# Application passband filter of multiply cascaded phase-shifted long-period fiber gratings

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**Abstract**: The transmission characteristics of multiply cascaded phase-shifted long-period fiber gratings (LPFGs) will be investigated theoretically and experimentally. Their passband can be changed by increasing the number of $\pi$-shifted LPFGs. When two $\pi$-shifted LPFGs with different grating lengths are cascaded in series, the bandwidth of the rejection band and passband can be controlled by the pristine characteristics of two gratings.

**Keywords:** long-period fiber gratings, phase-shifted long-period fiber gratings

## 1. INTRODUCTION

Long-Period Fiber Gratings (LPFGs) have been attractive devices for application to optical communication systems and physical sensors due to their enormous advantages and applicability like wavelength selectivity, mass production, low backreflection, and so on [1]. Their spectrally selective nature, for example, makes them suitable for applications to various kinds of optical filters, gain flattening filters, and mechanical sensors [1-3]. Recently, the phase-shifted LPFGs have been proposed to adjust the transmission characteristics of LPFGs for application to the gain flattening filter of optical amplifiers [4]. By including the phase shift in the middle of LPFGs, the versatile optical filters like passband filter can be fabricated [4].

In this work, the transmission characteristics of multiply cascaded phase-shifted LPFGs will be investigated. The theoretical analysis based on the transfer matrix method is performed. When $\pi$-shifted LPFGs are cascaded in series, the bandwidth of passband is broadened as the number of gratings increases. If two $\pi$-shifted LPFGs with different lengths are cascaded, the transmission characteristics like bandwidth of rejection band and passband strongly depend on their pristine properties. Therefore, the high functional passband filter with the broad bandwidth can be realized by cascading several phase-shifted LPFGs with the different bandwidth. The theoretical results will be compared with experimental ones.

## 2. Phase-shifted long-period fiber gratings

The principle of LPFGs is based on the interaction between the core mode and cladding modes. The fundamental $HE_{11}$ core mode can be coupled with several cladding modes ($HE_{1m}$) via LPFGs. Based on the co-directional coupled mode theory, the modal amplitudes of the core and cladding modes in a single LPFG with length $L$ can be written as

$$\begin{pmatrix} a_{Co}(L) \\ a_{Cl}(L) \end{pmatrix} = \begin{pmatrix} e^{-i(\frac{\Delta\beta}{2})L} & 0 \\ 0 & e^{i(\frac{\Delta\beta}{2})L} \end{pmatrix} \times$$

$$\begin{pmatrix} (\cos\ sL + i\frac{\Delta\beta}{2s}\sin\ sL) & i\frac{\kappa}{s}\sin\ sL \\ i\frac{\kappa^*}{s}\sin\ sL & (\cos\ sL - i\frac{\Delta\beta}{2s}\sin\ sL)) \end{pmatrix} \times$$

$$\begin{pmatrix} a_{Co}(0) \\ a_{Cl}(0) \end{pmatrix} = \mathrm{T}\begin{pmatrix} a_{Co}(0) \\ a_{Cl}(0) \end{pmatrix}$$

Where

$$s = \left(\kappa^*\kappa + \frac{\Delta\beta^2}{4}\right)^{\frac{1}{2}} \quad \text{and} \quad \Delta\beta = \beta_{co} - \beta_{cl} - \frac{2\pi}{\Lambda}$$

$a_{co}$ and $a_{cl}$ represent the modal amplitudes of the core and cladding modes, respectively, $\kappa$ is the coupling constant, and $\Lambda$ is the grating period. $\beta_{co}$ and $\beta_{cl}$ indicate the propagation constants of the core and cladding modes, respectively. Once the transfer matrix of a unit ($T$) composed of an LPFG is obtained, the modal amplitudes of the core and cladding mode after phase-shifted LPFGs, can be easily obtained by the following equations

$$\begin{pmatrix} a_1 \\ a_2 \end{pmatrix}_{Out} = T_N \cdot \begin{pmatrix} e^{i\frac{\phi}{2}} & 0 \\ 0 & e^{-i\frac{\phi}{2}} \end{pmatrix} \cdot T_{N-1} \cdot \begin{pmatrix} e^{i\frac{\phi}{2}} & 0 \\ 0 & e^{-i\frac{\phi}{2}} \end{pmatrix} \times$$

$$\cdots T_2 \cdot \begin{pmatrix} e^{i\frac{\phi}{2}} & 0 \\ 0 & e^{-i\frac{\phi}{2}} \end{pmatrix} \cdot T_1 \begin{pmatrix} a_1(0) \\ a_2(0) \end{pmatrix}$$

where $\phi$ is the amount of the phase shift within gratings.

Fig. 1 shows the theoretical results of the transmission spectra of phase-shifted LPFGs with the phase shift of 0, $\pi/4$, $\pi/2$, $3\pi/4$, $3\pi/2$, respectively. Fig. 2 shows the theoretical results of $\pi$-shifted LPFGs when the number of gratings increases. The bandwidth of the passband increases as the number of gratings with the phase shifted of $\pi$ increases. Therefore, the broad bandpass filter can be fabricated by cascading $\pi$-shifted LPFGs.

