Optical pulse shaping based on a double-phase-shifted fiber Bragg grating*

DONG Xiao-wei (董小伟)** **and GUO Pan** (郭盼)

College of Information Engineering, North China University of Technology, Beijing 100144, China

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Based on the transfer matrix method, a detailed theoretical and numerical study on double-phase-shifted fiber Bragg grating (FBG) is investigated. Temporal responses of the double-phase-shifted FBG to optical pulse are analyzed and the influence of the two phase-shifts' position on the reflected output pulse is evaluated. Results demonstrate that very different temporal pulse waveforms can be achieved by adjusting the length ratio ($\alpha=L_2/L_1$). Specifically, a transform-limited Gaussian input optical pulse can be shaped into flat-top square pulse (α=1.81) or two identical optical pulse sequences (α=1.93).

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Pulses with the time scales of picosecond and femtosecond have attracted considerable attention in many applications. The mode-locked lasers are by far the most common sources of optical pulses. But the temporal shapes generated by mode-locked lasers are typically Sech^2 or Gaussian style, which are unsuitable for some special applications[1]. In order to obtain a customized optical pulse waveform, pulse shaping and processing technologies are indispensable[2,3]. The well-known approach is the 4f Fourier transform setup[4], in which an appropriately designed amplitude or phase mask is used to reshape the spectrum of incident pulse. However, devices employed by the 4f system are bulky, lossy, and expensive. This has prompted recent efforts on the implementation of fiber-based optical shaping elements[5,6]. For example, shaping filters based on fiber Bragg grating[7,8], superstructured Bragg gratings[9] or long-period-grating co-directional coupler[10,11] have been demonstrated. In this paper, we focus on investigating the optical pulse shaping capabilities of a double-phase-shift fiber Bragg grating (FBG). By properly locating the two phase-shifts, different output pulse shapes, including flat-top square pulse and two identical optical pulse sequences, can be obtained flexibly.

Fig.1 shows a schematic diagram of the proposed optical pulse shaper. A double-phase-shifted FBG can be modelled by combing the transfer matrix method with the coupled-mode theory[12]. By dividing the double-phase-shifted FBG into three uniform FBGs and two phase-shifted elements, the transfer matrix related to the forward propagating mode (R) and the backward propagating mode (S) can be expressed as:

$$\begin{bmatrix} R(0) \\ S(0) \end{bmatrix} = \boldsymbol{T}_1 \cdot \boldsymbol{\Phi} \cdot \boldsymbol{T}_2 \cdot \boldsymbol{\Phi} \cdot \boldsymbol{T}_1 \begin{bmatrix} R(2L_1+L_2) \\ S(2L_1+L_2) \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} R(2L_1+L_2) \\ S(2L_1+L_2) \end{bmatrix}, \quad (1)$$

where $R(0)$, $S(0)$ and $R(2L_1+L_2)$, $S(2L_1+L_2)$ are the field amplitudes at the input end ($z=0$) and the output end ($z=2L_1+L_2$), respectively. $\boldsymbol{\Phi}$ represents the phase shift perturbation in the grating:

$$\boldsymbol{\Phi} = \begin{bmatrix} \exp(\mathrm{j}\varphi/2) & 0 \\ 0 & \exp(-\mathrm{j}\varphi/2) \end{bmatrix}. \quad (2)$$

$\boldsymbol{T}_m$ ($m=1,2$) represents the transfer matrix of uniform FBG with length L_m, which can be obtained by solving the coupled-mode equation[13]:

$$\boldsymbol{T}_m = \begin{bmatrix} \cosh(\varOmega\cdot L_m) - \mathrm{j}\dfrac{\sigma}{\varOmega}\sinh(\varOmega\cdot L_m) & -\mathrm{j}\dfrac{\kappa}{\varOmega}\sinh(\varOmega\cdot L_m) \\ \mathrm{j}\dfrac{\kappa}{\varOmega}\sinh(\varOmega\cdot L_m) & \cosh(\varOmega\cdot L_m) + \mathrm{j}\dfrac{\sigma}{\varOmega}\sinh(\varOmega\cdot L_m) \end{bmatrix}, \quad (3)$$

where $\kappa = \dfrac{\pi}{\lambda}\Delta n_{\mathrm{eff}}$ is the grating coupling coefficient, Δn_{eff} is refractive index modulation depth, λ is the light wavelength; $\sigma = \beta - \pi/\varLambda$ is the mismatch factor,

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** E-mail: way7803@163.com

β is the mode propagation constant, Λ is the grating period; $\Omega=\sqrt{\kappa^2-\sigma^2}$ and $\mathrm{j}=\sqrt{-1}$.

