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Novel ultra-narrowband transmission tunable optical fiber filter technique based on cascading nonlinear chirped fiber gratings

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A transmission fiber filter that can provide ultra-narrow transmission bandwidth and flexible tunable abilities is proposed based on cascading two nonlinear chirped fiber gratings, whose reflection spectra have apparent asymmetric shapes. The spectrum envelope slope parameter is defined to describe the spectrum asymmetry, and then, the relationship between the parameter and the filtering ability is analyzed. The expected filter performances, such as the working wavelength, transmission band width and tunable range are discussed as well.

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1. Introduction

It is well known that narrow-band filtering characteristics have significances in fiber systems [1]. Optical narrow bandwidth filters used at present are mainly as follows: multilayer thin film [2], volume diffraction grating [3] and fiber Bragg grating (FBG) [4, 5, 6]. The first two are not suitable to be integrated in fiber systems, especially in photonic networks that require compatibilities and low attenuations. However, the FBG generally works as narrow band-stop filter, and usually need to be combined with an optical circulator or coupler, which will obviously aggravate optical power attenuations and increase system complexity [6, 7].

The reflection spectra of the fiber gratings are influenced by the refractive index phase modulation and apodization [8]. Our results show that the chirped fiber grating spectra have asymmetric characteristics using proper refractive index modulation, and the asymmetries overturn accordingly when using the opposite phase modulation. Based on these properties, this work proposes a transmission tunable fiber grating filter by cascading two chirped fiber gratings with asymmetric spectra, which can provide the natural compatibility with fiber systems, independent working ability, ultra-narrow band width, and tunable ability.

2. The simulation model

In chirped fiber gratings written by ultra-violet lasers, the refractive index change $\delta n_{eff}(z)$ can be expressed as [9]

$$\delta n_{eff}(z) = \overline{\delta n_{eff}} \left\{ 1 + V(z)\cos[\frac{2\pi}{\Lambda(z)} z + \phi(z)] \right\} \quad (1)$$

where $\overline{\delta n_{eff}}$ is the "dc" index change spatially averaged over a grating period, $\phi(z)$ is the slowly varying grating phase, $\Lambda(z)$ is the period of the refractive index modulation, and $V(z)$ is the slowly varying envelop of the induced refractive index modulation.

The electric field distribution along the grating can be regarded as the superposition of two oppositely traveling waves $u(z)$ and $\upsilon(z)$, described by a set of two coupled-mode differential equations. After introducing a local reflection coefficient $\rho(z) = u(z)/\upsilon(z)$, they can be combined in a single *Riccati* differential equation [10]

$$\frac{d\rho(z)}{dz} = 2j\hat{\sigma}(z)\rho(z) + i\kappa(z)L[1+\rho^2(z)] \quad (2)$$

where $\hat{\sigma}(z)$ is a general "dc" self-coupling coefficient and $\kappa(z)$ is the "ac" coupling coefficient [11],

$$\hat{\sigma}(z) = \Delta(z) + \frac{2\pi}{\lambda}\overline{\delta n_{eff}} - \frac{1}{2}\phi'(z) \quad (3)$$

$$\kappa(z) = \kappa^{*}(z) = \frac{\pi}{\lambda}V(z)\overline{\delta n_{eff}} \quad (4)$$

Here, the derivative term $(1/2)\phi'(z)$ describes the chirp of the fiber grating, and $\Delta(z)$ is the wavenumber detuning from the reference wavenumber $\pi/\Lambda(z)$,

$$\Delta(z) = \beta(z) - \frac{\pi}{\Lambda(z)} = 2\pi n_{eff}(z)\left(\frac{1}{\lambda} - \frac{1}{2n_{eff}(z)\Lambda(z)}\right) \quad (5)$$

where $\beta(z) = (2\pi/\lambda)n_{eff}(z)$ is the mode propagation constant.

