

Theoretical analysis of plasmonic unidirectional propagation at visible frequency based on subwavelength waveguide



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ABSTRACT

A quasi-plasmonic circulator is proposed based on metal–insulator–metal waveguides. Four bus waveguides connected to the corners of a square cavity with dual-narrow-slit waveguides are performed as the input/output ports. According to the enhanced emission and the interference effects, unidirectional propagation for surface plasmon polaritons is achieved. The spectrum and propagation characteristics are numerically investigated by using the finite-difference time-domain method. The transmittance for the matched output port is higher than 71% at the wavelength of 481.2 nm, while the ones for other output ports are all lower than 6%. Therefore, high-transmission and high-isolation are achieved. In addition, the linear relationship between the wavelength and the waveguide length or the refractive index of insulator has also been confirmed.

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1. Introduction

Surface plasmon polaritons (SPPs) have been considered as one of the most confident ways to overcome the diffraction limits of optical waves [1], and thus have attracted lots of attention in various areas, such as wavelength waveguides [2], combiners or couplers [3,4], semiconductor device [5–7], and so on. Usually, subwavelength slits or gratings in a metal film are employed to reduce the momentum mismatch between the SPP modes and the p-polarized light, so that SPPs will propagate along both directions on the metal/insulator interfaces for all those symmetrical structures, such as rectangle grooves, slot cavities, and so on [8–13]. This character may limit the development of the plasmonic devices which need the directional propagation of SPPs. To solve these problems, various nano-devices with asymmetrical structures have been proposed to realize the unidirectional SPPs propagation for the last few years [14–18]. Conventionally, by adding periodical gratings to only one side of the metal film, SPPs can be unidirectionally launched to the other side due to the Bragg reflection of the periodical structures [19,20]. In addition, two subwavelength slits or cavities are also employed to obtain the unidirectional SPPs generations according to the SPPs interference effect [21–23]. The most concerns on these devices are the launching efficiency at the desired direction and the isolation at the opposite direction. However, these structures are usually operated in a free metal/insulator space and thus may not be suitable for the metal–insulator–metal (MIM) waveguide

devices for the reason that MIM waveguides with different widths support different SPPs modes [24]. It is interesting to study the performances of MIM waveguides and develop their functionalized devices because they can be easily integrated in the nano-photonic circuit. Recently, directional SPPs excitation and propagation by using MIM waveguides have received considerable interest. However, most of these researches mainly focus on the bidirectional SPP splitting in the MIM waveguides which usually consist of one input waveguide and two output waveguides [25–27]. The input and output waveguides can not be exchanged mutually for these schemes, and thus, their functions are limited. Many aspects for controlling the directional SPPs propagation remain to be developed.

Compared to the previous work, a four-port MIM waveguide is proposed in this paper to act as a quasi-optical circulator based on the SPPs unidirectional propagation at the visible frequency. Each port can be regarded as an input waveguide and the matched output must be the one at its counter-clockwise direction. Once the input waveguide is fixed, high transmission for the matched output port and high isolation for other ports are achieved. Another key contribution of the proposed device is its capability of providing on-chip light transmission at nanometer scale. The SPPs spectral responses and propagations are characterized by using the finite-difference time-domain (FDTD) method.

2. Theory and analysis

The structure is shown in Fig. 1. Four bus waveguides, which are connected to a square cavity with dual-narrow slits, perform as

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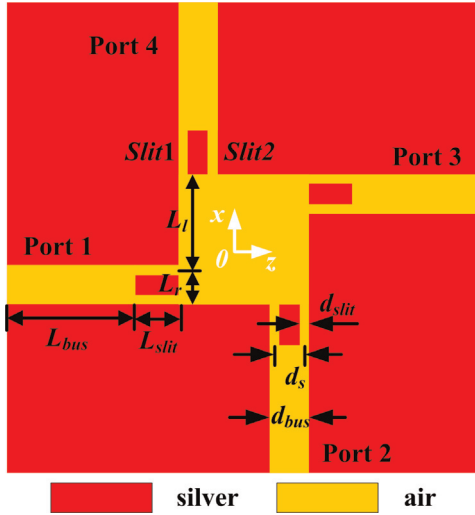


Fig. 1. Proposed scheme of the four-port SPPs quasi-circulator.

the input/output ports. It is noted that such a structure can be realized by using the nanoimprint lithography (NIL) technology with a resolution of sub-4 nm [28] or less [29]. For this structure, all the slits at the corners of the cavity are named as Slit1, and others are Slit2.

Assuming the metal and insulator to be silver and air respectively, the effective index n_{eff} can be obtained by the dispersion equation of the TM mode in the waveguide given by [24]: $\epsilon_i k_m + \epsilon_m k_i \tanh(-jk_i d/2) = 0$, where $k_{i,m} = \sqrt{\epsilon_{i,m} k_0^2 - \beta^2}$ is the transverse propagation constant in the air and the silver, respectively, d is the width of the waveguide, and ϵ_i and ϵ_m are the dielectric constants of air and silver, respectively. The propagation constant is represented as the effective index $n_{eff} = \beta/k_0$ of the waveguide. The real part $\text{Re}(n_{eff})$ and the imaginary part $\text{Im}(n_{eff})$ determine the optical phase retardation and the propagation loss coefficient of the plasmonic mode, respectively. Since the proposed structure is on a nanometer scale, $\text{Im}(n_{eff})$ can be ignored and more attention is paid to $\text{Re}(n_{eff})$ for obtaining the relative phase.

