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Phase-Shifted Fiber Bragg Grating Transmission Filters Based on the Fabry-Perot Effect

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We present the analysis of phase-shifted fiber Bragg gratings by coupled-mode equations. The transmission is expressed as that of a Fabry-Perot resonator with complex reflectance and complex transmittance. The transmission spectrum, the effective cavity length, and the behaviors with different phase-shifts are investigated. A very flattened transmission peak is obtained by introducing three phase-shifts in a grating.

I. INTRODUCTION

Transmission filters with phase-shifted fiber Bragg gratings (FBGs) have been made with very narrow linewidth within the FBG stop band by using a phase-shifted phase-mask [1] or post-fabricated exposure [2,3] or two cascaded FBGs [4]. A tunable transmission filter, which was made by making FBGs in a highly erbium-doped fiber and by introducing phase-shift from side point pumping through the resonant nonlinear refractive effect, was reported by Janos et al. [5]. Because of their very narrow linewidth and easy tunability by applied strain or temperature change, phase-shifted FBGs have many important applications in optical communications and as fiber sensors [6,7].

The physical mechanism of the π phase-shifted FBGs can be understood well in analogy with that of Fabry-Perot (F-P) resonators [8]. However, the π phase-shifted FBG is not a simple F-P cavity, as the reflections are distributed along the fiber length and the reflectivities depend on wavelength. The conventional analysis is based on matrix treatment [9], but it lacks a clear physical picture. In this paper, the transmission behaviors of phase-shifted FBGs are simulated. Analytical expressions with clear physical meaning for the gratings with one-, two-, and three-phase-shifts are given. A linewidth narrower than 100 MHz or a very flattened transmission filter is obtained in the simulation.

II. THEORY

For a single-mode fiber with core-index modulation, the transmitted amplitude $A^+(z)$ and the reflected amplitude$A^-(z)$ along the grating length can be derived from the coupled-mode equations [9]:

$$\begin{bmatrix} A^+(z) \\ A^-(z) \end{bmatrix} = \begin{bmatrix} 1/t_i^* & r_i/t_i \\ -r_i/t_i & 1/t_i \end{bmatrix} \begin{bmatrix} A^+(z_o) \\ A^-(z_o) \end{bmatrix} \tag{1}$$

where $0 < z < L$ and L is the grating length; r_i and t_i are the amplitude reflectance and transmittance of the grating G_i with length $L_i = z - z_0$ and are defined as

$$r_i = \frac{\mathbf{j}k sinh(SL_i)}{Scosh(SL_i) - \mathbf{j}\delta sinh(SL_i)} \tag{2a}$$

$$t_i = \frac{S}{Scosh(SL_i) - \mathbf{j}\delta sinh(SL_i)} \tag{2b}$$

where κ is the coupling coefficient; κL is coupling strength; $\delta = 2\pi n_{eff}/\lambda - \pi/\Lambda$ is the detuning from the Bragg wavelength; $S = \sqrt{\kappa^2 - \delta^2}$ is the effective detuning; n_{eff} is the effective index of the fiber core; Λ is the grating period.

Introducing phase-shift ϕ at $z = L_1$ along the grating length, the grating is divided into two parts with the length of L_1 and L_2 described by (r_1, t_1) and (r_2, t_2), respectively. The amplitudes at the end of the grating are written as

$$\begin{bmatrix} A^+(L) \\ A^-(L) \end{bmatrix} = \begin{bmatrix} 1/t_2^* & r_2/t_2 \\ -r_2/t_2 & 1/t_2 \end{bmatrix} \begin{bmatrix} e^{j\phi} & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1/t_1^* & r_1/t_1 \\ -r_1/t_1 & 1/t_1 \end{bmatrix} \begin{bmatrix} A^+(0) \\ A^-(0) \end{bmatrix} \tag{3}$$

