CHIN. PHYS. LETT. Vol. 26, No. 7 (2009) 074208

A Tunable Acousto-Optic Fiber Filter Based on Two Simultaneous Mode Coupling Processes

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(Received 21 March 2009)

A dynamically tunable fiber filter realizing complex spectra of phase-shifted long period fiber gratings (LPFGs) is proposed and demonstrated experimentally. The principle of the filter is based on two acousto-optic coupling processes occurring simultaneously. The first coupling process acts as a normal LPFG, while the second makes the coupling direction of the first process change continuously, leading to a similar transmission spectrum with the phase-shifted LPFGs, in which the changing of coupling direction is realized by the discrete phase shifts of the index modulation. By adjusting the acoustic drive signals, its transmission spectrum can be dynamically tuned to realize the phase-shifted LPFGs' spectra under different phase shift numbers and locations.

PACS: 42.79.Jq, 42.81.Qb

Phase-shifted long period fiber gratings (LPFGs) have attracted great interests for various applications in communications and sensor systems. By fabricating specific grating parameters such as phase shifts and section lengths, the desired spectral responses can be obtained.[1,2] However, there are some drawbacks. First, since the grating length is up to several centimeters, the phase-shifted LPFGs are environmentally sensitive and the filter characteristics could be influenced by temperature and strain.[3,4] Second, the phased shifts are usually achieved by the specific design of the template or overexposure at specific points. It is difficult to tune the phase shifts after the grating is fabricated, although it is necessary in numerous applications. To dynamically tune the spectral response, Chen[5] developed a technique of thermally tuning the phase shifts.

On the other hand, all-fiber acousto-optic tunable filters (AOTFs) have similar a coupling mechanism to the LPFGs and have the advantage of being tunable.[6] The refractive index along the fiber is periodical modulated by the acoustic wave, which can be tuned by simply adjusting the electrical driven signal. Although phase shifts can be easily achieved by the electrical driven signal, the phase-shifted AOTF cannot carry out the characteristics of phase-shifted LPFGs, because the corresponding acoustic wave travels along the fiber and static phase shifts cannot be realized on the acoustic grating.

In this Letter, we present a dynamic tunable filter based on two acousto-optic (AO) couplings occurring simultaneously, which can realize similar spectral responses of the standard phase-shifted LPFGs. The first AO coupling process acts as a normal LPFG, whose coupling direction can be continuously changed by the second AO coupling process. The mechanism is analyzed by coupled mode theory and the spectral responses and coupling processes are compared to the standard phase-shifted LPFG. Some special transmission spectra are demonstrated experimentally.

The device is set up by two acoustic waves traveling simultaneously on the same fiber section. One couples the input core mode LP_{01} to cladding mode LP_{11} (the first coupling process) and the other couples LP_{11} mode to LP_{21} mode. Taking no account of the frequency shifts, the coupled mode equation can be written as

$$\begin{aligned}\frac{dE_{01}}{dz} &= -i\kappa_1 e^{i2\delta_1 z}E_{11},\\ \frac{dE_{11}}{dz} &= -i\kappa_1 e^{-i2\delta_1 z}E_{01} - i\kappa_2 e^{i2\delta_2 z}E_{21},\\ \frac{dE_{21}}{dz} &= -i\kappa_2 e^{-i2\delta_2 z}E_{11},\end{aligned} \tag{1}$$

where the detuning $\delta_1 = (\beta_{01} - \beta_{11})/2 - \pi/\Lambda_1$, $\delta_2 = (\beta_{11} - \beta_{21})/2 - \pi/\Lambda_2$, β_{ij} is the propagation constant of LP_{ij} mode. $\Lambda_{1,2}$ are the acoustic wave lengths and $\kappa_{1,2}$ are the coupling coefficients corresponding to the two coupling processes respectively.

Since the cladding modes are considered, the fiber is modeled as a three-layer cylindrical dielectric waveguide with the core, cladding and air clothing. The fiber is single mode fiber (SMF) with core diameter 8.3 μm and refractive index difference between core and cladding 0.33%. For simplification, material dispersion is omitted and coupling coefficient is independent of λ because the wavelength range concerned is quite small.

