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Analysis and application of phase shift for identical multiple wavelength sampled fiber Bragg grating

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A novel identical multiple wavelength sampled fiber Bragg grating (FBG) is proposed. A phase shift between the two adjacent FBG units is achieved by increasing the direct current (DC) refractive index of the FBG. The FBG with identical reflective spectrum is optimized with a designed sampling function. DC phase shift FBGs are analyzed and fabricated, which shows a good agreement with a discrete phase shift method. A dual-wavelength (DW) filter with channel spacing 0.16 nm is fabricated, and the experiment results verified the feasibility of this proposed method. A four-wavelength filter with channel spacing 0.16 nm is then proposed and demonstrated. This method has the following advantages: wavelength design is flexible, fabrication precision and costs are low.

Keywords: fiber optics, fiber Bragg grating (FBG), phase shift, multiple wavelength.

1. Introduction

Fiber Bragg gratings (FBGs) are essential optical devices for optical communications and sensors [1, 2], thanks to the advantages such as small size, low loss, high reliability and compatibility with other fiber or waveguide components. Sampled fiber Bragg gratings (SFBGs) extend the application area of fiber grating, and have advantages of low manufacture precision and high design flexibility. SFBG, which is periodically modulated by the refractive-index amplitude in the fiber, has the capacity of generating multiple channels. However, the traditional SFBGs that have been utilized by simple binary sampling functions create multiple channels with uneven strength and unequal bandwidth.

On the other hand, identical multiple wavelength filters, especially identical dual--wavelength (DW) filters, are especially attractive for microwave signal generation, dense wavelength division multiplexing (DWDM) and radio over fiber (ROF) applications [3–10]. Therefore, the design of DW filter has received a considerable attention and many methods have been proposed. An equivalent phase shift (EPS) method can implement an ultra-narrow DW filter [11, 12], but the basic sampling structure makes the ±1 order channels much weak than the peak index modulation, which greatly decreases the efficiency of the devices. A direct phase shift induced by a piezoelectric transducer (PZT) or thermal head is another method [13, 14], but this method also needs to connect another fiber grating reflector, which is complex and hard to adjust. LIU proposed that when the sampling function is a rectangle with duty cycle 2/3, the Fourier spectral component at $m = 1$ is the same as the values at $m = -1$ [15, 16]. But if in the Fourier spectral still exist high-order spectral components, this will impact the DW filter performance. Moreover, a translation stage with nanometer precision is needed to induce a discrete phase shift.

In this paper, a novel identical multiple wavelength SFBG is proposed. The phase shift between the two adjacent FBG units is achieved by increasing the direct current (DC) refractive index of the FBG. The FBG with identical reflective spectrum is optimized with a designed sampling function. DC phase shift FBGs are analyzed and fabricated, which shows a good agreement with a discrete phase shift method. DW filter with channel spacing 0.16nm is fabricated, and the experiment results verified the feasibility of this proposed method. A four-wavelength filter with channel spacing 0.16 nm is then proposed and demonstrated. This method has the following advantages: wavelength design is flexible, fabrication precision and costs are low.

2. Theory

The refractive index $n(z)$ of FBG can be expressed as

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

where n_0 is the effective (background) refractive index, $\Delta n_{AC}(z)$ and $\Delta n_{DC}(z)$ are the AC and DC refractive index modulation, Λ is the grating period. The AC refractive index modulation of sampled grating along the propagation axis z can be given by [17]:

$$\Delta n_{AC}(z) = \left[f(z)\sum_{i=-\infty}^{\infty}\delta(z - iL_s)\,g(z)\right]\exp\left(\frac{2\pi z}{\Lambda}j\right) \tag{2}$$

where $f(z)$ is the sampling function, $g(z)$ is the whole grating profile function, L_s is the sampling period. The $\Delta n_{AC}(z)$ transformed by Fourier analysis is

$$K(\beta) = F(\beta)\left[G(\beta)\sum_{n=-\infty}^{\infty}\delta\left(\beta - \beta_0 - \frac{2\pi}{L_s}n\right)\right] \tag{3}$$

where $\beta_0 = 2\pi/\Lambda$, $F(\beta)$ and $G(\beta)$ is Fourier transform of $f(z)$ and $g(z)$, respectively. If the phase shift α is applied between each sample FBG, the reflective spectrum is:

$$K(\beta) = F(\beta)\left[G(\beta)\sum_{n=-\infty}^{\infty}\delta\left(\beta - \beta_0 - \frac{2\pi}{L_s}n - \frac{\alpha}{L_s}\right)\right] \tag{4}$$

