Diodelike asymmetric transmission in hybrid plasmonic waveguides via breaking polarization symmetry

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Abstract
The ability to control the asymmetric propagation of light in nanophotonic waveguides is of fundamental importance to optical communications and on-chip signal processing. However, in most studies so far, the design of such structures has been based on asymmetric mode conversion where multi-mode waveguides are involved. Here we propose a hybrid plasmonic structure that performs optical diode behavior via breaking polarization symmetry in single mode waveguides. The exploited physical mechanism is based on the combination of polarization rotation and selection. The whole device is ultra-compact with a footprint of 2.95\times14.18\,\mu m\textsuperscript{2}, and whose dimension is much smaller than the device previously proposed for a similar function. The extinction ratio is greater than 11.8\,dB for both forward and backward propagation at \lambda = 1550\,nm (19.43\,dB for forward propagation and 11.8\,dB for the backward one). The operation bandwidth of the device is as great as 70\,nm (form 1510 to 1580\,nm) for extinction >10\,dB. These results may find important applications in the integrated devices where polarization handling or unidirectional propagation is required.

Keywords: diodelike asymmetric transmission, hybrid plasmonic waveguides, polarization rotation, polarization selection

(Some figures may appear in colour only in the online journal)

1. Introduction

In 2008, Zhang \textit{et al} proposed the concept of hybrid plasmonic waveguides (HPWs) \textsuperscript{[1]}. Since then, this topic has attracted considerable interest as a promising candidate for integrated photonic circuits (IPCs) \textsuperscript{[1–4]}. The typical HPW structure consists of a dielectric nanowire and a metal strip, which are separated by a low-index dielectric material \textsuperscript{[1, 5]}. Due to their unique characteristics in subwavelength optical confinement \textsuperscript{[1]}, significant birefringence effect \textsuperscript{[2]}, polarization rotation \textsuperscript{[5]}, and relative long range propagation \textsuperscript{[3]}, HPWs can push conventional optical components to the subwavelength scale \textsuperscript{[5–7]}. By manipulating the phase and polarization of the incoming light, the HPWs can control the propagation of light in unprecedented ways, enabling many applications, i.e. optical telecommunications and interconnects \textsuperscript{[4]}, polarization converter \textsuperscript{[5]}, nanofocusing \textsuperscript{[6]} and one-way mode conversion \textsuperscript{[7]}. The significant interest in fast, compact, and efficient optical computing and communications has led to the development of optical systems that perform one-way transmission or...
have optical diode behavior. Conventionally, this is achieved by mainly using magneto-optic materials that can break the Lorentz symmetry, i.e. Faraday rotation [8]. However, this technology suffers from difficulty of integration, because the magneto-optic effect is extremely weak and it requires bulk optics to achieve considerable polarization rotation. Another challenge of this technology is the mechanical complexity, since other moving bulk optical components, such as polarizers, mirrors and wave-plates, are required [9].

For many practical applications, it is more desirable to use compact, functional devices based on IPCs that are compatible with CMOS fabrication. For this reason, tremendous efforts have been devoted to create on-chip optical diodes, which can be generally divided into two main categories. The first type is a non-reciprocal method based on spatiotemporal modulations [10, 11] and Kerr non-linearities [12]. However, those designs are relatively large in size, the dimension of which can be anywhere from several tens of microns to several centimeters. Moreover, they require external modulations (strong light beam or dynamic electric field) as well, which is often undesired. The other category is to use reciprocal methods, differing from breaking the reciprocity of light to realize optical diodes. Various types of reciprocal diodes have been demonstrated recently based on sonic crystals [13, 14], HPWs [15] and photonic crystals [16–18]. Those devices offer asymmetric transmission mainly based on spatial symmetry breaking (asymmetric mode conversion). For example, they can convert an even fundamental mode to a higher order odd mode in the forward direction while blocking the propagation of the fundamental mode in the backward direction [16]. This, however, requires multimode waveguides. For on-chip signal processing, single mode waveguides are often more desired, because they have a smaller footprint, lower propagation loss, and higher tolerance of waveguide roughness compared with the multimode ones. Consequently, spatial-symmetry-breaking schemes face a fundamental limitation for single mode waveguides where higher order modes are suppressed. Polarization is another degree of light that is orthogonal to spatial modes. Although spatial-symmetry-breaking schemes have been widely demonstrated for optical diodes, the corresponding demonstrations based on polarization-symmetry-breaking, especially with single mode HPWs, have been elusive, only having been reported in the context of chiral metamaterials [19].

