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Phase error compensation for multilayered AWG in LCOS-based WSS

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Abstract: We propose a novel method to compensate for the phase errors of a multilayered arrayed waveguide grating (AWG) used in a liquid-crystal-on-silicon (LCOS)-based wavelength selective switch (WSS). In this scheme, an additional LCOS is employed to externally compensate for the phase errors of the AWG in a layer-by-layer manner for both planes of polarization. This compensation scheme enables us to improve the yield of the WSS: specifically, we demonstrate that the additional LCOS drastically reduces the loss and polarization-dependent loss (PDL) of the WSS.

Keywords: wavelength selective switch, liquid crystal on silicon, arrayed waveguide grating, multilayered waveguide, phase error compensation

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

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1 Introduction

A hybrid of planar waveguide and free-space components can be used to realize functional devices such as a wavelength selective switch (WSS) composed of a multilayered arrayed waveguide grating (AWG) and a liquid-crystal-on-silicon (LCOS) device [1, 2]. Compared with other WSS configurations [3, 4], such a hybrid device have the advantages of greater compactness, reliability, and spectral resolution. To enlarge the port count of the LCOS-and-AWG-based WSS and maintain high yield, the phase errors of the AWG should be compensated for. Furthermore, a layer-by-layer and polarization-by-polarization phase error compensation scheme is essential. However, the conventional phase error trimming method employing UV irradiation [5] is not applicable to a multilayered waveguide.

In this paper, we propose the introduction of an additional LCOS into the WSS to externally compensate for the phase errors for both polarizations. This technique drastically improves the yield of large-port-count WSSs.

2 Principle

2.1 Device structure and switching principle

Fig. 1 (a) shows a schematic of the proposed WSS configuration with the newly introduced LCOS-2. It consists of the multilayered AWG, Lens-1, Lens-2, a Wollaston prism, a half-waveplate, LCOS-1, and LCOS-2. Both LCOSs are reflective type. The lenses are arranged into a telescope configuration between the AWG's facet and LCOS-2, as shown in Fig. 1 (b) and 1 (c). Lens-1 is a cylindrical compound lens and its effective focal lengths in x-z and y-z plane, f_{x1} and f_{x2}, are asymmetrically designed in order to adjust the beam diameters in the optics. The focal length of Lens-2 is f_2 in both directions. The longitudinal axes of the lenses are off-centered along the y-axis. The Wollaston prism is placed at the central Fourier plane. The switching mechanism is as follows: First, the WDM signal from the input AWG (AWG-1) passes through the two lenses to create a relayed equivalent image of the AWG's facet on the surface of LCOS-2. This image is spatially separated into two groups corresponding to the orthogonal linear polarization