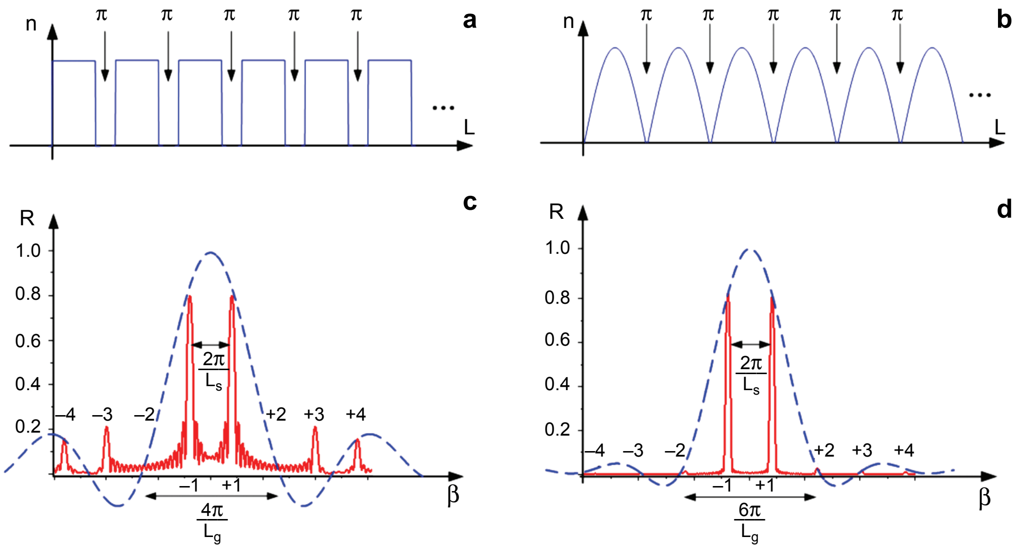

Fig. 1. Rectangular sampled grating (**a**) and its reflective spectrum (**c**). Cosine sampled grating (**b**) and its reflective spectrum (**d**).

When $\alpha = \pi$, all order channels are symmetrical to β_0. LIU proposed that when the sampling function is rectangle with duty cycle 2/3, the Fourier spectral component at $m = 1$ is the same as the values at $m = -1$. But the Fourier spectral components at ±3, ±4, ±6, ±7, …, still exist, and this will impact the DW filter performance, as shown in Figs. 1**a** and 1**c**. With the help of the signal processing theory, when the sampling function is cosine with duty cycle 1, and the phase shift between the two adjacent FBG units is π, there will exist only ±1 spectral component. The other spectral components are eliminated, as shown in Figs. 1**b** and 1**d**. The cosine sampling function and the corresponding Fourier transform can be expressed as:

$$f_{\cos}(z) = \begin{cases} \cos\left(\dfrac{\pi z}{L_g}\right) & -\dfrac{L_g}{2} \le z \le \dfrac{L_g}{2} \\ 0 & \text{otherwise} \end{cases} \tag{5}$$

$$F_{\cos}(\beta) = \frac{\cos\left(\dfrac{\beta L_g}{2}\right)}{1 - \left(\dfrac{2\beta L_g}{\pi}\right)^2} \tag{6}$$

where L_g is the grating segment length of the sampling period.

The next problem is how to introduce a phase shift. According to (1), if $\Delta n_{DC}(z)$ changes, the phase can be introduced correspondingly. This is because when $\Delta n_{DC}(z)$

increases, the transmission time of light for the same length is increased, so the phase of light is changed. If the phase shift $\Delta\varphi_{\text{shift}}$ is introduced in grating, the DC refractive index changing can be expressed as

$$\Delta n = \frac{\Delta\varphi_{\text{shift}}\lambda}{4\pi L_{\text{DC}}} \tag{7}$$

where L_{DC} is the DC refractive index modulation length and λ is the wavelength of the light. By increasing the DC refractive index, the phase shift can be introduced (DC phase shift). As compared with a traditional discrete phase, the translation stage with submicrometer precision is enough to introduce a precise phase shift. There are two kinds of the DC phase shift grating. One is the DC phase shift at the position with AC refractive index (uniform DC), the other is the DC phase shift at the position without the AC refractive index (sample DC), as shown in Fig. 2.