where the phase-shift ϕ is with respect to the grating period: π phase-shift means missing half the grating period. Using boundary condition $A^-(L) = 0$, the amplitude reflectance $r = A^-(0)/A^+(0)$and the transmittance $t = A^+(L)/A^+(0)$ are obtained from Eq.(3)

$$r = \frac{r_1 - e^{j\phi} r_1 r_2 / r_1^*}{1 - e^{j\phi} r_1 r_2} \quad (4a)$$

$$t = \frac{e^{j\phi} t_1 t_2}{1 - e^{j\phi} r_1 r_2} \quad (4b)$$

where the (i=1, 2) have been used. Eqs.(4) are just the expressions of a F-P resonator that consists of two mirrors with complex reflectance and complex transmittance. For a strongly coupled grating (i.e. $\kappa L \geq 3$), we have $\Delta\beta \ll \kappa$ in the narrower wavelength region of the transmission, and Eqs.(4) can be simplified as those for a conventional F-P resonator with the power reflectance of $tanh^2(\kappa L/2)$ and the cavity length of $tanh(\kappa L/2)/\kappa$.

The grating is subjected to a focused UV beam exposure to raise the refractive index in a selected region. The gratings within the spot of the UV beam are erased partly or fully and a F-P resonator is formed [3]. This gap length of the spot size increases the F-P effective cavity length and leads to a narrower linewidth transmission, which can be considered by replacing "ϕ"wherever it appears in Eq.(4) by "$\phi + 4\pi n_{eff} d/\lambda$".

Using Eqs.(1) and (2), the transmittance of the grating with two- and three-phase-shifts can be expressed as a composite F-P resonator:

$$t|_{\phi_1,\phi_2} = \frac{e^{j(\phi_1+\phi_2)} t_1 t_2 t_3}{1 - e^{j\phi_1} r_1 r_2 - e^{j\phi_2} r_2 r_3 - e^{j[\phi_1+\phi_2+2 \cdot arg(t2)]} r_1 r_3} \quad (5)$$

and

$$t|_{\phi_1,\phi_2,\phi_3} = \frac{e^{j[\phi_1+\phi_2+\phi_3]} t_1 t_2 t_3 t_4}{\begin{bmatrix} 1 - r_1 r_2 e^{j\phi_1} - r_2 r_3 e^{j\phi_2} - r_3 r_4 e^{j\phi_3} - r_1 r_3 e^{j[\phi_2+\phi_1+2arg(t2)]} - r_2 r_4 e^{j[\phi_2 \phi_3+2arg(t3)]} \\ -r_1 r_4 e^{j[\phi_1+\phi_2+\phi_3+2arg(t2)+2arg(t3)]} + (-e^{j\phi_1} r_1 r_2)(-e^{j\phi_3} r_3 r_4) \end{bmatrix}} \quad (6)$$

where r_i and t_i (i=1, 2, ... N+1) describe the part-gratings G_i with grating length L_i between the neighboring phase-shifts, and N is the number of the phase-shifts. Every term except the first in the denominator of Eqs.(5) and (6) represents a round trip resonance in every F-P resonator, which consists of the two part-gratings at both sides of one phase-shift. The last term in the denominator of Eq.(6) is the resonance between two F-P cavities. The term $2arg(t_i)$ is the phase-shift of a round trip of light through the ith part-grating Gi. Eq.(6) is self-consistent. We can demonstrate that the case of the grating with two- or one- or zero-phase-shifts can be derived from Eq.(6) by replacing one or two or three phase-shifts by zero.

