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RESEARCH ARTICLE

Tunable fiber Bragg grating filters realized by chirp rate tuning with a cantilever beam

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Abstract An efficient scheme to change the chirp rate of a fiber Bragg grating (FBG) has been developed based on a specially-designed cantilever beam with the beam-bending method. It allows, to date, the largest tuning range of 36 nm in reflection bandwidth of a chirped-FBG (CFBG) while keeping the center wavelength nearly fixed during the tuning process. Using this method, bandwidth-tunable fiber grating filters with tunable chromatic dispersion or differential group delay have been demonstrated. Channel spacing-tunable multi-wavelength filters based on both sampled- and superimposed-CFBGs have also been realized. Moreover, tuning of the bandwidth and channel spacing is continuous with this scheme that makes the achieved devices more flexible.

Keywords optical filter, fiber Bragg grating, multi-wavelength filter, bandwidth-tunable filter

1 Introduction

Chirped-fiber Bragg gratings (CFBGs) are an important class of fiber gratings that consist of a continuously-varying modulation period or amplitude of the refractive index in the fiber core along the grating length. In addition to their wide reflection spectra, CFBGs also possess unique chromatic dispersion property, which can be used to compensate signal distortion caused by fiber dispersion especially in the high bit-rate, ultra-long haul optical communication systems. Chirp rate tunable CFBGs are wanted in most applications as they provide flexibility to system designers. Various approaches have been reported to tune the chirp rate of CFBGs by using thermal, mechanical, electrical, and magnetic effects. Since the Bragg wavelength of an FBG is sensitive to applied strain, chirp rate tuning can be achieved by applying a strain gradient along the length of the grating with a flexible beam. Several techniques based on the beam-bending method have been proposed [1–6]. However, all these methods show drawbacks such as small tuning range (typically less than 6 nm in bandwidth), relatively large nonlinear chirp caused by non-pure bending and difficulty in operation and precise control. More seriously, most techniques also shifted the center wavelength of the CFBG's reflection during the chirp rate tuning process. This may cause the signal wavelength to locate outside or at the edge of the effective band of the CFBG when it is used as a filter in an optical system or a dispersion compensator in a long-haul communication link.

A simple and efficient scheme based on beam-bending method with a specially-designed cantilever beam has been developed by us [7], which can tune the chirp rate of an FBG over a much larger range up to 6 nm/mm, while keeping the center wavelength nearly unchanged [8]. Bandwidth-tunable filters with tunable chromatic dispersion or differential group delay have been demonstrated [7,9]. Channel spacing-tunable multiwavelength filters based on both sampled- and superimposed-CFBGs have also been demonstrated [8,10]. Moreover, tuning of bandwidth and channel spacing is continuous with this scheme which makes the achieved devices more flexible.

2 Chirp rate tuning scheme

The technique we proposed is based on the beam-bending method but it is in a quite different way from the techniques reported in Refs. [1–5]. The FBG is glued on the lateral surface of the beam in a slanted direction, not on the upper or lower surface along the beam length direction. The working principle is shown in Fig. 1. When the beam

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is bent, different grating segments will experience different strains as they are attached on different beam layers and the strain field generated on the beam lateral surface is dependent on thickness. Here we use coordinate t to describe layers with different thicknesses. The strain on the neutral layer of the beam is zero. As a result, half of the CFBG is under varying tension whereas the other half is under a varying compression. The degree of chirp of the FBG can be varied by bending the beam with different radius of curvature. If the center of the grating is located precisely onto the neutral layer of the beam, there will be no strain effect at the center of the grating. Therefore, the center wavelength of the grating may stay fixed during the process of chirp rate tuning since the strain field is symmetrical at the two halves of the grating.

