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A Novel Compact-Structure Arrayed-Waveguide Grating Device*

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Abstract: Arrayed-waveguide grating (AWG) device, a novel compact-structure, is presented based on silicon-on-insulator (SOI) material. A total internal reflection (TIR) waveguide mirror is fabricated at the middle of each arrayed waveguide. An approach of compensating TE-TM mode polarization is presented by using the phase difference, which is caused by TIR at the waveguide mirror. This AWG device has advantage for its small size and simple technigue of fabrication. The experimental results are given and the feasibility of fabrication is tested.

Key words: AWG; DWDM; waveguide mirror; polarization compensation

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1 Introduction

Dense wavelength division multiplexing (DWDM) is an important technique in fiber optical communication system. Arrayed-waveguide grating (AWG) devices have important prospects in the application of DWDM. It is an important component in some devices, such as the wavelength router and optical add/drop multiplexer (OADM). With further development of fiber optical communication network and DWDM systems, AWG devices will have wide fields of application. Many researchers have focused on the study of AWG devices[1~7].

The materials of AWG devices include SiO_2, silicon-on-insulator (SOI) material, InP and polymer. SOI material is widely used now. It has some advantages in fabrication. Integrated optical devices can be fabricated with microelectronic devices in a single chip by using SOI material. And the cost of SOI material is relatively cheap. However, the SOI waveguide, which is generally a large cross-section waveguide, is a weak-confined waveguide. The radius of the curved waveguide is large enough to reduce the curved waveguide loss, which would increase the size of the device[2]. And the SOI waveguide has higher TE-TM polarization shift than SiO_2 waveguide.

In order to reduce the size of the device and to solve the problem of polarization, a novel compact-structure AWG device is presented based on SOI material, in which the total internal reflection (TIR) mirror structure is used. The phase changes of TE and TM modes are compensated by the TIR mirror. There are some successful methods of compensating TE-TM polarization, such as half waveplate method[3], different array orders for TE and TM method[4], and zero-birefringent waveguide method[5]. TIR waveguide mirror structure has been used in waveguide fabrication[6,7] too. But it has not been used as a method of compensating the TE-TM polarization shift.

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As an example, a 1×8 AWG device was designed with TIR waveguide mirror. Through mathematical calculation, some results of simulation were obtained, which show the effect of the method of compensating TE-TM polarization by using TIR waveguide mirrors. We have fabricated a 1 × 4 AWG with TIR waveguide mirror. And the experimental results are given.

2 Design principle

In this type of AWG device, a TIR waveguide mirror is inserted at the middle of each classical arrayed waveguide. The TIR waveguide mirror has two functions. One is compensating TE-TM polarization shift, the other is reducing the size of the device. The AWG with TIR waveguide mirror structure is shown in Fig. 1.

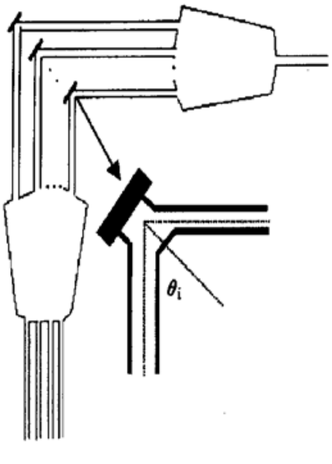


Fig. 1 AWG with the TIR waveguide mirror structure

The TIR waveguide mirror consists of a trench (the black rectangle in Fig. 1) and a waveguide. Using two-step photolithography and wet etching technique, the trench is etched beside the junction of the two straight waveguides, thus the waveguide mirror is fabricated. The crystal face of silicon is used as the TIR mirror face, using the wet etching technique and the anisotropic character of the face (100) of silicon.