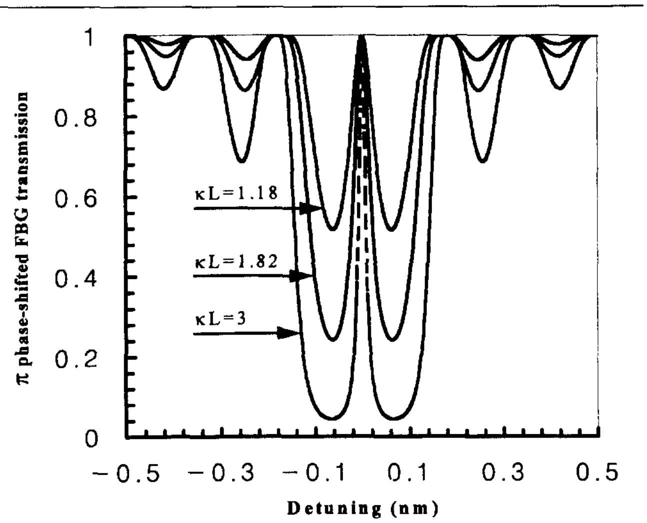

FIG. 1. Transmission for different coupling strengths (L=10 mm, λ=1.55 μm, $\phi=\pi$, κL=1.18, 1.82, 3.0).

III. RESULTS AND DISCUSSION

For the gratings with $\kappa L3$, L=10 mm, and the π phase-shift in the middle of the grating length, the transmission linewidth is 0.017 nm and the stop bandwidth is 0.28 nm. A strongly coupled grating has a narrower linewidth. The transmission spectra of phase-shifted gratings with different coupling strengths are shown in Fig. 1. When $\kappa L \geq 5$ and $L \geq 40$ mm, the transmission linewidth is less than 100 MHz.

With the increase of the phase-shift, the simulation shows that the transmission peak moves from the short to the long wavelength side in the Bragg stopband, which is in agreement with the result of Ref [5]. The transmission spectra for the phase-shifts of $\pi/4, \pi/2, 3\pi/4$, and π are shown in Fig. 2. A phase-shift less than π makes the transmission peak deviated from the center Bragg wavelength and located at the short side while the linewidth keeps constant. When the π phase-shift is located at one side of the grating length specified by $q = L_1/L < 0.5$, a weak transmission peak appears at the Bragg resonance wavelength, as illustrated in Fig. 3.

For coupling strength of $\kappa L \geq 3$ (L=10 mm), the π(phase-shifted grating can be treated as a conventional F-P cavity in the narrow transmission wavelength region. The F-P effective cavity length with the coupling strength is shown in Fig. 4. A strongly coupled grating has a shorter effective F-P cavity length.

For the π phase-shifted grating ($\kappa L = 3$, L=10 mm)

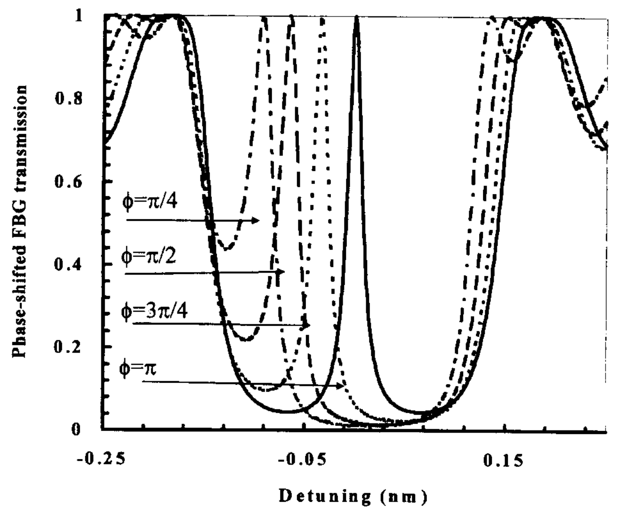

FIG. 2. Transmission for different phase-shifts (κL=3, L=10 mm, λ=1.55 μm, q=0.5, $\phi=\pi/4$, $\pi/2$, $3\pi/4$, π).