When the two acoustic frequencies are chosen such that the resonant wavelengths for two AO coupling processes are both 1550 nm, the calculated transmission spectra are shown in Figs. 1(a) and 1(c). If only the coupling of LP_{01}-LP_{11} exists ($\kappa_2 = 0$) and $\kappa_1 = \pi/2L \equiv \kappa_0$ (κ_0 is defined by $\pi/2L$), the LP_{01} mode at the center wavelength couples to the LP_{11} mode completely, as shown by the solid curve in Fig. 1(a). When the second acoustic wave is applied, the center reduces and two new rejection bands appear. When κ_1 and κ_2 are approximately equal to $1.41\kappa_0$ and $3.74\kappa_0$ respectively, the center reaches the maximum and the

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two minima in the spectra reach zero simultaneously, as shown by the dashed and dot-dashed curves in Fig. 1(a). For comparison, we calculate the spectra of phase shifted LPFGs coupling LP_{01} to LP_{11} by the F-matrix under all the same parameters used above, as shown in Fig. 1(b). The solid curve is the LPFG spectrum without phase shift. The dashed and dot-dashed curves are the LPFG spectra with one π phase shift ($N = 2$) at the center of the LPFG under two coupling coefficients, respectively. The coupling coefficient of the LPFG is denoted by κ_p. Comparing Figs. 1(a) and 1(b), it can be seen that the transmission spectra realized by two simultaneous coupling AOTFs are similar to the LPFGs with a π phase shift at the center.

When $\kappa_2 = 1.73\kappa_0$ and $\kappa_2 = 3.16\kappa_0$, the spectral responses of the AOTF are shown by the dashed curve and dotted curve in Fig. 1(c). They are similar to the spectral responses of the LPFG with one π phase shift at two different locations, shown in Fig. 1(d). It can be seen that the two simultaneous coupling AOTFs with different values of κ_2 can realize the spectra of the LPFGs with one π phase shift at different locations.

The spectra of the LPFGs with N uniform sections divided by $N-1$ π phase shifts can also be realized by the two simultaneous coupling AOTFs. As shown in Fig. 2, when $\kappa_1 = 1.41\kappa_0$ and $\kappa_2 = 10\kappa_0$ the spectrum of the AOTFs (solid curve) is similar to the $N = 5$ phase-shifted LPFG (dashed curve). The two main transmission notches overlap, while their side lobe peak wavelengths also match well.

To show the feasibility of realizing LPFG spectra under any π phase shift number N, the corresponding parameters of two simultaneous coupling AOTFs are calculated, as shown in Fig. 3. In two simultaneous coupling AOTFs, κ_2 determines the separation of the troughs in the spectra and κ_1 determines their depth. By increasing κ_2, the separation between the two troughs in the spectra ($\Delta\lambda$) can be linearly increased, as shown by the solid curve in Fig. 4. For comparison, the relation of $\Delta\lambda$ versus N in the phase-shifted LPFG is shown by the squares. It can be seen that increasing N in the phase-shifted LPFGs also leads to increasing $\Delta\lambda$, which is close to the curve of $\Delta\lambda$ versus $|\kappa_2|/2\kappa_0$. Thus the trough separation corresponding to different N in the phase-shifted LPFG can be tuned by changing κ_2 in the two simultaneous coupling AOTFs. On the other hand, in the AOTFs κ_1 determines the depth of the two troughs. The dashed curve shows the required κ_1 for the minimum of the two troughs to be zero under different $\Delta\lambda$. It converges to $1.41\kappa_0$ and it is almost unchanged when $\Delta\lambda > 20$ nm. When changing $\Delta\lambda$ by tuning κ_2, we do not need to change the first AO coupling, which acts as a normal LPFG. For comparison, the circles show the required κ_p in a phase-shifted LPFG with zero troughs under different $\Delta\lambda$. It converges to $1.57\kappa_0$ and is almost unchanged under large N ($N > 5$).