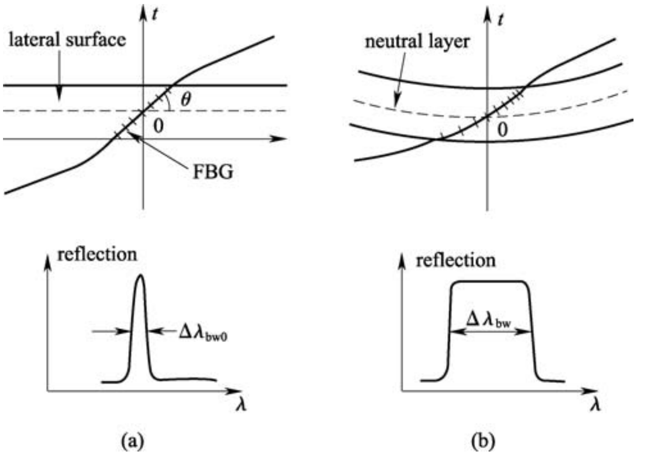

Fig. 1 Principle of proposed beam-bending technique for chirp rate tuning of FBG. (a) Before beam bending; (b) after beam bending

Based on the theory of mechanics of materials, strain introduced by pure bending of the beam with respect to thickness, t, can be expressed as

$$\varepsilon(t) = \kappa t, \quad -0.5h \leqslant t \leqslant 0.5h, \tag{1}$$

where κ is the curvature of the neutral layer of the beam, t is coordinate that describes the layers at different thicknesses with the zero point being set to the neutral layer, h is the total thickness of the beam. The strain is transferred to the FBG and produces an axial strain gradient along the grating, which can be expressed as

$$\varepsilon_{\mathrm{ax}}(t) = C\kappa t\cos\theta, \tag{2}$$

where θ is the angle between the axis of the FBG and the neutral layer of the beam. The effectiveness of the strain transferred from the beam to the FBG depends on a number of factors such as rigidity of the glue and hardness of the material of the beam. This is accounted for by introducing a constant C $(0 < C < 1)$ to Eq. (2). By considering $t = z\sin\theta$, where $-0.5L_{\mathrm{g}} \leqslant z \leqslant 0.5L_{\mathrm{g}}$ and L_{g} is the length of the FBG, the strain field along the grating can be rewritten as

$$\varepsilon_{\mathrm{ax}}(z) = 0.5C\kappa z\sin(2\theta). \tag{3}$$

With such a linear strain gradient applied to the FBG with a center Bragg wavelength of λ_{B} and an initial chirp rate of $\Re_{\mathrm{ch0}}$, chirp rate may be described as

$$\Re_{\mathrm{ch}} = \Re_{\mathrm{ch0}} + 0.5C\lambda_{\mathrm{B}}\kappa(1-p_{\mathrm{e}})\sin(2\theta), \tag{4}$$

where p_{e} is the effective photoelastic constant (~0.22 for silica fibers) of the fiber core material.

The chirp rate of the FBG will change linearly with the beam curvature, so whether the curvature is uniform will be a key factor for achieving or keeping a linear chirp rate. That is why the specially-designed triangle cantilever beam, as shown in Fig. 2, was used. Its curvature, after strict mechanical analysis, is given by

$$\kappa(x) = \frac{2f}{L_{\mathrm{b}}^2}, \tag{5}$$

where x means different position along the beam length, f and L_{b} are deflection at the free end and length of the beam, respectively. Thus, it is independent of x, or uniform along the beam length. Therefore, by simply varying the deflection of the free end of the cantilever beam, tunable chirp rate and bandwidth of the grating can be attained.

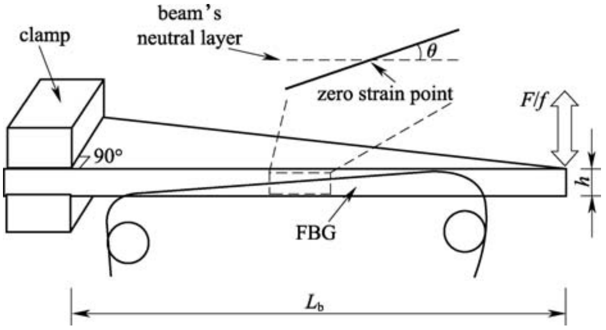

Fig. 2 Experimental setup with a specially-designed triangle cantilever beam for chirp rate tuning