In this work, we report optical diode behavior in a novel hybrid plasmonic structure that breaks polarization symmetry. A quasi-TM polarized mode (the dominant polarization component \( \mathbf{E}_T \) points along the \( x \)-axis) is converted into another quasi-TE polarized mode (\( \mathbf{E}_T \) points along the \( y \)-axis) in the forward propagation (from port \( C \) to port \( A \)). While the same polarized mode cannot travel back in the counter-propagation with the energy leaking away to another port \( B \) (figure 1(a)).

2. Functionality and geometry details

Figure 1(a) shows the schematic configuration and function of the proposed structure. This includes a half-wave plate section and a directional coupler section, which respectively...
function as a polarization rotator and a polarization beam splitter. Three kinds of nanophotonic waveguides are involved in the hybrid system. A dielectric waveguide (DW) whose height and width are equal \( h = w_2 \) (figure 1(b)), and a birefringent hybrid waveguide (BHW) with a metal (silver, Ag) cap on the top. Together they make a polarization beam splitter, where 4 S-bend structures are used to couple and decouple light. The third kind is a rotating hybrid waveguide (RHW) with an L-shaped metal (silver, Ag) on the top left side of the Si core, which works as a half-wave plate. The whole structure is surrounded by silica (SiO₂) and the operating wavelength is \( \lambda = 1.55 \) μm.

There are four physical ports (A, B, C and D) in the proposed device, and each of them support both quasi-TE and -TM polarized modes. For the diodile-like asymmetric transmission, we only use three ports, A, B and C. When light travels from port C to port A (forward direction), a fundamental quasi-TM mode will first couple from the BHW to the adjacent DW and then get converted into a fundamental quasi-TE mode by the RHW at the output port A. However, in the counter propagation (A to C) (backward direction), a fundamental quasi-TM mode cannot travel back to the C port but instead, it gets converted into a quasi-TE mode and goes to output port B, since the newly converted quasi-TE mode cannot couple into the BHW due to phase-mismatch, which will be discussed later.

Figure 1(b) shows the detailed geometry parameters of the device. For the RHW, the width (\( w_2 \)) and height (\( h \)) of the Si waveguide are equal, \( h = w_2 = 0.34 \) μm; the thickness of the L-shaped Ag cap (\( t \)) is \( t = 0.1 \) μm, and the spacer (\( s \)) between L- shaped Ag cap and silicon waveguide is \( s = 0.05 \) μm, and the whole polarization rotator length (\( L_1 \)) is 4.78 μm. For the polarization beam splitter part, the width (\( w_3 \)) and height (\( h \)) of the DW are \( w_2 = h = 0.34 \) μm, while the width (\( w_1 \)) and height (\( h \)) of the lower Si waveguide are 0.26 μm and 0.34 μm respectively; the thickness (\( t \)) of the metallic Ag cap \( t = 0.1 \) μm, the spacer (\( s \)) between Ag cap and the Si waveguide \( s = 0.05 \) μm, the gap (\( g \)) between two adjacent waveguides \( g = 0.2 \) μm, and the whole polarization beam splitter part length \( L_2 = 5.4 \) μm. The size of each S-bend is \( 2 \times 2 \) μm² (the S-bend structures are taken from the structure database of Lumerical FDTD Solutions). The whole device is ultra-compact with a footprint of 2.95 × 14.18 μm². The dielectric constants (\( \varepsilon \)) of the materials (Ag, Si, SiO₂) we used are \( \varepsilon_{Ag} = -116.843 + 11.6819i, \varepsilon_{Si} = 12.0852, \varepsilon_{SiO2} = 2.08514 \), respectively.

