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A novel polarizer based on directional coupler and surface plasmon polaritons*

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A novel polarizer with a silver nanoribbon added into a traditional waveguide directional coupler is designed to realize the polarized output of TE mode. A high extinction ratio can be obtained because of the selectivity of surface plasmon polaritons (SPPs) on polarization. The effects of the polarizer parameters on coupling efficiency and extinction ratio are discussed. Simulation results indicate that the coupling efficiency for TE mode can reach about 95%, but only 3% for TM mode, with the extinction ratio of TE mode about 15 dB when the light wavelength is 1550 nm. The polarizer may have potential applications in photonic integrated circuits and quantum information technology.

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As one of the most important optical components, the polarizer is widely used, especially in micro-nano integration with rapid development of nano-technology[1-3]. Polarization is widely applied in nonlinear optics and quantum information technology. However, the control of polarization is still a challenge, especially in photonic integrated circuits (PICs). Optical directional coupler[4,5] can be realized from traditional dielectric waveguide and photonic crystal waveguide[6,7]. Surface plasmon polaritons (SPPs) can guide and manipulate optical signals in PICs, which propagate in the form of electromagnetic surface waves along metal-dielectric interface[8]. Many kinds of novel polarizers have been put forward. In 2008, Lee et al[9] presented a silicon-layer guided-mode resonance polarizer with 40 nm bandwidth. In 2011, Sun et al[10] showed a fiber polarizer based on an asymmetric dual-core photonic crystal fiber. In the same year, Lee et al[11] demonstrated a resonant wideband polarizer with single silicon layer. The performance of a polarizer is determined by both coupling efficiency and extinction ratio. The recent researches show that the coupling efficiency of the novel polarizer could reach 90% and the extinction ratio could be as high as 20 dB. A better polarizer should be good at both coupling efficiency and extinction ratio.

In this paper we show a novel polarizer by adding a silver nanoribbon to a traditional directional coupler. SPPs can be excited along metal-dielectric interface and they depend on polarization, so SPPs can enhance the sensitivity of polarization in the coupling region and lead to the change of the coupling periods for TM mode and TE mode. Then it can realize the polarized output of TE mode.

The basic type of traditional directional coupler is formed by two rectangular waveguides a and b with air in the middle. Supposing that the optical fields in separated waveguides are $\Phi_a(z)$ and $\Phi_b(z)$, the coupled mode equations read[12]

$$\mathrm{d}\Phi_a(z)/\mathrm{d}z= \mathrm{i}n_a k\Phi_a(z)+\mathrm{i}\kappa\Phi_b(z), \tag{1}$$

$$\mathrm{d}\Phi_b(z)/\mathrm{d}z= \mathrm{i}n_b k\Phi_b(z)+\mathrm{i}\kappa\Phi_a(z), \tag{2}$$

where $n_a=n_b$ are the effective propagation indices, $k=2\pi/\lambda$ is the wave number, and κ is the coupling efficiency. $\Phi_a(0)=1$ and $\Phi_b(0)=0$ are the boundary condition at $z=0$. For a coupling region with length of L, the output optical field can be obtained as[12]

$$\Phi_{a(b)}(L)=[\exp(\mathrm{i}n_e kL)+(-)\exp(\mathrm{i}n_o kL)]/2, \tag{3}$$

where $n_e=n_{a(b)}+\kappa/k$ and $n_o=n_{a(b)}-\kappa/k$ are effective indices. Fig.1 shows that the output energy ($|\Phi|^2$) transfers periodically between the two waveguides for different values of L.

Therefore, we propose a novel polarizer with a silver nanoribbon added into the middle of two waveguides of traditional directional coupler. Schematic diagram of the novel polarizer is shown in Fig.2. It consists of two silicon waveguides (a and b) whose widths both are W=300 nm and a silver nanoribbon whose width is t. L is the length of coupling region, the input light is at the left of waveguide a, and the angle of output light is α. The

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thicknesses of waveguide and silver nanoribbon both are 220 nm. The length of waveguide b should be longer than that of waveguide a for making the light coupled to waveguide b enough, and the difference of the lengths of two waveguides is L_1=0.15 μm. λ is the working wavelength, the corresponding refractive indices of Si and air are 3.5 and 1.0, respectively, and the permittivity of silver is $\varepsilon_m = -129+3.3i$[13]. The polarizer is based on silicon-on-insulator (SOI) material structure and compatible with the current fabrication facilities for complementary metal oxide semiconductor (CMOS) technology with vertical coupling. So it is easy to be fabricated by modern nanotechnology.