3 Bandwidth tunable filters

In the first experiment, a 6-cm long CFBG was glued onto the lateral surface of a right-angled triangle cantilever beam with length L_{b} = 18 cm, base width b_0 = 3 cm, and thickness $h = 0.8$ cm. The CFBG was written in a hydrogen-loaded photosensitive fiber using beam scanning method with a 244 nm ultra violet (UV) laser and a chirped phase mask. After annealing at 100°C for ~15 hours, it showed high reflectivity better than 0.999. The original 3-dB bandwidth was 19.46 nm. The central Bragg wavelength was 1554.2 nm. The angle (θ) between the axis of the gratings and the natural layer of the beam was 6.5°.

The bandwidth of the initially chirped FBG can be tuned in a much larger range than an initially uniform one since its chirp rate can be reduced in addition to being increased, while for the originally uniform one the chirp rate can only be increased. Figures 3(a) and 3(b) show the reflection and transmission spectra measured at different beam deflections of −4.2, 0, and 4.4 cm (3.8 cm for the transmission spectra). The 3-dB bandwidths are 1.83, 19.46, and 37.85 nm (35.42 nm for the transmission spectra), respectively. The largest recorded bandwidth of the transmission spectra is slightly smaller than that of the reflection one, because the grating was broken after we measured the reflection spectrum at beam deflection of 4.4 cm and the corresponding transmission spectra was not able to be recorded.

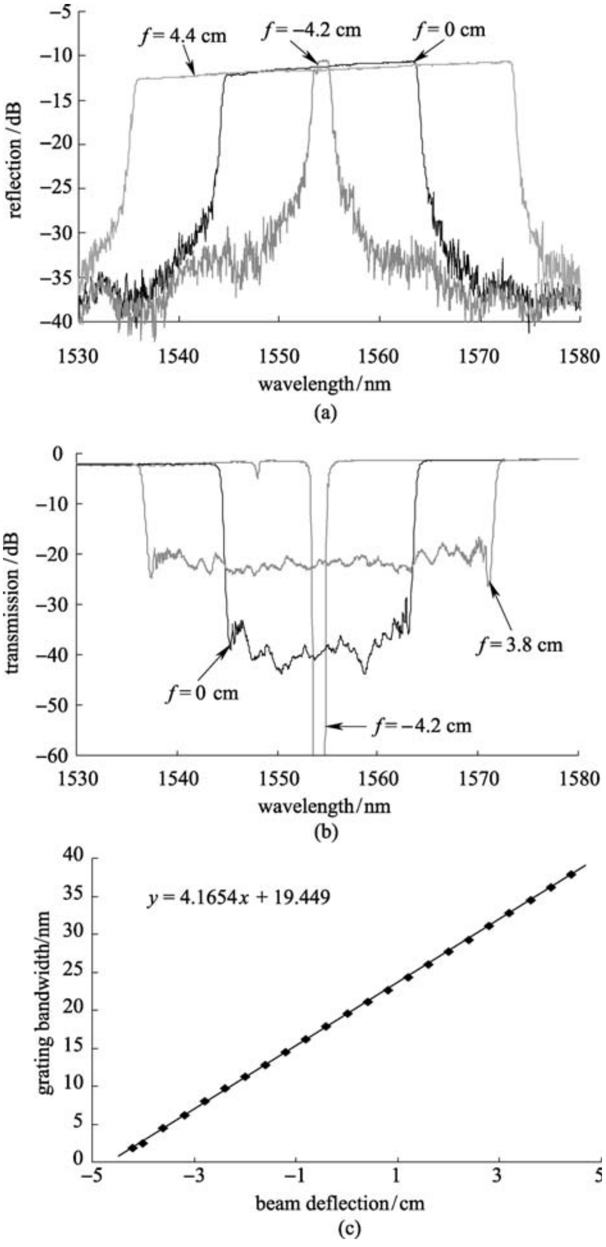

Fig. 3 Some parameters of initially-chirped FBG measured at different beam deflections. (a) Reflection; (b) transmission spectra; (c) bandwidth

