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Optical spectrum control circuit using an arrayed-waveguide grating and tunable phase shifters

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Abstract: We proposed and fabricated an optical spectrum control circuit using an arrayed-waveguide grating (AWG) and an array of channel waveguides with tunable phase shifters. We found that the spectral phase and amplitude of a modulated optical signal could be arbitrarily controlled if the number of channel waveguides was set to be more than twice the number of waveguides in the AWG. As a first demonstration, we successfully obtained a flat band-pass filter function with the fabricated device by controlling the tunable phase shifters to control the interference between the light propagating through them.

Keywords: optical waveguide, arrayed-waveguide grating, planar lightwave circuit

Classification: Optoelectronics, Lasers and quantum electronics, Ultrafast optics, Silicon photonics, Planar lightwave circuits

References

[1] A. M. Weiner, J. P. Heritage, and E. M. Kirschner, "High-resolution femtosecond pulse shaping," *J. Opt. Soc. Am. B*, vol. 5, no. 8, pp. 1563–1572, Aug. 1988.

[2] K. Takiguchi, K. Okamoto, T. Kominato, H. Takahashi, and T. Shibata, "Flexible pulse waveform generation using silica-waveguide-based spectrum synthesis circuit," *Electron. Lett.*, vol. 40, no. 9, pp. 537–538, April 2004.

[3] T. Kurokawa, H. Tsuda, K. Okamoto, K. Naganuma, H. Takenouchi, Y. Inoue, and M. Ishii, "Time-space-conversion optical signal processing using arrayed-waveguide grating," *Electron. Lett.*, vol. 33, no. 22, pp. 1890–1891, Oct. 1997.

[4] H. Tsuda, Y. Tanaka, T. Shioda, and T. Kurokawa, "Analog and digital optical pulse synthesizers using arrayed-waveguide gratings for high-speed optical signal processing," *IEEE J. Lightw. Technol.*, vol. 26, no. 6, pp. 670–677, March 2008.

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[5] H. Tsuda, K. Okamoto, T. Ishii, K. Naganuma, Y. Inoue, H. Takenouchi, and T. Kurokawa, "Second- and Third-Order Dispersion Compensator Using a High-Resolution Arrayed-Waveguide Grating," *IEEE Photon. Technol. Lett.*, vol. 11, no. 5, pp. 569–571, May 1999.
[6] K. Seno, K. Suzuki, N. Ooba, K. Watanabe, M. Ishii, H. Ono, and S. Mino, "Demonstration of channelized tunable optical dispersion compensator based on arrayed-waveguide grating and liquid crystal on silicon," *Opt. Express*, vol. 18, no. 18, pp. 18565–18579, Aug. 2010.
[7] V. J. Hernandez, Y. Du, W. Cong, R. P. Scott, K. Li, J. P. Heritage, Z. Ding, B. H. Kolner, and S. J. B. Yoo, "Spectral Phase Encoded Time Spreading (SPECTS) Code Division Multiple Access for Terabit Optical Access Networks," *IEEE J. Lightw. Technol.*, vol. 22, no. 11, pp. 2671–2679, Nov. 2004.
[8] K. Okamoto, *Fundamentals of Optical Waveguides*, Academic Press, 2006.
[9] K. Kato, Y. Ikuma, H. Takahashi, T. Mizuno, and H. Tsuda, "Phase and Amplitude Spectrum Control Circuit Using an Arrayed-Waveguide Grating and Tunable Phase Shifters," *16th Microoptics Conference*, Hsinchu, Taiwan, WP17, pp. 120–121, Nov. 2010.

