An ultra-broadband nano-plasmonic reflector with an asymmetric nano-ring resonator

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ABSTRACT

We propose a broadband nano-plasmonic reflector by using an asymmetric nano-ring resonator directly connected to the input and output waveguides based on metal-insulator-metal waveguides. Due to direct connection, both clockwise and counterclockwise traveling modes propagate inside the ring resonator, giving rise to resonator resonances and Mach Zehnder interference. Ultra-broad bandwidth is realized by adjusting the lengths of the ring to manipulate the resonant wavelengths and varying its widths to minimize the low-transmission ripples. An example of the plasmonic reflector with the dimensions of 200×522 nm×nm and the bandwidth of 1000 nm is numerically accomplished

Keywords: Plasmonic waveguide, optical resonator, broadband reflector, integrated photonics

1. INTRODUCTION

Plasmonics provides a promising on-chip platform for the ultra-density photonic integrated circuits (PICs) because surface plasmon-polariton (SPP) modes are highly confined in the plasmonic waveguides at sub-wavelength scale. Among various plasmonic waveguides, metal-insulator-metal (MIM) waveguides have a potential for future ultra-density PICs due to strong field confinement of SPP modes, relatively low bending and propagation losses and easy fabrication. Plasmonic ring resonators based on MIM waveguides are essential components in the ultra-density PICs due to its compactness, wide free-spectral range and potential in monolithic integration. Various devices with this scheme have been proposed and investigated, including Mach Zehnder interferences, power splitters, bandpass filters, notch filters and sensors. In this paper, we use an asymmetric plasmonic ring resonator to design a broadband reflector. This device consists of a plasmonic nano-ring resonator directly connected to the input and output waveguides based on MIM waveguides. We use an equivalent circuit model to analyze the performance of this structure, and then observe that either Mach Zehnder interference (MZI) or the ring resonance (RR) results in high reflectance of the device. Subsequently, we manipulate the resonant wavelengths of RR and of MZI for completely destructive interference in the output waveguide to achieve an ultra-broadband plasmonic reflector. Design example to obtain a broadband reflector with given specifications is numerically demonstrated, and simulation results show that this device has the dimensions of 200×522 nm×nm, the maximum reflectance of -0.8 dB and a bandwidth of 1000 nm.

2. BROADBAND REFLECTOR

The structure of the proposed ultra-broadband nano-plasmonic reflector based on MIM waveguides is shown in Fig. 1. An asymmetric rectangular ring resonator with a width W and a height H is directly connected to the input and output waveguides. The waveguide width of the input and output waveguides are w₀. Due to direct connection between the input/output waveguides and the rectangular ring resonator, the rectangular ring resonator is divided into two branches C₁ and C₂. Let the waveguide width and the length of the branch Cᵢ be wᵢ and Lᵢ, respectively, for i=1 and i=2. Then, L₁+L₂=2(W+H).
Because the propagation behavior of MIM waveguides in optical region is similar to that of a parallel-plate transmission line in microwave domain\(^8\), we use the equivalent circuit model of the transmission line to analyze this proposed structure. The characteristic impedances of the input and output waveguides are calculated by 
\[
Z_0 = \frac{\beta_0 w_0}{\omega \varepsilon_0 \varepsilon_d}
\]
where \(\beta_0\) is the propagation constant, \(\omega\) is the incident frequency, \(\varepsilon_0\) is permittivity of free space and \(\varepsilon_d\) is relative permittivity of the insulator. Each waveguide segment of the branch \(C_i\) is represented by a symmetric T-type equivalent circuit\(^9\) with the impedances of 
\[
Z_{ia} = jZ_i \tan(\beta_i L_i/2) \quad \text{and} \quad Z_{ib} = -jZ_i / \sin(\beta_i L_i)
\]
where \(\beta_i\) and \(Z_i = \frac{(\beta_i w_i)}{\omega \varepsilon_0 \varepsilon_d}\) are the propagation constant and of the characteristic impedance of the branch \(C_i\), for \(i=1\) and \(2\). Then, the equivalent input impedance of this structure is illustrated in Fig. 2.

This equivalent input impedance is then calculated by
\[
Z_{in} = Z_a + \frac{(Z_a + Z_b)(Z_b)}{Z_0 + Z_a + Z_b}
\]
where \(Z_a = Z_{1a} + Z_{2a}\) and \(Z_b = Z_{1b} + Z_{2b}\).

