in spacing [4-9]. In this paper, based on the successful demonstration of a free-spectral-range (FSR)-tunable comb filter with a superimposed chirped-fiber Bragg gratin (CFBG), we obtain a novel multiwavelength Raman fiber laser with a continuously-tunable spacing and an independently adjustable channel number.

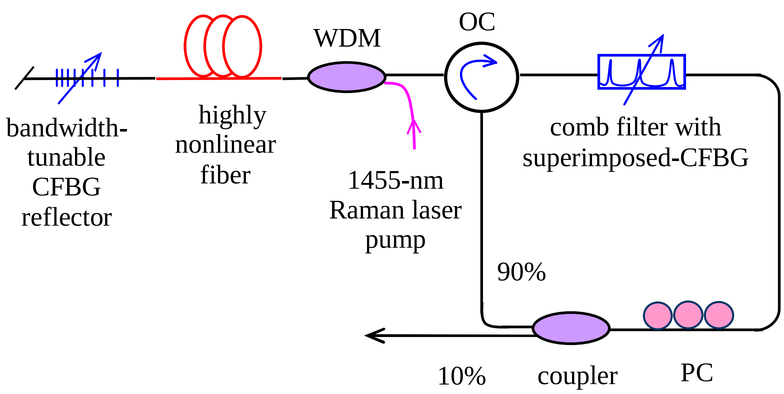

Fig. 1. Proposed laser configuration. CFBG, chirped-fiber Bragg grating; OC, optical circulator; PC, polarization controller; WDM, wavelength division multiplexer.

2. Laser design

The proposed multiwavelength Raman fiber laser, as shown in Fig. 1, has a linear cavity formed by a bandwidth-tunable CFBG reflector, a length of highly nonlinear fiber and an optical circulator (OC)-based loop mirror. In the experiment, the highly nonlinear fiber [a 3-km-long dispersion-compensating fiber (DCF)] is pumped through a 1480/1550 nm WDM coupler by a 1455-nm Raman laser, which has a high output power of ~800 mW. The wavelength of the peak Raman gain is around 1554 nm and the 3-dB gain bandwidth may be up to 20 nm [10]. A novel FSR-tunable comb filter based on a superimposed-CFBG, with details given in following paragraphs, is inserted in the OC-based loop to provide multiple-channel transmission filtering (the reflected light is isolated by the OC) in a wide band of over 20 nm centered at ~1546 nm. The CFBG reflector has an initial bandwidth of 2.6 nm, a center wavelength at 1551.8 nm and a reflectivity higher than 30 dB. Its bandwidth is tuned by using the beam-bending method reported in Ref. [11]. Since the CFBG reflector has a smaller bandwidth than the comb filter, only selected transmission channels with a channel number jointly determined by the bandwidth of the CFBG reflector and the FSR of the comb filter can

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be at resonant. A polarization controller (PC) is used to adjust the polarization state of the intra-cavity light. A 10:90 optical fiber coupler is used to output the laser light through the 10% port.

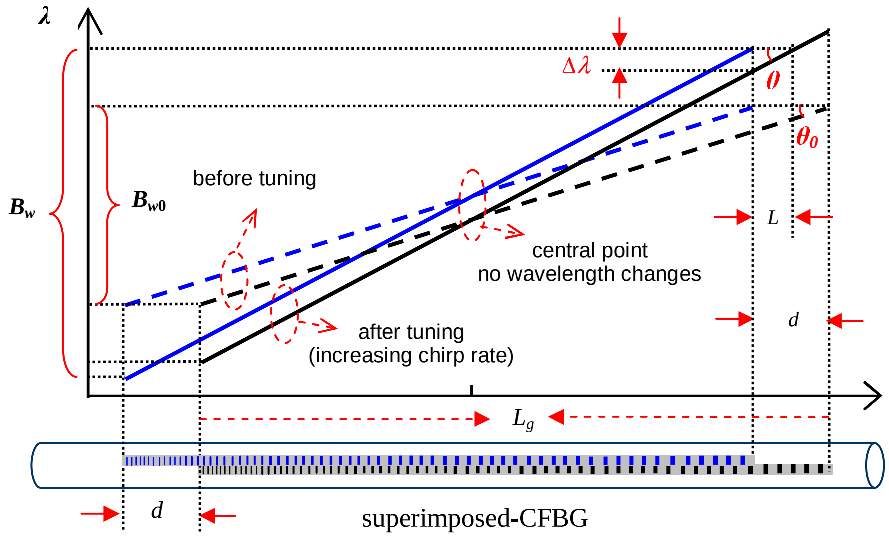

Fig. 2. Schematic diagram of the FSR tuning principle of the superimposed-CFBG comb filter.