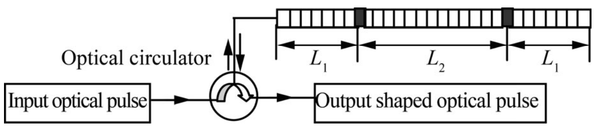


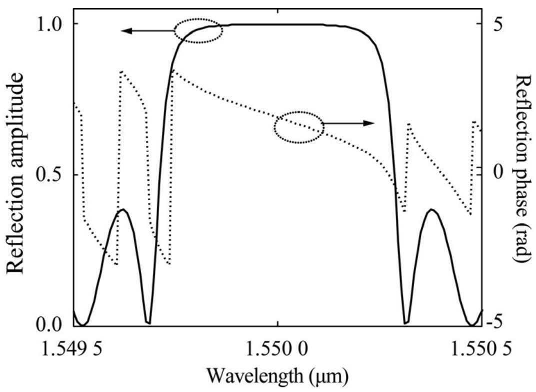
Fig.1 Optical pulse shaping based on a double-phase-shifted fiber Bragg grating

Then, substituting the initial condition $R(0)=1$ and $S(2L_1+L_2)=0$ into Eq.(1), the transmission coefficient $\tau=1/T_{11}$ and reflection coefficient $r=T_{21}/T_{11}$ of the double-phase-shifted FBG can be obtained correspondingly. Thus, if an optical pulse $A_{\text{in}}(t)$ with spectral response $A_{\text{in}}(\lambda)$ is input, the temporal waveform at the output port is the inverse Fourier transform of the product of input spectrum $A_{\text{in}}(\lambda)$ and the grating's reflection spectrum $r(\lambda)$:

$$A_{\text{out}}(t)=\int\left[A_{\text{in}}(\lambda)\cdot r(\lambda)\right]\exp(\mathrm{j}\lambda t)\mathrm{d}\lambda\,. \tag{4}$$

In the following, we assume the grating to be inscribed into conventional SMF-28 single-mode fiber with the parameters: phase shift perturbation $\varphi=\pi$, grating length L_1=1 mm, $L_2=\alpha\times L_1$ (α is the length ratio coefficient), refractive index modulation depth $\Delta n_{\text{eff}}=5\times10^{-4}$ and the grating period $\Lambda=532$ nm so as to make the Bragg resonance wavelength at 1 550 nm.

Firstly, the spectral responses of reflection amplitude $|r|$ and phase angle $\arg(r)$ of the double-phase-shifted FBG are numerically analyzed. Compared with the uniform FBG with the same length, two resonance notches and significant phase angle variations are introduced by the two phase-shifts, as shown in Fig.2. And the length ratio coefficient ($\alpha=L_2/L_1$) plays an important influence on the spectral responses. As the length ratio coefficient increasing, the interval of two resonance notches decreases gradually. When $\alpha=2$, the two resonance notches are merged into one notch. If the length ratio coefficient increases furthermore, the maximum depth of the central resonance notch cannot reach zero anymore.



(a)

