

Broadband integrated polarization beam splitter with surface plasmon

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A broadband integrated waveguide polarization beam splitter consisting of a metal nanoribbon and two dielectric waveguides is proposed and numerically investigated. This surface plasmon based device provides a unique approach for polarization sensitive manipulation of light in an integrated circuit and will be essential for future classical and quantum information processes. © 2011 Optical Society of America

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Polarization is one of the most important properties of light, especially in the studies and applications of modern optics, such as nonlinear optics and quantum optics. It especially plays a main role in linear optical quantum information technology [1]. In traditional free-space optical technology, the polarization has been well manipulated with linear optical elements, such as polarization beam splitters (PBSs) and wave plates. In another way, with rapid progress in material science and nanofabrication technology, there is a tendency to integrate optical devices on a single chip. This integrated circuit, composed of basic integrated optic components, including a laser source, low loss waveguides, a power splitter, and a modulator, has the same functions as traditional optical components but can significantly save space, reduce power consumption, and enhance processing stability. Thus the integrated circuit holds great potential for applications in both classical [2] and quantum [3] information processes. Recently, integrated photonic quantum logic gates and Shor's quantum factoring algorithm have been demonstrated on a chip [4], showing great feasibility and high operation fidelity. In this chip-scale nanophotonics, light is confined and transmitted in a dielectric waveguide. However, the control of polarization is still a difficult challenge. Although several proposals for integrated PBSs have been studied theoretically [5], it is still very recent that the mode conversion based PBS has been realized, which has been considered a milestone of integrated photonics technology [6].

Meanwhile, the surface plasmon (SP) [7] is extensively studied both experimentally and theoretically, as an important component of nanophotonics [8]. At the interface of metal and dielectric materials, the coupled electromagnetic waves can be guided and confined beyond the diffraction limit. More importantly, the coupling between light and SPs is polarization dependent. Only light with an electric field perpendicular to the metal surface can be converted to SP mode. This property of polarization sensitivity offers a unique approach to manipulating the polarization of light and designing polarized nanophotonic devices on a chip.

In this Letter, we propose and numerically demonstrate an integrated surface plasmon based polarization beam splitter (SPPBS). Different from a traditional

waveguide directional coupler, an additional metal nanoribbon offers great polarization sensitivity and broadband characteristics. With reasonable parameters, we numerically demonstrate a broadband PBS with an efficiency above 92%, which is mainly limited by the absorption loss of metal. A 1/3 PBS [9] for linear optical quantum information technology is also designed with high quality. This SPPBS will enable further integrated optics and linear optics computation by polarization modes and also can be integrated with on-chip microcavity quantum electrodynamics (QED), permitting the two-qubit gate for quantum computation [10] based on light-matter interaction.

The proposed SPPBS is shown in Fig. 1, which consists of two silicon waveguides on a silica substrate with a silver nanoribbon sandwiched by them. The width of the nanoribbon and silicon waveguide are t and w , and the height of both is h . The working wavelength is $\lambda = 1550$ nm, and the corresponding permittivities of silicon and silver are $\epsilon_d = 3.5^2$ and $\epsilon_m = -129 + 3.3i$, respectively, at room temperature [11]. Each waveguide slowly approaches the silver nanoribbon with a bending waveguide and connects to a uniform dielectric-metal-dielectric hybrid waveguide with length L . When light enters at the input port, the TE mode will be converted to SP modes adiabatically with a conversion efficiency over 99%, but the TM mode is not significantly changed [12].

The function of PBS is to divide the input light into orthogonal polarizations, TE and TM, and output at separate ports. In the present proposal, the polarization

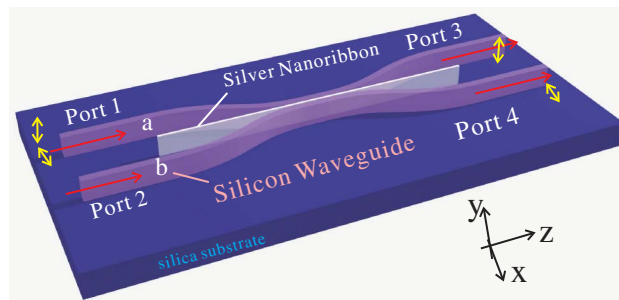


Fig. 1. (Color online) Schematic illustration of the integrated surface plasmon based polarization beam splitter.