3. FSR-tunable filter

The superimposed-CFBG based comb filter can be formed by inscribing two identical CFBGs successively into the same part of a fiber with only a small longitudinal offset between them. Distributed Fabry-Perot interference is then generated in the fiber core due to the reflections of the two CFBGs. This produces a small size, in-fiber comb filter whose FSR is inversely proportional to the longitudinal offset and the effective bandwidth is roughly equal to the reflection bandwidth of the CFBG [12, 13]. Usually, the FSR is fixed once the superimposed-CFBG is fabricated. But, in this work, we found that it can be tuned continuously by changing the chirp rate of the superimposed-CFBG. A schematic diagram of the tuning principle is shown in Fig. 2, where d is the offset between the two CFBGs (also the initial cavity length), L is the cavity length after chirp tuning, L_g is the length of each CFBG, B_{w0} and B_w are bandwidths of the CFBG before and after tuning, respectively. It shows clearly that the cavity length of the distributed Fabry-Perot interference is changed by chirp tuning.

The central point of the superimposed-CFBG is supposed to experience no strain effect by using the chirp tuning method reported in Ref. [11], thus there are no wavelength shifts for the two CFBGs at that point. For each individual point along the superimposed-CFBG, the two CFBGs experience the same strain so that the difference in Bragg wavelength, $\Delta\lambda$, keeps fixed. Based on a geometric analysis of Fig. 2, one can get the following relationship

$$\Delta\lambda = L \cdot tg\theta = d \cdot tg\theta_0 , \tag{1}$$

where

$$tg\theta = B_w / L_g = R_c , \tag{2}$$

$$tg\theta_0 = B_{w0} / L_g = R_{c0} , \tag{3}$$

R_c and R_{co} are the chirp rates of the CFBGs with and without tuning, respectively. Therefore the FSR of the comb filter can be expressed by

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$$FSR = \frac{\lambda^2}{2nL} = FSR_0 (1 + \Delta R_c / R_{c0}) \quad (4)$$

where n is the fiber group index, $FSR_0 = \lambda^2/(2nd)$ is the FSR before tuning, and $\Delta R_c = (R_c - R_{c0})$ is the variation in chirp rate after tuning. It shows that FSR of the comb filter can be changed linearly by tuning chirp rates of the CFBGs.

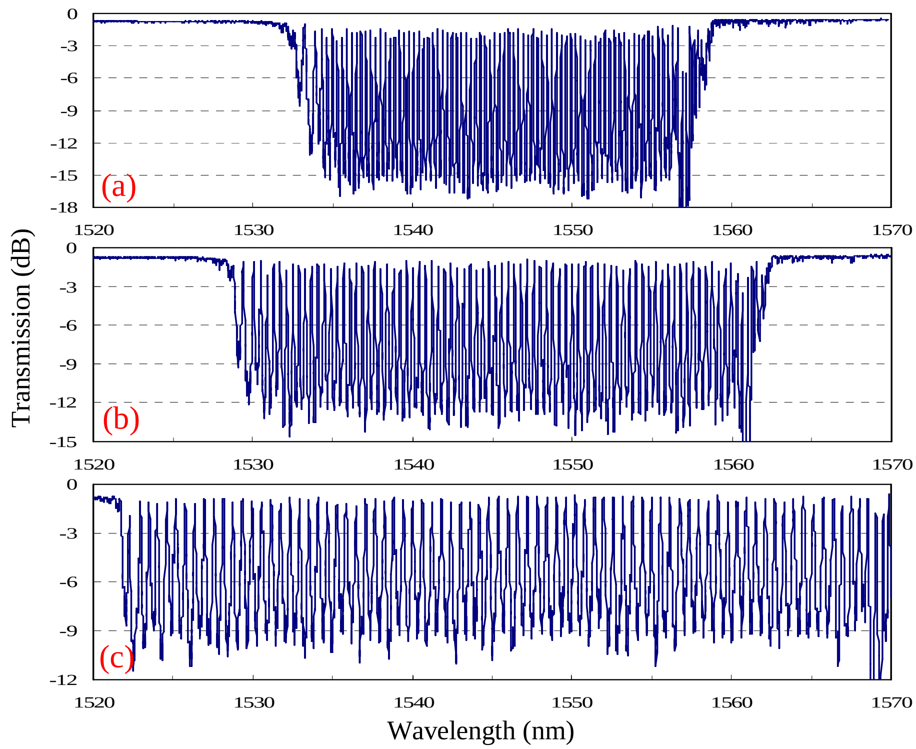

Fig. 3. Transmission spectra of the superimposed-CFBG comb filter (a) with reducing chirp rate, (b) without chirp-tuning and (c) with increasing chirp rate.

