Tunable plasmonic filter and variable optical attenuator based on ring metal–insulator–metal waveguide

Jianping Guo[1,2], *Jiahu Zhu*[1], *Wen Zhou*[1]

[1]*Laboratory of Photonic Information Technology, South China Normal University, Guangzhou 510006, People's Republic of China*
[2]*School of Physics and Telecommunication Engineering, South China Normal University, Guangzhou 510006, People's Republic of China*
E-mail: guojpgz@163.com

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Abstract: A tunable nanoscale plasmonic filter and variable optical attenuator structure based on a rectangular ring metal–insulator–metal waveguide cavity containing electro-optic (EO) material is proposed and numerically demonstrated by using the finite-difference time-domain technique. The simulation results show that the output of the device can be electrically controlled by tuning the refractive index of the EO material and the structure can be used as tunable filter and variable optical attenuator alternatively under very low voltage.

1 Introduction

Plasmonic devices, based on surface plasmon polaritons (SPPs) propagating at metal-dielectric interfaces, have shown the potential to guide and manipulate light at deep subwavelength scales [1]. A number of plasmonic waveguide structures have been proposed during the past decade. Among those structures, waveguides consisted of an insulator sandwiched between two metals, serving as metal–insulator–metal (MIM) waveguides, can support propagating surface plasmon modes that are strongly confined in the insulator region with an acceptable propagation length. Their fundamental transverse magnetic (TM)-polarised symmetric mode exhibits adequately low propagation losses, permitting also efficient end-fire coupling with fibres. Therefore MIM waveguides are promising for the design of nanoscale devices with a relatively easy fabrication according to the current state of the art. Several MIM waveguide-based structures have been demonstrated numerically or experimentally [2]. However, most of them are passive components. One of the main challenges in plasmonics is to achieve active control of optical signals in nanoscale. Up to now, several approaches have been proposed such as thermally-induced changes in the refractive index [3], direct ultrafast optical excitation of the metal [4], as well as the incorporation of nonlinear media in plasmonic devices [5]. On the other hand, the effective refractive index of an MIM plasmonic waveguide is highly sensitive to the thickness, width and the refractive index of the dielectric core [2], hence, the SPPs waveguides in combination with highly non-linear organic electro-optic (EO) materials are expected to strongly enhance the performance of active EO plasmonic devices [6].

In this Letter, a nanoscale tunable plasmonic filter and variable optical attenuator is proposed and numerically demonstrated by using the finite-difference time-domain (FDTD) technique with a perfectly matched layer boundary condition. The device is based on a rectangular ring metal–insulator–metal waveguide cavity containing EO material. We show theoretically that the structure can be used as filter and variable optical attenuator (VOA) alternatively depending on the input signal under very low voltage.

2 Design and simulation

The proposed filter structure is shown in Fig. 1. It consists of a sub-wavelength MIM waveguide coupled with a rectangular ring metal–insulator–metal waveguide cavity, which is filled with highly non-linear organic EO materials. The waveguide is divided into two segments by the cavity, acting as input port and output port. Metal here is assumed to be silver, whose frequency-dependent complex relative permittivity is characterised by the Lorentz model [7], and the EO material is chosen to be 4-dimethyl-amino-Nmethyl-4-stilbazolium tosylate which possesses a relatively large EO coefficient ($dn/dE = 3.41$ nm/V) compared with most inorganic EO materials such as $LiNbO_3$ ($dn/dE = 0.16$ nm/V). The relation between the refractive index EO and external voltage U could be denoted as: $n_{EO}(U) = n_{EO}(0) + \kappa U$, where $\kappa = dn/dE(U/d)$, for $U = 0$, $n_{EO}(0) = 2.2$.

