Phase-Shifted Fiber Bragg Gratings and their Application for Wavelength Demultiplexing

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Abstract—**It is shown that the transmission spectrum of a fiber Bragg grating can be tailored by incorporating single or multiple phase-shift regions during the fabrication process. Phase shifts open up narrowband transmission windows inside the stop band of the Bragg grating; transmitted wavelength can be changed by adjusting the amount of phase shift. As a specific application, we discuss how phase-shifted Bragg gratings can be used to make an all-fiber demultiplexer for multichannel lightwave systems.**

FIBER Bragg gratings have attracted considerable attention recently because of their numerous applications in fiber-optic technology [1], [2]. Such gratings generally act as a narrowband reflection filter centered at the Bragg wavelength because of the stop band associated with an one-dimensional periodic medium. Many applications, such as channel selection in a multichannel communication system, would benefit if the fiber grating could be designed as a narrowband transmission filter. Although techniques based on Michelson and Fabry-Perot interferometers have been developed for this purpose [2], their use requires multiple gratings and may introduce additional losses. In this paper we show that a technique commonly used for distributed feedback (DFB) semiconductor lasers [3]–[5] can be used to tailor the transmission spectrum to suit specific requirements. The technique consists of introducing multiple phase shifts across the fiber grating whose location and magnitude can be adjusted to design a specific transmission spectrum. It is a generalization of an idea first proposed in 1976 by Haus and Shank [6].

To demonstrate how suitably placed phase shifts can be used to tailor the transmission spectrum of a fiber grating, consider the general case in which phase shifts $\phi_1, \phi_2, \ldots, \phi_M$ occur at locations $z_1, z_2, \ldots, z_M$. The transmittivity of such a grating with multiple phase shifts can be calculated by using a scattering-matrix approach based on the coupled-mode theory [4]. Specifically, transmission through a uniform section between neighboring phase-shift regions is governed by:

$$\begin{pmatrix} A_{\text{out}} \\ B_{\text{out}} \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} A_{\text{in}} \\ B_{\text{in}} \end{pmatrix} \tag{1}$$

where A and B represent the amplitudes of forward and backward propagating waves and the matrix elements of the S matrix are obtained by using the standard coupled-mode theory [5] and are given by [4]:

$$S_{11} = (1 - r^2)^{-1}\left[\exp(iqh) - r^2 \exp(-iqh)\right] \tag{2a}$$

$$S_{22} = (1 - r^2)^{-1}\left[\exp(-iqh) - r^2 \exp(iqh)\right] \tag{2b}$$

$$S_{21} = -S_{12} = (1 - r^2)^{-1} r[\exp(iqh) - \exp(-iqh)] \tag{2c}$$

In (2), h is the section length, $q = \pm\left[(\delta\beta)^2 - \kappa^2\right]^{1/2}$, and $r = (q - \delta\beta)/\kappa$. Further, $\kappa = \pi\delta n/\lambda_B$ is the coupling coefficient of the grating and $\delta\beta = 2\pi(\lambda^{-1} - \lambda_B^{-1})$ is the detuning from the Bragg wavelength λ_B related to the grating period Λ as $\lambda_B = 2n_{\text{eff}}\Lambda$. Here n_{eff} is the effective mode index and δn is the depth of index modulation.

The phase shift ϕ_j at a given location z_j can be incorporated by multiplying the S matrix with the diagonal matrix with elements $\exp(\pm i\phi_j)$, corresponding to the phase shifts experienced by the counterpropagating waves. The same process can be repeated to calculate the final S matrix for the entire fiber grating of length L. The transmission and reflection spectra are then obtained by imposing the boundary condition $B_{\text{out}}(L) = 0$ and are given by:

$$T = \left|\frac{A_{\text{out}}}{A_{\text{in}}}\right|^2 = \left|S_{11} - \frac{S_{12}S_{21}}{S_{22}}\right|^2 \tag{3}$$

$$R = \left|\frac{B_{\text{in}}}{A_{\text{in}}}\right|^2 = \left|\frac{S_{21}}{S_{22}}\right|^2. \tag{4}$$

