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Routing properties of the T-structure based on Au/SiO_2 nanorings in optical nanophotonic devices

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In the present paper, we have utilized Au nanoring arrays in an SiO_2 host to provide a T-structure for the purpose of routing and switching optical energy in optical integrated devices to operate at optical communication band ($\lambda \approx 1550$ nm). To employ this router at spectral region considered, localized surface plasmons resonance (LSPR) must be red-shifted around 1550 nm. This T-shaped router includes Au nanorings with a 175 nm inner diameter, a 35 nm thickness and a 35 nm height, and the intercenter distance between two nanorings is 330 nm. To demonstrate the routing properties, we utilized the finite-difference time-domain (FDTD) method. It is shown that the non-straight chain can transport and route the optical energy with certain velocity of light and transmission coefficient. In addition, the percentage of transmitted or power ratio for this structure has been calculated as almost 90%. The optical energy transport can take place at group velocity of approximately 25% of the velocity of light ($0.25c_0$, where c_0 is the velocity of light in the vacuum). The router based on nanoring chains shows better performance in switching and transporting the optical energy in comparison to other nanoparticles (nanospheres, nanodisks and nanorods).

Keywords: nanoring, optical communication band, finite-difference time-domain (FDTD) method, localized surface plasmons resonance (LSPR), routing and switching.

1. Introduction

The electrodynamic characteristics of sub-wavelength sized metal nanoparticles have been examined and investigated by most of the researchers in recent years [1, 2]. Interaction of visible light with specific noble metal nanoparticles (Au, Ag and Cu, for example) produces a collection of coherent electron motions inside the metal. These groups of electron motions are plasmons (SP) [1–3]. If the frequency of the incident light is near to the plasmon frequency of the metal nanoparticle, as a result disturbances in the energy flux of the light has appeared [4]. These disturbances and excitations take place when the dimensions of the metal nanoparticle are very small in comparison to the wavelength of incident light ($d \ll \lambda$) [4]. In addition, to determine the surface

Table 1. Geometrical parameters of an Au nanoring in a SiO_2 substrate.

	Description of nanoring dimensions and quantities			
	Inner diameter	Total diameter	Thickness	Height
Parameter	D_i	D	t	H
Dimension	175 nm	210 nm	35 nm	35 nm

plasmon resonance frequency of a certain metal nanoparticle, we have to consider some important parameters, such as: 1) material of nanoparticle, 2) refractive index of the substrate material, and 3) size and shape of the nanoparticle [5].

In this paper, we design a T-shaped plasmon waveguide to operate at optical communication band. Hence, to employ the plasmon waveguide at 1550 nm, localized surface plasmon resonance (LSPR) must be red-shifted [5]. Earlier research and works have shown that in order to provide LSPR close to 1550 nm, nanospheres and nanorods must be encompassed by a host material with relative permittivity of almost 55, which is not applicable [5]. Accordingly, nanoring is a fine choice in this case due to its extra degree of freedom (DoF) in its geometrical components. Adjusting the geometrical dimensions (inner diameter, thickness and height) helps to tune the LSPR near the given wavelength [5].

In order to determine the acceptable sizes (to provide LSPR at 1550 nm), we assume a single Au nanoring surrounded by SiO_2 substrate with the typical refractive index of 1.46. This Au nanoring is excited by Gaussian electric field. Changing geometrical sizes in a principal procedure leads to obtaining appropriate geometrical sizes that are listed in Tab. 1 [5]. Our structure has been devised by using Au nanorings based on the parameters given in Tab. 1. Thus, the T-structures with these nanoring arrays show better performance during guiding and propagating of light in comparison to other types of metal nanoparticles, such as nanospheres, nanodisks and nanorods, due to lower extinction effect and better near-field coupling [6]. Therefore, employing nanorings can help us to have a plasmon waveguide with lower losses, higher transmission efficiency and also higher percentage amount of the output power. Material of nanoring is another important issue in this work. Examination of most of the materials such as Ag and Cu showed that they did not demonstrate acceptable behavior in optical energy transmission and in routing process. Additionally, Ag and Cu have shown higher radiation to the far field that makes the plasmon waveguide highly lossy [7]. The material of Au is another fundamental factor in design of the plasmon waveguide. The Johnson–Christy and Palik constants for Au have considered mostly designing and fabricating metal-dielectric components. According to our research, an Au nanoring with Johnson–Christy constants is the best choice for use in the given structure. Comparing two kinds of Au, shows that Au with Johnson–Christy constants demonstrates better performance during light guiding.