Since the width of the waveguide is much smaller than the operating wavelength, only the fundamental TM mode could be excited in the waveguide. When the SPPs are excited in the input port, part of the waves will be reflected at the front surface of metal gap, whereas the other part of the waves could be coupled into the cavity because of the small width of the gap. The forward and backward waves in the cavity will be reflected in the interfaces until a standing wave is formed and then would be coupled into output port. The resonance condition for the rectangular ring cavity is given by Hosseini and Massoud [8]

$$\lambda_m = \frac{\lambda_0}{n_{eff}} = \frac{(L_1 + L_2)}{m}, \quad (m = 1, 2, 3 \ldots) \tag{1}$$

where λ_0 is the free space wavelength, n_{eff} is the real part of effective index in the ring cavity, whose value can be obtained by solving the dispersion relation of the fundamental TM mode in an MIM

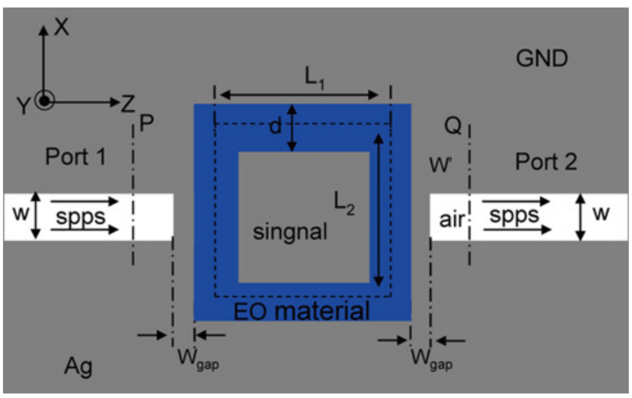

Fig. 1 *Basic two-dimensional schematic map of the plasmonic structure*

waveguide

$$\tanh\left(-\frac{ik_{z1}}{2}w'\right) = -\frac{\varepsilon_m k_{z2}}{\varepsilon_{EO} k_{z1}} \quad (2)$$

With k_{z1} and k_{z2} defined by momentum conservations [7]

$$\begin{cases} k_{z1}^2 = \varepsilon_{EO}k_0^2 - \beta^2 \\ k_{z2}^2 = \varepsilon_m k_0^2 - \beta^2 \end{cases} \quad (3)$$

where $\beta = \beta_R + i\beta_I$ is the complex propagation constant, ε_{EO} and ε_m are the dielectric constants of the EO material and metal, respectively. $k_0 = 2\pi/\lambda_0$ is the wave number of light in vacuum, w' is the width of the ring cavity. The real part of the effective index in the ring cavity n_{eff} is given by $n_{eff} = \beta_R/k_0$. The relationship between n_{eff} and external voltage U is calculated and shown in Fig. 2. It can be seen that the n_{eff} is linear to the U at all wavelengths. Based on (1), we can predict that the output of the device can be electrically controlled by tuning the refractive index of the EO material.

In the FDTD simulation, both the width of waveguide w and the width of the cavity d are fixed to be 50 nm. The total length of the MIM waveguide in the ring cavity (cavity length) is the average length of the inner and outer perimeter, $L = 2(L_1 + L_2) = 800$ nm ($L_1 = L_2 = 200$ nm), as illustrated by the dashed line in Fig. 1.

For a wideband light input, the transmission spectra of the proposed structure with different external voltage is shown in Fig. 3. It can be seen that there are three resonant peaks in the range 800–2100 nm. If the external voltage U is increased, the whole transmission spectrum experiences a redshift. When U is tuned from 0 to 1 V, the resonant wavelength of the first mode would shift from 1516 to 1563 nm, whereas the full width at half maximum (FWHM) almost remains unchanged ($\sim$52 nm). The inset figure show that the resonant wavelength of the first mode increases linearly with the applied voltage. The resonant wavelength of the second and third mode has a similar relationship as the first mode. That is to say, the output wavelength can be tuned by changing the voltage applied on the EO material.

Fig. 4 illustrates the output intensity of the proposed structure with different external voltage for a monochromatic input wavelength of 1060 nm. One can see that change in the refractive index of the EO material can greatly affect the output of the structure. The output at port 2 is over 74% when there is no external voltage, whereas the output will be below 4% when the external voltage is tuned to 3 V. In this situation, the structure will achieve a tuning range of 12.77 dB which functions as a VOA.