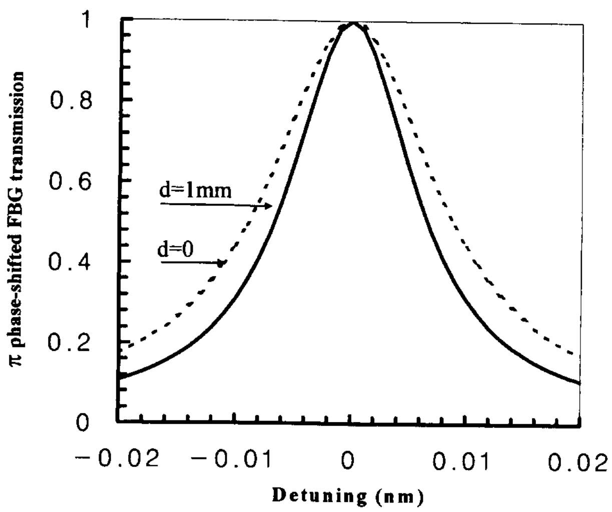

FIG. 5. Transmission for different gap lengths (κL=3, L=10 mm, λ=1.55 μm, $\phi=\pi$, d=0, 1 mm).

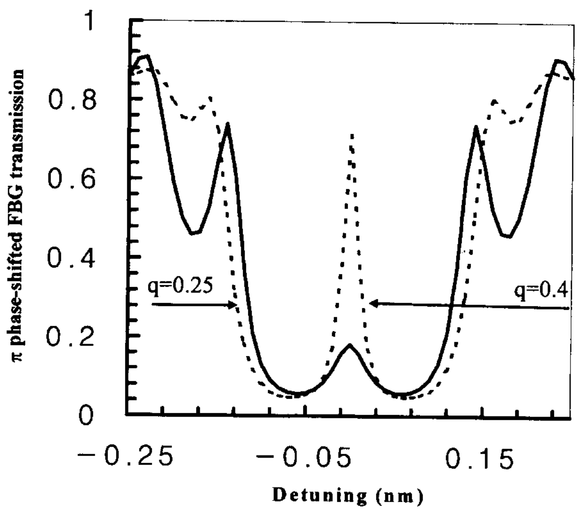

FIG. 3. Transmission for different phase-shift locations (κL=3, L=10 mm, λ=1.55 μm, $\phi=\pi$, q=0.4, 0.25).

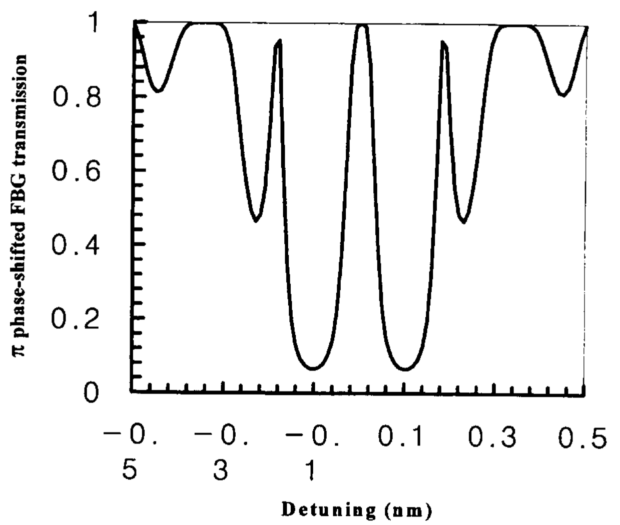

FIG. 6. Transmission for the grating with two π phase-shifts (κL=3, L=10 mm, λ=1.55 μm, L_1:L_2:L_3= 1:2:1).

