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Multichannel comb filter based on linearly chirped fiber Bragg grating and DC phase shift

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A novel approach to implement high channel-count comb filters based on a DC phase shift is proposed. Various channel spacings can be achieved by a single chirped phase mask and a submicrometer-precision translation stage. Simulation and experiment show that arbitrary phase shifts introduced by DC refractive index modulation can be achieved. An multichannel comb filter with channel spacing of 100 GHz, 50 GHz and 40 GHz is implemented with the same phase mask. A comparison between the proposed DC phase shift and traditional discrete phase shift is made.

Keywords: optical communication, fiber Bragg grating, comb filter, DC refractive index modulation, phase shift.

1. Introduction

Fiber Bragg gratings (FBGs) are essential optical devices ranging from optical communications to sensor applications. In recent years, multichannel FBG filters (MCFBGFs) are especially attractive for dense wavelength division multiplexing (DWDM) applications and increasing system capacity in the existing long-haul fiber transmission systems because of their compactness, low insertion loss, and comb filter response [1–3]. Therefore, the design of MCFBGFs has received considerable attention and many methods have been proposed in this respect.

In [4], multiple phase shifts (MPS) are introduced in sampled fiber Bragg gratings (SFBGs) to realize dense channel spacing. It can densify spectrum of SFBGs both spectrally and spatially. However, the main limitation is that the frequency comb exhibits discrete phase shifts among the individual wavelength channels, and the side band suppression ratio (SBSR) is low, which potentially limits the range of applications of this filter. However, the phase fluctuations can be compensated by concatenating in series a second filter identical to the first one, only with opposite phase shift [5]. But, this method can only improve SBSR about 3 dB. Periodically chirped sampled fiber Bragg gratings (PC-SFBGs) are proposed as multichannel comb filters by ZOU *et al*. [6]. But this method needs a periodically chirped phase mask, which is hard to apply. Another approach has been demonstrated based on linearly chirped SFBG (LC-SFBG). This method has the advantage that high-performance comb filters can be fabricated by simple technology. However, for a given phase mask, only FBGs with special channel spacing can be fabricated [7, 8]. CHINHUA WANG showed that for specific conditions between the grating chirp and sampling period, the channel spacing can be reduced compared to the value obtained using conventional sampling techniques [9]. However, channel spacing can only be densified for the times of *N*. This method is developed in [10], in which varying channel spacing can be achieved by a single strongly chirped phase mask with phase shifts. The required phase shift is obtained by a precise translation stage, so it is complex and expensive.

In this paper, a novel approach to implement high channel-count comb filters based on DC phase shift is proposed. Various channel spacing can be achieved by a single chirped phase mask and a submicrometer-precision translation stage. A comparison between the proposed DC phase shift and traditional discrete phase shift is made, which shows a good agreement. The proposed method is cost-effective, flexible and simple compared to traditional ones.

2. Principle

The index modulation $\Delta n(z)$ of LC-SFBG can be expressed as

$$n(z) = n_0 + \Delta n_{AC}(z)\frac{1}{2}s(z)\exp\left(j\frac{2\pi z}{\Lambda}\right) + \Delta n_{DC}(z) \tag{1}$$

where n_0 is the effective core index, $\Delta n_{AC}(z)$ and $\Delta n_{DC}(z)$ stand for the AC and DC refractive index modulation. The sampling function $s(z)$ can be as follows:

$$s(z) = \sum_k f(z - kP)\exp\left(-j\frac{\pi C}{\Lambda_0^2}z^2\right)\exp\left(-j\sum_{l=1}^{k-1}(2l-1)\alpha\right) \tag{2}$$

where $f(z)$ is the index modulation amplitude of each sample, P is the sampling period, $(2l-1)\alpha$ is a phase shift introduced after the k-th sample, Λ_0 is the central period of chirped-fiber Bragg grating (CFBG), C is the chirp coefficient. With the theory of spectral Talbot effect, when C and α satisfy

