Second-Order Differentiator Based on Long-Period Waveguide Grating

Ailing Zhang, Hongyun Song, and Bo Geng

Abstract In this paper, a structure of second-order differentiator based on long-period waveguide grating (LPWG) is proposed. The second-order differentiator consists of two segment uniform gratings, one segment waveguide and electrode correspondingly deposited on both sides of waveguide on x-cut lithium niobate (LN) crystal. The performances of the second-order differentiator are analyzed and simulated. It shows that it can be implemented by introducing π-phase shift by adjusting voltage according to the electro-optic effect of LN.

Keywords Long-period waveguide grating (LPWG) · Differentiator · Lithium niobate (LN) · Electro-optic effect

1 Introduction

An N-th photonic differentiator can realize the N-th time derivative of input optical signal and has important applications in analog–digital conversion, pulse shaping, and optical processing of microwave signals [1]. In recent years, second-order differentiators based on long-period fiber grating (LPFG) have been proposed and experimentally verified [2, 3]. It normally uses the elastic-optical effect in fiber to obtain the differentiated function, resulting in low tuning speed. Lithium niobate (LN) has advantages of good electro-optic effect and fast tuning speed. Therefore, second-order differentiator based on LN long-period waveguide grating (LPWG) has potential applications in high-speed differentiator.

In this paper, a structure of second-order differentiator based on LPWG is proposed. And the second-order differentiator is analyzed theoretically and simulated by MATLAB. The fabrication of LPWG based on LN is investigated.

A. Zhang (✉) · H. Song · B. Geng
School of Electrical and Electronic Engineering, Engineering Research Center of Ministry of Education for Optoelectronic Devices and Communication Technology, Tianjin Key Laboratory of Film Electronic and Communication Devices, Tianjin University of Technology, Tianjin, China
e-mail: alzhang07@163.com

L. Xu and L. Zhou (eds.), *Proceedings of the 8th International Multidisciplinary Conference on Optofluidics (IMCO 2018)*, Lecture Notes in Electrical Engineering 531,
https://doi.org/10.1007/978-981-13-3381-1_14

2 Principle

The structure of second-order differentiator based on LPWG is shown in Fig. 1. It consists of two segments of uniform LPWG gratings, one segment of waveguide and electrodes correspondingly deposited on both sides of waveguide on x-cut LN crystal.

According to transfer-matrix method, the matrix of differentiator can be expressed as [6].

$$F = F2 \times P \times F1 \tag{1}$$

where F_1 is the transfer matrix of the 1-th grating and F_2 is the transfer matrix of the 2-th grating. P is transfer matrix of the waveguide.

F_1 is expressed as

$$F_i = \begin{bmatrix} \cos(sl_i) + j\frac{\delta}{s}\sin(sl_i) & j\frac{\kappa}{s}\sin(sl_i) \\ j\frac{\kappa}{s}\sin(sl_i) & \cos(sl_i) - j\frac{\delta}{s}\sin(sl_i) \end{bmatrix}$$
$$i = 1, 2 \tag{2}$$

where l_i is length of the ith grating ($i = 1, 2$), $\delta = \frac{\pi(N_{co}-N_{cl})}{\lambda} - \pi/\Lambda$ and $\kappa = \frac{\pi}{\lambda}\Delta N$ are the detuning and coupling coefficient of the grating, respectively. N_{co} and N_{cl} are effective refractive index of the core and cladding of waveguide, ΔN is modulation amplitude of the grating, Λ is the period of the grating and $s = \sqrt{\kappa^2 + \delta^2}$.