The calculation results in Fig. 3 demonstrate that by selecting proper acoustic wave parameters, the filtering function of phase-shifted LPFG under different phase shift numbers can be realized by two simultaneous coupling AOTFs; even the LPFG spectra under non-integral N can be realized. Furthermore, the characteristics of the AOTFs lead to the tuning function of the spectral responses.

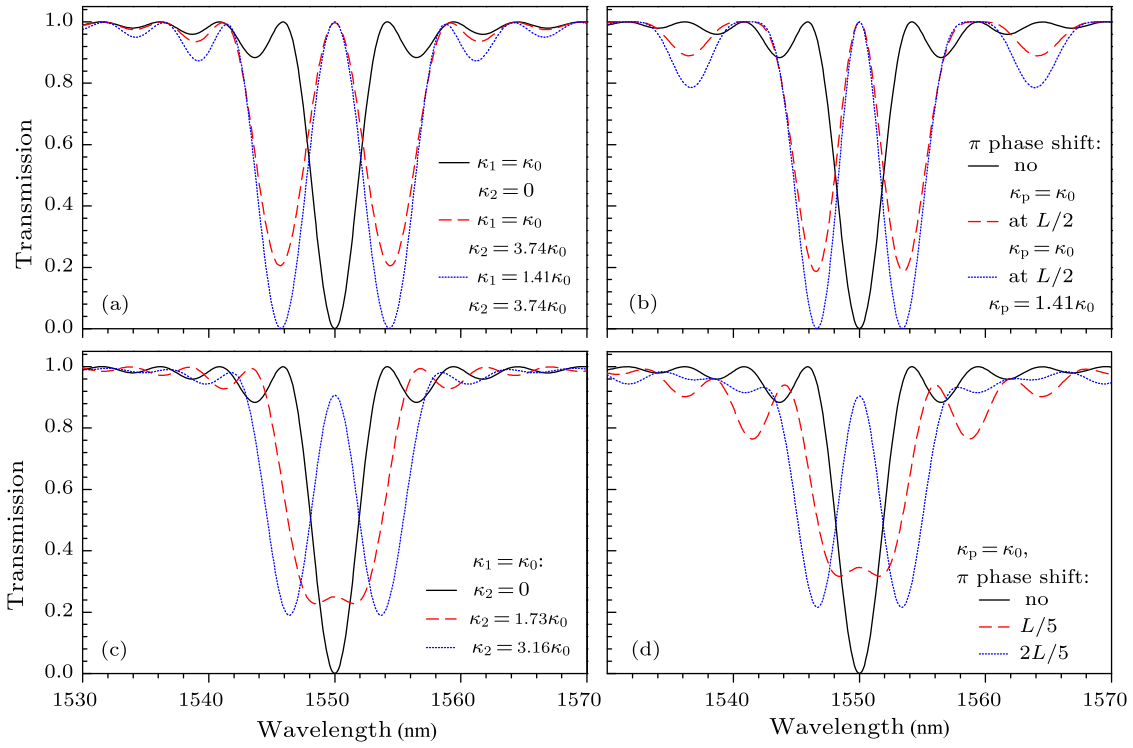


Fig. 1. Spectral responses for cascaded AOTFs [(a),(c)] and phase shifted LPFGs [(b),(d)].

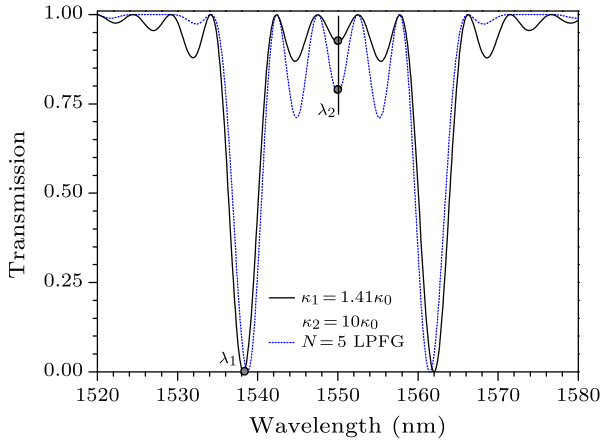


Fig. 2. Spectral responses for cascaded AOTFs (solid curve) and phase-shifted LPFG (dot-dashed curve).