The bandwidth of the passband and rejection band of the phase-shifted LPFGs strongly depends on the grating length. When the grating length increases, the bandwidth of LPFGs becomes broad and the phase-shifted LPFGs have the same characteristics. Therefore, the bandwidth of passband and rejection band of the $\pi$-shifted LPFGs increases as the grating length decreases. When two $\pi$-shifted LPFGs with different grating lengths is cascaded in series, the bandwidth of passband is determined by the $\pi$-shifted LPFGs with the narrow bandwidth. The bandwidth of rejection bands is determined by other LPFGs with the broad bandwidth.

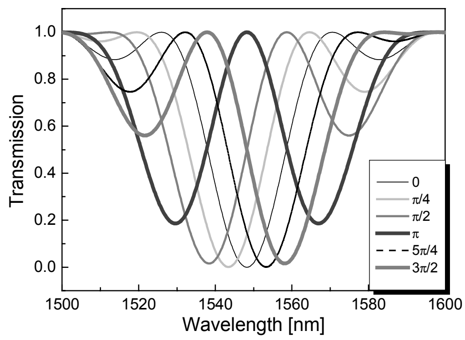


Figure 1. Theoretical results of the transmission spectra of phase-shifted LPFGs with the phase shift of 0, $\pi/4$, $\pi/2$, $3\pi/4$, $3\pi/2$, respectively.

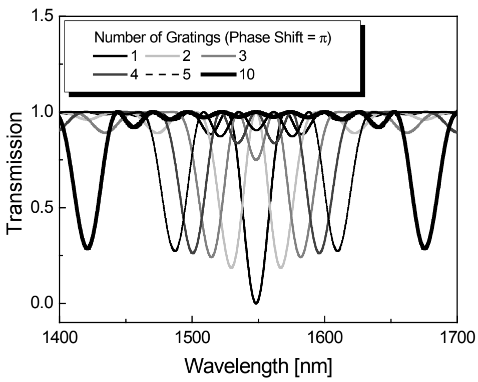


Figure 2. Theoretical results of $\pi$-shifted LPFGs when the number of gratings increases.

Fig. 3(a) and 3(b) shows the theoretical and experimental results of the cascaded $\pi$-shifted LPFGs (black line) with a different length of grating. The gray and dark gray lines show the $\pi$-shifted LPFG with 2 and 5 cm, respectively. The bandwidth of the grating with 2 cm is broader than that of 5 cm grating. After cascading the two gratings, the passband is similar to that of the $\pi$-shifted LPFG with 5 cm as shown in Fig. 3(a) and 3(b). The 2 cm grating determined the bandwidth of rejection band. Therefore, the transmission characteristics of passband filters based on $\pi$-shifted LPFGs can be controlled by cascading two gratings with different lengths.

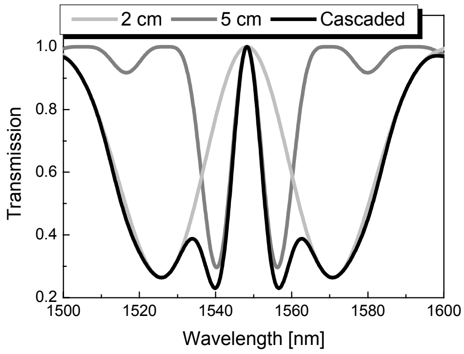


Figure 3(a)

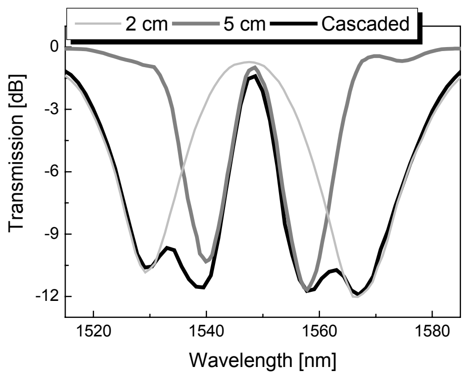


Figure 3(b)

Figure 3. (a) Theoretical and (b) experimental results of cascaded $\pi$-shifted LPFGs (black line) with different grating length of 2 and 5 cm. Gray line: $\pi$-shifted LPFG with 2 cm, dark gray line: $\pi$-shifted LPFG with 5 cm.

## 3. CONCULTION

The transmission characteristics of multiply cascaded phase-shifted long-period fiber gratings (LPFGs) were investigated. Based on the transfer matrix method, their properties like the bandwidth of passband and rejection band were analyzed. The bandwidth of the passband increased as the number of $\pi$-shifted LPFGs increased. When two $\pi$-shifted LPFGs with different grating lengths were cascaded in series, the bandwidth of the rejection band and passband strongly depends on the pristine characteristics of two gratings. When two $\pi$-shifted LPFGs with different grating lengths is cascaded in series, the bandwidth of passband is determined by the $\pi$-shifted LPFGs with the narrow bandwidth. The bandwidth of rejection bands is determined by other LPFGs with the broad bandwidth. The theoretical and experimental results are very useful for designing versatile passband filters with the broad bandwidth or rejection band for optical communication systems.

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