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A nonlinear plasmonic waveguide based all-optical bidirectional switching

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ABSTRACT

In this paper, an all-optical switching with a nanometer coupled ring resonator is demonstrated based on the nonlinear material. By adjusting the light intensity, we implement the resonance wavelength from 880 nm to 940 nm in the nonlinear material structure monocyclic. In the bidirectional switch structure, the center wavelength (i.e. 880 nm) is fixed. By changing the light intensity from $I = 0$ to $I = 53.1\ \mathrm{MW/cm^2}$, the function of optical switching can be obtained. The results demonstrate that both the single-ring cavity and the T-shaped double-ring structure can realize the optical switching effect. This work takes advantage of the simple structure. The single-ring cavity plasmonic switches have many advantages, such as nanoscale size, low pumping light intensity, ultrafast response time (femtosecond level), etc. It is expected that the proposed all-optical integrated devices can be potentially applied in optical communication, signal processing, and signal sensing, etc.

1. Introduction

Metal surface plasmon polaritons (SPPs) are considered to be one of the most promising research directions in the field of integrated optics because of its ability to overcome the limitation of optical diffraction [1–4]. Due to the interaction of light with metal free electron, light propagation at the interface of metal and dielectric rapidly decays in the perpendicular to the direction of the interface. Light is tightly bound on the metal–dielectric interface, it provides a new method that the people control light in the sub-wavelength even a smaller scale.

Recently, many devices based on SPPs [5–7], such as Bragg grating [8], Mach–Zehnder interferometers, ring resonators [9], Y-shaped combiners, couplers [10], and splitters, have been demonstrated by numerical simulations and/or experiments. The metal–dielectric–metal (MDM) structures have been confirmed by the numerical and/or experimental results. There are also many other MDM structures, such as Bragg grating reflectors, tooth-shaped plasmonic waveguide filters nanodisk resonators, and wavelength-selective waveguide. Recently, all-optical switchings [11,12] have been proposed, whose structures are usually in nano-scale. Due to the large and complex structure, low utilization, and difficulty to integrate these structures into the light path, the traditional structure cannot satisfy the real applications.

In this paper, a surface plasmonic optical switching based on the nano ring structure has been proposed. First, we study the transmission characteristics of the single nano-ring cavity based on silver and air structure. By analyzing the influence of the ring radius and the refractive index of the medium in the center wavelength, it is found that it is a linear relationship between the refractive index of the medium and the center wavelength. Then we fill the ring cavity structure with the optical nonlinear material and adjust the external beam to realize optical switching. In the end, a T-shaped structure of nano-ring cavity bidirectional switching is proposed. Due to the advantage of small size, requirement of low pumping light intensity and ultrafast response time, the device has great application potentials in all-optical photonic integrated circuits [13]. In the short wavelength range, i.e. from 800 to 950 nm, the proposed structure can realize optical switching well. It is easy to control the optical switching precisely with low light intensity variation (such as from 40 to 60 $\mathrm{MW/cm^2}$).

2. The transmission response of the single nano-ring cavity structure

We firstly study the transmission characteristics of a nano-ring cavity structure that shown in Fig. 1(a). It is composed of a sub-wavelength metal–dielectric–metal waveguide with unidirectional coupling into a ring cavity. The parameters of the structure are chosen as: waveguide width $w = 50$ nm, waveguide and ring gap $G = 20$ nm, and ring outside diameter $R = 210$ nm. The metal is assumed to be silver. Its dielectric

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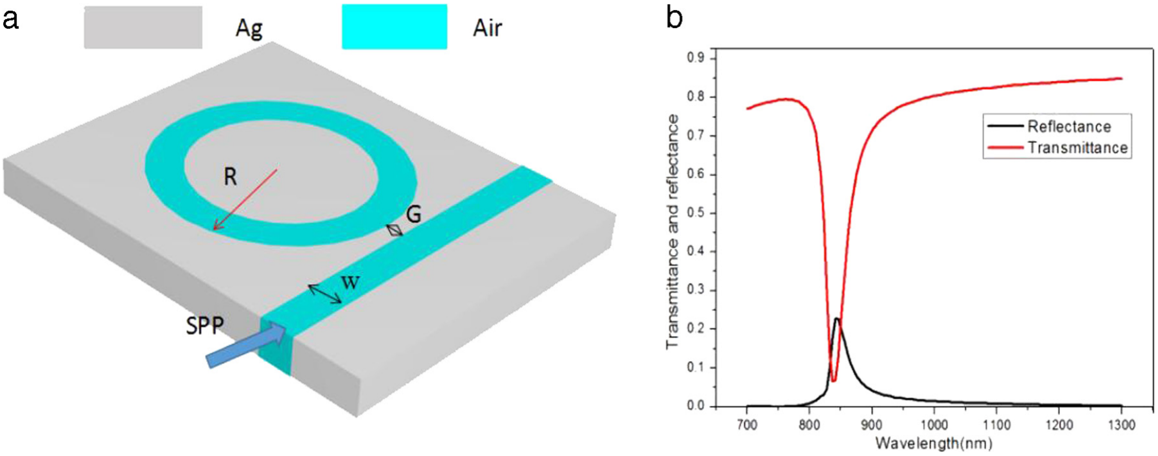

Fig. 1. (a) Single ring cavity nano-structure coupled waveguide structure; (b) Transmittance and reflection spectra.

constant is taken from the experimental data including both the real and the imaginary parts. The dielectric waveguide and the nano-ring cavity are assumed to a refractive index ($n = 1$) in the air.