P is expressed as

$$\mathrm{P} = \begin{bmatrix} e^{-j\frac{\theta}{2}} & 0 \\ 0 & e^{j\frac{\theta}{2}} \end{bmatrix} \tag{3}$$

According to electro-optic effect of LN [7], θ is

$$\theta = \frac{2 \cdot \pi \cdot L}{\lambda} \cdot \left(N_{co} - \frac{V}{2d}\gamma_{33}N_{co}^3\right) \tag{4}$$

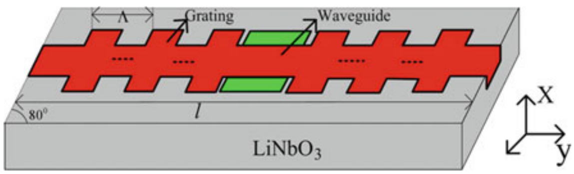

Fig. 1 Structure of second-order differentiator based on long-period waveguide grating

where L is the length of waveguide, V is the voltage added on electrode with gap d. $\gamma_{33} = 30.8\,\text{pm/V}$ is used for the electric field is parallel to the optical axis z.

Suppose a voltage is applied across the waveguide to produce π phase shift, the transfer function of the differentiator is

$$F[1,1] = -j\frac{\delta^2}{s^2}\cos s(l_1 + l_2) - j\frac{\kappa^2}{s^2}\cos s(l_1 - l_2) + \frac{\delta}{s}\sin s(l_1 + l_2) \quad (5)$$

Expanding F(1,1) into Taylor series analytically around the central frequency ω_0.

$$F[1,1] = F(\omega_0) + \frac{1}{2}F'(\omega_0)(\omega - \omega_0) + \frac{1}{6}F''(\omega_0)(\omega - \omega_0)^2 + \dots \quad (6)$$

For the second-order differentiator, it is required that the constant term and the first-order term are zero. According to Eqs. (5) and (6), we can obtain

$$\kappa l_1 = \frac{3\pi}{4} \quad \kappa l_2 = \frac{\pi}{4} \quad (7)$$

As a result, in order to obtain a second-order differentiator, θ should be equal to π, and length ratio of two segments LPWG should be l_1:l_2 = 3:1. According to Eq. (4), π phase shift can be achieved by adjusting the voltage V.

3 Results

The second-order differentiator is verified by MATLAB in the following. In simulation, we set $N_{co} = 2.139$, $N_{cl} = 2.137$, $\Delta N = 0.5 \times 10^{-4}$, $\Lambda = 775\ \mu\text{m}$, $L = 3.6$ mm, $d = 7\ \mu\text{m}$, and set $l_1 = 20.4$ mm, $l_2 = 6.8$ mm according to theoretical analysis.

Figure 2 shows the relationship between the phase shift and voltage. It can be seen that the tuning efficiency of the phase is 0.1 π/V, which will be increased by using a longer length of waveguide. From Fig. 2, π-phase shift can be obtained by applying 10 V voltage.

According to theoretical analysis, the second-order differentiator can be implemented by π-phase shift inserted between two LPWG with l_1:l_2 = 3:1, and the spectra of two LPWG are shown in Fig. 3.

The spectrum of the second-order differentiator is shown in Fig. 4. As can be seen from Fig. 4, the transmission spectrum of it is approximately a quadratic function near the resonance frequency.

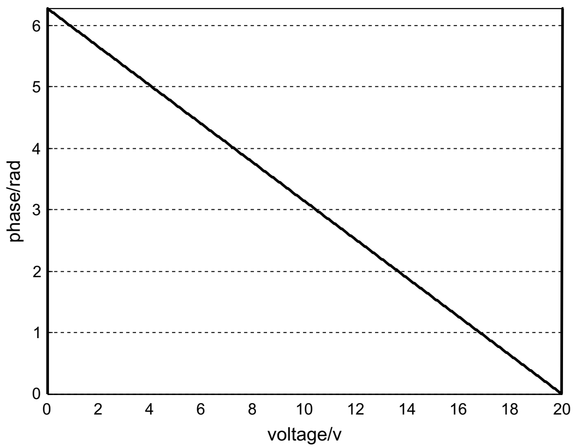

Fig. 2 Phase shift versus voltage *V*

Gaussian pulse was spectrally centered at the LPWGs' resonance frequency and subsequently propagated through the LPWG structure. The output waveform is shown in Fig. 5. From Fig. 5b, there is a fairly good agreement between the theoretically predicted and output time-domain waveform. Thus, it verifies feasibility of second-order differentiator based on LPWG.

