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Gold nano-elliptic arrays used in plasmonic waveguides in near infrared spectrum

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In this paper, we investigated plasmonic waveguides in near infrared spectrum, especially at original (λ = 1310 nm) and also communication bands (λ = 1550 nm) using gold nano-elliptic rings. It is possible to shift localized surface plasmon resonance, by appropriate geometrical properties, to the desired wavelength. Three-dimensional simulations utilizing the finite-difference time-domain algorithm are used to determine the set of geometrical parameters of gold nano-elliptic rings for exciting localized surface plasmon resonance at 1310 and 1550 nm. Employing different configurations of gold nano-elliptic rings chains, waveguides are designed, with –3 dB transmission loss coefficients and group velocities calculations for different modes. In comparison with circular nanorings, elliptic rings showed better characteristics, such as high electric field enhancements and low loss transmission coefficients.

Keywords: loss coefficient, group velocity, finite-difference time-domain.

1. Introduction

Confinement of light in nanoscale structures, using noble metallic particles, is one of the targets in nanophotonics [1]. Miniaturization of optical integrated circuits, as one of the main aims, has been attended and progressed recently [2–4]. Plasmon waveguides are fundamental elements in optical integration technology because of highly localized field enhancement and enable guidance and confinement of electromagnetic waves under the diffraction limit [5]. The plasmonic properties of metallic nanostructures are dominated by the oscillations of free electrons of the nanostructure in resonance with the incident electromagnetic field. It is well known that surface plasmons polaritons (SPPs) could be generated inside the noble metal nanoparticles such as copper, gold, and silver [3, 6, 7]. The optical properties of remarked nanostructures are controlled by the coherent electron fluctuations in result of resonance during illumination by an incident light at a certain frequency, which is referred as localized surface plasmon resonance (LSPR) [3, 6]. LSPR results in a strongly enhanced electric near field localized at the particle surface [7, 8], which has achieved tremendous attention because of its potential for various technologies such as field enhancement spectroscopy [9–12], nano-trapping [13], nonlinear optics [14] and optical waveguiding [15]. Recently, numerous researches in relation to coupled metallic nanostructures including silver cube clusters [16], gold necklaces [17] and gold particle chains [18], have been conducted in order to understand the plasmon coupling between nanometals.

A chain of nano-metal particles gives rise to very large field enhancements in their near region because of the near-field coupling of two adjacent particles. It is well known that LSPR oscillations are dependent on the geometry of the nano-metal, and then, by variation of geometrical parameters and nano-metal shape, the resonance wavelength and field enhancement could be engineered [19]. Recently, nanoring particles are especially noteworthy because of high local electric field generation by them as a result of powerful plasmon coupling of the outer and inner surfaces; therefore it is possible to tune plasmon frequency resonance from the visible to near-infrared (NIR) region by variation of the diameter and width of the ring [20, 21].

In this paper, plasmonic waveguides are investigated in the NIR region, especially at original (O-band, $\lambda = 1310$ nm) and also communication bands (C-band, $\lambda = 1550$ nm) using gold nano-elliptic rings, then they are compared with circular nanoring waveguides.

This paper is organized in the following way: in Section 2 we described gold nano -elliptic rings characteristics in the SiO_2 host material; in Section 3, the nano-elliptic rings have been used in plasmonic waveguides and their characteristics have been obtained; in the last section, the paper is finalized by discussing the obtained results and conclusions.

2. Design of gold nano-elliptic rings

Host material of the proposed waveguide is SiO_2, where arrays of Au nano-elliptic rings are embedded. Plasmon resonance wavelength of the gold nanostructures is in

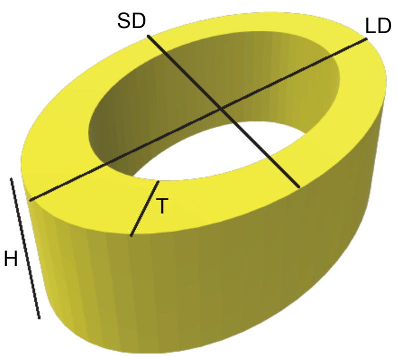

Fig. 1. Schematic illustration of nano-elliptic ring surrounded by SiO_2. The four independent geometrical parameters LD, SD, H and T are demonstrated (p = SD/LD).