Assuming that the grating structure extends from z =0 to L, the boundary condition is $\rho(L) = 0$. The grating reflectivity is given by $R(z) = \rho(z)\rho^{*}(z)$, and the quantity of interest is $R(0)$ that corresponds to the total reflectivity. Because the local reflection coefficient $\rho(z)$ in equation (2) can't be expressed as exact analytical solution for chirped fiber gratings, we numerically solved it using the fourth-order *Runge-Kutta* method with the wavelength step $d\lambda$ =0.02 nm, the grating length L =30 mm, and the fiber effective refractive index n_{eff} =1.447. The phase modulation $\phi'(z)$, namely the chirp term, is chosen as a *Cosine* function

$$\phi'(z) = 2.5\cos(5z) \quad (6)$$

We used a *Gaussian* apodization function in order to suppress side lobes of the reflection spectrum,

$$\kappa(z) = 0.01\exp(-16z^{2}) \quad (7)$$

3. Results

The reflection characteristic of the chirped fiber grating is shown in Fig. 1. The full-width at half-maximum (FWHM) bandwidth is $\Delta\lambda$ =5.32 nm, and the spectrum side lobes are suppressed effectively by the apodization function. We define a spectrum envelope slope parameter $\gamma_i = |dR_i / d\lambda_i|$ to describe the reflection spectrum, and its absolute difference value $\Delta\gamma$ can be used to measure the asymmetric characteristic.

In Fig. 1, the maximum slope value of the left edge is γ_1 =6764.085 at 1550.66 nm that is greater than the right one γ_2 =2310.603 at 1556.02 nm, and the difference value $\Delta\gamma$ is 4453.482 which indicates an apparent overall asymmetry.

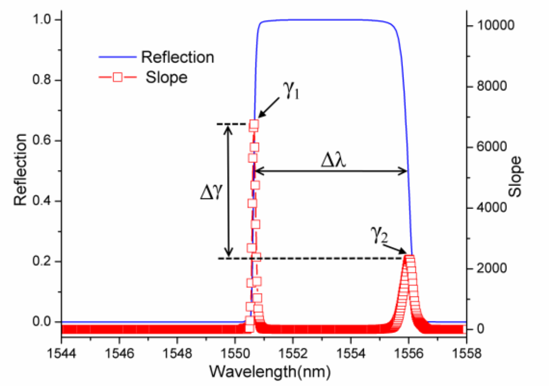

Fig. 1. The asymmetric reflection spectrum and the variation of the slope parameter.

Moreover, if the chirp term (6) is replaced by its opposite form, namely $-2.5\cos(5z)$, the overall asymmetry of the spectrum will overturn accordingly. Hence, if a pair of opposite chirped fiber gratings is cascaded together, whose spectrum edges with the greater slope value are adjacent, a very narrow spectrum with steep edges will transmit out between the two reflection spectra. As the structure shown in Fig. 2 and its corresponding spectra shown in Fig. 3, two adjacent reflection spectra work as stop bands and a very narrow transmission spectrum comes into being, which illustrate the transmission filtering process. On the other hand, if the two slope values of their adjacent spectrum edges are not the greater ones, the cascaded fiber gratings will still have the transmission filtering ability, but the band width will be broader and two edges of the transmission spectrum will not be steep accordingly, which means a deteriorated filtering performance.

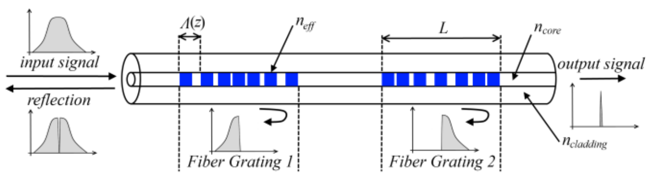

Fig. 2. Structure of the transmission fiber filter using cascaded chirped fiber gratings with opposite asymmetric reflection spectra.