It can be seen that the reflectivity was slightly decreased with broadening of the bandwidth. It is very close to 1 (less than −60 dB in the transmission spectrum) in the narrowest case, and ~0.99 (20 dB in Fig. 3(b)). The variation in 3-dB bandwidth versus the applied deflection at the free end of the cantilever beam is shown in Fig. 3(c). The achieved tuning rate in bandwidth was 4.17 nm/cm, indicating a relatively higher strain transfer efficiency factor C of ~0.83. During the tuning process, the measured maximum variation in the center wavelength was less than 0.5 nm. The measured polarization-dependent loss (PDL) was around 0.4 dB and no additional PDL was introduced within the beam-bending chirp rate tuning process.

For measurement of the chromatic dispersion property of the chirp rate-tunable CFBG, we used another 10-cm long CFBG, which was fabricated with an apodization function of half-tangent along the grating length by varying the scanning speed of the UV laser beam. The relatively long length is helpful for increasing the capability of dispersion compensation. The CFBG, which was deeply written in a H_2-loaded single-mode fiber, has a reflectivity higher than 0.999. The original 3-dB bandwidth and center wavelength of the CFBG are 1.61 and 1562.5 nm, respectively. We used the same cantilever beam setup as described above. The only difference is that the angle between the axis of the CFBG and the neutral layer of the beam is $\theta = 4.5°$.

Figure 4 shows the measured reflection spectra and group time delay of the CFBG under different beam deflections. The 3-dB bandwidth can be tuned over a large range from 0.42 to 5.04 nm with high reflection maintained while the variation in center wavelength is only 0.18 nm. Group delay curves show good linearity and low ripples as expected. Chromatic dispersion can be tuned continuously from 178 to over 2100 ps/nm. By taking the value of chromatic dispersion of standard single-mode transmission fibers (~17 ps/nm/km) into account, the length of the transmission fiber, which can be compensated by using the demonstrated dispersion tunable CFBG, is between 10.5 and 125 km. The great flexibility in chromatic dispersion makes it a useful and cost-effective device for applications in different optical fiber systems with different span distances between amplifier stages.

The same method can be used to achieve tunable differential-group-delay (DGD) from a linearly chirped FBG written in a highly-birefringent (Hi-Bi) fiber. A Hi-Bi fiber has two axes, i.e., the fast and slow axes, along which the refractive index and therefore the transmission speed of a signal is different. Once a CFBG is written into such a Hi-Bi fiber, the high birefringence of the fiber gives two almost identical gratings for the orthogonal polarization directions. The wavelength difference of the gratings ($\Delta\lambda$) is determined by the refractive index difference between the two polarization states, i.e., the birefringence. For a

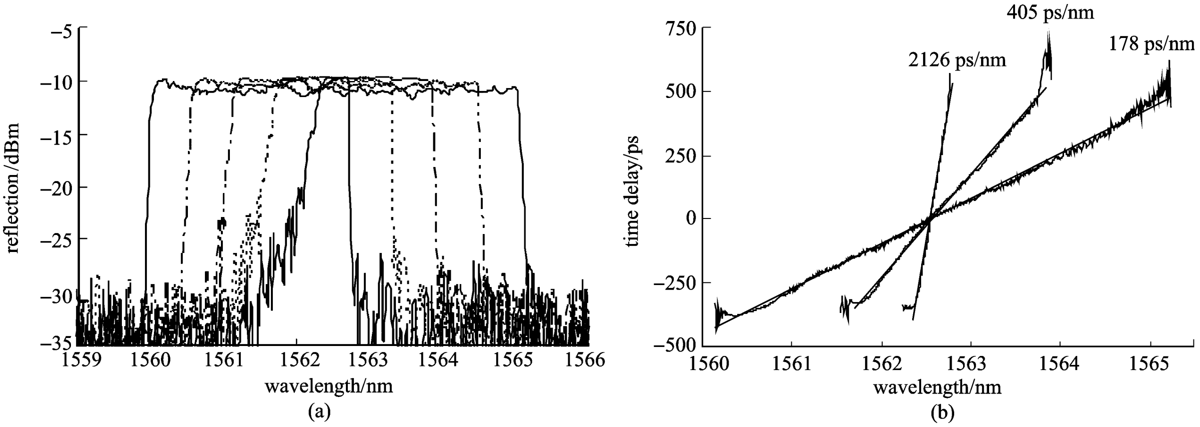

Fig. 4 Chirp rate tuned 10-cm long CFBG. (a) Reflection spectra; (b) time delay curves