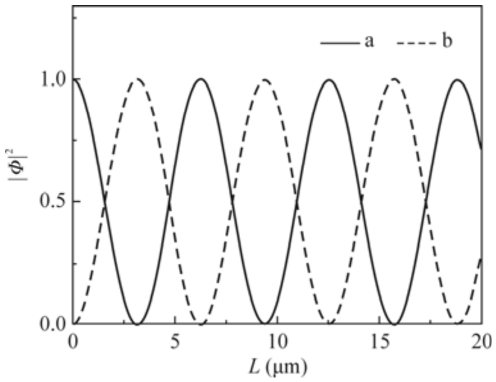


Fig.1 The relationship between output energy $|\Phi|^2$ and the length *L* of the coupling region

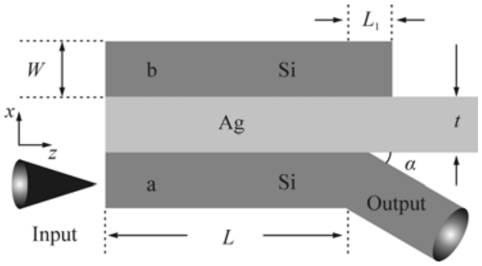
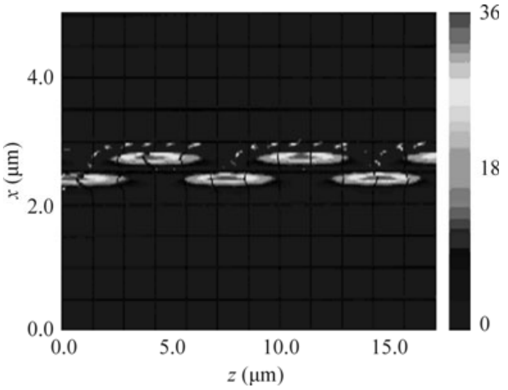


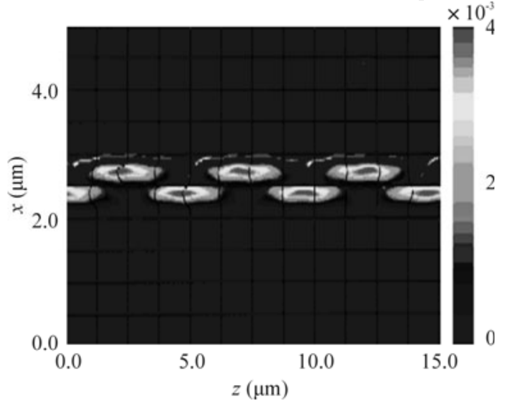
Fig.2 Schematic diagram of the novel polarizer

Two kinds of structures are simulated by finite-difference time-domain (FDTD) method. The first is a traditional directional coupler with air between two silicon waveguides, and the distance between two waveguides is 40 nm. The second is the novel polarizer with a silver nanoribbon between two silicon waveguides, and the width of the silver nanoribbon t is 40 nm. The input light wavelengths are both 1550 nm.

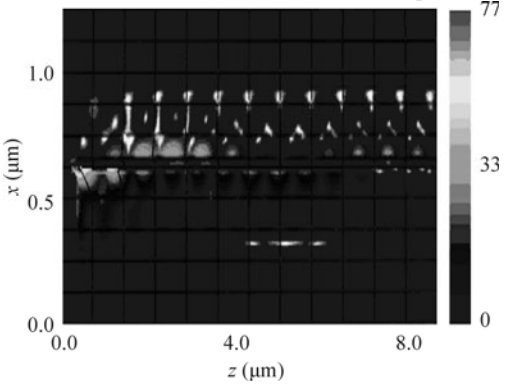
Fig.3(a) and (b) show the optical field distributions of TM mode and TE mode for traditional directional coupler. We can see that both of TM modes and TE modes are mainly confined in silicon waveguides and periodically oscillate between two waveguides. It's consistent with the phenomenon as shown in Fig.1. Simulation results indicate that the periods of TM mode and TE mode are 6.1 μm and 4.5 μm, respectively, and the difference is only 1.6 μm, so the traditional directional coupler couldn't realize the polarized output effectively.



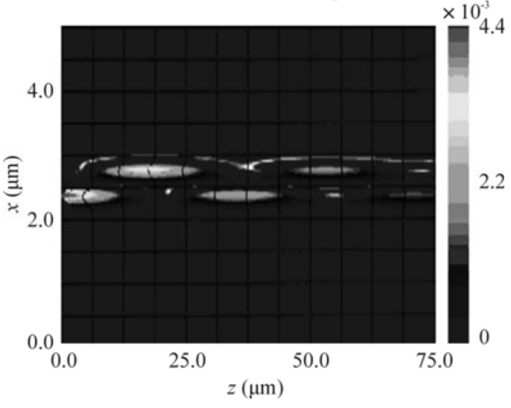
(a) TM mode for traditional directional coupler