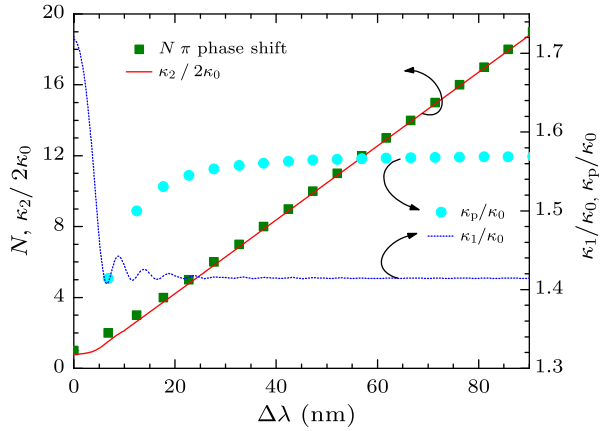


Fig. 3. Required parameters versus trough span.

To explain the principle of the two simultaneous coupling AOTFs, the power evolution along the AOTFs and the LPFG shown in Fig. 2 are calculated under two typical wavelengths, which are marked in Fig. 2. Here $\lambda_1 = 1538.5$ nm is the peak wavelength of one of the transmission troughs, and $\lambda_2 = 1550$ nm is the wavelength where the two AO coupling processes satisfy the phase matched conditions. Figures 4(a) and 4(b) show the power evolution in the phase-shifted LPFG at λ_1 and λ_2, respectively. It can be seen that the coupling directions between the core mode and cladding mode change at each π shift point, which act as a series of discrete reversers. As a result, the input power in the LP_{01} mode is entirely coupled to the LP_{11} mode at λ_1; on the other hand, the coupling at phase matched wavelength λ_2 is insufficient.

The characteristics of the power evolution are different in the two simultaneous coupling AOTFs, as shown in Figs. 4(c) and 4(d). Though the power evolution tendencies are the same in the case of the LPFG, there is no discrete point to realize changes of coupling direction, and the power evolution under both wavelengths is continuous. This can be explained by the fact that the second AO coupling process between the LP_{11} mode and the LP_{12} mode changes the coupling direction of the first AO coupling process continuously by changing the phase and intensity of the field in the LP_{11} mode gradually. This mechanism difference in coupling direction between the two simultaneous coupling AOTFs and phase-shifted LPFG leads to a small difference of lobes in their spectra.

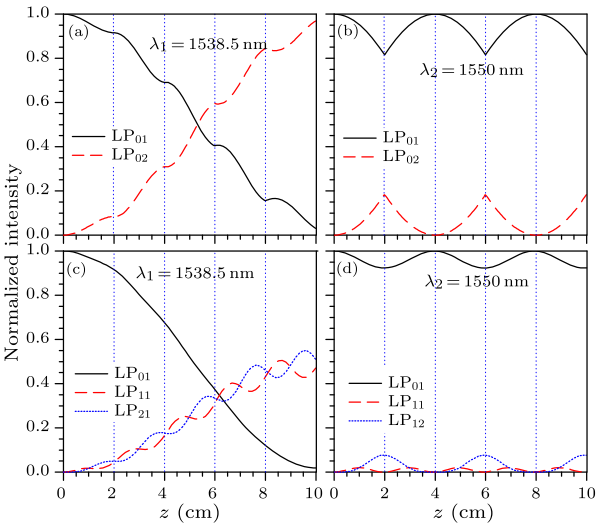


Fig. 4. Power evolution in phase-shifted LPFG [(a),(b)] and two simultaneous coupling AOTFs [(c),(d)].