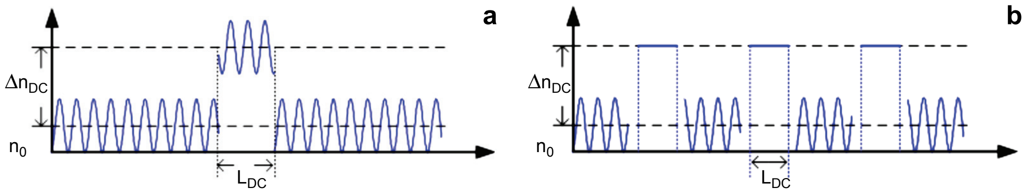

Fig. 2. Principle of two different DC phase shifted FBGs. Uniform DC phase shift (**a**), and sampled DC phase shift (**b**).

Figures 3**a** and 3**b** is a comparison of the reflective spectrum of the uniform DC phase shift and the discrete phase shift. The total length of grating is 2 mm and 30 mm, and the DC phase length is 0.5 mm which is located at the centre of the grating. The proportion of the DC phase shift length within the total FBG length can affect the profile of reflective spectrum dramatically. When the length with DC index modulation is comparable with the total length of grating, there will exist a strong side-lobe in the short wavelength side. If the length with DC index modulation is much less than the total length of grating, the DC phase shift gets closer to a discrete one, and there will be a negligible side-lobe in the short wavelength side. However, the DC length is limited by the maximum refractive index modulation. So, there is a tradeoff between the proportion of the DC length and the symmetry of reflective spectrum. Figures 3**c** and 3**d** is a comparison reflective spectrum of a sample DC phase shift and a discrete phase shift. The total length of grating is 2 mm and 60 mm, the sample period is 1 mm, the sample function is Gaussian shape with full width half maximum (FWHM) 100 μm. The alternative DC phase shift of 0 and π is introduced between two adjacent FBG units, and the DC length is 0.5 mm. The proportion of the DC phase shift length within the total FBG length has no affect on the profile of reflective spectrum. This is