(b) TE mode for traditional directional coupler



(c) TM mode for the novel polarizer



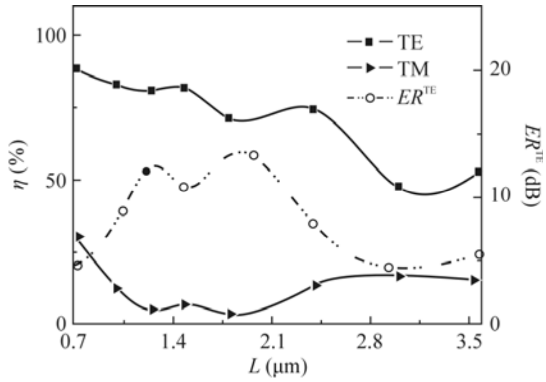
(d) TE mode for the novel polarizer

Fig.3 Optical field distributions of TM mode and TE mode for the traditional directional coupler (with air) and the novel polarizer (with silver)

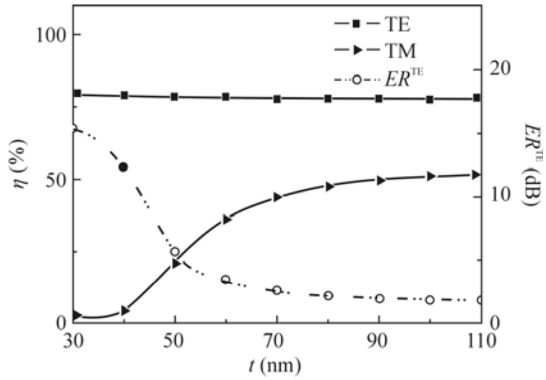
Fig.3(c) and (d) present the optical field distributions of TM mode and TE mode for the novel polarizer. We find that the energy of TM mode and TE mode almost periodically oscillates between two waveguides and gradually attenuates with the increase of L. The field of TM mode is bound to the silicon-silver interface, the energy of TM mode presents the faster attenuation, and the period of TM mode comes to be 5.15 μm, while the field of TE mode is still confined in silicon waveguides center, and the period of TE mode is larger to be 31 μm. The difference between the periods of TM and TE modes could be 25.85 μm. The input light can couple to surface plasmon, as SPPs can be excited along silver-silicon interface when a silver nanoribbon is added into the middle of two waveguides. What's more, the coupling between light and surface plasmon (SP) is polarization dependent. Only the light with electric field perpendicular to the metal surface can be converted to SP which is confined in silver-silicon interface[14]. The energy of TM and TE modes gradually attenuates with the increase of L because of the absorption loss in the silver. Considering that SP penetrates the silver nanoribbon in x direction, the electric field intensity of $E_{SP}(x)=E_0\exp(-k_x|x|)$ can faster attenuate according to exponential form with the increase of penetrable depth $|x|$. So the energy loss of TM (SP) is much larger than that of TE. More attention, SPPs can enhance the sensitivity of polarization in the coupling region and lead to the change of the coupling periods of TM and TE modes. The period difference between TM and TE modes is large enough to realize the polarized output. Therefore, when the length of coupling region L is shorter than 2 μm, the energy of TE mode whose period (31 μm) is much larger than 2 μm can be kept mostly in the waveguide a. In contrast, the energy of TM mode can be fast coupled to the waveguide b as 2 μm is about half of the TM period (5.15 μm), and there is a large absorption loss in penetrating silver nanoribon. Consequently, it can realize polarized output of the TE mode at the right of waveguide a.

In this paper, we discuss the effects of the polarizer parameters, including the length of coupling region L, the width of silver nanoribbon t, wavelength λ and the angle of the output light α, on the coupling efficiency and the extinction ratio. One parameter is simulated every time while the other parameters are kept constant (L=1.25 μm, t=40 nm, λ=1.55 μm and α=13.9°). The power is detected at the input and output. The coupling efficiency can be computed by $\eta=P_{out}/P_{in}$. The extinction ratio is $ER^{TE}=-10\log(\eta_{TM}/\eta_{TE})$.