the range of λ = 520–600 nm [22, 23], which is changed by varying geometrical parameters of nanostructures. Then the peak of their optical response is adjusted to the O-band or C-band. The object's geometrical degree of freedom provides the advantage of waveguide's performance optimizations. In nano-elliptic ring, the geometrical parameters are the elliptic large-diameter (LD), the elliptic small-diameter (SD), thickness T and height H (see Fig. 1); then we have four degrees of freedom in comparison with the cases of nanorings, where thickness, height and diameter are their degrees of freedom and sphere, where its radius is the only one degree of freedom.

Now, parameter p is introduced, where it is defined as the ratio of a SD to LD. In the sample, nano-elliptic ring parameters are LD = 235 nm, H = 35 nm, and T = 30 nm. Figure 2 demonstrates LSPR blue shifting by decreasing p. On the other hand, when

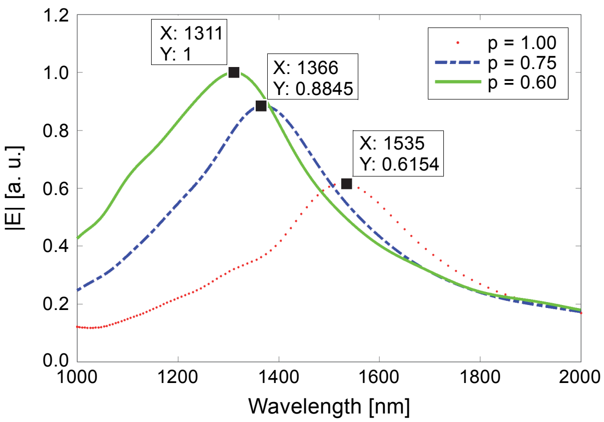

Fig. 2. Effect of parameter p on LSPR wavelength. By decreasing p, the LSPR is confronted to blue shift as well as higher electric field enhancement. The other geometrical parameters are LD = 235 nm, H = 35 nm, and T = 30 nm.

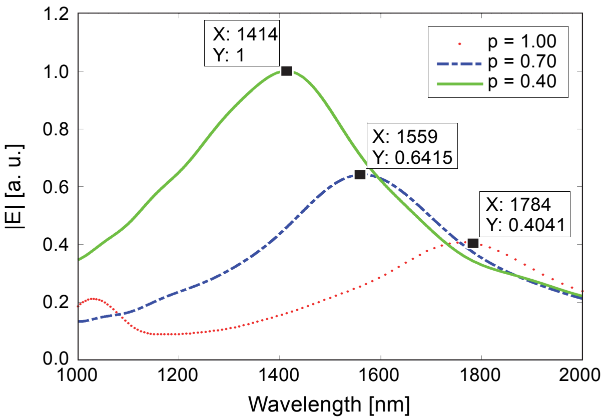

Fig. 3. Effect of parameter p on LSPR wavelength. By decreasing p, the LSPR is confronted to blue shift as well as higher electric field enhancement. The other geometrical parameters are LD = 290 nm, H = 35 nm, and T = 30 nm.

Table 1. FDTD simulation parameters.

Parameter	Values
Yee cell size ($d_x = d_y = d_z$)	4 nm
Simulation time	1000 fs
Boundary conditions	PML
PMLs number	12
Background index	1

a circular ring converts to an elliptic ring, LSPR wavelength is confronted to the blue shift as well as higher electric field enhancement. With $p = 0.5$, the nano-elliptic ring is appropriate for the waveguide to operate at $\lambda = 1310$ nm. Notice that $p = 1$ is represented as the circular ring and its LSPR is consistent with previous works [5].

Figure 3 demonstrates LSPR wavelength for the nano-elliptic ring with LD = 290 nm, $D = 35$ nm, and $T = 30$ nm. Here the nano-elliptic ring with $p = 0.5$ is selected for the waveguide to operate at $\lambda = 1550$ nm. Hence, Figs. 2 and 3 demonstrate that the proposed plasmonic waveguide can operate at the O-band or the C-band, depending on the geometrical parameters. The FDTD simulation parameters have been listed in Table 1.