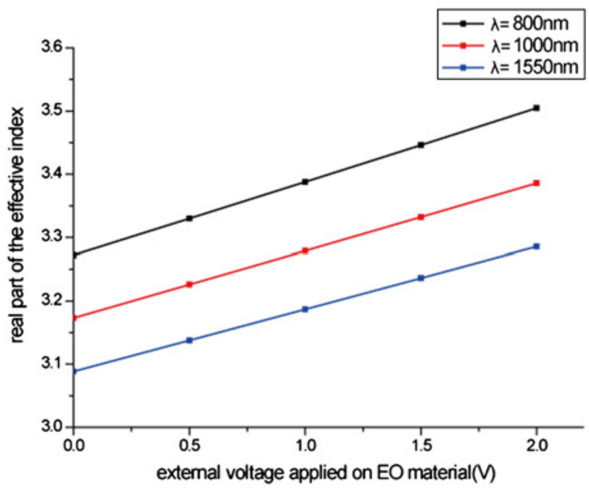

Fig. 2 *Real part of the effective index n_{eff} against the external voltage applied on the EO material*

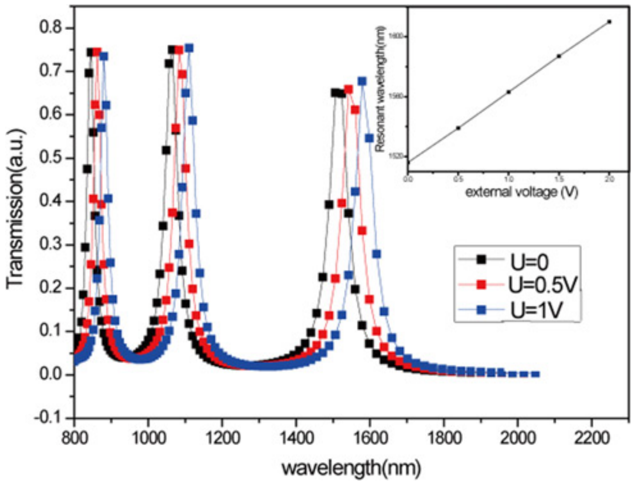

Fig. 3 *Transmission spectra of the proposed structure with different external voltage*
Inset: relationship between the resonant wavelength and applied voltage

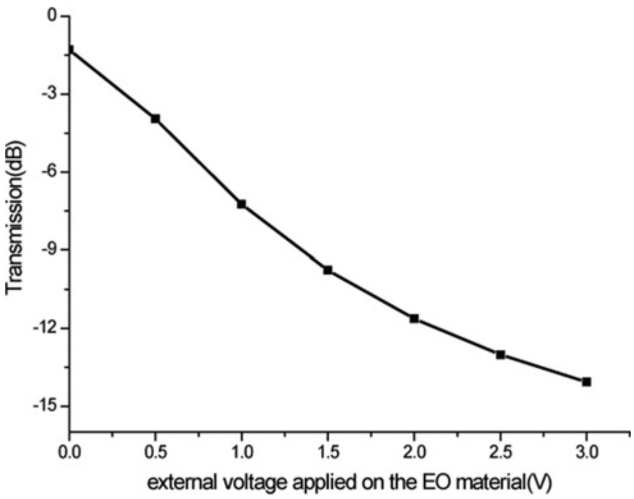

Fig. 4 *Output intensity of the proposed structure with different external voltage for a input wavelength of 1060 nm*

Thus, the structure can be used as a filter or VOA according to the input signal. The electrical field intensity in the EO material at extra voltage $U = 2.5$ V is calculated to be about 60 V/µm, which is acceptable experimentally. The performance of the device could be further improved by structure optimisation, which would be discussed elsewhere.

3 Conclusion

We theoretically demonstrate an ultra-compact tunable plasmonic ring MIM waveguide structure, which can be used as filter and variable optical attenuator alternatively. The device is of sub-wavelength size and low-drive voltage. The proposed structure can find flexible applications in optical data processing, wavelength switching, or modulation in nanoscale photonic integration circuits.

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