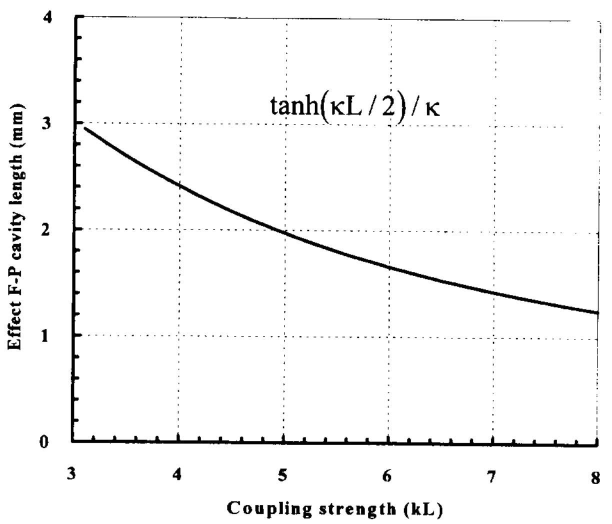

FIG. 4. F-P cavity length versus the coupling strength (L=10 mm, λ=1.55 μm, $\phi=\pi$).

with a gap length d=0 and 1 mm, the transmission spectrum is shown in Fig. 5. The linewidths are 0.017 nm and 0.015 nm, respectively. The influence of the gap length on the linewidth depends on the ratio of gap length to the F-P effective cavity length. For a strongly coupled grating such as a phase-shifted chirped grating, the effective F-P cavity length is relatively short at a specific wavelength; the linewidth, therefore, depends strongly on the gap length [3].

For the grating with two- or three-phase-shifts, the transmission spectrum can be designed by using different phase-shifts and their different locations along the grating length. For the two π phase-shifted grating with $L_1 : L_2 : L_3 = 1 : 2 : 1$ (κL=3, L=10 mm), the transmission is shown in Fig. 6. The three π phase-shifted grating with $L_1 : L_2 : L_3 : L_4 = 1 : 2 : 2$

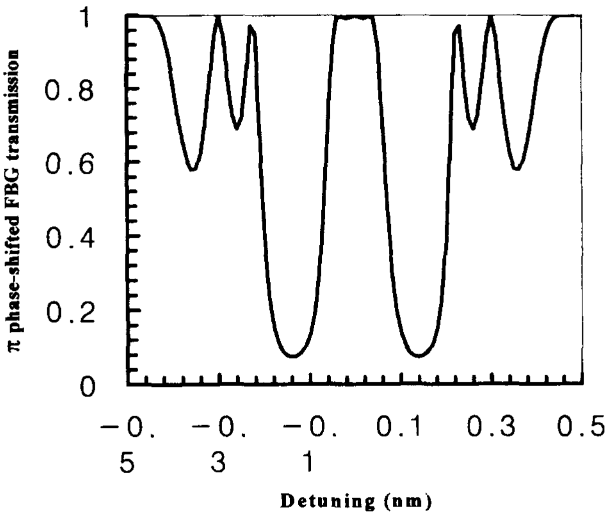

FIG. 7. Transmission for the grating with three π phase- shifts (κL=3, L=10mm, λ=1.55 μm, L_1:L_2:L_3:L_4 = 1:2:2:1).

: 1 (κL=3, L=10 mm), the transmission spectrum is shown in Fig. 7. A very flattened transmission with 0.08 nm linewidth is obtained, which can be used as a channel filter in WDM systems.

IV. CONCLUSIONS

We have presented an interesting and useful relationship between the phase-shifted fiber Bragg-gratings and the conventional Fabry-Perot resonators. A simplified analytical expression for one-, two- and three-phase-shifted fiber Bragg grating with clear physical picture was obtained. For the grating with π phase-shift,$\kappa L \geq 5$ and L$\geq$40 mm, the transmission linewidth was less than 100 MHz. A strongly coupled grating can be treated simply as a conventional Fabry-Perot resonator with the power reflectivity of $tanh^2(\kappa L/2)$ and the cavity length of $tanh(\kappa L/2)/\kappa$. Through introducing three π phase-shifts with the locations of 1:2:2:1 along the grating length, a very flattened transmission peak with 0.08 nm linewidth was obtained.

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