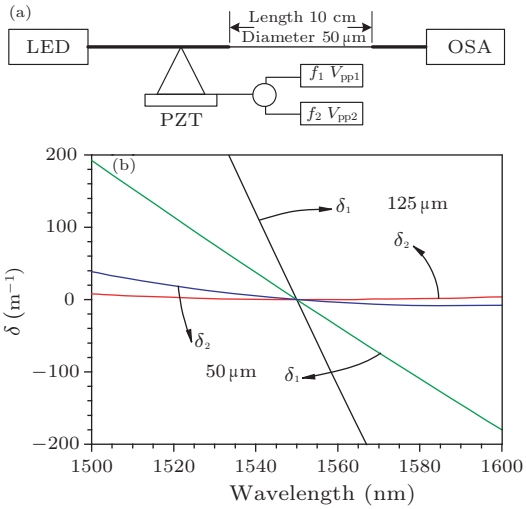


Fig. 5. (a) Experimental schematic setup for simultaneous coupling AOTFs. (b) Phase mismatchings δ_1 and δ_2 with diameters of 125 μm and 50 μm, respectively.

The experimental setup is shown in Fig. 5(a), which is a regular AOTF setup except that two rf signals are applied to the piezoelectric transducer (PZT) simultaneously. In order to increase the AO coupling coefficient, the fiber is etched to 50 μm in a 10 cm long section. To show the influence of the fiber diameter on the phase mismatching of the simultaneous coupling AOTFs, δ_1 and δ_2 in fibers with diameters of 125 μm and 50 μm are calculated and shown in Fig. 5(b), respectively. Calculation shows that in both the cases, δ_1 is much larger than δ_2 and the bandwidths of the second AO coupling are all larger than 100 nm.

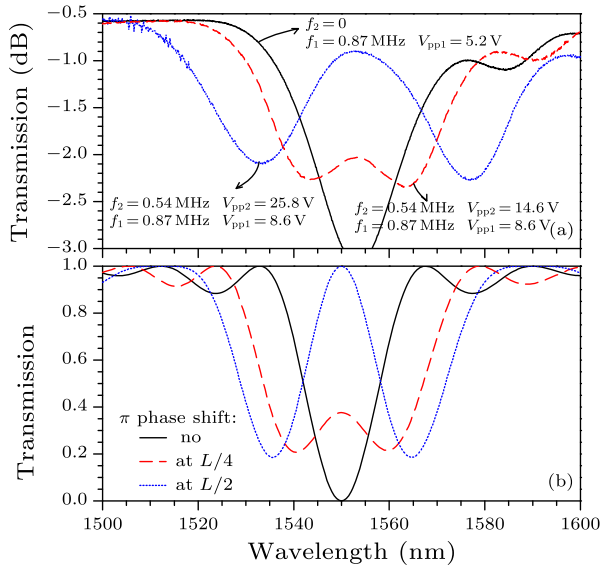


Fig. 6. Transmission spectra of experimental two simultaneous coupling AOTFs (a) and numerical phase-shifted LPFG (b) when the fiber diameter is etched to about 50 μm.

Figure 6 shows the experimentally measured spectra of the two simultaneous coupling AOTFs and the numerical results of the phase-shifted LPFG with a diameter of 50 μm. When the acoustic frequency f_1 and drive voltage V_{pp1} of the first AOTF are 0.87 MHz and 5.2 V, the spectrum is shown as the solid curve in Fig. 5(a). When the second acoustic frequency $f_2 = 0.54$ kHz is added, the transmission spectra are shown as the dashed and dotted curves, corresponding to $V_{pp2} = 14.6$ V and 25.8 V, respectively. Comparing the numerical spectra of the phase-shifted LPFG with one π shift at $L/4$ and $L/2$ ($N = 2$) in Fig. 5(b), we can see that the experiments agree well with the simulations.

In summary, a dynamically tunable fiber filter for two simultaneous coupling AOTFs realizing complex spectra of phase-shifted LPFGs is proposed and demonstrated experimentally. The principle of the device is based on two acousto-optic coupling processes occurring simultaneously ($LP_{01} \rightarrow LP_{11} \rightarrow LP_{21}$). The first AO coupling process acts as a normal LPFG, while the second changes the coupling direction of the first process continuously, leading to a similar transmission spectrum with the phase-shifted LPFG, in which the coupling direction changes are realized by discrete phase shifts of the index modulation. By adjusting the acoustic drive signals, its transmission spectrum can be dynamically tuned to realize the phase-shifted LPFG spectra under different phase shift numbers and locations.

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