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Assessment of optical bistability criteria in metal-insulator-metal plasmonic resonator containing Kerr nonlinear medium

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Abstracts: In the current exploration, we numerically assessed the optical bistability occur criteria in a metal-insulator-metal structure that consists of two side coupled waveguides to a race-track-shaped resonator (RTSR). This particular RTSR contains a Kerr nonlinear material for filled medium. We happened to understand that any increase in the incident intensity, can cause a redshift for the resonance wavelength that is due to the refractive index shift induced by enhancing intensity. Moreover, the bistability loop that occurs within this RTSR could be a good candidate for application in any desired all-optical platform such as sensors, switches and analog-to-digital convertors and other integrated optical circuits.

Keywords: race-track-shaped resonator (RTSR), Optical bistability, Kerr nonlinear material

1. Introduction:

Surface plasmon polaritons (SPPs) are considered the new hope for ultra-tiny scale integrated chips. These SPPs are electromagnetic waves (EM) that move on the surface of any metal-dielectric hetro-structure. Their most important character is that their EM energy field exponentially decays in both sides of the interface. The SPPs are carried on the surface by means of free electrons of the metal [1]. The unique properties of SPPs is that they are able to overcome the diffraction limit of conventional optics and the more important part is that they are able to manipulate the light (EM waves) on the subwavelength scale [1, 2]. The SPP features are easily custom-made by changing the structure of metallic surfaces, which in return provides the potential for developing any required photonic device [3]. In recent studies, devices based on SPPs have been interestingly proposed by means of numerical and experimental investigations, such as Bragg reflectors [4], wavelength demultiplexers [5, 6], filters [7], Mach–Zehnder interferometers [8], Y-shaped channel junctions and combiners [9, 10], couplers [11], splitters [12], and sensors [13-15]. As an important optical phenomenon, nonlinear optics has attracted increasing interest and attention of scientists. Some devices based on nonlinear materials have been investigated, such as all-optical switching, modulators, and amplifiers [16].

All-optical signal processing in photonic integrated circuits (PIC) needs the resources to control light with light [17]. Nonlinear based optical bistability is a very important optical effect that helps us to pave the way of creation of required resources for light control. This effect is usually considered for the design of all-optical switching and other nonlinear optical devices [1].

In the current study we bring a schematic type of a ring resonator based RTSR to develop the nonlinear optical bistability. Here we propose a metal-insulator-metal structure that consists of two side coupled waveguides to a race-track-shaped resonator (RTSR). The bistability loop that occurs within this RTSR could be a good candidate for application in any desired all-optical platform such as sensors, switches and analog-to-digital convertors and other integrated optical circuits. This particular RTSR contains a Kerr nonlinear material for filled medium. We happened to understand that any increase in the incident intensity, can cause a redshift for the resonance wavelength that is due to the refractive index shift induced by enhancing intensity.

2. Structures and Model

It is known that there are two important categories of plasmonic waveguides, i.e., insulator-metal-insulator (IMI) and metal-insulator-metal (MIM) waveguide. The IMI waveguide preserves lower loss but it comes with poor capability to confine light on subwavelength scale [3], while MIM waveguide reveals more strong light confinement and hence the propagation length for SPPs is acceptable [18]. In our proposed structure, the resonant mode within the RTSR enhances the nonlinear effect and yields the optical bistability.

Figure 1 shows the schematic diagram of the proposed plasmonic structure, which is composed of input and output waveguides as well as an RTSR in the middle of the MIM structure. The dielectric in the metal slit is air with refractive index n = 1 and the RTST colored as yellow area, hosts the Kerr nonlinear medium.

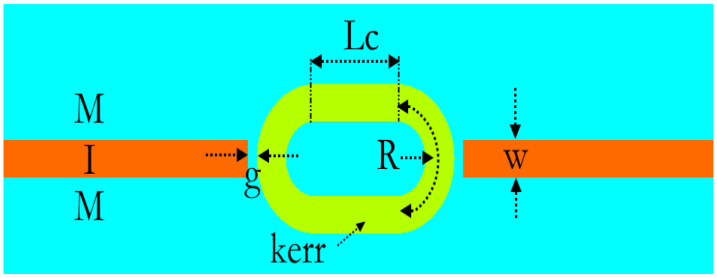


Fig. 1. Schematic diagram of the proposed MIM plasmonic waveguide with a race-track shaped resonator (RTSR). R: the radius of the resonator, W: the width of the waveguide, g: the coupling length between the waveguide and resonator and LC: is coupling length and the straight section of RTSR.