linearly chirped FBG, the reflective spectra of the two polarization states are mostly overlapped, as shown in Fig. 5.

For a given signal wavelength component (λ_i), the Bragg reflection from the chirped grating occurs at different locations along the grating for different polarization states, producing a difference in time delay (Δt) between the two polarization states, i.e., DGD. When the chirp rate of the linearly chirped FBG written in Hi-Bi fiber is changed, the slope of the time delay, i.e., dispersion, of each polarization state will also be changed. This will result in a variable DGD between the two polarization states, as shown in Fig. 5, because $\Delta\lambda$ is consistent.

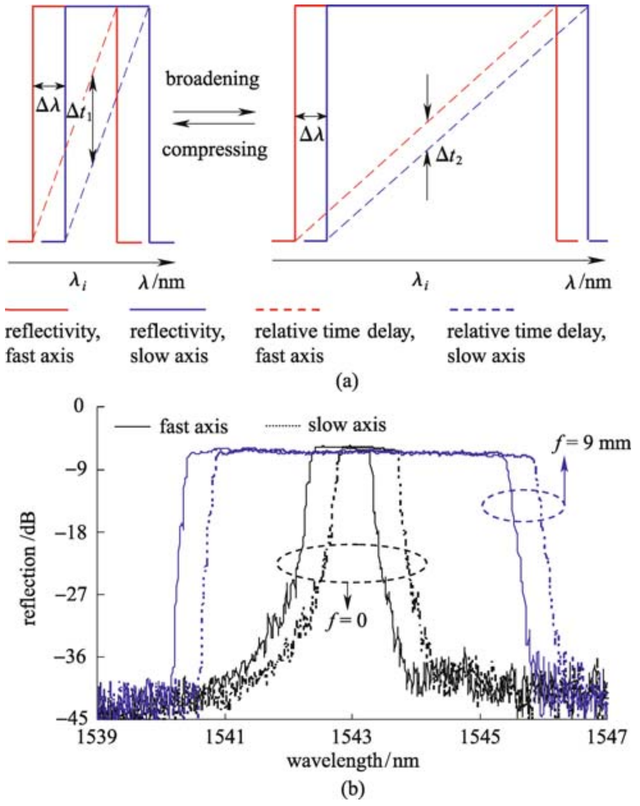

Fig. 5 Tuning DGD in a chirp rate tunable linearly chirped FBG written in Hi-Bi fiber. (a) Principle; (b) measured reflection spectra

In the experiment, the linearly chirped FBG was fabricated by exposing a hydrogen-loaded high-birefringence fiber to a 244 nm laser beam through a linearly chirped phase mask. The length of the grating was 11.4 cm. The 3-dB bandwidth for each polarization state was 0.96 nm, and the central Bragg wavelengths were 1542.82 and 1543.24 nm for the fast and slow axes, respectively (i.e., $\Delta\lambda = 0.42$ nm). To avoid signal loss due to the leakage of the grating, the reflectivity of the original grating was about 99.9% within the effective bandwidth. We used the same beam-bending tuning setup as used in the above experiments. The angle between the axis of the grating and the central axis of the lateral side of the beam was 4° in this case.

By applying vertical deflection at the free end of the beam, the bandwidth of the grating for both the polarization states can be broadened significantly to 5.02 nm with high reflectivity being maintained, and compressed to less than 0.42 nm (where the two spectral peaks for both polarization states were separated and even without any overlapping). Figure 5(b) shows the measured reflection spectra for displacements of $f = 0$ and 9 mm, where the 3-dB bandwidths are 0.96 and 5.02 nm, respectively.