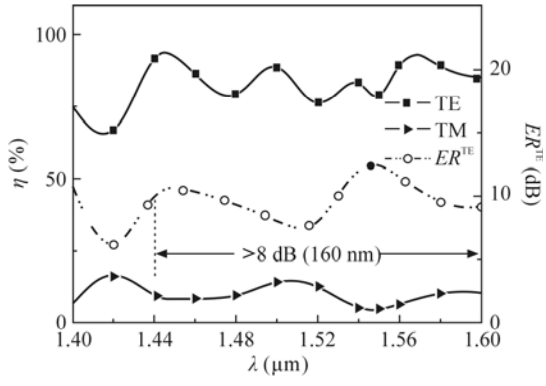
In Fig.4(a), the coupling efficiencies of TE mode and TM mode and the extinction ratio of TE mode are tested by varying the length of coupling region L. We can see that the coupling efficiency of TE mode is much higher than that of TM mode. We obtain high coupling efficiency and low extinction ratio of TE mode when the coupling length L is 1.25 μm. The effects of the width of silver nanoribbon t on coupling efficiency and extinction ratio are shown in Fig.4(b). Increasing t, the coupling efficiency of TE mode is kept around 80%, but that of TM mode gradually increases, and the extinction ratio of TE mode ER^{TE} increases. So when we decrease t, the coupling efficiency of TM mode decreases, and the extinction ratio of TE mode can be much larger. Considering the limit of facture, we choose t=40 nm. The incident wavelength dependence of the polarizer is shown in Fig.4(c). The coupling efficiency of TE mode is kept around 80%, and that of TM mode is kept about 10%. Especially, the coupling efficiency of TM mode is about 5% in the range of 1.54 μm–1.56 μm. The result indicates that the polarizer is not sensitive to wavelength. The wavelength range is from 1440 nm to 1600 nm when the extinction ratio of TE mode is larger than 8 dB. ER^{TE} is the largest as λ is 1550 nm. In Fig.4(d), the influence of the angle of the output light α is presented. Increasing α, the coupling efficiency and extinction ratio of TE mode both gradually decrease as a whole, so the coupling efficiency of TE mode can decrease if α is much larger. The extinction ratio of TE mode is kept high in the range of 0°–40°, and can reach 15 dB when α=13.9°.



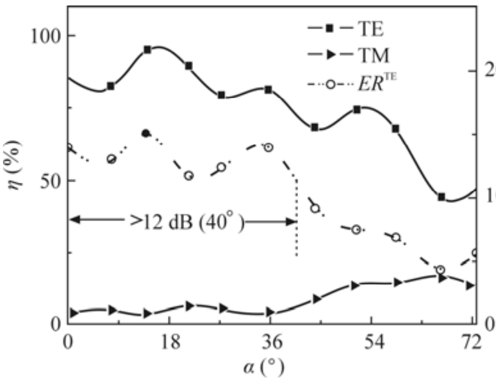
(a) Length of coupling region



(b) Width of silver nanoribbon



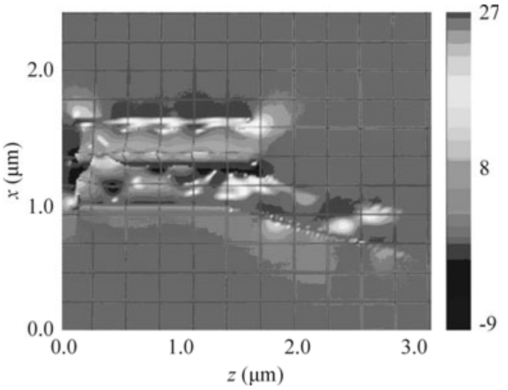
(c) Wavelength



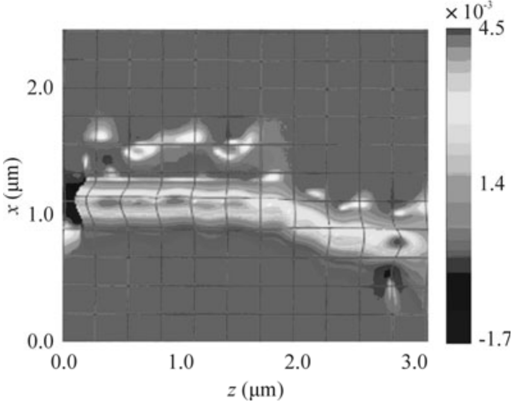
(d) Angle of the output light

Fig.4 The effects of the polarizer parameters on coupling efficiencies of TM and TE modes and extinction ratio of TE mode

Fig.5(a) and (b) show the optical field distributions of TM and TE mode with the optimized parameters (L=1.25 μm, t=40 nm, λ=1.55 μm, α=13.9°, W=300 nm and L_1=0.15 μm). Simulation results indicate that the coupling efficiency of TE mode is 95%, but that of TM mode is only 3%, and the extinction ratio of TE mode can reach 15 dB at the wavelength of 1550 nm.



(a) TM mode



(b) TE mode

Fig.5 Optical field distributions of TM mode and TE mode in the novel polarizer with optimized parameters

In summary, we propose a novel polarizer based on directional coupler and SPPs to realize the polarized output of the TE mode. The polarizer is designed by adding a silver nanoribbon to a traditional waveguide directional coupler. The parameters of the polarizer structure are optimized by FDTD. Research results indicate that the novel polarizer has the characteristics of broad bandwidth, big angle tolerance and extremely compact dimension. With reasonable parameters, the extinction ratio of TE mode can reach 15 dB with the coupling efficiency of 95%. This kind of polarization device will enrich the application of integrated optics on chip.

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