$$\frac{CP^2}{\Lambda_0^2}\pi + \alpha = \frac{\pi}{T} \tag{3}$$

where T is positive integers, then the channel spacing $\Delta\lambda$ is

$$\Delta\lambda = \frac{2n\Lambda_0^2}{TP} \tag{4}$$

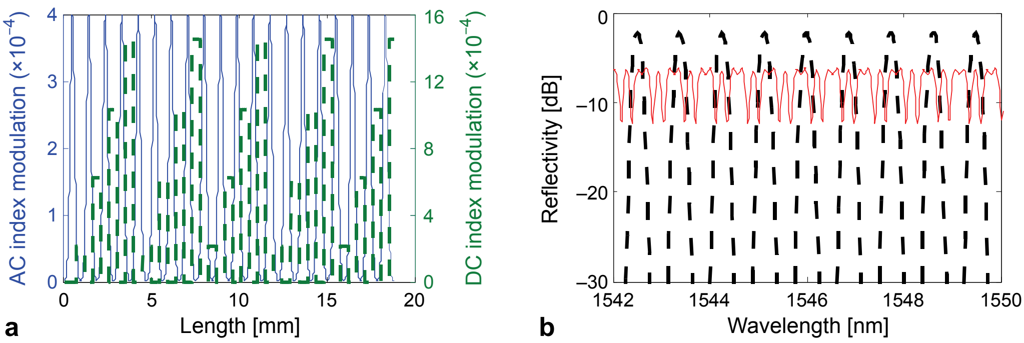

Fig. 1. Simulation example of comb filter: DC refractive index modulation (dotted line) and AC refractive index modulation (solid line) distribution (**a**); reflectivity with (dotted line) and without (solid line) DC phase shift (**b**).

It can be seen that when $\alpha = 0$, the sampled FBG is exactly the LC-SFBG demonstrated in [7] ($T = 1$) and ($T \geq 1$) [9]. However, through the introduction of α, various channel spacing can be achieved with the same phase mask (the same C).

According to Eq. (1), if $\Delta n_{\mathrm{DC}}(z)$ change, a phase can be introduced correspondingly. This is because when $\Delta n_{\mathrm{DC}}(z)$ increase, the time needed for the light to be transmitted the same length is increased, so the phase of light is changed. With DC phase shift we will not need a precise translation stage of nanometer dimension, a submicrometer--precision translation stage is enough. Figure 1**a** shows an AC index and DC index refractive modulation distribution of the proposed multichannel FBG. Figure 1**b** shows the reflectivity spectrum with and without DC phase shift. In the simulation, $n = 1.4775$, $\Lambda_0 = 534.16$ nm, $C = 2.4$ nm/cm, $T = 1$, $P = 1.086$ mm and then $\alpha = 0.25\pi$ from (3). The apodization profile of each sample is a Gaussian function with a full-width at half-maximum (FWHM) of about 0.3 mm.

3. Experiment

To implement the proposed comb filter based on DC phase shift, it is important to control the precision of DC refractive index change. We use the MPS technique to make sure the DC refractive index change [4]. When applying the DC phase shifts $\varphi_k = 2\pi k/m$, between the k-th and the $(k+1)$-th FBGs, the channel spacing Δf_{MPS} becomes

$$\Delta f_{\mathrm{MPS}} = \frac{\Delta f}{m} = \frac{c}{2mnL_s} \tag{5}$$

where c is the velocity of light, n is the effective refractive index, and L_s is the sampling period.

Figure 2 shows a simulated reflective spectrum with DC phase shift ($m = 2$). When DC phase shifts of 0 and π are introduced alternatively to the FBGs, the reflective spectrum (bold line) is symmetrical to the initial reflectivity (thin line). When DC

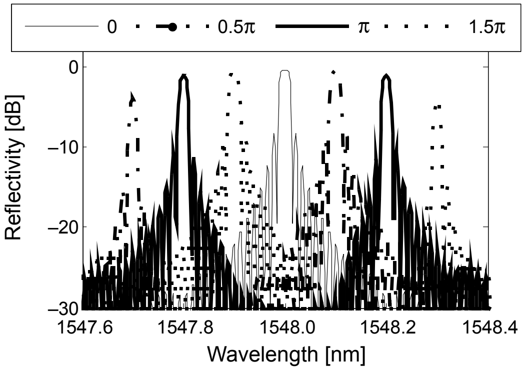

Fig. 2. Simulated reflective spectrum with different DC phase shifts ($m = 2$).

phase shift is not alternative 0 and π, the reflectivity is asymmetrical to the initial reflectivity, as indicated by the dotted line and dashed line. Through this method, we can test the DC phase shift at the position without AC refractive index modulation precisely.