As the narrow slit can be regarded as a Fabry–Pérot (FP) cavity, thus the resonance wavelengths should satisfy the phase condition:

$$\lambda_m = 2n_i L_{slit} / (m - \varphi_l/\pi - \varphi_r/\pi), \quad m = 1, 2, 3, \dots \quad (1)$$

where $\varphi_i = k_0 n_{bus} L_{bus}$ is phase delay caused by the SPPs reflection from the bus waveguide, n_{bus} and n_i are the real parts of the effective indices for the bus waveguides and slits, L_{bus} and L_{slit} are the lengths of the bus waveguides and the slits, respectively, and φ_r denotes the SPPs reflection phase shift at the FP faces. Another key point worth noting in Fig. 1 is the dual-slit connection. When SPPs arrive at the end of the bus waveguide, parts of them will transmit into one slit and others will propagate toward the partner slit entrance aperture into a transmission mode. Therefore, the electric field intensity at the exit aperture of the slit is enhanced by its next slit, and this phenomenon can be expressed as [30]

$$E_{out} = \eta E_{in} (1 + \alpha \exp(jn_{bus} d_s/\lambda)) \quad (2)$$

where E_{in} and E_{out} are the electric fields at the entrance and exit of the slit, respectively, η is the SPPs transmission coefficient, and α represents the contribution of the electromagnetic field from the partner slit. Moreover, the size design of the square cavity will be the last step to obtain high isolations for those unmatched ports. After transmitting through Slit1, SPPs will usually propagate along

both directions of the cavity interface, unless the phase difference caused by the SPPs reflection from the left-side or right-side wall of the cavity satisfies.

$$\theta = 2k_s(L_l - L_r) = N\pi + \pi/2, \quad N = 1, 2, 3 \dots \quad (3)$$

where L_l and L_r are the distances from Slit1 to the left-side and right-side wall of the cavity, respectively, and k_s is the propagation constant for the square cavity. Then SPPs will only propagate along the cavity interface at the right side of the incident direction because of the interference effect.

3. Simulation and discussion

To further study the transmission spectra, FDTD simulation method is used to characterize the SPPs propagation under perfect-matching-layer (PML) absorbing boundary conditions. The mesh accuracy is set to be 5 nm and the incident light is defined as a plane wave. Moreover, the tabulation of the optical constants of silver [31] is used. In the following simulation and analyses, only the first resonance order mode in the slits is considered (i.e. $m = 1$ in Eq. (1)) and Port1 is set to be the input waveguide firstly. The parameters are defined as $L_{bus} = 470$ nm, $L_{slit} = 100$ nm, $L_r = 185$ nm, $L_l = 615$ nm, $d_{bus} = 200$ nm, and $d_{slit} = 30$ nm. In view of the running time during the simulations, we just perform the 2D model, which can provide the results with comparable accuracy. In this case, the light source with a width of 200 nm (same as the width of the waveguide) is placed in the entrance of the input waveguide. This method is equivalent to the use of nano-silica wires (the size is down to 50 nm [32]), which can be employed to launch light into subwavelength waveguide in 3D system. Therefore, all the light can be transmitted into the waveguide and will not detour the device. When SPPs arrive at the end of Port1, most of them can be transmitted through the dual-slit structure due to their enhanced emission effect. After transmitting through Slit1, SPPs will usually propagate along both directions of the cavity interface. However, destructive interference will occur at the exit of Slit1, because the phase difference caused by the SPPs reflection from the left-side or right-side wall of the cavity satisfies the condition of Eq. (3). SPPs are prohibited to propagate towards the slits that are connected to Port4, which is therefore with a low transmittance. Then SPPs will only propagate along the cavity interface parallel to incident direction. Likewise, due to the enhanced emission of the slits, most of the SPPs will be transmitted to Port2 and few of them will continue to propagate to Port3, which leads to a high transmittance for Port2 and a low transmittance for Port3. The transmission spectra based on FDTD method are shown in Fig. 2(a). The transmittances are respectively 0.71, 0.03, and 0.06 for Port2, Port3, and Port4 at the center wavelength of 481.2 nm, which indicates that the matched output port is Port2. Besides, we can obtain $\theta \approx 7\pi/2$ at the center wavelength according to Eq. (3).

Considering the symmetry characteristics of the structure, when SPPs are launched into Port2 at the same wavelength, they can be only transmitted through Port3 but can not be transmitted through Port1. Therefore, unidirectional SPPs propagation is achieved. To further investigate the performances of the structure, the cases of the bus waveguides connected to the cavity with only one slit (Slit1 or Slit2, see the inset figures in Fig. 2(b) and (c)) are also considered. The spectra show that the transmittances for all the output ports at the wavelength of 481.2 nm are lower than 0.12 in Fig. 2(b) and lower than 0.01 in Fig. 2(c). These results indicate that the unidirectional propagation performance can only be obtained by using the dual-slit structure according to its enhanced emission and interference effects. Besides, the operation wavelength of the proposed structure is in the range of

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