Figure 6 shows the relationship between amplitude of second-order differentiator and ΔN. As can be seen, amplitude of second-order differentiator is inversely proportional to ΔN.

4 Conclusion

In this paper, a structure of second-order differentiator based on long-period waveguide grating (LPWG) is proposed. The second-order differentiator is verified theoretically by MATLAB. The second-order time derivative of Gaussian pulses is obtained by introducing a π phase shift by adjusting voltage at 3/4 of the length of the grating.

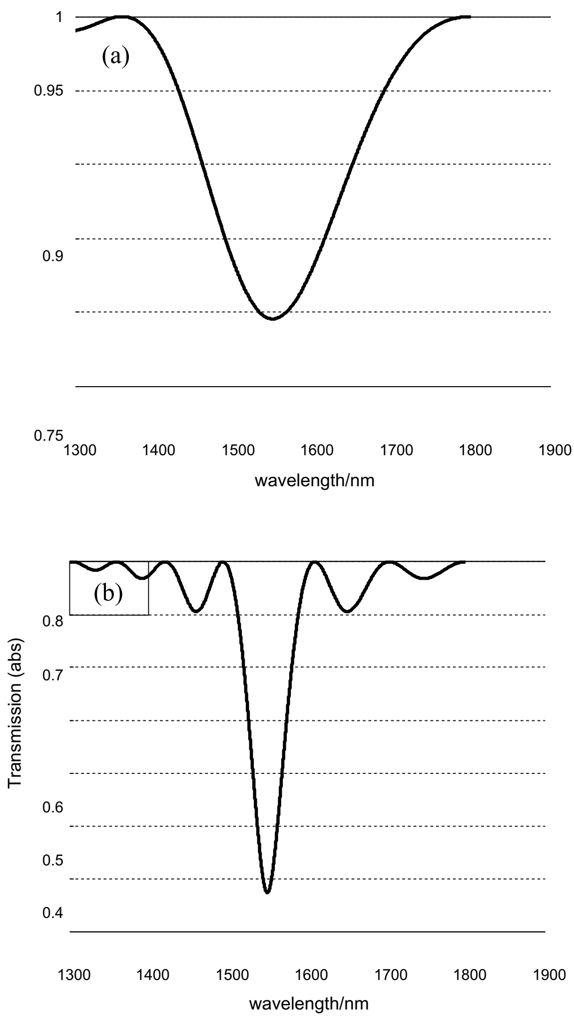

Fig. 3 Transmission spectra of two-segment grating **a** spectrum of the 1th grating, **b** spectrum of the 2th grating