The measured DGD and 3-dB bandwidth versus the beam deflections are shown in Fig. 6. A broad DGD tuning range of 447 ps (106 to 553 ps) and a large bandwidth tuning rate of 4.5 nm/mm were achieved. The measured shift in the center Bragg wavelength for both the polarization states was less than 0.15 nm. In the experiment, a micrometer of 10-μm resolution was used to adjust the deflection at the free end of the cantilever beam. Thus, high precision control with a resolution of 0.0045 nm can be achieved for 3-dB bandwidth, which corresponds to a DGD resolution of 2.6 ps at a bandwidth of 0.96 nm and a higher DGD resolution for a broader bandwidth.

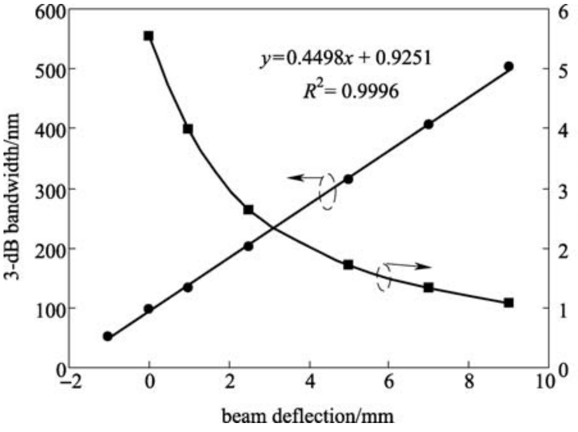

Fig. 6 3-dB bandwidth and DGD against beam deflection for chirp rate tunable linearly chirped FBG written in Hi-Bi fiber

4 Spacing-tunable multichannel filters

Sampled-CFBG is an excellent optical fiber multichannel filter, whose channel number is determined by the number of grating samples and, most importantly, the channel spacing can be continuously tuned by using the chirp rate tuning technique proposed here. In the experiment, the sampled-CFBG composed ten 2.5-mm-long grating samples and nine 3.5-mm-long spaces. There were ten reflection peaks or channels around the wavelength of 1545 nm and the initial wavelength spacing was 1.96 nm. The reflectivity for each channel was no less than 18 dB (~98.4%).

In the experiment, the channel spacing of the sampled-CFBG was tuned continuously in a large range of over 2 nm. Figure 7 shows the measured reflection spectra of the multichannel filter under two different tuning conditions of $f = -1.8$, 0, and 3.1 cm. The measured channel spacing were 1.21 ± 0.02, 1.96 ± 0.03, and 3.32 ± 0.05 nm, respectively. The small errors were caused by errors in grating sample separation and inscription intensity control of different grating samples. The tuning rate of wavelength spacing against beam deflection was 0.42 nm/cm. It is worth noting that the bandwidth for each channel was also increased when the channel spacing was increased. The average 3-dB channel bandwidths were 0.9, 1.1, and 1.4 nm for the above three spacing, respectively.

Multichannel filters based on sampled-CFBG showed continuously tunable channel spacing; however, the channel number was limited by the number of grating samples, which is difficult to be increased largely due to the relatively large bandwidth of each channel over the total reflection bandwidth. To increase the number of channels, we developed a new design based on distributed Fabry-Perot filters (FPFs) with superimposed-CFBGs. Figure 8 shows the schematic diagram and its working principle of channel spacing (or free-spectral range, FSR) tuning. Two identical CFBGs were written into the same part of the fiber core with a small longitudinal offset of *d* (*d* is also the initial cavity length). If the chirp rates of both CFBGs are changed by using the beam-bending method, this ensures the Bragg wavelengths at the central point of the grating is unchanged by gluing the grating center at the neutral layer of the cantilever beam. Because of the existence of the longitudinal offset between the two CFBGs, the corresponding grating segments with the same resonant wavelengths at the two CFBGs will experience different strain level. That is, changes in their resonant wavelengths are different. As a result, the cavity length and therefore the FSR of the FPF are changed. It can be seen in Fig. 8 that the cavity length after chirp rate tuning, L_c, is obviously different from the initial one, *d*.