After several tests, SFBGs with 2/3π, π, 4/3π and 2π phase shifts are fabricated with a frequency doubled argon-ion laser operating at 244 nm and Physik Instrumente's

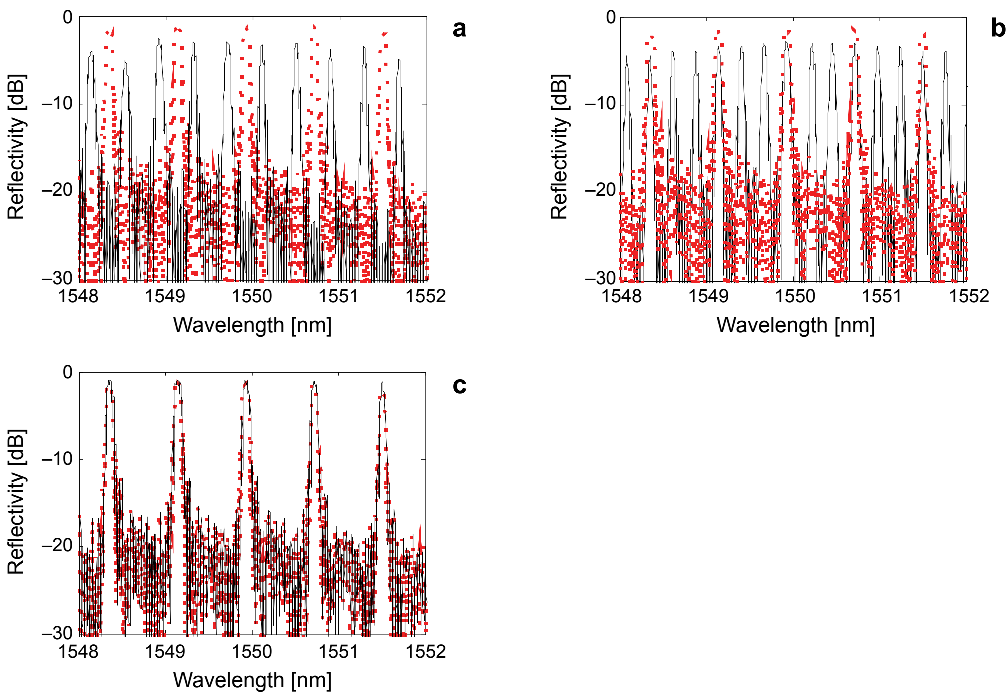

Fig. 3. Measured reflectivity of fabricated fiber with (solid line) and without DC phase shift (dotted line): 0, π DC phase shift, alternately (**a**); 0, 2π/3, 4π/3 DC phase shift, alternately (**b**); 0, 2π DC phase shift, alternately (**c**).

translation stage (submicrometer-precision) on hydrogen-loaded Ge-doped photosensitive fibers and then measured by a Luna optical vector analyzer. Figure 3 shows the measured reflective spectrum of fabricated fiber with and without DC phase shift. The total length of the FBG is 6 cm and the DC length (located in the middle of each sampling period) is 500 μm. The power of ultraviolet (UV) light is 15 mW. The DC refractive index is increased by 5.167×10^{-4}, 7.750×10^{-4}, 1.033×10^{-3}, 1.550×10^{-3} for $2\pi/3$, π, $4\pi/3$, 2π phase shifts, and the exposure times are 14.2 s, 21.5 s, 28.8 s, 43.3 s, respectively. The exposure time is nearly linear to the phase shift, as refractive index change is not at the saturated status.

4. Results

Based on the DC phase shift method, the reflectivity responses of comb filters with different channel spacing are achieved with a given phase mask, which are plotted in Fig. 4.