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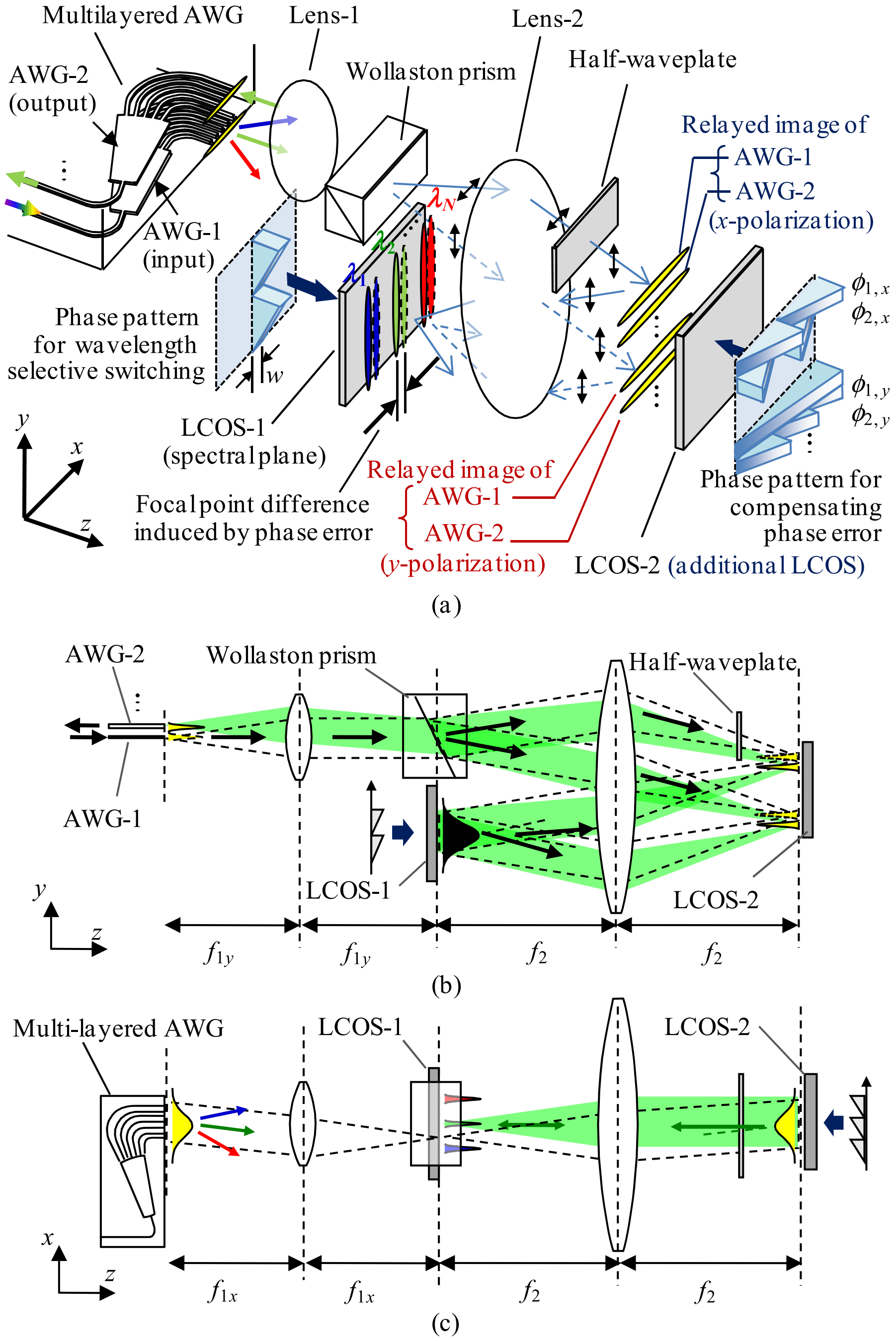

Fig. 1. Schematic configuration of proposed WSS: (a) perspective view; (b) y-z sectional view; and (c) x-z sectional view.

states, which are split by the Wollaston prism. One group passes through the half-waveplate, where the polarization plane is rotated by 90°. LCOS-2 reconstructs the wavefront of the relayed image of AWG-1, which is distorted by the phase error. The reflected light from LCOS-2 is focused onto LCOS-1 by Lens-2. Hence, the spatial Fourier transform by the lens is executed three times until the light reaches LCOS-1. The Fourier images of the AWG's facet (i.e., spectrally decomposed signals) appear on LCOS-1.

By modulating the wavefront of the selected light of each wavelength with LCOS-1, the reflected light is switched to the offset position on LCOS-

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2. LCOS-2 modulates the wavefront of the switched lights to accommodate it with that of the relayed image of the output AWG (AWG-2). The reflected light from LCOS-2 is polarization-multiplexed with Wollaston prism and couples to AWG-2. The green ray shown in Fig. 1 (b) and 1 (c) indicates the reflected light from LCOS-1 and LCOS-2, respectively, with certain wavelength. The input signal polarized in the x-direction couples with the y-polarization mode of the output AWG, and the input y-polarized light couples with the x-polarization mode of the output AWG.

2.2 Phase error problem in WSS

The coupling efficiency between the input and output AWGs is determined by the correlations between their corresponding beam profiles on LCOS-1. The phase errors in the AWG affect the beams on LCOS-1, causing 1) focal point mismatch and 2) beam profile deformation, which degrade the coupling efficiency. The former derives from the phase errors of the linear term (i.e., the value of the phase error is proportional to the array number) and the latter derives from the phase errors of the nonlinear term. Moreover, as the values of the phase errors depend on the incident polarization state because of the birefringence in the AWG, these phase errors also lead to polarization-dependent loss (PDL) in the WSS.