The single nano-ring cavity in the structure behaves as a resonant cavity and supports a resonant mode at a frequency of w_0 (corresponding to a resonant wavelength λ_0). By using the temporal coupled theory [14], the transmission and reflection coefficients of the structure are described, respectively, as follows:

$$T(\omega) = \frac{(\omega - \omega_0)^2 + (1 + \tau_i)^2}{(\omega - \omega_0)^2 + \left(1 + \tau_i + 1/\tau_e\right)^2},$$
$$R(\omega) = \frac{\left(1/\tau_e\right)^2}{\left(\omega - \omega_0\right)^2 + \left(1/\tau_i + 1/\tau_e\right)^2}, \tag{1}$$

where ω is frequency of the incident wave, and ω_0 the frequency at resonance, $1/\tau_i$ is the decay rate of the field due to the internal loss in the nano-ring cavity. $1/\tau_e$ is the decay rate due to the power escape through the waveguide. The resonant wavelength of the ring resonator [15] is determined by:

$$Ln_{eff} = m\lambda/4, \tag{2}$$

where m, the mode number, is an integer, and n_{eff} and λ are the ring effective refractive index and the free space wavelength, respectively.

The two-dimensional finite-difference time-domain (2D-FDTD) numerical method [16] with a convolutional perfectly matched layer (CPML) as the absorbing boundary condition has been used for the numerical study. Since the width of the waveguide is much smaller than the operating wavelength, only the fundamental TM mode is supported. The incident light for excitation of the SPP mode is a TM-polarized (the magnetic field is parallel to y axis) fundamental mode. In the following FDTD simulations, the grid size in the x and the z directions are chosen to be $\Delta x = \Delta z = 5$ nm and $\Delta t = \Delta x/c$, which are sufficient for the numerical convergence. The width w of the bus waveguide is set to be 50 nm and the ring outside diameter $R = 210$ nm. As shown in Fig. 1(b), one can see that there is a sharp transmission notch with minimum transmittance 6% at the resonant wavelength of 847 nm. The full width at half maximum (FWHM) of the notch is 40 nm. The intensity of the reflection peak cannot be one due to the internal loss from the silver in the nano-cavity.

Fig. 2(a) shows the transmittance of the single air-coupled ring cavity structure in a notch filter characteristic with different radii of R. It demonstrates that the central wavelength of the notch moves to a long wavelength with the increase of the R and the peak value is also increasing. Fig. 2(b) shows that the central wavelength of the notch has a linear relationship with the radius of the nano-ring cavity as expected in resonance condition.

Fig. 3(a) shows the transmission spectra of the couple ring cavity with different dielectric refractive indexes at a fixed radius of 190 nm. One can see that the center wavelength changes by the black line to the blue line, and the maximum transmittance of the non-resonant wavelength can reach 80%. From Fig. 3(b), it is found that the wavelength of the notch has a linear relationship with the dielectric index of the cavity.

3. All-optical switching based on coupled nano-ring cavities structure

We consider a silver–dielectric–silver MDM waveguide coupling to a nano-ring cavity filling with a Kerr nonlinear material. As shown in Fig. 4(a), we can change the refractive index of the material by adjusting the pumping beam intensity. The metal–electric composite materials are chosen in the structure, because they have a large third-order optical nonlinear susceptibility (gold) [17] and ultra-fast response time which are important for switching function. The typical value of the third-order nonlinear susceptibility χ^3 is up to 10^{-7} esu with a pulse laser duration of 200 fs at the wavelength 550 nm. In this paper, Au/SiO$_2$ with $\chi^3 = 1.7 \times 10^{-7}$ esu ($2.37 \times 10 - 15$ m^2/v^2) [18] is chosen to fill in the ring cavity and the bus waveguide. It needs to be mentioned that the filling materials could be extended to other Kerr nonlinear materials. The refractive index of the nonlinear material Au/SiO$_2$ can be expressed as $n = n_0 + n_2 I$, where $n_0 = 1.47$ is the linear refractive index, $n_2 = 2.07 \times 10^{-9}$ cm^2/W is the nonlinear refractive index coefficient and I is the pumping beam intensity.

Fig. 4(b) shows the transmission spectra at two different intensities of the pumping light, the structure parameters: $w = 50$ nm, $G = 10$ nm, Outer ring radius $R = 154$ nm. As can be seen from Fig. 4(b), the transmission of the notch red-shifts from 880 to 940 nm when pumping intensity I increases from $I_0 = 0$ (in the absence of pumping light) to $I_1 = 48.31$ MW/cm^2 (corresponding to optical power of 50 mW). Therefore, the ring cavity filled with a nonlinear Kerr material, which can realize an all-optical switching function, in which the (on/off) states correspond to (with/without) the optical pumping. The magnetic field profiles of the SPP propagation at the wavelength of 880 nm through the structure are displayed in Fig. 5. Fig. 5(a) shows the "off" state in the absence of pumping light and the *SPP* wave is completely blocked to the right port. While Fig. 5(b) shows "on" state in the presence of the optical pumping (intensity $I_1 = 48.31$ MW/cm^2). We can clearly see the results of optical switching from the picture by changing the pumping light intensity when the input wavelength is 880 nm. When pumping light is turned off, the light could propagate through the straight waveguide with low loss. The ring cavity resonance wavelength is changed when the pumping light is turned on. The principle of achieving optical

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