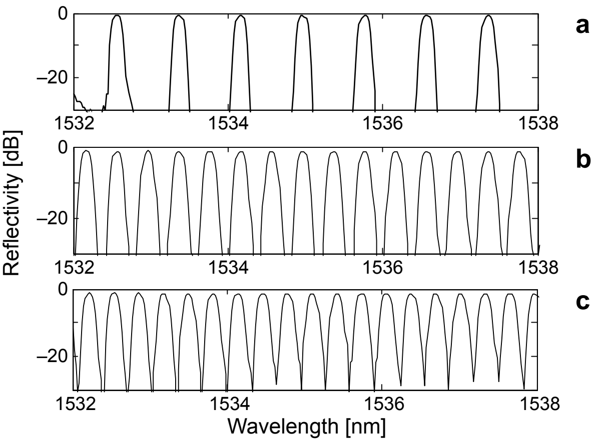

Fig. 4. Reflective spectrum of comb filter with DC phase shift (C = 1.15 nm/cm): $\Delta\lambda$ = 100 GHz, T = 1, P = 0.99 mm, α = 0.5855π (**a**); $\Delta\lambda$ = 50 GHz, T = 2, P = 0.99 mm, α = 0.0877π (**b**); $\Delta\lambda$ = 40 GHz, T = 3, P = 0.825 mm, α = 0.047π (**c**).

In the design, Λ = 530.65 nm, C = 1.15 nm/cm. The apodization profile of each sample is a Gaussian function with a full-width at half-maximum (FWHM) of about 0.3 mm. The length of DC refractive index modulation is 500 μm, and the maximum DC refractive index change is 1.544×10^{-3}, 1.509×10^{-3} and 1.493×10^{-3}, respectively.

Figure 5 shows the reflectivity responses with direct phase shift and DC phase shifted method with the parameter as that of Fig. 4**a**. It can be seen that the proportion of DC length to the total sampling length can affect the SBSR of reflective spectrum. With an increase of DC length, the SBSR decreases. This is because the shorter length of a DC phase shift means that the DC phase shift gets closer to a discrete one. The longer length of a DC phase shift means the more of interchannel phase

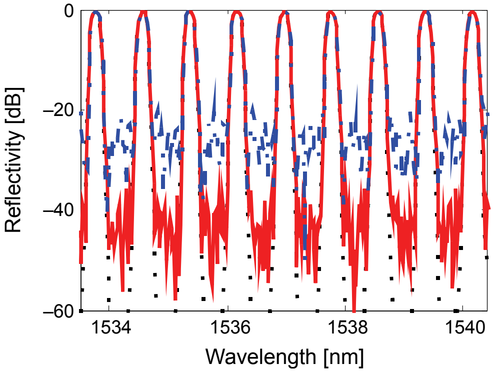

Fig. 5. Comparison of direct phase shift and DC phase shifted method. Direct phase shift (dotted line), the length of subgrating with DC phase shift is 500 μm (solid line) and the length of subgrating with DC phase shift is 800 μm (dashed line).

fluctuations, so the SBSR decreases. However, the DC length is also limited by the maximum refractive index modulation. So, there is a trade-off between the proportion of DC length and the SBSR. Through changing the proportion of DC length, we can fabricate a comb filter with different SBSR as we needed, if only the DC refractive index change is not at saturated status.

5. Conclusions

In this paper, a novel approach to implement high channel-count comb filters based on DC phase shift is proposed. Various channel spacing can be achieved by a single chirped phase mask and a submicrometer-precision translation stage. Simulation and experiment show that arbitrary phase shifts introduced by DC refractive index modulation can be achieved. Multichannel comb filter with channel spacing of 100 GHz, 50 GHz and 40 GHz is implemented with the same phase mask. A comparison between the proposed DC phase shift and traditional discrete phase shift is made. With the decrease of DC length proportion, the SBSR increases. However, the DC length is also limited by the maximum refractive index modulation. So, there is a trade-off between the proportion of DC length and the SBSR. The proposed method is cost-effective, flexible and simple compared to traditional ones.

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