To fabricate the optical integrated devices, we use plasmon waveguides based on metal nanoparticle arrays [4, 8]. Applying these nanoparticle arrays in devices causes some initial limitations to appear. One of these limitations is the diffraction limit.

The electromagnetic energy transportation takes place below the diffraction limit of the light [4, 9]. This condition leads to lower dimension limit on the propagated light mode. Another fundamental limitation factor is the guiding geometry. In recent works, there have been more attempts to demonstrate the guiding properties around sharp corners and bends (90° corners and 60° bends, *etc*.). Guiding of the optical energy by sharp corners includes radiation leakage and field escaping [4].

This paper is organized as follows: in Section 2, we will show the properties of the T-structure and the behavior of nanoring chains in transportation of electromagnetic energy. We have shown the switching properties and the crosstalk effect in the structure by means of diagrams and snapshots. In addition, we have demonstrated the effect of corner in changing transverse and longitudinal modes with each other. In Section 3, we have presented the results of the simulations for structure at $\lambda \approx 1550$ nm by computing the group velocity of the structure and the power ratio at the output branch of the switch.

2. Principal properties of the Au nanorings based T-structure

It is shown that a chain of Au nanorings with specific geometrical dimensions can be used in transporting and routing or switching of the optical energy at $\lambda \approx 1550$ nm. When the electromagnetic energy is coupled in a certain nanoparticle of a chain, the dipoles and higher orders of the poles are produced [10]. Due to the dominance of near-field coupling the effects of higher order of poles (quadrapoles, *etc*.) are negligible and only the influence of dipoles is considered. Accordingly, dipole fields have been induced in the nearest metal nanoparticle via near-field coupling [11].

Transporting energy through the waveguide includes losses. Radiation into the far-field and internal damping are two important loss factors in this case [10]. During the light-matter interaction, most of the electromagnetic energy is coupled to the closest nanoring but some of this energy is scattered into the far field. In a nanoring chain the radiation losses are negligible due to the dominance of near-field coupling between the nanorings [11]. Internal damping is the result of the resistive heating of the surface plasmon modes [4, 9]. To afford these losses and attain high transmission efficiency we use nanorings instead of other shapes of nanoparticles because of their particular features.

To design the desired T-structure, we consider three arrays that include five nanorings in each branch (arm) (Fig. 1). In these arrays the intercenter distance between two series of nanorings is 330 nm and the Gaussian field is located at 330 nm of the first particle of each branch. These distances have been examined and studied, and are illustrated in Fig. 1. Launching the Gaussian electric field in the same phase (In-phase) from branches 1 and 2 leads to a constructive interference in the middle nanoring of the structure. Hence, the electromagnetic energy can be guided through the third branch 3. In this state, the plasmon waveguide is working as a router and is operating as an ON state switch. Furthermore, this figure shows the logarithm of the peak amplitude squared of the electric field along the y-axis of plasmon waveguide