We can compensate for the phase errors by driving LCOS-2 because the output field on the AWG is projected onto LCOS-2 with the relay optics. Since it is necessary to adjust the phase profiles of four beams (corresponding to the two waveguide layers and two polarization states), we separated the phase modulation pattern on LCOS-2 into four areas and gave individual phase modulations.

3 Phase error compensation

3.1 Adjusting focal positions in spectral plane

We employed a double-layered AWG in the WSS optics. Fig. 2 shows the

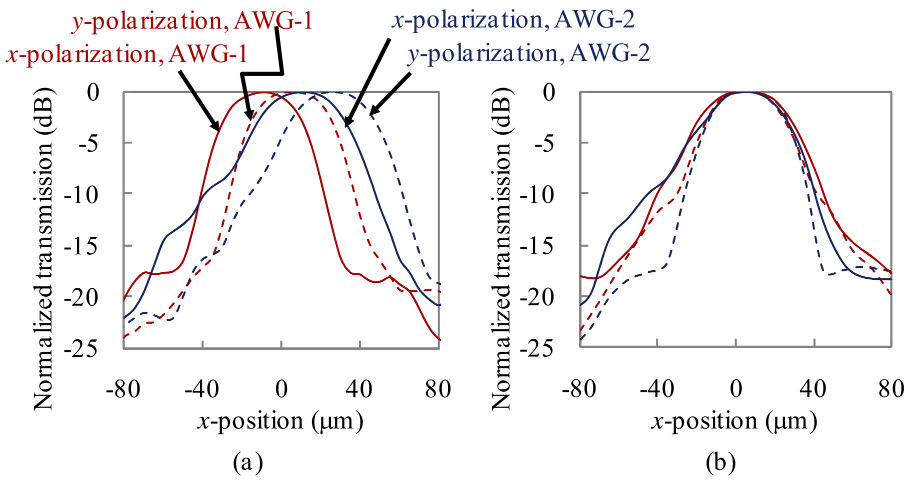

Fig. 2. Measured beam profile on LCOS-1: (a) before compensation and (b) after compensating for the phase errors of the linear term.

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beam profiles on LCOS-1 measured by scanning a pinhole photodetector along the x-direction. The input wavelength was fixed at 1550 nm and guided to each layer of the AWG via a polarization controller. The LCOSs had 512×512 pixels in the active area and the pixel size was $15\,\mu\text{m} \times 15\,\mu\text{m}$. When no phase modulation was applied to LCOS-2, the peak position of the beam deviated from -10 to $+25\,\mu\text{m}$, depending on the incident layer and the incident polarization state, as shown in Fig. 2 (a). This result indicates that the multilayered AWG used in this experiment had a large phase error of the linear term.

However, we successfully adjusted the peak positions of the four beams by applying four blazed phase modulation patterns on LCOS-2, as shown in Fig. 2 (b). The profile distortions at the tails stem from the residual phase errors not of the linear term.

3.2 Compensation of beam profile deformation

To compensate for the residual phase errors in the AWG, we should determine the optimum phase patterns on LCOS-2, $\phi(x)$, whose values are nonlinear with respect to the coordinate x. We express $\phi(x)$ as a combination of Legendre orthogonal polynomials:

$$\phi_{layer,pol}(x) = 2\pi \sum_{n=1}^{n_{\max}} a_n L_n(x),$$

$$\begin{pmatrix} L_1(x) = x/R, & L_2(x) = \frac{1}{2}\{3(x/R)^2 - 1\}, \\ L_3(x) = \frac{1}{2}\{5(x/R)^3 - 3x/R\}, & L_4(x) = \frac{1}{8}\{35(x/R)^4 - 30(x/R)^2 + 3\}, \end{pmatrix} \quad (1)$$