3. Transmission performances of gold nano-elliptic rings array in plasmonic waveguide

In this section, plasmonic waveguides are designed taking into account the Au nano-elliptic rings arrays. Electromagnetic energy transmission through the plasmonic waveguide depends on the excitation of non-collective modes $(k \neq 0)$ [5, 24]. Launching a temporal Gaussian pulse in time at a particular distance from the first particle, leads to the excitation of these modes. Here, the simulations are validated with waveguide

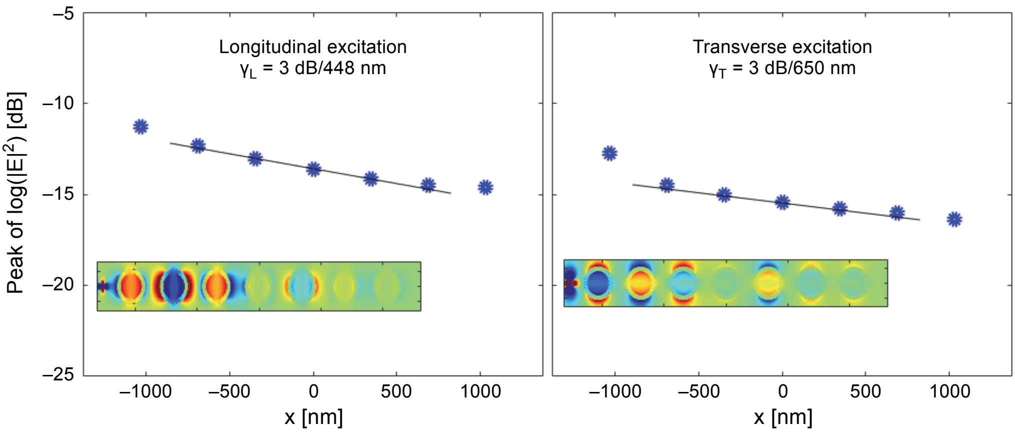

Fig. 4. Waveguide set up with the gold nanorings.

using circular nanorings arrays. Figure 4 shows that the results are consistent with previous works [5, 25]. Figure 5 demonstrates the electric field distributions in the logarithmic scale for the nano-elliptic rings, with geometrical parameters which are listed in Table 2. With the use of a linear fitting technique, except for the first and the last particle, in order to reduce the error, the waveguide transmission losses are obtained for different modes. The intensity of the propagating field decays according to an exponential function, *i.e.*, $|E|^2 \propto \exp(-\gamma x)$, where x is the propagation direction and γ is the transmission loss coefficient [5]. We obtained longitudinal and transverse –3 dB trans-