3. Polarization rotator

We will first discuss the RHW and then the BHW and DW. The geometric details of the RHW is displayed in figure 2(a) while figure 2(b) shows the corresponding eigenmodes, whose dominant polarization components polarized at the angle \( \varphi = \pm \pi/4 \), where \( \varphi \) is the angle down from the positive x-axis. The eigenmodes are obtained via the eigenmode solver that is available in the finite-different time-dominant (FDTD) solutions package from Lumerical Inc.

As an example of non-paraxial light, the electric field of light in nanophotonic waveguides is not purely transverse. Unlike the plane wave in free space, where every point of the wavefront shares the same polarization state, the polarization of each point in nanophotonic waveguides is highly position-dependent [21, 22]. However, the electric field of light at the central point of the Si DW is purely transversal regarding a fundamental 0th order mode, where the amplitude of the dominant transverse polarization component (\( E_p \)) reaches its peak whilst the one of the longitudinal component (\( E_z \)) equals zero. Therefore, we use the center point polarization state to represent the predominant polarization state of a certain mode, and we use the word ‘quasi-’ to make the description more accurate. Thus, it is reasonable to use the polarization state at the central point to represent the dominant polarization and phase of a certain fundamental mode [20].

Here, we choose the parameters as \( (h, w_2, t, s) = (0.34, 0.1, 0.34, 0.05) \) μm. Correspondingly, the effective indices for the two eigenmodes are respectively calculated to be \( n_{r4} = 2.47169 + 0.00352783i \) and \( n_{s4} = 2.30951 + 0.0020423i \). When a quasi-TM mode (\( E_{TM} = \exp[−i(w_2 − n_{r4}k_{0}z)]E_x = \exp[−i(w_2 − n_{s4}k_{0}z)]E_x \), where \( E_TM \) is the unit vector) travels in the RHW, it will undergo a polarized modes coupling process. According to the polarized mode coupled theory [20], the dynamics of the output mode can be described by

\[
\begin{align*}
\frac{dE_{TE}}{dz} + \imath v_{TE} k_0 E_{TE} - \imath n E_{TM} &= 0 \\
\frac{dE_{TM}}{dz} + \imath v_{TM} k_0 E_{TM} - \imath E_{TE} &= 0
\end{align*}
\]

where \( E_{TE/M} \) represents the amplitude of two orthogonal modes at the output port, and \( \kappa = \pi/(2L_C) \) is the coupling coefficient with the coupling length \( L_C = \pi/\{\text{Re}(n_{r4}) - \text{Re}(n_{s4})\} \). \( k_0 = 2\pi/\lambda \) is the free space wave number. For the output modes energies (\( P \propto |E|^2 \)), they can be written as,

\[
\begin{align*}
P_{TE}(z) &= |\imath \text{sin}(kz)|^2 e^{-2\imath \kappa z} \\
P_{TM}(z) &= |\cos(kz)|^2 e^{-2\imath \kappa z}
\end{align*}
\]

provided that \( P_{TE}(z = 0) = P_{TM}(z = 0) = 1 \), where \( z \) is the device length and \( \pi = |\text{Im}(n_{r4}) - \text{Im}(n_{s4})|/2 \). The term \( e^{-2\kappa z} \) denotes the propagation loss. In particular, the \( -\imath \) term in \( P_{TE} \) indicates that there is an intrinsic phase lag of \( \pi/2 \) between the output quasi-TE and -TM modes (\( \Delta \varphi = \varphi_{TM} - \varphi_{TE} = -\pi/2 \)). This characteristic is important, since it allows the design of different kind of wave plates with different equivalent optical axis orientations by the choice of different device lengths (\( z \)), i.e. quarter-wave plates (QWPs), half-wave plates (HWPs) and full-wave plates (HWPs). For example, the choice of \( z = 0.5L_C \) leads to a QWP with the equivalent optical axis orienting at \( \varphi = \pi/4 \) while a choice of \( z = L_C \) results in a HWP with the equivalent optical axis pointing along \( \varphi = \pi/4 \), where \( \varphi \) is the angle down from the positive x-axis. To illustrate this point, we plot the theoretical dependence of the output energies (\( P_{TE/TM} \) and relative phase lag (\( \Delta \varphi \)) on the device length (\( z \)) in figure 2(c). In this work, we choose \( z = L_C \approx 4.78 \) μm, so that the RHW can
convert an input quasi-TM mode into a quasi-TE mode, and vice versa.

