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Theoretical investigation and optimization of fiber grating based slow light

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ABSTRACT

On the edge of bandgap in a fiber grating, narrow peaks of high transimittivity exist at frequencies where light interferes constructively in the forward direction. In the vicinity of these transmittivity peaks, light reflects back and forth numerous times across the periodic structure and experiences a large group delay. In order to generate the extremely slow light in fiber grating for applications, in this research, the common sense of formation mechanism of slow light in fiber grating was introduced. The means of producing and operating fiber grating was studied to support structural slow light with a group index that can be in principle as high as several thousand. The simulations proceeded by transfer matrix method in the paper were presented to elucidate how the fiber grating parameters effect group refractive index. The main parameters that need to be optimized include grating length, refractive index contrast, grating period, loss coefficient, chirp and apodization functions, those can influence fiber grating characteristics.

1. Introduction

Slow light technology is a kind of technology that can slow down the light speed in the medium. In recent years, the realization of controllable slow light and its applications in optical communication, optical storage, optical buffer and optical sensor have been becoming the leading edge and hotspot in the field of optics research [1]. Especially, slow light in fiber Bragg grating shows attractive prospect in practical application because of its advantages of simple structure and easy integration, which can realize the distortionless pulse transmission with slow speed [2]. In 1992, Harris [3] use lead steam condition to make the speed of light reduce two orders of magnitude compared with the vacuum condition. In 1999, Hau [4] using sodium atoms steam in the super cooling conditions to achieve slow light speed of 17 m/s. With the implementation of slow light, more and more scholars began to research slow light, and various novel slow light generation methods was put forward, and then the study of slow light application was promoted [5]. A few years later, slow light technology got a rapid development, people gradually turn to how produce slow light at room temperature and make it a more realistic and extensive application [6].

In 2004, Zhang [7,8] got slow light speed of 43.215 m/s in ruby crystal at room temperature by using spectral hole burning phenomenon due to coherent population oscillation, which made slow light research more practical significance. Recently, fiber based slow light has got more and more widely attention in sensing and communication for the advantages of long transmission distance, small loss, resistance to electromagnetic interference, high temperature resistant [9]. In 2005, Okawachi [10] has made an optical pulse delay of 25 ns by using stimulated Brillouin scattering in fiber for the first time. In 2006, Zhu [11] increased slow light bandwidth to 12.6 GHz with pulse delay to 47 ps in a fiber by using stimulated Brillouin scattering. In 2007, Song [12] used stimulated Brillouin scattering to generated slow light with bandwidth of 25 GHz and delay of 10.9 ps. In 2015, Wang [13] proposed the fiber ring resonator technology to slow down the velocity of light, with the maximum delay time of 34.18 ns at wavelength of 1531.63 nm. Compared with above all of these methods, the method obtaining slow light in a fiber grating has many advantages, such as simple construction, small size, strong anti-interference ability, and excellent slow light speed.

This paper described the method to control slow light in a fiber grating and analyzed grating parameters influences on slow light characteristics.

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2. Theory

The speed of a single frequency light in a uniform medium with refractive index n is c/n. Due to the medium refractive index is greater than 1, the speed of light in a medium is lower than light speed in vacuum. Actually, monochromatic light does not exist, and light emitted from a light source must have a bandwidth in the frequency domain, which can be considered as a group of monochromatic light with different frequencies. According wave beat phenomenon, if two frequency of transmission waves close to each other and different from each other, the amplitude of the wave will change, an envelope is formed, the moving speed of the envelope is called group velocity. Therefore, the speed of light contains phase velocity and group velocity [14].

For a light signal with a center frequency ω_0, the group velocity v_g is shown in Eq. (1).

$$v_g = \left.\frac{d\omega}{dk}\right|_{\omega_0} = \frac{c}{n_g} \tag{1}$$

where n_g represents group index. The expression of wavevector is shown in Eq. (2).

$$k_x = n_x k_0 \tag{2}$$

where k_0 represents normal fiber core dielectric constant ,k_x is dielectric constant on different locations. The group index of a light signal with the center frequency ω_0 is shown in Eq. (3).

$$n_g(\omega_0) = c\frac{dk}{d\omega} = n + \omega_0 \left.\frac{dn}{d\omega}\right|_{\omega_0} \tag{3}$$

The group velocity is shown in Eq. (4).

$$v_g = \left.\frac{d\omega}{dk}\right|_{\omega_0} = \frac{c}{n + \omega_0 \left.\frac{dn}{d\omega}\right|_{\omega_0}} \tag{4}$$

According to Eq. (4), in the non-dispersive medium ($dn/d\omega = 0$), the group velocity v_g and phase velocity v_p are equal. In an anomalous dispersion medium ($dn/d\omega < 0$), the group velocity is greater than the phase velocity, and fast light can be obtained. In a normal dispersion medium ($dn/d\omega > 0$), the group velocity is less than the phase velocity, and slow light can be obtained. When the dielectric constant is changed sharply along with frequency change, that is $dn/d\omega \gg 0$, and that means $v_g \ll v_p = c/n$, a significant slow light phenomenon is produced.