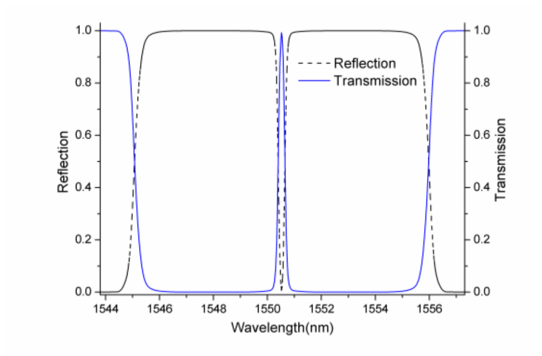

Fig. 3. Narrow band transmission spectrum forms between two asymmetric reflection spectra.

4. Discussion

It is a mature method proved by theoretical and experimental researches to tune the central wavelength of the fiber grating by axial stress compression [12, 13], which also plays a role in this work. Since it's a complementary relationship between the transmission spectrum and the two adjacent reflection spectra, the tunable ability of the filter can be achieved by tuning each cascaded chirped fiber grating in the same wavelength direction and shift. As shown in Fig. 4(a) and (b), the transmission spectrum T1 is tuned to T2 along with the reflection spectra moved from R1 to R2. The total tunable wavelength range is determined by the tunable chirped fiber grating with less tunable range.

Furthermore, if the tuning wavelength directions and shifts are different, the transmission band width will be changed, that is to say, the transmission band width is another tunable parameter besides the central wavelength. As shown in Fig. 4(d), the bandwidth of T3 corresponding to the distance between the reflection spectra in Fig. 4(c) has been tuned much broader than that of T1 and T2 in Fig. 4.

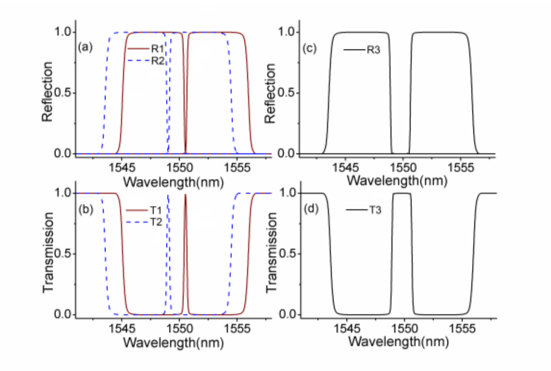

Fig. 4. Tuning the working wavelength and transmission band width by moving reflection spectra.

The minimum bandwidth value is determined by slopes of the adjacent spectrum edges, and the greater the slopes, the narrower the transmission band width. If they are realized to be infinitely great, the transmission spectrum can be infinitely narrow in theory. The transmission bandwidth at FWHM is 0.252 nm in Fig. 3, where the bottoms of the adjacent edges match together, and it can reach ~0.08 nm in the simulation beyond caring about the transmission rate when the sample points with maximum slope values match. On the other hand, the maximum bandwidth forms when the fiber grating in short wavelength area is tuned to its shortest working wavelength and the other one to the longest in their tunable ranges.

The transmission rate is ~99.31% in Fig. 3 for the reason that there is still a weak side lobe at the bottom of the reflection spectrum which is influenced seriously by the apodization function. If the side lobes are not suppressed effectively, it will make the top shape of the transmission spectrum vary irregularly.

5. Conclusions

The ultra-narrowband transmission tunable fiber filter proposed in the paper can implement the independent operation in fiber systems along the optical propagation direction without other auxiliary fiber components for its working mode. And its filter mechanism that a very narrow pass band forms between two relatively broad stop bands is studied. The relationship between the transmission band width and the spectrum asymmetric characteristic is analyzed, which can be regarded as the fundamental to construct such optical fiber filter. Besides the advantage of the ultra-narrowband transmission filtering ability, both of the central wavelength and the transmission band width are able to be tuned, which is different from usual FBG filters and bring conveniences and flexibilities to applications.

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