In the experiment, the superimposed-CFBG was fabricated in a hydrogen-loaded photo-sensitive fiber using a beam scanning method with a 244-nm, 100-mW, continuous-wave UV laser through a 5-cm-long, 4.8-nm/cm-chirped phase mask. The longitudinal offset between the two CFBGs was ~2 mm. After annealing, it was glued in a slant direction onto the lateral surface of a flexible, right-angled, triangle cantilever beam and tuned by applying a deflection to the cantilever beam at its free end [11]. A linear response can be expected for the FSR-tunable comb filter to the deflection variation since the chirp tuning is also a linear process.

A tunable laser source and an optical spectrum analyzer were used for measurement. Figure 3 shows the transmission spectra of the superimposed-CFBG comb filter measured under the following three situations: with reducing chirp rate (FSR = 0.3 nm), without chirp-tuning (FSR = 0.41 nm), and with increasing chirp rate (FSR = 0.6 nm). It can be seen that the total bandwidth increased greatly with FSR, while the isolation was reduced (from ~15 to 9 dB) because the reflectivity of individual CFBGs was decreased with increasing chirp rate. Within the most part of total bands except for both edges, the insertion losses were slightly reduced and the loss uniformity became better with increasing FSR. The average transmission losses with fluctuations were 1.3 ± 0.5 dB, 0.6 ± 0.4 dB and 0.3 ± 0.3 dB for various FSRs of 0.3, 0.41 and 0.6 nm, respectively. The measured peak linewidths were around 0.05, 0.09 and 0.16 nm for FSRs of 0.3, 0.41 and 0.6 nm, respectively. The small deviations of FSR

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(originally ± 4%) became smaller with increasing FSR. This may be related to the improvement of reflectivity uniformity of the two CFBGs with increasing chirp rate, as well as the reduction of measurement errors as the peak linewidths became larger.

4. Experimental results and discussion

Stable multiwavelength laser operation at room temperature was achieved, and the channel spacing was tuned smoothly through chirp-tuning of the superimposed-CFBG comb filter. Figure 4 shows the measured laser output spectra with different channel spacing of 0.3, 0.4, 0.5 and 0.6 nm, while the CFBG reflector was not tuned. The channel numbers are 9, 7, 6 and 5 and the 3-dB peak linewidths are ~0.055, 0.06, 0.065 and 0.08 nm for different spacing of 0.3, 0.4, 0.5 and 0.6 nm, respectively. The power difference among the laser channels and the side-mode suppression ratio (SMSR) were improved with increasing channel spacing. The minimum power uniformity of 1.7 dB and the best SMSR of 34 dB were achieved in the case of 0.6-nm spacing. The inset shows the laser channel spacing against beam deflection at the free end. A linear tuning rate of 0.054 nm/cm was achieved.