4. Polarization beam splitter

Another section involved in our device is a polarization beam splitter, which consists of a BHW and a DW. HPWs can exhibit a huge birefringence effect due to the asymmetry between the vertical and horizontal directions of the structures. This effect can be steered to fabricate a polarization beam splitter. Figure 3(a) shows the calculated results of the real part of effective indices of a BHW and a DW. In our calculation, the spacer between the Ag strip and the Si core for the BHW is \(s = 50 \text{ nm}\) and the gap between the two adjacent waveguides is \(g = 200 \text{ nm}\) (figure 1(b)).

For the DW, the TE- and TM-like polarized modes have the same effective index \(n_{D-TE} \approx n_{D-TM} \approx 2.33\) when the width and height are equal \((w_2 = h = 0.34 \mu \text{m})\). By choosing \(w_1 = 0.26 \mu \text{m}\), the BHW has the same effective index as the DW for the TM-like polarized light \(n_{D-TM} = n_{H-TM} \approx 2.33\). The odd and even modes for TE-like and TM-like polarization states in the coupling region are shown in figure 3(b). In case of perfect phase-matching, that is, \(n_{D-TM} = n_{H-TM}\), the optical mode initially in the DW can make a complete transition to the BHW after propagating over a distance of \(z_{c} = \pi/[(n_{r,e} - n_{r,o})k_0]\), and vice versa (figure 3(c)), where \(n_{r,e}\) and \(n_{r,o}\) are the real parts of effective indices of the even and odd modes in the coupling region for the TM-like polarized light. However, due to the birefringence effect, the effective indices of the DW differs dramatically from the one of the BHW, since their difference is as great as 0.53 \(n_{D-TE} - n_{H-TE} \approx 2.33 - 1.80 = 0.53\). In this case of strong phase-mismatch, the TE-like polarized light initially in the DW can hardly couple into the adjacent BHW, as shown in figure 3(c). Therefore, it is clear that the function of the polarization splitter is that the complete energy exchange is allowed for a quasi-TM mode, while it is forbidden for the quasi-TE mode.

For the choice of the gap \(g = 200 \text{ nm}\) between the DW and BHW, the effective indices of the even and odd modes for the quasi-TM mode is \(n_{TM,e} = 2.38718 + 0.00174273i\) and \(n_{TM,o} = 2.27618 + 0.00217367i\). Thus, the coupling length \(z_{c} = \pi/[(n_{r,e} - n_{r,o})k_0] = \pi/[(2.38718 - 2.27618) \times 6.98 \mu \text{m}] = 6.98 \mu \text{m}\). Considering that there are some undesired couplings between the S-bend parts, we choose the length of the straight part of BHW/DW as \(L_2 = 5.4 \mu \text{m}\), to be a little shorter than \(z_{c}\), so as to obtain a complete energy transition for the TM-like polarized light.

5. The whole structure simulation results

Figure 4(a) shows the monitor planes positions. It is now clear how this system functions. In the forward propagation, a quasi-TM mode launched in the input port \(C\) will firstly couple into the adjacent DW and then get converted into a
quasi-TE mode after passing the RHW and finally reaches the output port A (figure 4(b)). In the backward propagation, the input quasi-TM mode at port A will firstly get converted into a quasi-TE mode via the RHW. However this newly quasi-TE mode cannot be coupled into the adjacent BHW due to the strong phase-mismatch, but instead, goes straight forward to the output port B (figure 4(c)).