dependent manipulation is achieved at the hybrid waveguide region, where light can penetrate the metal and transfer between dielectric waveguides. Denoting the fields in separated waveguides as $\phi_a(z)$ and $\phi_b(z)$, the coupled mode equations read [13]

$$\begin{aligned} \frac{d}{dz}\phi_a(z) &= in_a k \phi_a(z) + i\kappa \phi_b(z), \\ \frac{d}{dz}\phi_b(z) &= in_b k \phi_b(z) + i\kappa \phi_a(z), \end{aligned} \quad (1)$$

where $n_a = n_b$ are the effective propagation indices, $k = 2\pi/\lambda$ is the wave number, and κ is the coupling efficiency. Thus, the field of the coupled waveguides can be represented in the basis of even [symmetric, $\phi_e(z) = \phi_a(z) + \phi_b(z)$] and odd [antisymmetric, $\phi_o(z) = \phi_a(z) - \phi_b(z)$] normal modes, with the propagation function as

$$\frac{d}{dz}\phi_{e(o)}(z) = in_{e(o)} k \phi_{e(o)}(z), \quad (2)$$

where $n_{e(o)} = n_a + (-)\kappa/k$ are effective indices. By the finite element method (FEM), the field profiles of fundamental TE and TM normal modes at the cross section are solved numerically, as shown in Fig. 2(a). Obviously, the energy of the TE modes is bound to the silver-silicon interface, formed as a SP mode. In contrast, the TM modes are mainly confined in dielectric waveguides, with only a small portion of energy in the silver nanoribbon due to the continuous boundary condition. For the input field at Port 1 in Fig. 1, i.e., $\phi_a(0) = 1$ and $\phi_b(0) = 0$, with a numerically solved $n_{e(o)}$, we can obtain

$$\phi_{a(b)}(z) = (e^{in_e k z} + (-)e^{in_o k z})/2. \quad (3)$$

Therefore, for a coupling region of length L , the output optical fields at Ports 3 and 4 are $\phi_{3(4)} = (e^{in_e k L} + (-)e^{in_o k L})/2$. Figure 2(b) shows the energy ($|\phi|^2$) output at Ports 3 and 4 for different values of L . The oscillations indicate the energy transferring between the two silicon waveguides. The oscillation period, inversely proportional to the coupling strength, can be approximately expressed as $L_p = \frac{1}{(n_o - n_e)k}$. As shown in Fig. 2, the oscillation period of the TE mode ($L_p \approx 5.3 \mu\text{m}$) is much

shorter than that of the TM mode ($L_p \approx 40 \mu\text{m}$), while for the traditional direct coupled waveguides without the silver nanoribbon (air between the two silicon waveguides), the L_p values of the TE and TM modes are very close to each other. Thus, it is very easy to separate the two orthogonal polarization modes in a short coupling region for the SPPBS. It is because the silver nanoribbon gives rise to polarization dependent coupling between the dielectric waveguides that the oscillation period is shorter (longer) in the proposed SPPBS than in the traditional direct coupled waveguides for the TE (TM) mode, indicating a larger (smaller) coupling strength. For the same reason, the TE mode also shows much faster attenuation, arising from the absorption loss in the silver nanoribbon.

As denoted by the blue dashed line in Fig. 2(b), when $L = L_p/2$, all of the TE polarized light at Port one will drop at Port 4, and most of the energy of the TM input will drop at Port 3. For convenience, we denote T_{TE}^{13} as the transmission of the TE polarized mode from input Port 1 to output Port 3, which is the same for T_{TE}^{13} , T_{TM}^{13} , and T_{TM}^{14} . A perfect PBS requires $T_{\text{TE}}^{14} = T_{\text{TM}}^{13} = 1$ and $T_{\text{TE}}^{13} = T_{\text{TM}}^{14} = 0$. In the following, L is fixed at $L_p/2$ to ensure $T_{\text{TE}}^{13} \approx 0$ for a simple design with a broadband application. Because of the continuous boundary condition, a very small fraction of the energy of the TM mode will inevitably penetrate the metal, leading to $T_{\text{TM}}^{13} < 1$ and $T_{\text{TM}}^{14} > 0$. In addition, as a result of the absorption of the silver nanoribbon, when light propagates along the hybrid waveguide, $T_{\text{TE}}^{14} < 1$ and $T_{\text{TM}}^{13} + T_{\text{TM}}^{14} < 1$.

Some parameters of the SPPBS can be adjusted to optimize the structure. In Figs. 3(a) and 3(b), the performance of the SPPBS is tested by varying the width of the silver nanoribbon and waveguides. Increasing t , T_{TM}^{14} is kept around 5%, but T_{TM}^{13} and T_{TE}^{14} decrease, because the larger thickness will give rise to a larger oscillation period L and a much larger absorption loss. In order to reduce the absorption loss, the width of the silver nanoribbon t should be as small as possible. For a different waveguide width w , T_{TE}^{13} is almost unchanged, but T_{TM}^{13}

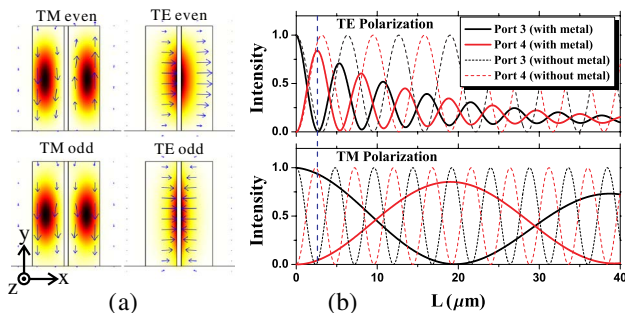


Fig. 2. (Color online) (a) Normal modes in the waveguides with a silver nanoribbon in the middle, with $t = 40 \text{ nm}$, $w = 300 \text{ nm}$, and $h = 1 \mu\text{m}$; (b) the energy transfer between two waveguides with (solid curves) and without (dashed curves) silver nanoribbon with the same parameters. The input port is Port 1.