The reflectance of the proposed structure is expressed by
\[
R = \left| \frac{Z_{in} - Z_0}{Z_{in} + Z_0} \right|^2
= \left| \frac{Z_0^2 - 2Z_a Z_b - Z_a^2}{Z_0^2 + 2Z_a Z_0 + 2Z_a Z_b + 2Z_a Z_b + Z_a^2} \right|^2
\]

As shown in Fig. 2, we find that the maximum reflectance may be obtained as the load voltage at \(Z_0\) (i.e., the output port) is zero in order to obtain zero transmission. Then, zero transmission is obtained as (i) \(\beta_1 L_1 = p\pi\) and \(\beta_2 L_2 = (p+q)\pi\), where \(p\) is an integer and \(q\) is an odd number, or as (ii) \(Z_0^2 = 0\), that is \(Z_0 \sin(\beta_2 L_2) + Z_2 \sin(\beta_1 L_1) = 0\). In our proposed structure, the wave inside the resonator can propagate either clockwise or anticlockwise owing to the impedance mismatch of the T-branch at each intersection. As the wave in the branches \(C_1\) and \(C_2\) propagates oppositely, MZI occurs. Contrarily, the RR occurs as the wave circulates in the branches \(C_1\) and \(C_2\) either clockwise or anti-clockwise. Then, the first condition
shows that the phase difference between the branches \( C_1 \) and \( C_2 \) is an odd multiple of \( \pi \), as a consequence of destructive interference of MZI in the output waveguide. On the other hand, the second condition shows the interference of the clockwise and anti-clockwise circulating waves inside the resonator is completely destructive in the output waveguide, where \( Z_1 \) and \( Z_2 \) are relevant to the transmission coefficients of the two branches in an opened T-branch splitter. This expression corresponds to the condition of the zero-transmission RR. Due to lossy SPP modes, these two conditions are too difficult to be satisfied, and thereby the transmission is impossible to reach zero. However, the high reflectance still can be obtained as real parts of the conditions are taken into account for a comparatively low loss structure, i.e., (i) \( \text{Re}\{\beta_1 L_1\} = p\pi \) and \( \text{Re}\{\beta_2 L_2\} = (p+q)\pi \), and (ii) \( \text{Re}\{Z_1 \sin(\beta_2 L_2) + Z_2 \sin(\beta_1 L_1)\} = 0 \). Then, in order to obtain a broadband reflector, we manipulate the resonant wavelengths of these two conditions. For a reflector with a squared reflection spectrum, the upper and lower edge wavelengths are \( \lambda_{1\text{R}} \) and \( \lambda_{2\text{R}} \), respectively. Because the difference between the adjacent resonant wavelengths of the RR is smaller than that of the MZI, the first- and second-order resonant wavelengths of the RR, \( \lambda_{1\text{RR}} \) and \( \lambda_{2\text{RR}} \), are assigned as \( \lambda_{1\text{L}} \) and \( \lambda_{2\text{L}} \), respectively. The wavelength for the destructive interference of the MZI \( \lambda_{\text{MZI}} \) is the center wavelength of the reflector because the reflection is rather higher at \( \lambda_{1\text{RR}} \) and \( \lambda_{2\text{RR}} \) as a result of higher circulating propagation loss for the RR. The relative locations of these resonant wavelengths are delineated in Fig. 3.

Then, to realize a broadband reflector, the design parameters of this structure can be obtained by satisfying the following conditions:

\[
\text{Re}\{\beta_1 (\lambda_{\text{MZI}}) L_1\} = \pi \tag{3}
\]

\[
\text{Re}\{\beta_2 (\lambda_{\text{MZI}}) L_2\} = 2\pi \tag{4}
\]

\[
\text{Re}\{\beta_1 (\lambda_{\text{RR},1}) w_1 \sin(\beta_2 (\lambda_{\text{RR},1}) L_2) + \beta_2 (\lambda_{\text{RR},1}) w_2 \sin(\beta_1 (\lambda_{\text{RR},1}) L_1)\} = 0 \tag{5}
\]

\[
\text{Re}\{\beta_1 (\lambda_{\text{RR},2}) w_1 \sin(\beta_2 (\lambda_{\text{RR},2}) L_2) + \beta_2 (\lambda_{\text{RR},2}) w_2 \sin(\beta_1 (\lambda_{\text{RR},2}) L_1)\} = 0 \tag{6}
\]