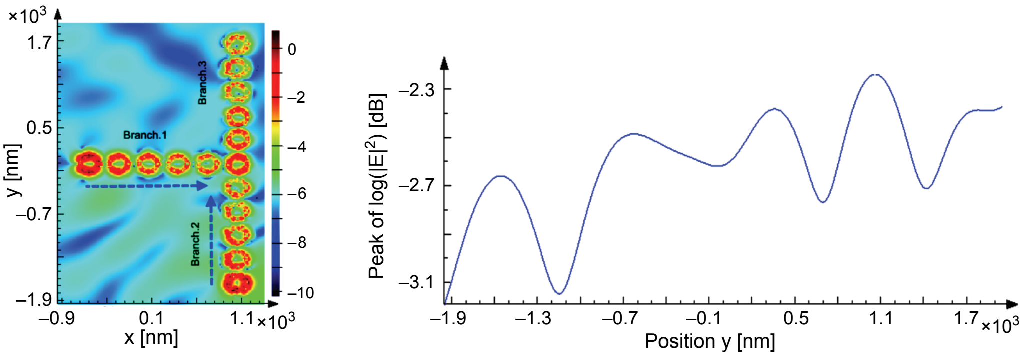

Fig. 1. A snapshot of the T-structure as a switch. In-phase excitations of inputs (1) and (2) lead to constructive interference at the junction and an enhanced signal at output (3), (which demonstrates the ON state). In addition, the logarithm of the peak of amplitude squared of the electric field along the plasmon waveguide (y-axis) is illustrated. Accordingly, the field intensity $\{(V/m)^2\}$ along y-axis after junction ring is increased in an exponential fashion.

(the field intensity in branch 3 is going to increase due to constructive interference). In this figure, the intensity of optical energy after the center nanoring of T-structure is increased.

On the other hand, if the Gaussian electric fields are in opposite polarization (out-of-phase), this situation leads to a destructive interference in the middle nanoring, and consequently, the router is in OFF state; this interference is illustrated in Fig. 2. In ideal situation, the energy flow must be zero in the branch 3. But due to the absorption in Au nanoparticles and also small radiations into the far field, there are field leaking and energy escaping to branch 3. According to Fig. 2 routing

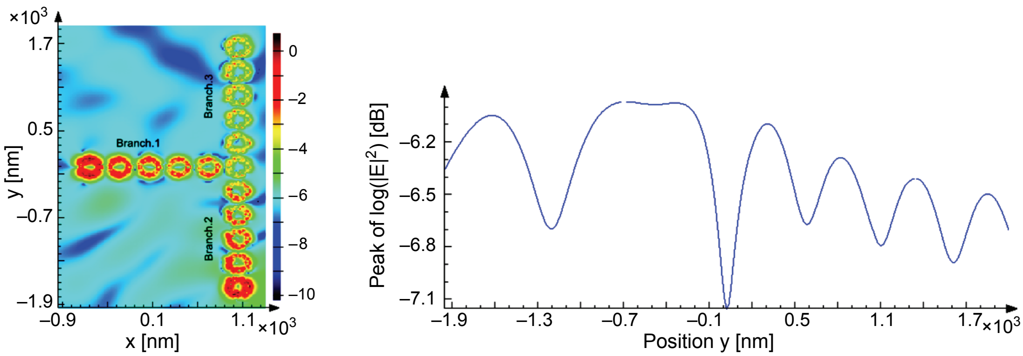

Fig. 2. A snapshot of the T-structure as a switch. Out-of-phase excitations of inputs (1) and (2) lead to destructive interference at the junction and a reduced signal at output (3), (which demonstrates the OFF state). In addition, the logarithm of the peak of amplitude squared of the electric field along the plasmon waveguide (y-axis) is illustrated. Accordingly, the field intensity $\{(V/m)^2\}$ along y-axis after junction ring is decreased in an exponential fashion.

efficiency is less than 100% because there is still energy escaping into branch 3. This escape is due to the coupling between nanorings which are more aside. T-structure based on nanoring arrays shows lower losses than similar structures based on nanospheres and nanorods.

Eventually, according to simulation results, this structure operates as an ON/OFF switch at optical communication band. Due to small leaking, there is still crosstalk effect as expected in the plasmon waveguide, but in comparison to other T-shaped plasmon waveguides crosstalk has been reduced.