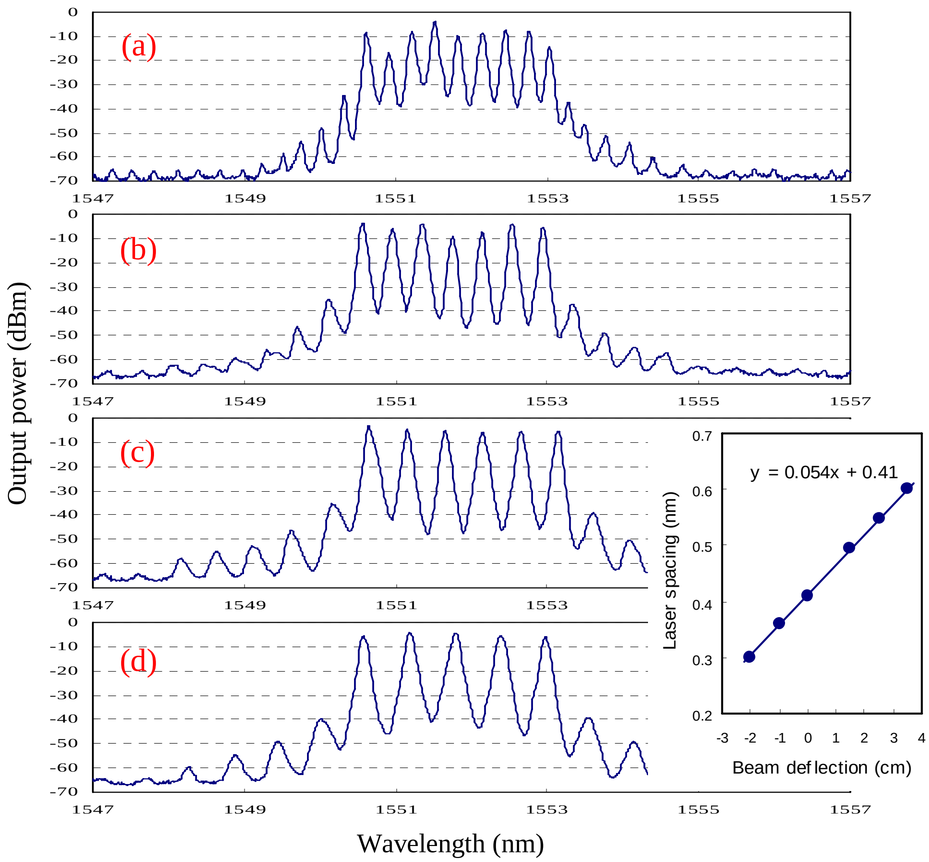

Fig. 4. Laser output spectra with various channel spacing of (a) 0.3, (b) 0.4, (c) 0.5 and (d) 0.6 nm, without tuning of the CFBG reflector. The inset shows the laser spacing against beam deflection. A linear tuning rate of 0.054 nm/cm was achieved.

When the bandwidth of the CFBG reflector was tuned, the channel number can be adjusted independently. In this case, the channel number was jointly determined by the bandwidth of the CFBG reflector and the channel spacing. Laser operations with different channel numbers from 2 to 10 and even more can be achieved. Figure 5 shows the measured laser output spectra with various channel numbers of 2, 4 and 10 at 0.5-nm channel spacing. The corresponding reflection spectra of the CFBG reflector are also shown in this figure by dashed lines; the 3-dB bandwidths are 1.2, 2.2 and 5.2 nm, respectively. Due to the high initial reflectivity of the CFBG reflector, no obvious reduction in reflectivity was observed even when the bandwidth was broadened by two fold. This may help to maintain the good laser performance by keeping a nearly fixed intra-cavity loss when the channel number was changed. The capability of independently adjustable channel number may be very useful in some situations where a specific channel number is required.

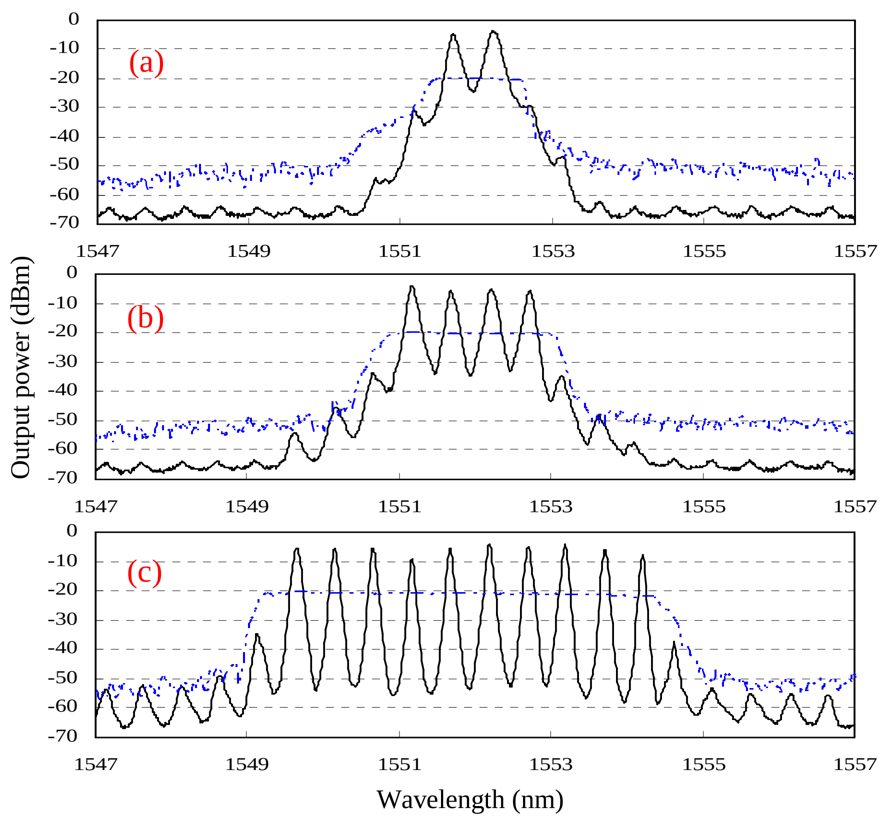

Fig. 5. Laser output spectra with different channel numbers of (a) 2, (b) 4 and (c) 10. The channel spacing is 0.5 nm.

5. Summary

In summary, we have proposed and demonstrated a novel multiwavelength Raman fiber laser source with a continuously-tunable channel spacing and an independently adjustable channel number. The spacing was tuned by using a special FSR-tunable comb filter based on a superimposed-CFBG, and the channel number was adjusted by a bandwidth-tunable CFBG reflector. Multiwavelength laser operations at room temperature with spacing of 0.3 to 0.6 nm, and channel number of 2 to 10 have been achieved.

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