When reflected on this waveguide mirror, TE and TM modes have different phase-changes:

$$\delta_{iTE'} = \tan^{-1}\left[\frac{(\sin^2\theta_i - n_2^2/n_1^2)^{1/2}}{\mathrm{con}\theta_i}\right] \quad (1)$$

$$\delta_{iTM'} = \tan^{-1}\left[\frac{n_1^2(\sin^2\theta_i - n_2^2/n_1^2)^{1/2}}{n_2^2\cos\theta_i}\right] \quad (2)$$

where θ_i represents the incidence angle (Fig. 1), n_1 and n_2 represent the refractive indices of silicon and air, respectively. The modes, in equations (1) and (2), are TM and TE modes in array waveguide. So, the total phase-changes of TE and TM modes (in array waveguide) transmitting through an arrayed waveguide are:

$$\phi_{iTE} = 2\pi n_1 L_i/\lambda - \delta_{TM'} \quad (3)$$

$$\phi_{iTM} = 2\pi n_1 L_i/\lambda - \delta_{TE'} \quad (4)$$

where L_i represents the length of the ith arrayed waveguide, and $L_{i+1} = L_i + \Delta L$. ΔL represents a constant in the AWG device. λ represents the wavelength in free space. Using the method of different orders for TE and TM, we can get

$$(\phi_{iTE} - \phi_{iTM}) + (\varphi_{iTE} - \varphi_{iTM}) = 2\pi k \quad (5)$$

where k represents an integer (for example $k=1$ or 2). φ_{iTE} and φ_{iTM} represent the phases of TE and TM modes transmitting through the plane waveguide areas, which are fixed. If we make the geometrical structure of array waveguides as in Fig. 2, the structure consists of three components: two curved

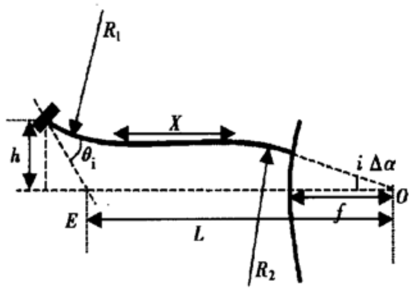


Fig. 2 Geometrical structure of one arrayed wavugide, which being connected with a TIR mirror and waveguides

waveguides with radii R_1 and R_2, respectively, and a straight waveguide with length X. Thus, the lightwaves of TE and TM modes, which are at the adjacent order, can converge into the same output waveguide, so the TE-TM shift is diminished.

For this TIR waveguide mirror design, the total length of curved waveguides is reduced, and more straight waveguides are used. So the curved waveguide loss is reduced. The device size is also diminished.

3 Numerical simulation

The compensation characteristic of a 1 × 8 AWG device with TIR waveguide mirrors was simulated in detail. The waveguide material is SOI , which has Si with 5-μm-thickness on the top of a 1μm SiO_2 layer. The rib waveguide has a rib height of 2μm and a rib width of 5μm. The parameters of the geometrical structure of arrayed waveguide, which are shown in Fig. 2, satisfy the following condition:

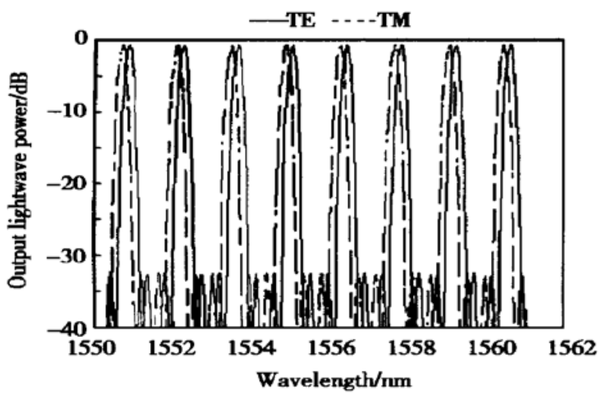
$$h = R_1[1 - \cos(\pi/4 - \theta_i)] + R_2[1 - \cos(i\Delta\alpha)] + f\sin(i\Delta\alpha) \quad (6)$$

$$h + L + f = R_1\sin(\pi/4 - \theta_i) + X + R_2\sin(i\Delta\alpha) + f\cos(i\Delta\alpha) \quad (7)$$

$$L + i\Delta\alpha/2 = R_1(\pi/4 - \theta_i) + X + R_2 i\Delta\alpha \quad (8)$$

where the incidence angle θ_i is smaller than $\pi/4$. If the arrayed waveguide is below OE, the horizontal line in Fig. 2, which makes θ_i bigger than $\pi/4$, we can also get the condition the parameters satisfied.