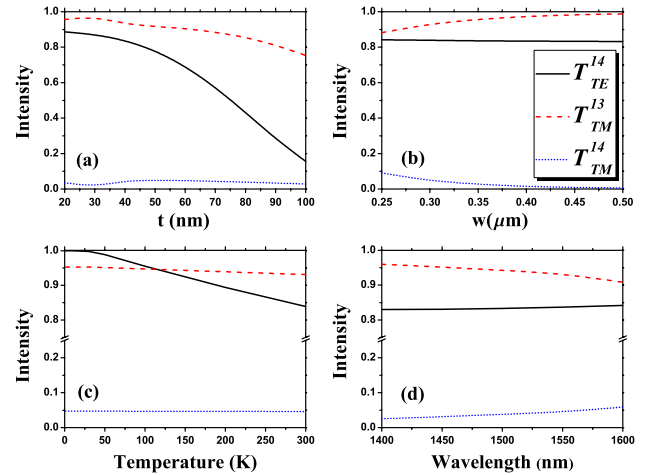


Fig. 3. (Color online) Dependence of a SPPBS on (a) thickness of the nanoribbon, (b) width of the waveguide, (c) temperature, and (d) wavelength. For each figure, the fixed parameters are $t = 40 \text{ nm}$, $w = 300 \text{ nm}$, $T = 300 \text{ K}$, and $\lambda = 1550 \text{ nm}$.

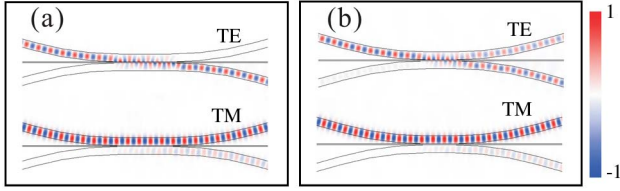


Fig. 4. (Color online) Field distribution of (a) the PBS and (b) the 1/3 PBS with TE or TM polarization input at Port 1.

and T_{TM}^{14} are affected. Here, a larger w corresponds to better TM mode confinement and a smaller tunneling rate between waveguides. When $w = 500$ nm, $T_{\text{TM}}^{14} \approx 0$. In addition, the TE mode is not affected because the SP mode at the interface is not sensitive to the waveguide width. It should be noted that the above discussion only considers fundamental modes. If w is large, the waveguide will work in the multimode region, but both the adiabatic conversion at the bending region and the energy transfer between waveguides in the coupling region are complex [12].

The efficiency of the SPPBS is limited by the absorption in metal, which can be greatly reduced at low temperatures. Figure 3(c) shows the temperature dependence of SPPBS. We adapt the approximate relationship between permittivity and temperature as $\epsilon_m(T) = -129 + \sigma(300 \text{ K})/\sigma(T) \times 3.3i$ [14], where $\sigma(T)$ is the conductivity of silver at temperature T [15]. From Fig. 3(c), T_{TE}^{14} is greatly increased by reducing the temperature. The increment of T_{TM}^{13} is minor, since the metal absorption is small for TM modes. The broadband property is one of the most important advantages of such a design. The wavelength dependence of SPPBS is shown in Fig. 3(d), where the dispersive silver permittivity values are obtained from the fitting of experimental data [11]. The results directly indicate that the SPPBS is not sensitive to wavelength, extending its application in classical and quantum optical communications.

Finally, we demonstrated the PBS by two-dimensional FEM simulation in the xz plane, with reasonable parameters as $t = 40$ nm, $w = 340$ μm , the bending radius of waveguide as 15 μm , and $T = 80$ K as the liquid nitrogen cryostat temperature. The field distribution is shown in Fig. 4(a), with $L = 2.4$ μm , $T_{\text{TE}}^{13} = 0.0004$, $T_{\text{TE}}^{14} = 0.9308$, $T_{\text{TM}}^{13} = 0.9258$, and $T_{\text{TM}}^{14} = 0.0688$. In addition, the 1/3 PBS [9] is also an important optical element for quantum information technology. With this 1/3 PBS, a quantum Controlled-NOT gate can be well realized [9]. Here, we investigated a 1/3 PBS with $L = 1.2$ μm and obtained $T_{\text{TE}}^{13} = 0.3192$, $T_{\text{TE}}^{14} = 0.6366$, $T_{\text{TM}}^{13} = 0.9571$, and $T_{\text{TM}}^{14} = 0.0386$ [Fig. 4(b)].

In conclusion, an integrated PBS is proposed and numerically demonstrated. The dependencies of the performance of PBS on the device size, temperature, and wavelength are investigated. With reasonable parameters, the efficiency of SPPBS is above 92%. This on-chip nanophotonic polarization device will enrich the application of integrated optics, such as in further classic and quantum information coded with polarization modes. It can also be integrated with on-chip microcavity QED systems for quantum computation [10].

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