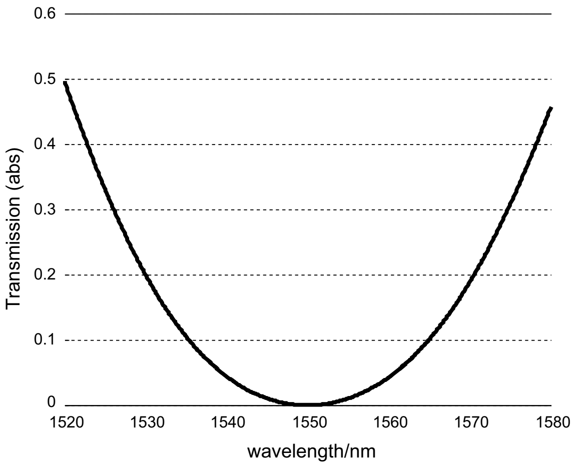

Fig. 4 Transmission function of second-order differentiator based on LPWG

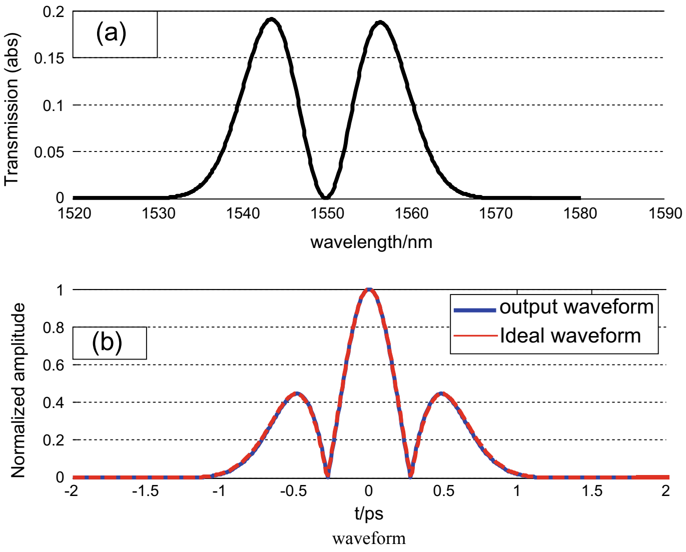

Fig. 5 Spectrum and time domain of Gaussian pulse derived by second-order differentiators based on LPWG. **a** Spectrum; **b** time domains

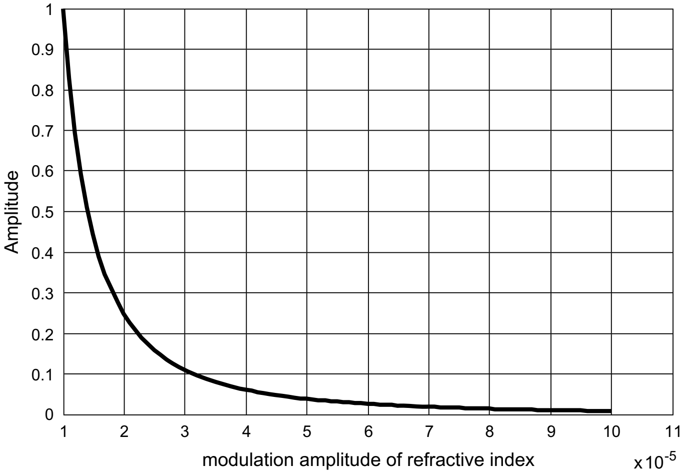

Fig. 6 Amplitude of second-order differentiator vesus ΔN

Acknowledgements This work was supported by National Natural Science Foundation of China (Project 61377075).

References

1. Slavík R, Park Y, Kulishov M et al (2006) Ultrafast all-optical differentiators. Opt Express 14(22):10699
2. Kulishov M, Krcmarík D, Slavík R (2007) Design of terahertz-bandwidth arbitrary-order temporal differentiators based on long-period fiber gratings. Opt Lett 32(20):2978–2980
3. Slavík R, Park Y, Azaña J et al (2009) Second-order photonic temporal differentiator based on a phase-shifted long period fiber grating. In: Leos meeting conference proceedings, Leos'09. IEEE, pp 185–186
4. Jin W, Chiang KS, Liu Q (2008) Electro-optic long-period waveguide gratings in lithium niobate. Opt Express 16(25):20409–20417
5. Chiang KS, Wei J (2012) Electro-optic long-period waveguide grating devices. In: Opto-electronics and communications conference. IEEE, pp 545–546
6. Erdogan T (1997) Fiber grating spectra. J Lightwave Technol 15(8):1277–1294
7. Zhou J, Fu S, Aditya S et al (2009) Photonic temporal differentiator based on polarization modulation in a $LiNbO_3$, phase modulator. In: International topical meeting on microwave photonics. IEEE, pp 1–3