Fiber grating is a fiber based photonic device that whose refractive index is periodic distribution in the fiber core along fiber axial direction. This periodic structure of fiber grating can be viewed formed by many mini Fabry–Perot interferometers. Therefore, slow light can be generated corresponding to the frequency at transmission spectrum peak of fiber grating [15]. According to Kramers–Kronig relations, optical signal intensity change and phase change are synchronized when it is passing through a length of the optical system. The phase of optical signal is defined in Eq. (5).

$$\varphi = nk_0 L \tag{5}$$

According to Eq. (5), the relationship between group index and phase can be obtained as Eq. (6).

$$n_g = \frac{c}{L}\frac{d\varphi}{d\omega} \tag{6}$$

Eq. (6) shows that the sharper the light signal phase changes along with light frequencies, the higher the group index value is. It can be seen, if there have dramatic changes in the optical transmission spectra of a material or device, then it is possible to form a clear slow light at that frequency location. For structural slow light based on fiber grating, it tends to produce slow light at the peak region of transmission spectrum.

The refractive index contrast of common fiber grating is a constant along fiber axis direction, and it is known as the uniform fiber grating. Corresponding to common fiber grating, non-uniform fiber grating is known as a kind of special fiber grating. The main differences between two type fiber gratings is that the refractive index contrast of uniform fiber grating has uniform distribution along fiber grating axis and the refractive index contrast is invariable along fiber axial direction, and the refractive index contrast of non-uniform fiber grating changes with a certain function along fiber axial direction. Due to special type fiber grating structure, non-uniform fiber grating has special form of transmission spectra and group index spectrum.

3. Numerical simulation

This paper will use mode transmission method to analyze uniform and non-uniform fiber grating. Non-uniform fiber grating refractive index profile is divided into a series of sections of equal length, the optical characteristics of fiber grating can be gotten through analyzing optical properties of each section and connects uniform every fiber grating sections by coupled-mode theory. Because mode transmission method has strong flexibility and adaptability, can be used for a variety of the analysis of the grating, and easy to implement, therefore is widely used to study the characteristics of fiber grating. Based on transfer matrix theory, in the case of refractive index section i and $i-1$, relationship between wave functions of forward transmission light and backward transmission light is shown in Eq. (7).

$$\begin{bmatrix} R_i \\ S_i \end{bmatrix} = [M_i] \begin{bmatrix} R_{i-1} \\ S_{i-1} \end{bmatrix} \tag{7}$$

where R_i and S_i are the wave functions of forward transmission light and backward transmission light in section i, $[M_i]$ is the transfer matrix of the light intensity relationship between refractive index section i and $i-1$. According to coupled mode theory, $[M_i]$ can be obtained as Eq. (8).

$$[M_i] = \begin{bmatrix} \cos h(\gamma_B \Delta z) - i\frac{\sigma}{\gamma_B}\sin h(\gamma_B \Delta z) & -i\frac{\kappa}{\gamma_B}\sin h(\gamma_B \Delta z) \\ i\frac{\kappa}{\gamma_B}\sin h(\gamma_B \Delta z) & \cos h(\gamma_B \Delta z) + i\frac{\sigma}{\gamma_B}\sin h(\gamma_B \Delta z) \end{bmatrix} \tag{8}$$

where Δz is the section length, $\sigma = 2\pi n_{eff}(\frac{1}{\lambda} - \frac{1}{\lambda_B}) + \frac{2\pi\Delta n}{\lambda} + i\frac{\alpha}{2}$ is DC coupling coefficient, $\kappa = \frac{\pi}{\lambda}\nu\Delta n$ is AC coupling coefficient, n_{eff} is effective refractive index, λ is input wavelength, λ_B is Bragg wavelength, Δn is the refractive index contrast, α is loss coefficient, $\gamma_B = \sqrt{\kappa^2 - \sigma^2}$. Based on Eq. (8), the fiber grating forward and backward wave function can be obtained after analyzing all sections in series as shown in Eq. (9).

$$\begin{bmatrix} R \\ S \end{bmatrix} = [M] \begin{bmatrix} R_0 \\ S_0 \end{bmatrix} \tag{9}$$

where R and S are forward wave function and backward wave function of fiber grating incident light respectively, R_0 and S_0 are forward wave function and backward wave function of fiber grating emergent light, the transfer matrix of fiber grating can be expressed as $[M]=[M_1] \times [M_2] ... [M_{N-1}] \times [M_N]$. The reflection coefficient and transmission coefficient of fiber grating is $r = S/R$ and $t = R_0/R$ respectively. The transmittivity spectrum and group index