1 Introduction

Optical signal processing based on time-space conversion can be applied to optical pulse waveform shaping [1, 2], optical pulse train generation [3, 4], dispersion compensation [5, 6], optical code division multiplexing [1, 7], and so on. An arrayed-waveguide grating (AWG) is a wavelength multiplexer/demultiplexer fabricated as a planar lightwave circuit. Silica-based AWGs have many advantages: low propagation loss, reliability, and good connectivity with optical fibers [8]. In this paper, we design and fabricate an optical spectrum control circuit that consists of an AWG and an array of channel waveguides with only tunable phase shifters [9]. We discuss the design condition that the spectral phase and amplitude of the modulated optical signals be arbitrarily controlled. In order to confirm the feasibility of the fabricated device, we demonstrated first that it could be operated as a flat band-pass filter (BPF), and good results were obtained.

2 Design of the optical spectrum control circuit

The proposed optical spectrum control circuit consists of an AWG, a tunable phase shifter placed on each channel waveguide and a reflector, as shown in Fig. 1 (a). Optical signals from the input/output (I/O) waveguide are demultiplexed by the AWG and each spectral component of the optical signal is output to the corresponding channel waveguide. The phase of each spectral component is controlled by the tunable phase shifters. The controlled spectral components are reflected at the reflector and are again multiplexed by the AWG, and are output to the I/O waveguide. In order to arbitrarily control the spectral phase and amplitude of the modulated optical signals, the transmission spectrum needs to be flat before driving the tunable phase shifters. Therefore, it is proposed that the pitch of the channel waveguides

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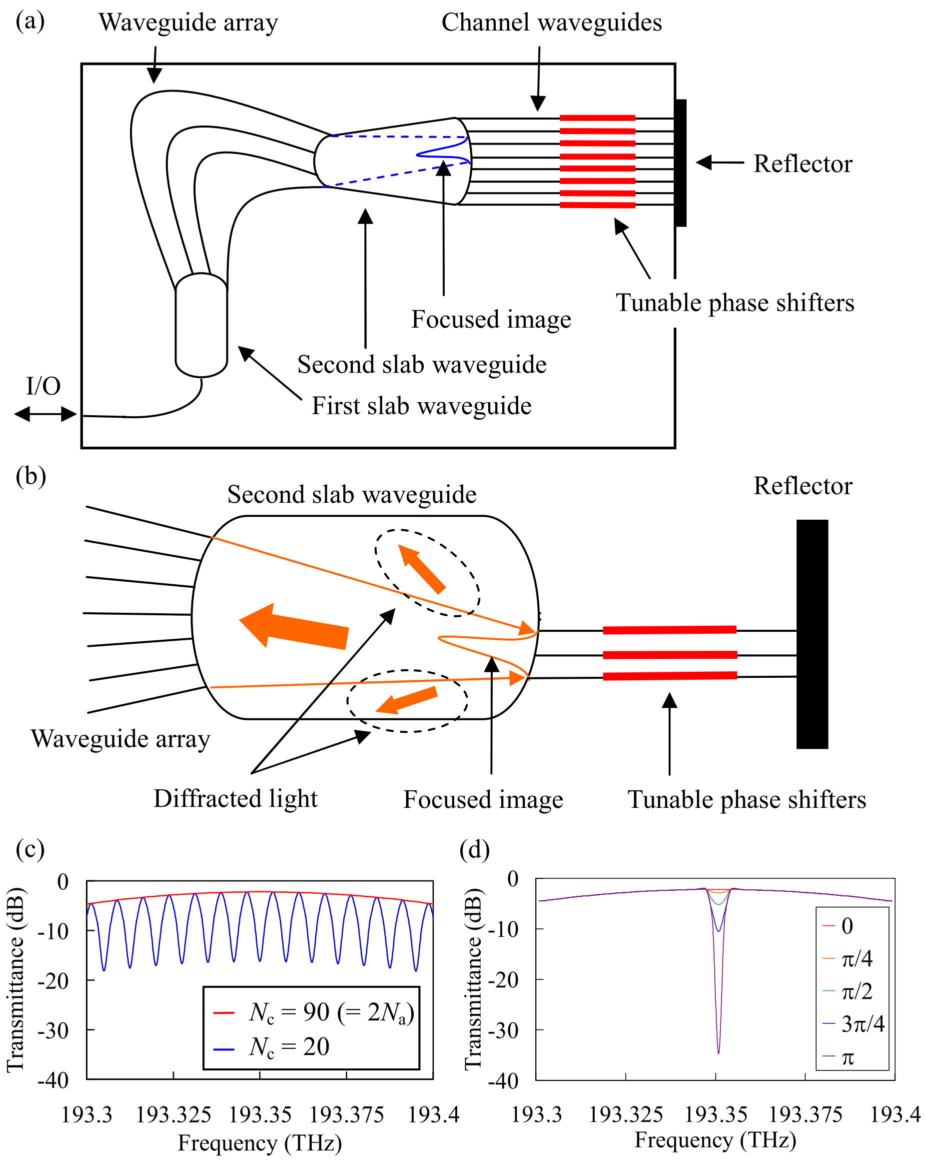