Note that there will be a small proportion of light that ends up going to an undesired port. For example, a little light goes to port D in the forward propagation. To evaluate the optical performance of this one-way operation, we defined the extinction ($E_x$) as the ratio between the energy transmission detected in the desired port and that in the undesired port, that is $E_x = 10 \times \log_{10}(P_d/P_u)$, assuming unit power entering the input port.
Figure 5. The transmission and extinction spectrum characteristics of forward (a) and (b) backward propagation directions. The blue curve indicates the output powers detected at the desired and undesired output ports. The red curve represents the dependence of the extinction on wavelength \( \lambda \). The rectangle of light green color shows the bandwidth where the extinction ratio is greater than 10 dB for both propagation directions.

For the forward propagation, the energy detected in port A (desired) and port D (undesired) are respectively \( P_A = 50.515\% \) and \( P_D = 0.576\% \). Thus the forward extinction is calculated as \( E_{A,F} \approx 19.43 \text{ dB} \) while the backward extinction calculated as \( E_{A,B} \approx 11.82 \text{ dB} \), provided that \( P_B = 65.38\% \) and \( P_C = 4.30\% \) in the backward propagation. The extinction ratio can be further improved by optimizing a few parameters, such as the gap (\( g \)) between two adjacent waveguides, the length of the straight part of BHW/DW (L2), and the size of S-bend structure (a).

6. Operation bandwidth discussion

The above calculation results are based on the wavelength of 1.55 \( \mu \text{m} \). In order to find out the spectral dependence of the proposed device, we carried out simulations on the full-structure simulations from \( \lambda = 1.50 \mu \text{m} \) to \( \lambda = 1.60 \mu \text{m} \) for both forward and backward propagations. The results are show in figure 5. For some logical computing circuits, it is desirable that the power in the desired port is much higher than the undesired port so that it is easier to make the judgement between two types of signals: 'high' (1) and 'low' (0). Therefore, a higher extinction is desirable in terms of logical level distinction (1 or 0). Figure 5 shows that the bandwidth for extinction \( > 10 \text{ dB} \) for both the forward and backward propagation is as large as 70 nm, from 1.51 \( \mu \text{m} \) to 1.58 \( \mu \text{m} \). These results demonstrate that the device is a broadband device that has potential application value in the fields of optical logical circuits.

7. Other functions and discussion

Interestingly, our proposed device can also be used as a polarization splitter-rotator [23, 24] by using the ports A, C and D (figure 6(a)). When light propagates from port C to port A, the quasi-TM mode launched at port C is efficiently coupled to the adjacent DW at the directional coupler section and then the TM-like polarized light in the DW is converted to a TE-like polarized mode after passing through the RHW section. On the other hand, if one launches a TE-like polarization at the same input port C, the quasi-TE mode in the BHW cannot couple to the adjacent DW because of phase mismatch (see section 4 for details). Instead, it is restricted in the BHW and ends up going to port D (figure 6(b)). This functionality is interesting. Not only can it separate different polarization state (TE- or TM-like polarization) in nanophotonic waveguide, but it can also guarantee the polarization state (TE-like polarized) of every output port (port A or port D).

The proposed device is expected to have potential applications in optical logical computing. In conventionally logical computing, ideally, it is very desirable to have a full voltage (1) for a 'high' state and zero voltage (0) for a 'low' state. However, in reality, these perfect limits cannot be guaranteed due to stray voltage drops in the transistor circuitry. Similarly, in our proposed device, full optical power (1) and zero intensity (0) cannot be obtained at the output ports. This is because the metallic structures in our device will inevitably cause some undesired optical losses, and there is a weak coupling in the directional coupling section for quasi-TE modes, which will cause undesired coupling to the undesired port. In this case, we defined the output port with strong optical output power as logical high state (1) while the rest ports (with relative much lower optical output power) as logical low state (0). Thus, the functionality of the whole device can be described by an \( 8 \times 8 \) matrix. Neglecting losses, its ideal form is as follows:

\[
\begin{bmatrix}
A_{TE_{out}} & B_{TE_{out}} & C_{TE_{out}} & D_{TE_{out}} \\
A_{TM_{out}} & B_{TM_{out}} & C_{TM_{out}} & D_{TM_{out}}
\end{bmatrix} =
\begin{bmatrix}
A_{TE_{in}} & B_{TE_{in}} & C_{TE_{in}} & D_{TE_{in}} \\
A_{TM_{in}} & B_{TM_{in}} & C_{TM_{in}} & D_{TM_{in}}
\end{bmatrix},
\]

where \( A/B/C/D \) denote the physical ports while in/out represent the input and output ports, and TE/TM are the polarization states of input and output modes.

Here we would like to emphasize that our device is conceptually different from chiral atom couplers [25–27], which can achieve unidirectional propagation of light by steering the handedness of transverse spin angular momentum (SAM) in the evanescent field of nanophotonic waveguides. The fundamental difference between those devices and our device is the underlying mechanism. They mainly take advantage of the transverse SAM in the evanescent field of nanophotonic waveguides to achieve chiral coupling, which is associated with the spin–orbit interaction of light [28]. They can achieve asymmetric propagation by changing the handedness of SAM of the input light while we achieve the asymmetric propagation by breaking the polarization symmetry. Besides, they mainly handle the light field in the vicinity of waveguides, while we mainly control the light inside nanophotonic waveguides.
We believe that these two kinds of mechanisms both have their own advantages and disadvantages, and they can find different applications in different fields. For example, the chiral coupler is much more compact compared with our device, but it suffers from low efficiency of chiral coupling, because only a small proportion of light can be coupled into the waveguides by atoms scattering [21]. On the other hand, our device is relative large in size, but it can handle all the light in nanophotonic waveguides.

Our device can be integrated into complex photonic circuits as well. Two kinds of waveguides are involved at the input and output ports, which are dielectric Si waveguide and hybrid plasmonic waveguide. In order to integrate this device into complex photonics circuits, where there are different kinds of waveguides, it requires some out-coupler structures to efficiently integrate it. For example, a tapper structure can be used as a coupler between the hybrid plasmonic waveguide and another kind Si waveguide [29]. Fortunately, this tapper coupler is also very compact, only several micrometers in size. Therefore, the use of an out-coupler structure will not significantly increase the compact dimensions of the device.

8. Conclusion

In summary, we proposed and numerically demonstrated a novel hybrid plasmonic structures which perform optical diode behavior. Unlike previous on-chip diodes based on asymmetric mode conversion, where multimode waveguides are involved, our diode is achieved in single mode waveguides via breaking the polarization symmetry. Moreover, our device has multiple functions as well, and it can be used as a new type of polarization splitter-rotator, who can separate different polarization states (TE- or TM-like polarization) of the input port while guaranteeing single polarization state (TE-like polarization) at the output ports. Besides, the proposed device is ultra-compact with a small footprint of $2.95 \times 14.18 \mu m^2$. The operation bandwidth of the device is as large as 70nm around $\lambda = 1550\text{nm}$. Our work highlights the potential of hybrid plasmonic waveguide for the controlling of optical modes' polarization and propagation, and it may open up new avenues for efficient on-chip optical logical circuitry and optical information processing.

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Figure 6. (a) Schematic illustration of the function of polarization splitter rotator. An input quasi-TE mode can travel from port C to port A without changing its original polarization state, while a quasi-TM mode launched in port C ends up going to port A with its original polarization state changing to TE-like polarization. (b) A quasi-TE mode or quasi-TM mode excited in port C will respectively take different paths in the proposed device. The inserted figures are the mode distribution detected from the monitor planes. The positions of monitor planes are shown in figure 4(a).
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