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

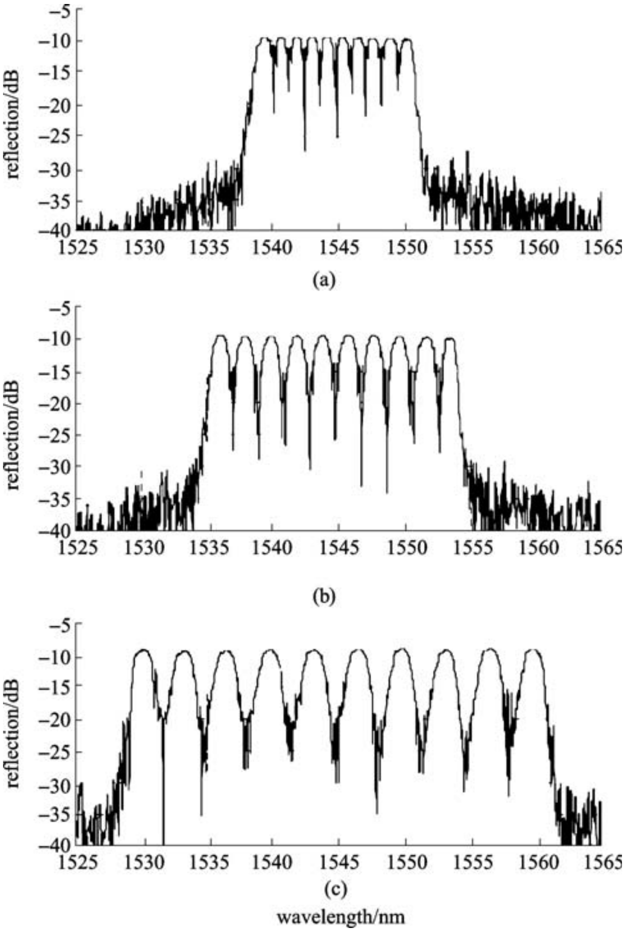

Fig. 7 Reflection spectra of sampled-CFBG based spacing-tunable filter for various displacement. (a) $f = -1.8$ cm (corresponding spacing is 1.21 nm); (b) $f = 0$ cm (corresponding spacing is 1.96 nm); (c) $f = 3.1$ cm (corresponding spacing is 3.32 nm)

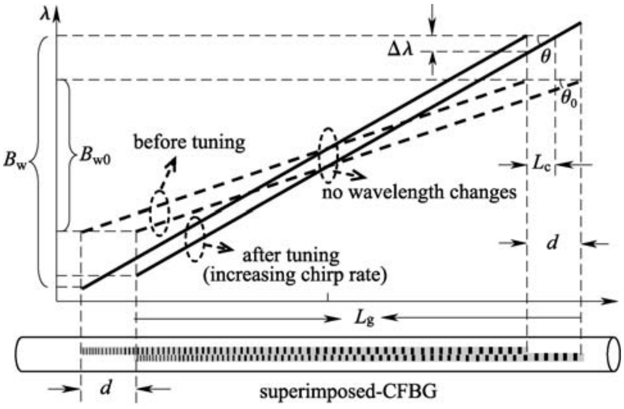

Fig. 8 Working principle of FSR-tunable Fabry-Perot filter with superimposed-CFBG

two CFBGs was ~2 mm. After annealing, it was glued to the cantilever beam with the same size parameters and tuned in the way as aforementioned. The angle between the axis of the CFBGs and the neutral layer of the beam was ~8.2°. A tunable laser source and an optical spectrum analyzer were used for measurement.