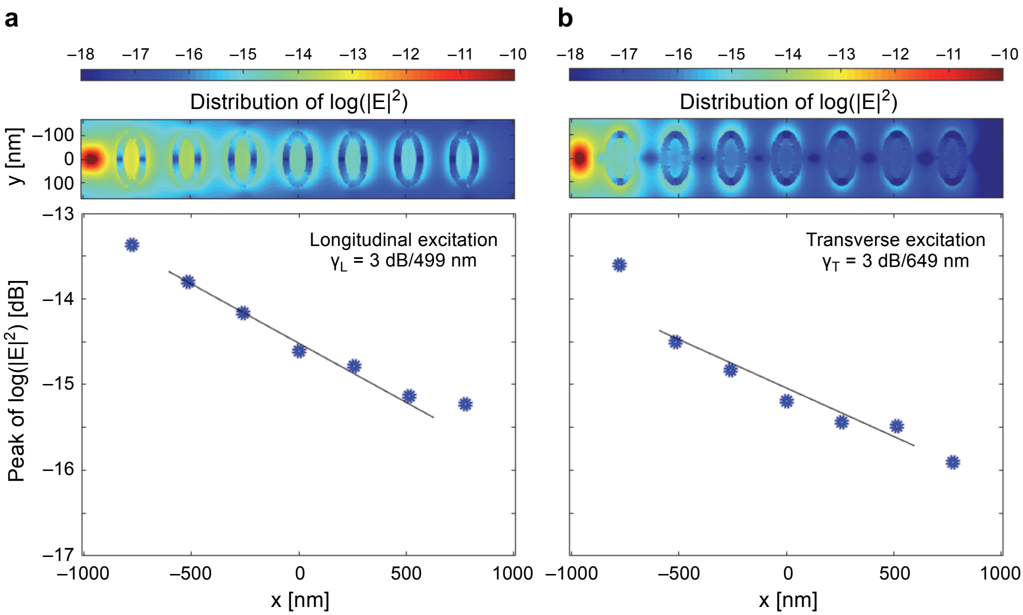

Fig. 5. Field distribution while propagating along a linear array of seven gold nano-elliptic rings chain in SiO_2, which is used to calculate the longitudinal and transverse transmission loss coefficients γ_L and γ_T at λ = 1310 nm. The value of γ_L equals to 3 dB/499 nm in longitudinal excitation (**a**). The value of γ_T equals to 3 dB/649 nm in transverse excitation (**b**).

T a b l e 2. Geometrical parameters for nano-elliptic arrays that operated at λ = 1310 nm.

Description	Values [nm]
Large diameter LD	235
Small diameter SD	117.5
p = SD/LD	0.5
Height H	35
Thickness T	30
Inter-center distance between two particles	1.5LD = 352.5
Distance between source and first particle	1.0LD = 235

mission loss coefficients of γ_L = 3 dB/499 nm and γ_T = 3 dB/649 nm at λ = 1310 nm, respectively.

Figure 6 shows the electric field distributions in the logarithmic scale for the nano -elliptic rings with geometrical parameters, which are listed in Table 3. The simulation results illustrate longitudinal and transverse –3 dB transmission loss coefficients of γ_L = 3 dB/737 nm and γ_T = 3 dB/791 nm at λ = 1310 nm, respectively. In comparison with circular rings, the elliptic rings also show minor losses, both of the modes loss coefficients are close to each other [5].

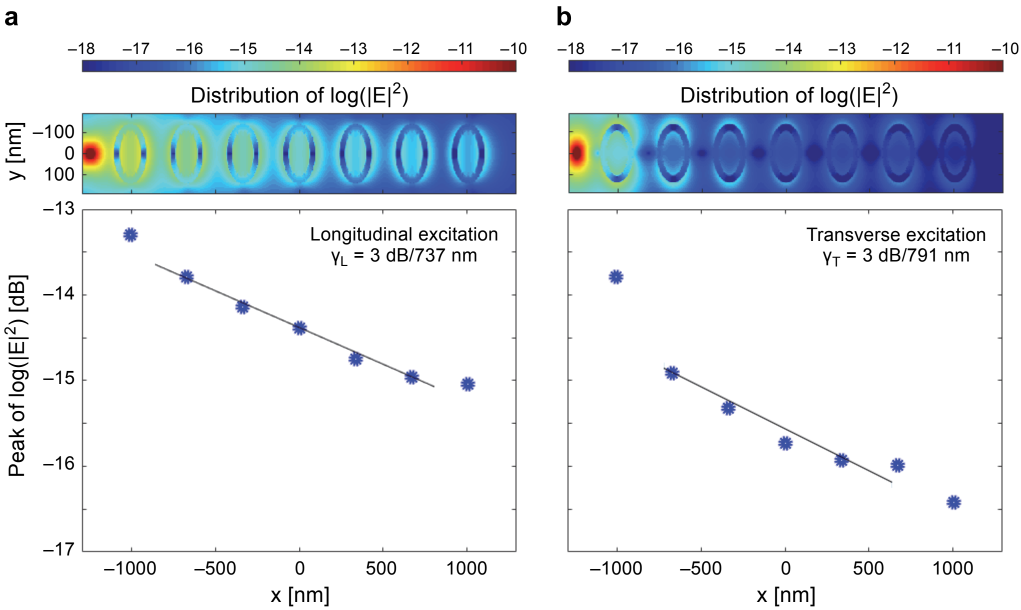

Fig. 6. Field distribution while propagating along a linear array of seven gold nano-elliptic rings chain in SiO_2, which is used to calculate the longitudinal and transverse transmission loss coefficients γ_L and γ_T at λ = 1550 nm. The value of γ_L equals 3 dB/737 nm in longitudinal excitation (**a**). The value of γ_T equals 3 dB/791 nm in transverse excitation (**b**).