Consider first the case of a grating with a single phase shift ϕ_1 located at the center of the grating ($z_1 = L/2$). Fig. 1 shows the transmissivity as a function of $\delta\beta/\kappa$ for three values of ϕ_1 in the range 0–90°, by choosing $\kappa L = 3$. The case $\phi_1 = 0$ (dotted curve) corresponds to a conventional fiber grating without any phase shift. The low-transmissivity central region for this case indicates that the grating acts as a reflection filter of bandwidth 2κ. For $\phi_1 = 90°$ (solid curve), a narrow central transmission peak opens up in the stop band. The spectral width of this peak is a fraction of κ and decreases with an increase in κL. Thus, a phase-shifted fiber grating acts as a transmission filter whose bandwidth can be quite small. An interesting application of such gratings consists of demultiplexing a multichannel communication link. If the entire multichannel signal falls within the stop band, a single channel can be transmitted while others are blocked by the grating. Moreover, the selected channel can be chosen anywhere within the stop band by changing the amount of phase shift. As the dashed curve for $\phi_1 = 45°$ in Fig. 1 shows, the transmissvity remains nearly 100% when ϕ_1 is varied in the range 30–150°. Transmissivity for $\phi_1 = 135°$ is just the mirror

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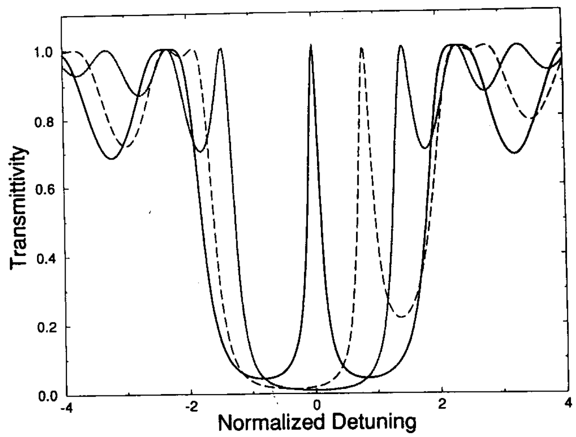

Fig. 1. Transmissivity versus normalized detuning $\delta\beta/\kappa$ for $\phi_1 = 0°$ (dottedcurve), 45°(dashed curve) and 90° (solid curve) for a fiber gratingwith $\kappa L = 3$ and a single phase shift ϕ occurring at $L/2$. Dottedcurve corresponds to a conventional fiber grating and exhibitsthe stop band of width 2κ. Phase shift opens up a transmission window whose location can be controlled by changing ϕ_1.

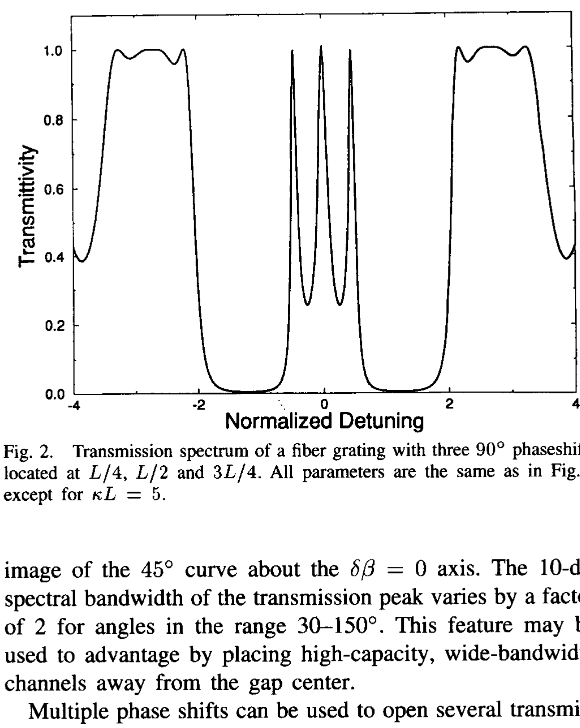

Fig. 2. Transmission spectrum of a fiber grating with three 90° phaseshifts located at $L/4$, $L/2$ and $3L/4$. All parameters are the same as in Fig. 1 except for $\kappa L = 5$.

image of the 45° curve about the $\delta\beta = 0$ axis. The 10-dB spectral bandwidth of the transmission peak varies by a factor of 2 for angles in the range 30–150°. This feature may be used to advantage by placing high-capacity, wide-bandwidth channels away from the gap center.