3. Simulation results

In this section, simulation results of the T-structure are presented. One of the important components of the light transmission is the group velocity for polarizations. The propagation velocity of the guided optical energy is given by the slope dω/dk of the dispersion relation [12]. This velocity has the highest value at the resonance frequency. Also, group velocity can be calculated by its relative equations for Au nanorings. In this case, we consider the relation of applied normalized frequency versus ky (units of $2\pi/d_c$) that d_c is the center to center distance between two neighboring nanoparticles. Utilizing the dispersion relation diagram (Fig. 3) shows that optical energy transmission occurs at a group velocity of $0.25c_0$, where c_0 is the velocity of light in the vacuum. Moreover, another important point that can be seen in this figure is the position of light line. Accordingly, the light line is above the guided mode of the structure mode and this factor demonstrates that the T-router presented is not highly lossy. It should be noted that any modes above the lower branch of the light line are lossy, although

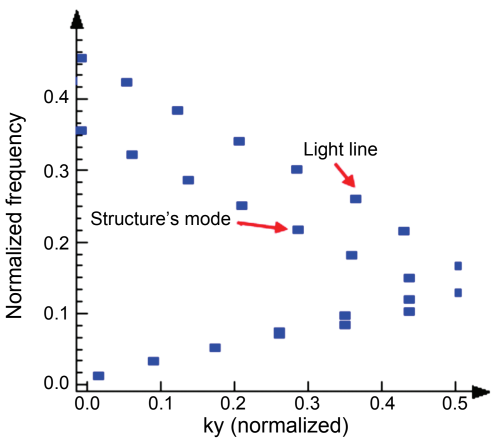

Fig. 3. Illustration of dispersion relation for plasmon waveguide (frequency versus propagation constant along the y-axis). The structure is not highly lossy due to the light line above the band structure. The slope of figure leads to light velocity of $0.25c_0$.

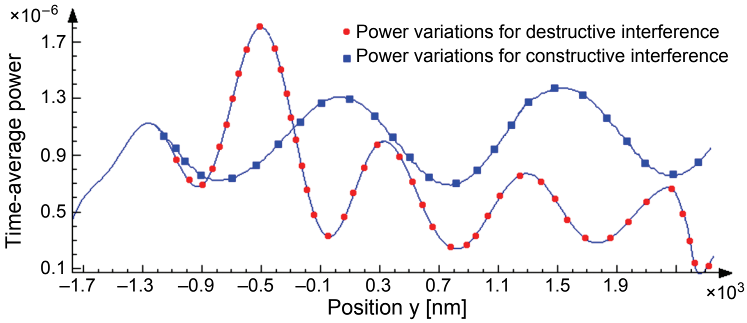

Fig. 4. Variations of the time-averaged power [W/m^2] along y-axis. Squares show the variation of power in ON state of switch and there is a peak in diagram at junction nanoring due to the constructive interference. Circles demonstrate the power variation in OFF state of switch, and also this power after junction nanoring is decreased (going to be zero at the last nanoring) due to the destructive interference.

the loss is very small, any modes above upper branch of the light line are highly lossy. Nanoring based plasmon waveguide is not highly lossy, because in this structure the band structure is under light line.

The time-averaged power variations are illustrated in Fig. 4. In this case, in order to calculate power ratio of the structure we are going to consider the complex Poynting vector:

$$\mathbf{P} = \mathbf{E}(\omega) \times \mathbf{H}^*(\omega) \tag{1}$$

This equation can be used to calculate the power flow in a particular direction (for example, propagation direction). Also, the time-averaged power flowing across a surface is given by:

$$\text{Power}(\omega) = \frac{1}{2}\int_S \text{Real}(\mathbf{P})\,\mathrm{d}\mathbf{S} \tag{2}$$