With deflection applied to the cantilever beam, continuously variable FSRs have been obtained with a tuning rate of 0.054 nm/cm. Figure 9 shows the transmission spectra of the FPF measured under the following three situations: with reducing chirp rate (FSR is 0.3 nm), without chirp-tuning (FSR is 0.41 nm), and with increasing chirp rate (FSR is 0.6 nm). As FSR was increased, the total effective bandwidth increased also, while the number of transmission channels kept unchanged. Figure 10 shows the measured FSR and finesse of the FPF against deflection of the cantilever beam at the free end. The increase in chirp rate of CFBGs reduced their reflectivity, resulting in a weakened extinction ratio of the interference pattern of the FPF, which were about 15, 12, 11, and 9 dB for FSR of 0.3, 0.4, 0.5, and 0.6 nm, respectively. The nonuniformity in extinction ratio and transmission was mainly caused by the nonuniformity in reflectivity of the CFBGs due to the smudged phase mask and small beam vibrations of UV laser during grating inscription.

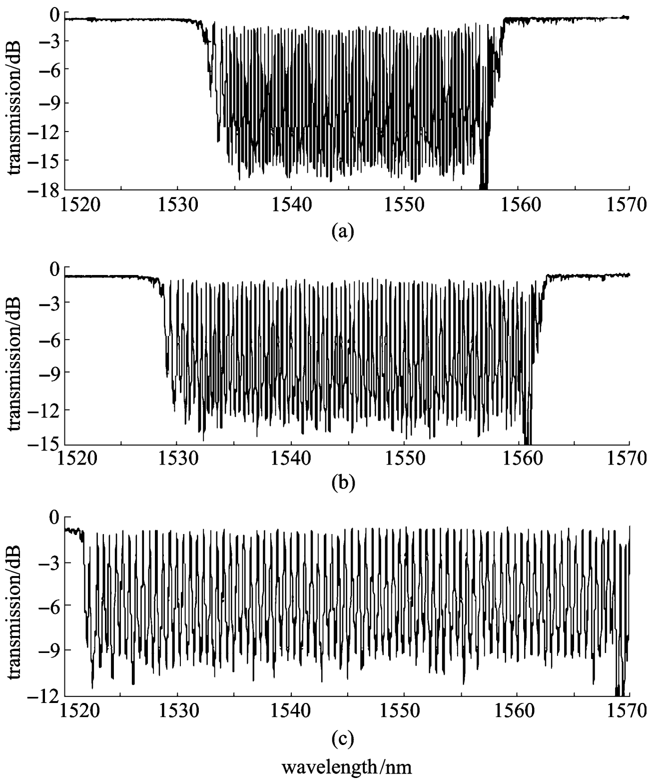

Fig. 9 Transmission spectra of superimposed-CFBG based FPF. (a) Reduced chirp rate; (b) initial chirp rate; (c) increased chirp rate

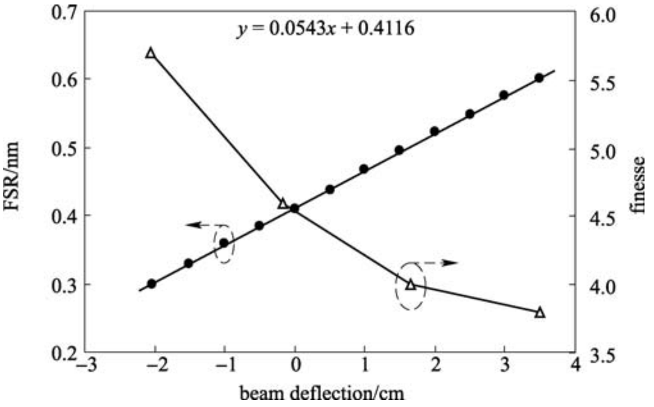

Fig. 10 FSR and finesse against beam deflection for FSR-tunable Fabry-Perot filter with superimposed-CFBG

5 Conclusion

A simple beam-bending technique has been developed to tune the chirp rate of FBGs over a large range, while the center wavelength can be kept nearly unchanged. Bandwidth tunable optical fiber filters with tunable chromatic dispersion or DGD have been demonstrated. Channel spacing-tunable multiwavelength filters based on sampled- or superimposed-CFBGs have also been demonstrated. Continuous tuning of bandwidth and channel spacing has been achieved, which makes the developed filters more flexible in practical applications.

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