The metallic section of structure is sliver whose frequency-dependent relative permittivity is characterized by the Drude model as [3]:

$$\varepsilon_m(\omega) = \varepsilon_\infty - \frac{\omega_p^2}{\omega(\omega + i\gamma)}, \qquad (1)$$

Here ε_∞ is the dielectric constant at infinite angular frequency, ω_p is the bulk plasma frequency, and represents the natural frequency of the oscillations of the metals free conduction electrons, and γ represents the damping frequency of the oscillations. The value of these parameters are set as $\varepsilon_\infty = 3.7$, $\gamma = 0.018$ eV, and $\omega_p = 9.1$ eV, respectively [15]. Here, ω is the angular frequency of the incident light. Moreover, a TM polarized plane wave is used to excite the movement of SPPs in the waveguide.

The transmission efficiency is usually defined as T= Tr/Ti [1], where Ti is the total interface incident power and Tr is the power of transmission.

The parameters of the structure are set as R = 150 nm, W = 50 nm, Lc= 100 and g = 20 nm. It's noteworthy to mention that these parameters are used for all simulations. We utilize the finite difference time-domain (FDTD) method to investigate the transmission response of this structure. In the simulations, the grid mesh sizes are set as $\Delta x = \Delta y = 5$ nm and the temporal step is set as $\Delta t = \Delta x/(2c)$, where c denotes the velocity of light in vacuum. Moreover, the perfectly matched layer (PML) is used in the both x and y directions to absorb the redundant radiations from edges of simulation [3].

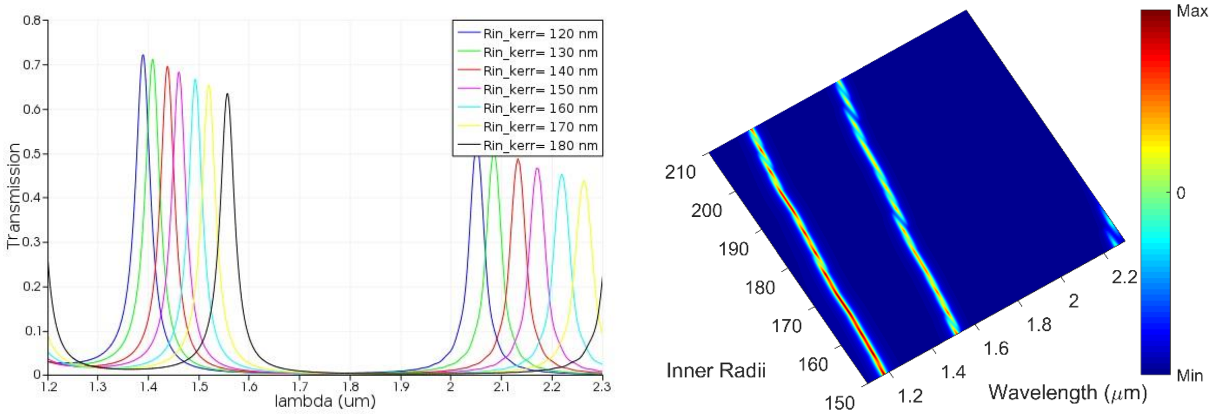
3. Simulation Results and Discussion

Figure 2(a) shows the transmission spectrum of RTSR with different radius varying form 120-180 nm. Also figure 2(b) shows map of spectrum peaks of RTSR with different radius varying form 150-210 nm. These figures reveal that the center wavelength has a blueshift when the R increases. As shown in current figure, the transmitted-peak wavelength decreases linearly with the R change in a wide spectral range. Fig. 3(a) shows the structure field snapshot in off-mode at 1.7 um, and figure 3(b) shows the field snapshot of the structure when it is on-resonance mode at 1.5 um where coupling length of RTSR, Lc is 150 nm and radius of RTSR, R is 170 nm.

Successively, the nanodisk resonator is filled with Kerr medium whose dielectric constant depends onthe intensity of the incident light [1]:

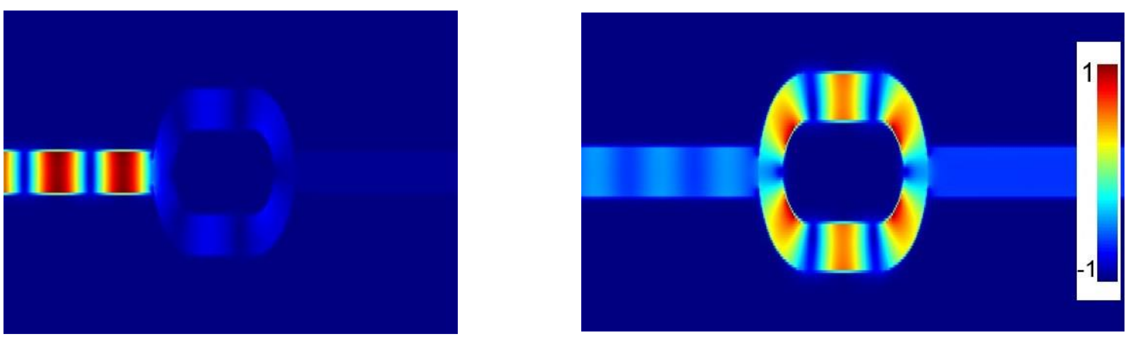
$$\varepsilon_d = \varepsilon_l + \chi^{(3)}|E|^2, \qquad (2)$$

Where ε_d is the dielectric constant of Kerr medium, ε_l is the linear dielectric constant and set as 2.25, and $\chi^{(3)}$ stands for the third-order nonlinear susceptibility. Here, the Kerr medium is chosen as InGaAsP.



(a) (b)

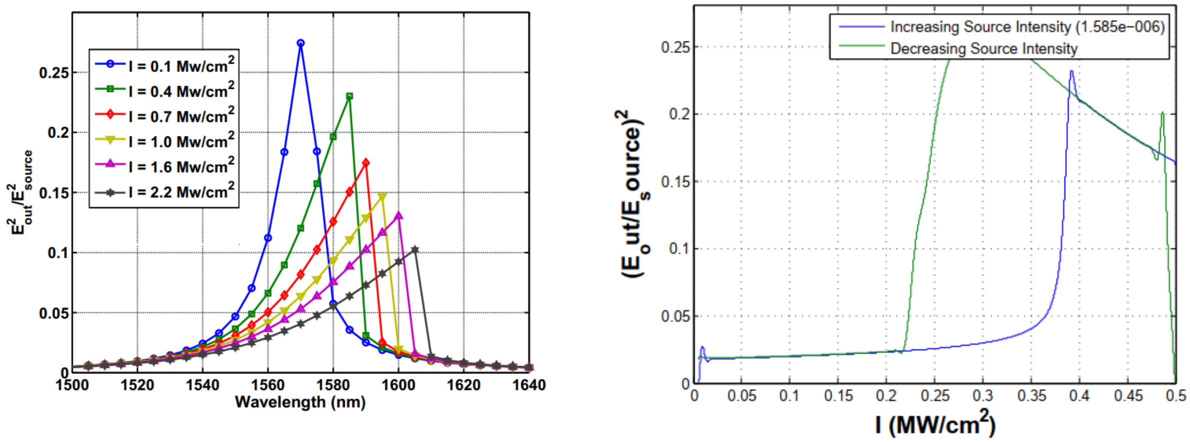
Fig. 2: (a) Transmission spectrum curves of RTSR with R=120-180 nm, (b) map of spectrum peaks of RTSR with R=150-210 nm.



(a) (b)

Fig. 3: (a) field snapshot of the structure in off-mode at 1.7 um, (b) field snapshot of the structure in on-resonance mode at 1.5 um where Lc = 150 nm, R=170 nm.

Because of the Kerr nonlinear effect, the resonance wavelength of the cavity exhibits a redshift with the increasing of the incident intensity. The transmission spectrum of this plasmonic structure possesses obvious and sharp peak. At the transmission peak, the local resonant mode is excited and, thus, enhances the nonlinear effect of the cavity. Additionally, an obvious bistability loop is achieved (Figure 4-b). It is well-known that optical bistability is one of the most important nonlinear optical effect and can be used to design optical devices such as all optical switching [1, 15]. So our structure has potential applications for nonlinear optical devices in highly integrated optical circuits.



(a) (b)

Fig. 4. Nonlinear response of the RTSR when (a) the incident power varies from 0.05 to 0.3 MW/cm^2. (b) bistability loop formation when incident power in a single wavelength increases from zero to 0.5 and conversely from 0.5 to 0 MW/cm^2.

Conclusion

In this work, the optical bistability regime criteria was assessed. The main suggestion of work was in a metal-insulator-metal structure that consisted of two side waveguides coupled to a race-track-shaped resonator (RTSR). This particular RTSR contained a Kerr nonlinear material for filled medium. It was learned from simulations that any increase in the incident intensity, caused a redshift for the resonance wavelength. This also was due to the refractive index shift induced by enhancing intensity. It was shown that the bistability loop within this spectacular RTSR was a good candidate for application in any desired all-optical platform such as sensors, switches and analog-to-digital convertors and other integrated optical circuits.

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