Fig. 1. (a) Schematic of the optical spectrum control circuit. (b) Principle of spectral amplitude control. (c) Calculation results of transmission characteristics with various N_c. (d) Calculation results of transmission characteristics with various phase shift settings of the 45th channel.

(D_c) should be much smaller than the spatial resolution at the input of the channel waveguides (d_x). When this condition is satisfied, the spectral components corresponding to the middle of the channel waveguides are coupled to both sides of the channel waveguides as shown in Fig. 1 (a). This condition is described as follows:

$$d_x = \frac{\lambda_0 L_2}{n_s N_a D_a} \geq 2D_c \qquad (1)$$

where λ_0 is the center wavelength of the AWG, L_2 is the length of the second slab waveguide, n_s is the effective refractive index in the slab region, and N_a is the number and D_a is the pitch of the waveguides in the AWG. L_2 can be

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described as follows:

$$L_2 = \frac{n_s N_c D_a D_c}{\lambda_0} \tag{2}$$

where N_c is the number of channel waveguides. Using Eq. (1) and Eq. (2), the design condition that the spectral phase and amplitude of the modulated optical signal be arbitrarily controlled is given by

$$N_c \geq 2N_a. \tag{3}$$

The same spectral component is output to several channels as shown in Fig. 1 (b), and the high-order diffraction components of the reflected light increase when the phase shift difference of adjacent channel is large. This diffracted light arrives at outsides of the waveguides in the AWG. Therefore, the spectral amplitude is changed without changing amplitude of demultiplexed spectral component. Table I shows the design parameters of the fabricated optical spectrum control circuit using the design conditions from Eq. (1) to Eq. (3). The number of channel waveguides is 90 and is twice as many as the number of waveguides in the AWG. The free spectral range (FSR) is 150 GHz and the number of tunable phase shifters is 64 in order that the control frequency range is the central 100 GHz of the FSR. The length of the first slab waveguide is determined such that most of the input light should be coupled to the waveguides in the AWG. Figure 1 (c) shows the results of a calculation of the transmission characteristics with various N_c. The transmission spectrum is almost flat when N_c is 90, but is comb-like when N_c is 20. Figure 1 (d) shows the results of a calculation of the transmission characteristics with various phase shift settings of the 45th channel. This results show the spectral amplitude can be controlled using only tunable phase shifters. On the other hand, the spectral phase can be controlled with slight change in amplitude when the phase shift difference of adjacent channel is small. The spectrum within a 100-GHz bandwidth can be controlled with a 1.67-GHz resolution.

Table I. Design parameters of the optical spectrum control circuit.