Multiple phase shifts can be used to open several transmission windows within the stop band. Fig. 2 shows the case of a fiber grating with $\kappa L = 5$ for three phase shifts of 90°, equispaced along the grating length ($z_1 = L/4, z_2 = L/2$ and $z_3 = 3L/4$). Three narrow transmission peaks open up within the stop band of the grating. Considerable control on the location of these peaks can be exercised by changing the amount and the location of the phase-shift regions. The main conclusion here is that the incorporation of multiple phase-shift regions permits a tailoring of the transmission spectrum to suit specific needs of an application.

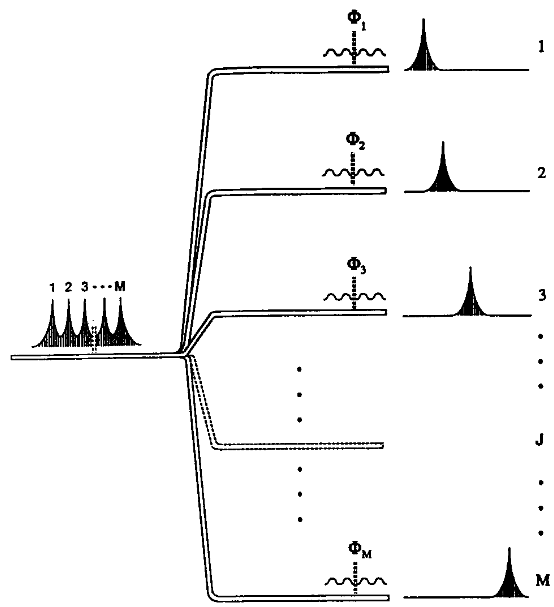

Fig. 3. Schematic illustration of an all-fiber demultiplexer used to select a different single channel in each branch by using a phase-shifted fiber-Bragg grating.

Implementation of phase shifts in fiber gratings is feasible with the current technology. Phase-shifted DFB lasers are routinely fabricated, and one may adopt the techniques used for them [5], Although it is possible to introduce phase shifts with the dual-beam holographic method, [2] the phase-mask technique [1], [7] is most suitable for introducing multiple phase shifts within the Bragg grating since phase shift can be manufactured inside the master phase mask by simply shifting the pattern by a fraction of the mask period. Depending on the fabrication method and the UV-beam spot size, the grating profile may be nonuniform across the fiber length. Numerical simulations for a Gaussian profile show that although such nonuniformities widen the transmission peak by about 40%, they do not alter the conclusions reported here. Moreover, a uniform grating can be fabricated by the point-by-point method of Hill *et al.* [1].

Phase-shifted fiber gratings should find a variety of applications because of their ability to produce tailored transmission spectra. An obvious application is for channel selection in a multichannel lightwave system. As an example, Fig. 3 shows the design of an all-fiber channel demultiplexer. The M-channel signal is split into M separate branches (similar to a star coupler). A Bragg grating is incorporated in each branch. The grating has a single phase-shift region in its middle, but the amount of phase shift is varied in the range 0 to 180° to vary the location of the transmission peak inside the stop band (see Fig. 1). Such a design allows transmission of a different channel from each branch. To estimate the number of channels that can be demultiplexed by this technique, consider a specific example of 1 mm long grating with $\kappa L = 5$. The stop band of such a grating is about 4 nm wide. The bandwidth of the transmission peak for a single central phase shift is about 0.2

nm. Allowing for the safety margin of a factor of 2 to account for nonuniform peak bandwidths within the stop band and to reduce interchannel crosstalk, such a device can demultiplex 10 channels. The number of channels increases with κL and can exceed 50 with a proper design of the grating. In fact, phase-shifted gratings with a stop band of $\sim$10 nm and a transmission-peak bandwidth $\sim$0.05 nm are feasible.

In conclusion, phase-shifted fiber-Bragg gratings can be used as narrowband transmission filters whose transmissivity can be tailored by changing the location and the amount of phase shifts. They can be used to design an all-fiber demultiplexer capable of demultiplexing more than 20 channels. Such grating should find many applications in the lightwave technology. It should be stressed that the results reported here are not specific to fiber gratings and can be applied to other kinds of waveguides. For example, an integrated semiconductor demultiplexer can be built by replacing fiber gratings in Fig. 3 with DFB amplifiers. Such a device can demultiplex channels while amplifying them simultaneously.

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