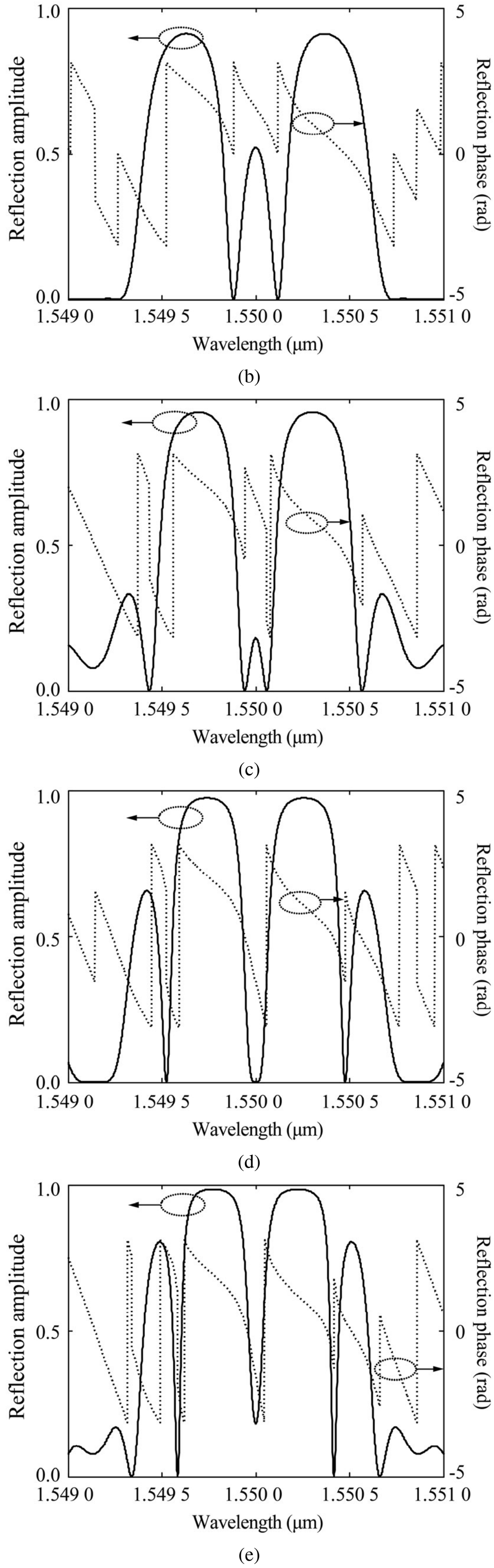
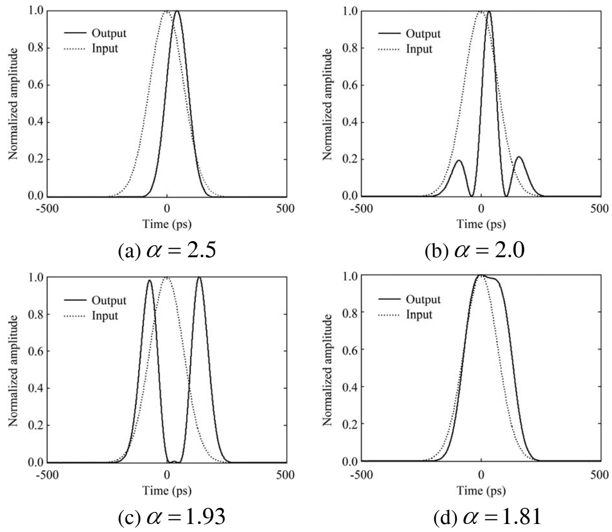


Fig.2 Spectral responses of reflection amplitude (solid line) and phase angle (dotted line):(a) Uniform FBG; (b)-(e) Double-phase-shifted FBGs with length ratios of *α*=1.0, 1.5, 2.0, 2.5

Then, the optical pulse shaping capabilities of the double-phase-shifted FBG are investigated. When a transform-limited Gaussian pulse $A(t)=\exp(-t^2/\tau_0^{\ 2})$ with full-width at half maximum (FWHM) of 100 ps is input, the temporal waveform of the output pulse is numerically simulated. Depending on the length ratio coefficient ($\alpha=L_2/L_1$), very different pulse shapes can be obtained, as can be seen from Fig.3. When $\alpha=2.5$, there is negligible waveform change except for a little time delay between output pulse (solid line) and the original input pulse (dotted line). The reason is that output pulse spectrum $A_{\text{out}}(\lambda)$ is approximately equal to the input pulse spectrum $A_{\text{in}}(\lambda)$ itself. However, by adjusting the length ratio coefficient to change positions of the two phase-shifts, different output pulse shapes can be obtained flexibly. When the length ratio coefficient α decreases, two side-lobes appear and the output waveform is transformed into two identical optical pulse sequences for $\alpha=1.93$. Specifically interesting, the two identical pulse sequences evolve into a nearly flat-top square pulse waveform for even lower length ratio ($\alpha=1.81$).



(a) $\alpha=2.5$ (b) $\alpha=2.0$ (c) $\alpha=1.93$ (d) $\alpha=1.81$

Fig.3 Pulse waveforms of output and input when the double-phase-shifted FBGs with different length ratios

In this paper, we numerically compare the amplitude and phase characteristics of double-phase-shifted FBG with those of uniform FBG. The pulse shaping capabilities of double-phase-shifted FBG are confirmed. And a transform-limited Gaussian input optical pulse can be shaped into flat-top square pulse or two identical optical pulse sequences by properly setting the length ratio as $L_2/L_1=1.81$ or $L_2/L_1=1.93$, respectively. These results will open important new perspectives towards the implementation of compact and practical fiber-based optical pulse shaping.

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