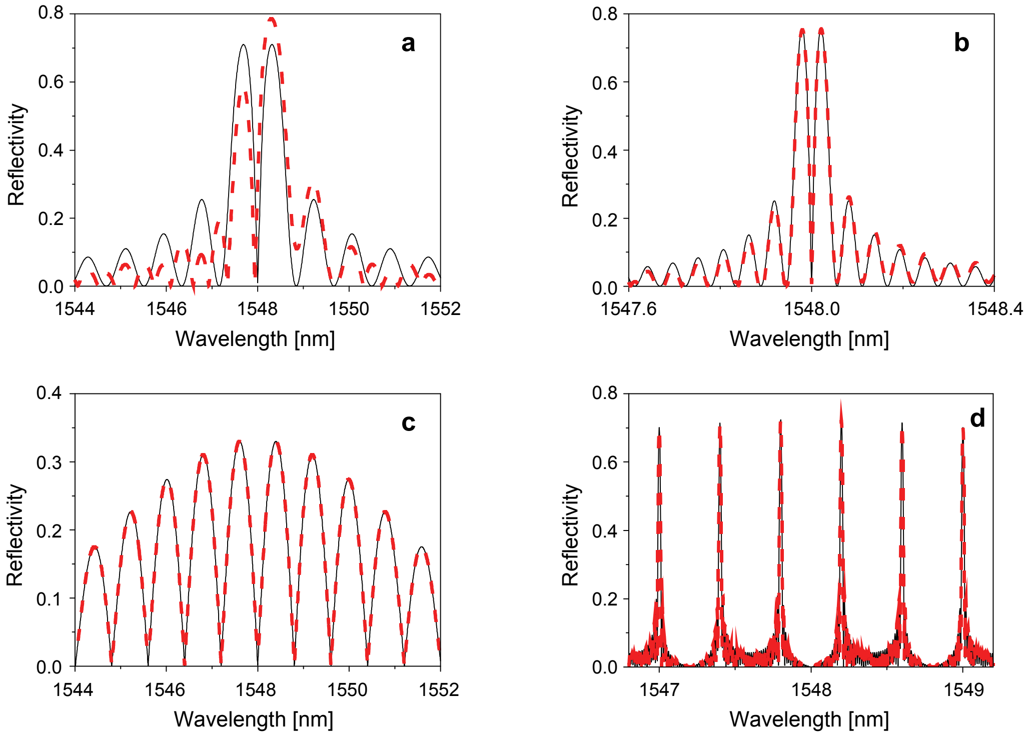

Fig. 3. Comparison of reflective spectrum of uniform DC phase shift $L = 2$ mm (**a**), $L = 30$ mm (**b**), sampled DC phase shift $L = 2$ mm (**c**), $L = 60$ mm (**d**) and discrete phase shift FBG. Solid line – discrete phase shift, dashed line – DC phase shift.

because the DC refractive index modulation and the AC refractive index modulation are separated, so they are independent.

The simulation results show when the DC phase shift length is far less than the total length of grating. The DC phase shift can replace discrete phase shift.

3. Experiment

Based on the analysis above, the uniform DC phase shift FBG and the sample DC phase shift FBG are fabricated with a doubled argon-ion ultraviolet laser operating at 244 nm and Physik Instrumente's translation stage (submicrometer-precision) on hydrogen-loaded Ge-doped photosensitive fibers and then measured by a Luna optical vector analyzer. The DC phase shift is realized by irradiation of the ultraviolet laser on FBGs without a phase mask. Figure 4**a** shows the reflective spectrum of the fabricated uniform DC phase shift FBG before and after phase shifts. The fabricated parameter is as that of Fig. 3**b**. Figure 4**b** shows the reflective spectrum of the fabri-

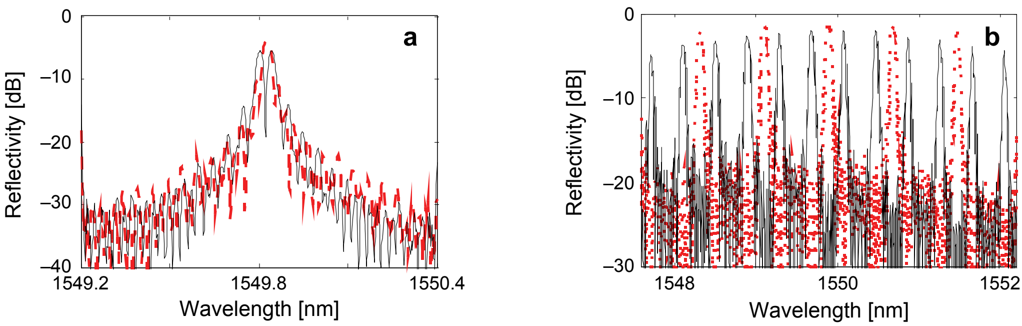

Fig. 4. Reflective spectrum of π DC phase shift FBG: uniform (**a**), and sampled (**b**). Dotted line – before DC phase shift, solid line – after DC phase shift.

cated sample DC phase shift FBG before and after phase shifts. The fabricated parameter is as that of Fig. 3**d**. Through this experiment we can see that the fabricated FBGs have a good agreement with the simulation, which verified the feasibility of this technology. In our experiment the π phase shift length is 0.5 mm, the laser power is 15 mW, and the exposure time is 21.5 s.

With the help of the experiment parameters obtained above, we fabricate the DW filter based on the DC phase shift. The gratings were written plane by plane and the cosine sample is obtained by an inverse calculation sampling function to determine the beginning and the ending position of every exposure plane. The higher number of planes, the sampling grating gets closer to the ideal result. In the experiment, the sampling period is 5.15 mm, and the grating length is 7.72 cm. The sampling function is cosine with duty cycle 1, so the DC refractive index modulation is partially superposition with the AC refractive index modulation in the experiment. But, through simulation, we show when the DC phase shift length is far less than the total length of grating. The DC phase shift can replace the discrete phase shift, no matter its position is with or without the AC refractive index modulation, as shown in Fig. 3. We have researched when the proportion of the DC length is less than 5%, our method can replace the discrete phase shift.