where R is the half-width of the active area in LCOS-1; the first subscript of $\phi(x)$, "*layer*," indicates the layer number of the AWG (1 or 2); and the second subscript of $\phi(x)$, "*pol*," indicates the polarization direction of the AWG's polarization mode (x or y). The lowest-order mode (L_1) is the linear term that corresponds to the blazed phase modulation, and the other higher-order modes ($L_2, L_3, \ldots, L_{n_{\max}}$) are the nonlinear terms. We obtained the optimum set of Legendre coefficients $\mathbf{a}$ ($= [a_1, a_2, a_3, \ldots, a_{n_{\max}}]$) with the following procedure: 1) connect AWG-1 to the light source and polarization controller, connect AWG-2 to the photodetector, and fix the input wavelength at 1550 nm; 2) drive LCOS-1 and apply a stripe-shaped blazed pattern so that the signal with the wavelength of 1550 nm is selectively switched; 3) fix the incident polarization state to x-polarization; 4) drive LCOS-2 and find the optimum $\mathbf{a}$ for $\phi_{1,x}(x)$ and $\phi_{2,y}(x)$ that reduces the coupling loss with the particle swarm optimization (PSO)-based method [6]; 5) fix the incident polarization state to y-polarization; 6) find the optimum $\mathbf{a}$ for $\phi_{1,y}(x)$ and $\phi_{2,x}(x)$ with the PSO-based method. With this optimization scheme, the profile of each AWG's image on LCOS-1 was concentrated inside the stripe switching pattern during the iterative trial-and-error procedure. The width of the stripe pattern, w, was set to 2 pixels, which is nearly equal to the spot size of the target beam profile.

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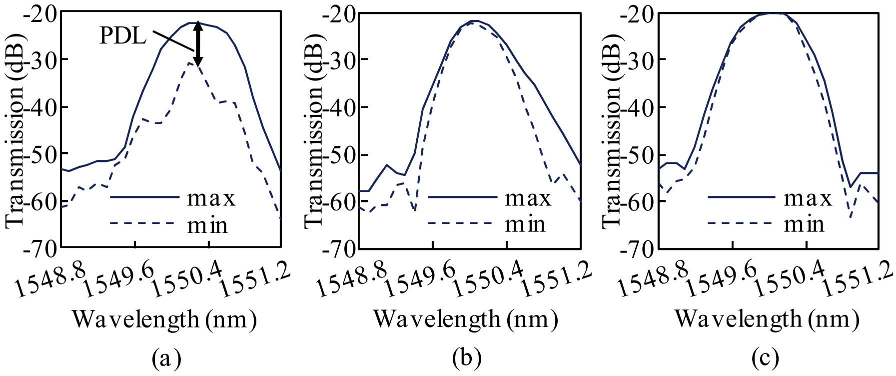

Fig. 3. Measured spectral response of the WSS. The power difference between the solid line and the broken line in the spectral response curve indicates the PDL. (a) Before compensation; (b) after compensating for the linear term ($n_{\max} = 1$); and (c) after compensating for the linear and nonlinear terms ($n_{\max} = 4$).

Fig. 3 shows the measured spectral response of the WSS, where the 100-GHz grid signal around the wavelength of 1550 nm ($w = 4$ pixels) was selectively switched with LCOS-1. With no phase modulation in LCOS-2, the WSS exhibited a large PDL of approximately 10 dB, as shown in Fig. 3 (a). Compensation for the phase errors of the linear terms led to a reduction in the PDL at the center of the switched channel. However, because of the asymmetrically deformed beam profile observed in Fig. 2 (b), significant PDL still remained at the bilateral tails of the passband, as shown in Fig. 3 (b). Nevertheless, after compensating for the phase errors of the linear and nonlinear terms, the PDL was almost completely eliminated across the entire passband, as shown in Fig. 3 (c). Further, the coupling efficiency and the flatness of the passband were also improved. This result indicates that the beam profiles on LCOS-1 were correctly reshaped with LCOS-2. The residual insertion loss of approximately 20 dB is attributed to the losses in the LCOSs, AWG, fiber connection, and free-space optics.

This compensation method can also be applied to higher-port-count AWGs by simply increasing the number of partitioned areas in the phase modulating pattern encoded on LCOS-2.

4 Conclusion

We proposed and demonstrated the novel method to compensate for the phase errors of the multilayered AWG in the LCOS-based WSS. The additional LCOS was employed to compensate for the phase errors of the AWG layer by layer and for both polarizations. By optimizing the phase pattern on the additional LCOS, the insertion loss and the PDL of the WSS, which were attributed to the AWG's phase errors, were effectively reduced among the entire passband. This technique is useful to improve the yield of the WSS.

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