Parameter [Unit]	Value
Relative refractive index difference [%]	1.5
Free spectral range [GHz]	150
Center frequency [THz]	193.35
Number of waveguides in the AWG	45
Number of channel waveguides	90
Pitch of the waveguides in the AWG [µm]	15.5
Pitch of the channel waveguides [µm]	7.5
Length of the first slab waveguide [µm]	3830
Length of the second slab waveguide [µm]	9832
Path length difference [µm]	1374
Diffraction order	1289
Number of tunable phase shifters	64
Control frequency range [GHz]	100

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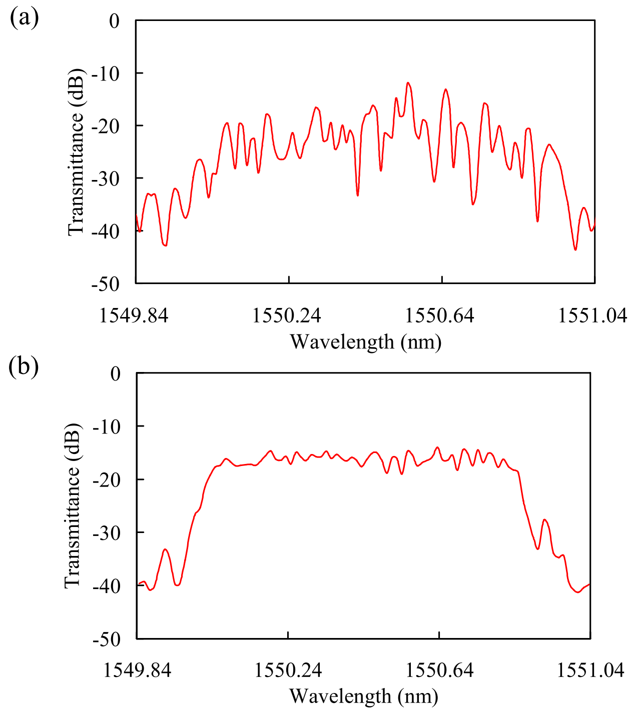

Fig. 2. Transmission spectrum of the fabricated device; (a) none of the tunable phase shifters was driven, (b) a flat BPF performance.

3 Experimental results

Figure 2 (a) shows a transmission spectrum of the fabricated device before driving the tunable phase shifters. The large ripple is due to phase errors in the channel waveguides. In order to confirm the feasibility of the fabricated device, we demonstrated that it can be operated as a flat BPF. The initial phase shift settings for each channel to give a flat BPF performance were obtained so that the transmission spectrum became flat. The steps to obtain the initial phase shift settings were as follows: (i) the spectral component corresponding to the first channel was input and the phase shift setting of the first channel (ϕ_1) was determined so that the transmittance was maximum, (ii) after the first channel phase shift was set to be ϕ_1, the spectral component corresponding to the second channel was input and the phase shift setting of the second channel was determined so that the transmittance should be maximum, (iii) this procedure was repeated until the 64th channel phase shift setting was obtained. The initial phase shift settings were determined by repeating this step five times. Figure 2 (b) shows the result of the demonstration of flat BPF performance. The transmission spectrum is nearly flat, but a small ripple remains because some phase errors exist in the channel waveguides. The loss was about 15 dB, including the coupling loss of the optical fiber to the fabricated device and the insertion loss of the circulator. It was confirmed by simulation that the phase response was nearly flat when the fabricated device operated as a BPF [9]. This result shows the amplitude of each spectral component can be arbitrarily controlled by the

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tunable phase shifters, although there is interference between light propagating through the channel waveguides. Although some loss is caused, the phase of each spectral component can be arbitrarily controlled within the allowable loss. With the proposed device the spectral phase and amplitude of optical signals can be controlled by tunable phase shifters only, and it is expected that the device can be used in future optical signal processing applications.

4 Conclusion

We have designed and fabricated an optical spectrum control circuit using an AWG and an array of channel waveguides with tunable phase shifters. In order to arbitrarily control the spectral phase and amplitude of the modulated optical signal, it was found that the number of channel waveguides needs to be more than twice the number of waveguides in the AWG. As a first demonstration, it was shown that the fabricated device could operate as a flat BPF. This demonstration shows that the phase and amplitude of each spectral component of the optical signal can be arbitrarily controlled using only tunable phase shifters.

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