It is known that the propagating power is proportional to the real part of the Poynting vector only, which is related to the conservation of energy for the time-averaged quantities. The factor of 1/2 is related to the time averaging of the clockwise (CW) fields. The imaginary part of the Poynting vector relates to the non-propagating reactive or stored energy, such as one might find in the evanescent tail of light being reflected by total internal reflection (TIR). So, we do not consider the imaginary part of the power in our calculations. In this case, the transmitted power can be obtained by considering the real time-averaged power variations along y-axis for monitor and Gaussian electric field source

$$T(\omega) = \frac{\frac{1}{2}\int \text{Real}(P_y^{\text{monitor}}(\omega))\,\mathrm{d}x}{\frac{1}{2}\int \text{Real}(P_x^{\text{source}}(\omega))\,\mathrm{d}x} \tag{3}$$

Thus, for the transmitted power via chains along the plasmon waveguide, the power ratio is:

$$\text{Power ratio} = \frac{\text{Monitored output power}\left(\text{Power}(\omega) = \dfrac{1}{2}\displaystyle\int_s \text{Real}(\mathbf{P})\,d\mathbf{S}\right)}{\text{Incident field power}} \tag{4}$$

According to Eq. (4) and Fig. 4 (power variations along y-axis for ON and OFF states), calculation of the time-averaged power proportion for output and input powers across the surface of waveguide shows that the efficiency of the power of the electric field at the last ring of the third branch in the constructive interference (ON state) is approximately 90%. This percentage is acceptable due to the nature of plasmon waveguides that they are highly lossy

Power ratio (constructive interference) = 0.905 ~ 90%

On the other hand, for destructive interference (OFF state), according to Fig. 4 and the power relations mentioned, it is shown that the power ratio (transmitted power) is almost near to zero (but not absolutely zero due to the field escaping while passing the bend)

Power ratio (destructive interference) = 0.0497 ~ 5%

Another important point is the mode changing along the structure. Figure 5 demonstrates the changing of modes due to 90° corner such that transverse electric

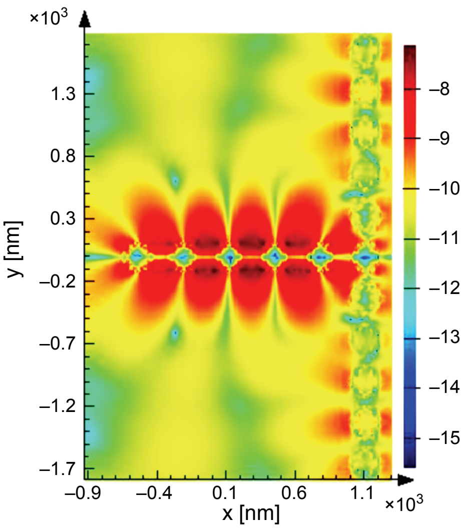

Fig. 5. A snapshot of electric transverse mode (T-mode) which is changed to electric longitudinal mode (L-mode) due to 90° corner of the structure.

modes have been changed to longitudinal mode due to the sharp corner. Therefore, the transverse modes change to longitudinal modes and *vice versa*.

4. Conclusions

In this paper, we have investigated and examined a T-shaped plasmon waveguide based on ordered array of Au nanorings as a router in order to employ in nanophotonic devices at optical C-band spectrum ($\lambda \approx 1550$ nm). According to our simulation results the power ratio (transmitted power) in the constructive interference is approximately 90%. Moreover, this power variation in destructive interference is less than 5%. We have shown that by utilizing arrays of Au nanorings, it is possible to transport and switch the optical energy with lower losses and higher efficiency. This transportation of the light can take place at the group velocity near to 25% of the velocity of light. In addition, we have demonstrated that nanorings like other shapes of nanoparticles change the transverse modes to longitudinal modes due to 90° corner and *vice versa*. Ultimately, according to the minimum amount of optical energy escaping due to the sharp corner, this switch shows lower crosstalk effect.

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