The wavelengths of the eight channels were 1560. 61, 1558. 98, 1557. 36, 1555. 75, 1554. 13, 1552. 52, 1550. 92 and 1549. 32nm, respectively, which accord with the standard of ITU-T. The wavelength spacing was 1. 6nm. Figure 3 shows the results of simulation before and after the compensation method was used. The TE-TM shift was 0. 1nm when compensation method was not used. After compensation with TIR mirrors, the TE-TM shift was reduced to 0. 01nm. The device core size was only 1. 2cm × 1. 2cm.



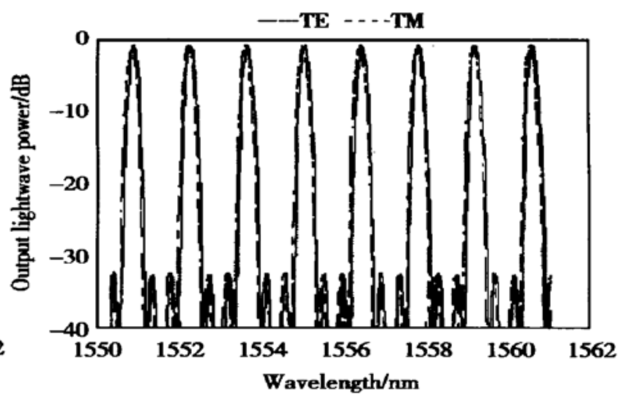


Fig. 3 Simulation results (a) Without compensation; (b) Compensation with TIR mirrors

4 Experiment results

A 1×4 AWG device with TIR waveguide mirrors based on SOI material was fabricated. Figure 4 shows the scanning electron microscopic (SEM) figure of this AWG with TIR waveguide mirrors. From this picture, we can see that the TIR mirror face is clear and smooth. The SOI material has Si with 5-μm-thickness on the top of a 1μm SiO_2 layer. The rib waveguides have a height of 2. 2μm and

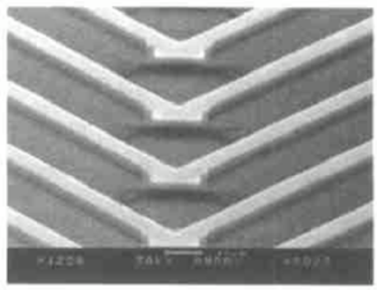


Fig. 4 SEM image of array waveguides with TIR waveguide mirrors

a width of 6μm. The depth of the trench of the TIR mirror is about 5μm. The trench was formed after the SOI chip had been dipped in 50% KOH for 20min at 50℃. Then the waveguides were fabricated after the chip had been dipped in 50% KOH for 25min at the same temperature.

The images of the output light of the four channels in the screen are shown in Fig. 5. These pictures are taken by digital camera from the monitor screen. The four channel wavelengths are approximately 1543.6, 1547.0, 1550.2, and 1552.8nm. These results are not very good. But the device's function of demultiplexing is realized. This indicates that fabrication of this type of compact-structure AWG device is feasible.

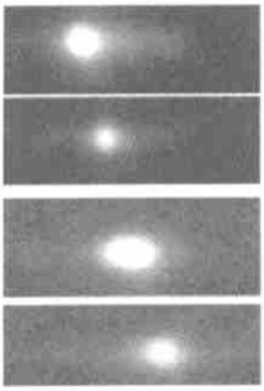


Fig. 5　Pictures of four channel wavelengths in the screen are taken by digital camera

5 Conclusion

AWG device, a novel compact-structure, with function of polarization compensation is presented. The structure of TIR waveguide mirror was used. The TE-TM shift can be reduced to 0.01nm by using the TIR waveguide mirror and the method of different array orders for TE and TM modes. Most curved waveguides were replaced by straight ones. The size of the device was diminished. A 1×4 demultiplexer with TIR waveguide mirrors was fabricated. Realization of function of demultiplexing indicates that fabrication of this type of AWG device is feasible.

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一种新颖结构紧凑的AWG器件*

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摘要: 给出一种基于SOI材料结构紧凑的新颖AWG器件, 它是将一个全内反射波导镜插入原波导阵列中间, 并且利用全内反射时产生的相位差进行TE、TM模偏振补偿的方法, 该器件具有尺寸小、制作工艺简单等特点. 同时, 给出一些实验结果, 实验结果证实这种结构的AWG器件是可行的.

关键词: 列阵波导光栅(AWG); 密集波分复用(DWDM); 波导镜; 偏振补偿

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