Figures 5**a** and 5**b** are reflectivity and transmission of a fabricated DW filter. The wavelength spacing of the two channels is 0.16 nm, the spectrum characteristic at the +1 order component is approximately the same as that at the –1 order component, and the power of the other order component is eliminated well. The experiment results show an excellent agreement with our theory.

This method can be used to fabricate the DW filter with grating longer than 1 cm. The grating in our experiment is longer than 7 cm. This can decrease the bandwidth of the ±1 order reflective spectrum to improve its filter performance for our application. This method has the following advantages: wavelength design is flexible, fabrication precision and costs are low.

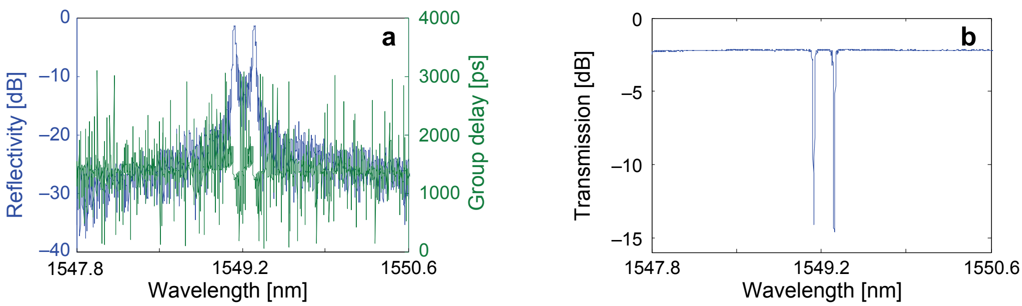

Fig. 5. Fabricated dual-wavelength FBG with 0.08 nm channel spacing reflection (**a**) and group delay transmission (**b**).

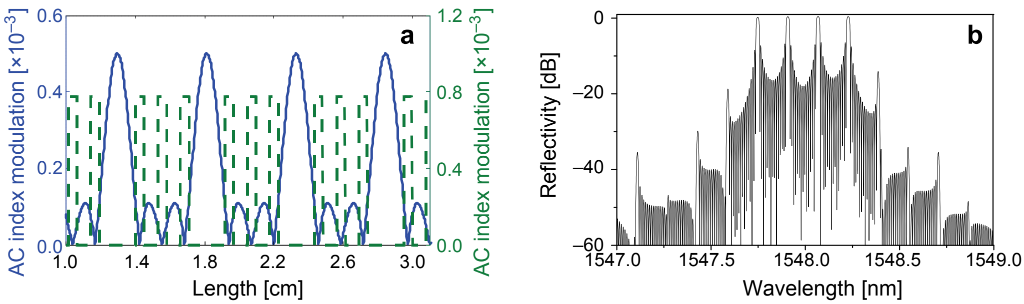

Fig. 6. Simulation example of four-wavelength filter AC refractive index modulation (solid line) and DC refractive index modulation (dotted line) distribution (**a**). Reflectivity with DC phase shift (**b**).

Sinc-sampled FBGs have demonstrated identical characteristics in all wavelength channels [18], but the translation stage with nanometer precision is needed. Since the phase shift can be achieved by changing the refractive index of grating, this method can be used to implement a multi-wavelength grating filter. Figure 6**a** shows the AC index and the DC index refractive modulation distribution of the proposed multichannel FBG. Figure 6**b** shows the four-wavelength reflectivity spectrum. In the simulation, the sample is sinc function, $P = 5.15$ mm, the DC phase length is 0.5 mm.

4. Conclusions

A novel identical multiple wavelength SFBG is proposed. The phase shift between the two adjacent FBG units is achieved by increasing the DC refractive index of the FBG. The FBG with identical reflective spectrum is optimized with designed sampling function. DC phase shift FBGs are analyzed, which show when the DC phase shift length is much less than the total length of grating, and the DC phase shift can replace discrete phase shift. DC phase shift FBGs are fabricated, which shows a good agreement with a discrete phase shift method. The DW filter with channel spacing

0.16 nm is fabricated, and the experiment results verified the feasibility of this proposed method. The identical four-wavelength filter with channel spacing 0.16 nm is then proposed and demonstrated. This method has the following advantages: wavelength design is flexible, fabrication precision and costs are low.

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