Table 3. Geometrical parameters for nano-elliptic arrays that operated at λ = 1550 nm.

Description	Values [nm]
Large diameter LD	290
Small diameter SD	145
p = SD/LD	0.5
Height H	35
Thickness T	30
Inter-center distance between two particles	1.5LD = 435
Distance between source and first particle	LD = 290

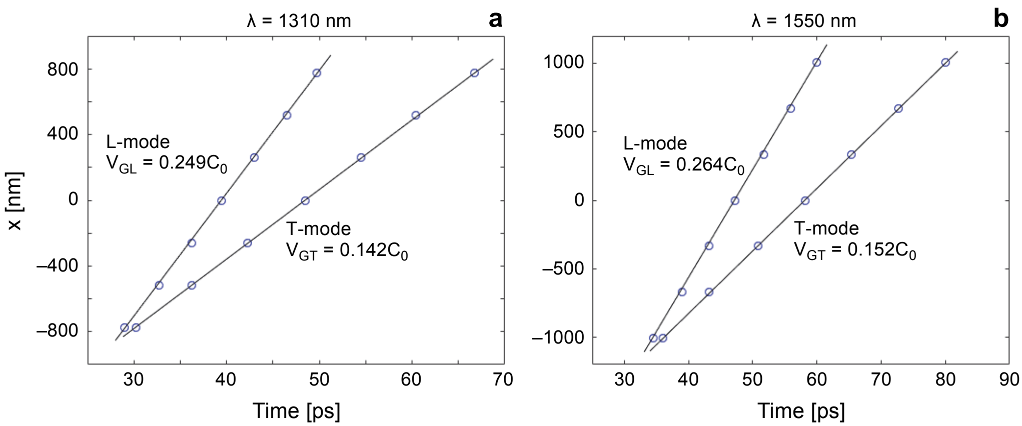

Fig. 7. Pulse peak positions over time in the plasmon waveguide consisting of arrays of nano-elliptic rings: $V_{GL} = 0.249C_0$, for longitudinal mode and $V_{GT} = 0.142C_0$ for transverse mode at $\lambda = 1310$ nm (**a**), and $V_{GL} = 0.264C_0$, for longitudinal mode and $V_{GT} = 0.152C_0$ for transverse mode at $\lambda = 1550$ nm (**b**); C_0 – speed of light in vacuum.

Figure 7 shows pulse peak positions over time in the plasmon waveguide consisting of arrays of nano-elliptic rings. The longitudinal and transverse group velocities for nano-elliptic rings are a little smaller than nano-circular rings [5].

4. Conclusions

Three-dimensional simulations employing the finite-difference time-domain algorithm are used to study and analyze the plasmonic waveguides made up of arrays of gold nano-elliptic rings in a SiO_2 host, in near infrared spectrum. Furthermore, the optical properties of an isolated gold nano-elliptic ring were studied to determine the set of geometrical parameters producing LSPR at 1310 and 1550 nm (original and communication bands). It has been found that a nano-elliptic ring with 235 nm large diameter, 117.5 nm small diameter, 30 nm metallic thickness, and 35 nm height in the SiO_2 host material generates LSPR at 1310 nm wavelength and elliptic ring with 290 nm large diameter, 145 nm small diameter, 30 nm metallic thickness, and 35 nm height generates LSPR at 1550 nm wavelength with higher electric field enhancements. The transmission loss and group velocity were obtained for both longitudinal and transverse polarized excitation. At $\lambda = 1310$ nm, the longitudinal mode was found to be more lossy than that at $\lambda = 1550$ nm. However, at both of wavelengths, the longitudinal modes are more lossy than transverse modes, where loss coefficients in nano-elliptic ring waveguide are smaller than that in nano-circular rings waveguide, while approximately equal loss coefficients are obtained for longitudinal and transverse modes at $\lambda = 1550$ nm. Moreover, the group velocities in the longitudinal mode are faster than the transverse mode at both wavelengths; while nano-elliptic rings behave a little slower than circular nanorings.

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