Figure 3. The relative location of the RR and MZI resonant wavelengths for a broadband reflector

3. SIMULATED RESULTS

Here, we use the Ag-air-Ag waveguides to demonstrate our design concepts. The permittivity of the silver \( \varepsilon_m \) is described by the Drude-Lorentz model\(^1\). Suppose that the targeted reflector has edge wavelengths of 1450 nm and 1650 nm. Then, \( \lambda_{\text{RR},1} = 1650 \text{nm} \), \( \lambda_{\text{RR},2} = 1450 \text{nm} \) and \( \lambda_{\text{MZI}} = 1550 \text{nm} \). Because (3)-(6) show the conditions of the high reflections are independent of \( w_0 \), we arbitrarily choose \( w_0 \) as 50 nm. In addition, (3)-(6) are related as the propagation constant of the fundamental SPP mode for a fixed waveguide width is an approximately linear function of the wavelength \( \lambda \). Then, we can arbitrarily choose \( w_1 \) and find the corresponding \( L_1 \) by (3). For example, let \( w_1 \) be 16 nm and then \( L_1 = 383 \text{nm} \). Subsequently, we obtain \( w_2 \) and \( L_2 \) by numerically or graphically solving (5) and (6). The graphical solution sets of \( \{w_2, L_2\} \) for (5) and (6) are shown in Fig. 4. These two curves intersect at \( \{w_2 = 43 \text{ nm}, L_2 = 1060 \text{ nm}\} \), and then \( w_2 \) and \( L_2 \) are set as 43 nm and 1060 nm, respectively. As we examine (4) with \( w_2 = 43 \text{ nm} \) and \( L_2 = 1060 \text{ nm} \), the assumption of linear dispersion of the fundamental SPP mode over the concerned wavelength range is valid.
To avoid the coupling between two adjacent waveguides, the resonator width $W$ is chosen as 200 nm, and then the corresponding height $H$ is 522 nm, i.e., the dimensions of the rectangular waveguide is $200 \times 522 \text{ nm} \times \text{nm}$. The reflectance spectra of this reflector both calculated by (2) and simulated by two-dimensional (2D) finite-difference time domain (FDTD) method are shown in Fig. 5. A maximum reflectance of roughly -0.8 dB is obtained at the wavelength of $\lambda_{MZI}=1550 \text{ nm}$, and the reflectance is larger than -0.9 dB over the wavelength range of $\lambda_{RR,1}=1650 \text{ nm}$ and $\lambda_{RR,2}=1450 \text{ nm}$. These indicate that the high-reflectance region is expectedly obtained. The 3-dB bandwidth is approximately 1000 nm. In addition, the calculated data and simulated FDTD results are closely consistent with a small deviation outside of the high-reflectance band.

Next, we discuss the influence of $w_1$ on the reflectance spectrum of a broadband reflector with the same design specifications. The aforementioned procedure is applied to obtain the design parameters with different $w_1$. Figure 6 shows the reflectance spectra for various designs with different $w_1$. To obtain a reflector with the same specifications, we find that the width of branch $C_2$, $w_2$, increases with the increase of $w_1$. However, the dimension of the device becomes larger as $w_1$ increases. As shown in Fig. 6, the maximum reflectance decreases with the decrease of $w_1$ because of rather large propagation loss for a narrow MIM waveguide. Furthermore, the high-reflectance region becomes flat and the 3dB-bandwidth is broader as $w_1$ decreases.
4. CONCLUSION

We numerically present an asymmetric nano-ring resonator to realize an ultra-broadband plasmonic reflector. An analytical formulation to describe the performance of this structure is obtained by using the equivalent circuit model based on the transmission line theory. Subsequently, a systematic design procedure is developed to obtain the design parameters of the broadband reflector with given specifications. An example of the plasmonic reflector with the dimension of 200 × 522 nm × nm and the bandwidth of 1000 nm is numerically accomplished. The calculated results are validated with the simulated ones obtained by the 2D FDTD method. The performance of the device can be improved by increasing $w_1$ with a rather large device's size.

REFERENCES