Properties of splitting light with metal nanoparticles arrays

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A model of a structure consisting of nonperiodic closely spaced metal nanoparticles array, in which electromagnetic energy can be transported and splitted below the diffraction limit, is founded. Based on finite difference time domain (FDTD) algorithm, we analyze the power transmission properties of nonperiodic silver nanoparticles arrays in a dielectric waveguide. The numerical results indicate the structure can split light along the array at the nanometer level with no radiative losses at the discontinuity.

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We are entering an age of integrated optics and optoelectronic devices, but for a guided mode in a conventional waveguide, the diffraction limit holds the minimum size to be on the order of at least $\lambda/2n$ which amounts to a few hundred nanometers for typical dielectric materials. Conventional planar waveguide devices are also limited in their geometry and layout by the need to avoid sharp bends that incur large radiative losses. Although the photonic crystal waveguides can overcome the bend problem, guiding light through sharp 90° corners, unfortunately, these structures are also limited in critical dimensions for the requirement of a periodic structure with the period size comparable to several wavelengths in order to confine light[1].

In recent years, several papers have focused on the localized surface plasmon resonance (LSPR) of metal nanoparticles and have shown the potential predominance in guiding light below the diffraction limit[2−4]. However, further analysis and calculation have not been carried out. In this paper, we analyze the power transmission properties of the 90° bending and Y arrays of silver nanoparticles.

The model is based on a direct numerical solution of the time-dependent TM set of Maxwell curl equations, so Maxwell equations take the following form:

$$\frac{\partial H_y}{\partial t} = -\frac{1}{\mu_0}\left(\frac{\partial E_x}{\partial z} - \frac{\partial E_z}{\partial x}\right), \tag{1}$$

$$\frac{\partial E_x}{\partial t} = -\frac{1}{\varepsilon}\frac{\partial H_y}{\partial z}, \tag{2}$$

$$\frac{\partial E_z}{\partial t} = \frac{1}{\varepsilon}\frac{\partial H_y}{\partial x}, \tag{3}$$

where μ_0 is the magnetic permeability of the vacuum and $\varepsilon = \varepsilon_0\varepsilon_r$ is the dielectric permittivity. Silver is Drude dispersive material[5], so the dielectric permittivity can be described as

$$\varepsilon_r(\omega) = \varepsilon_\infty + \frac{\omega_p^2}{i\Gamma\omega - \omega^2}, \tag{4}$$

where ω_p is the plasma angular frequency, Γ is the collision angular frequency, and ε_∞ is permittivity at infinite frequency. For Ag, $\omega_p = 1.3463 \times 10^{16}$ rad/s, $\Gamma = 9.61712 \times 10^{13}$ rad/s, and $\varepsilon_\infty = 1.999$.

For the discontinue of the dielectric permittivity ε, it is difficult to obtain analytic solutions in Eqs. (1)–(3), and some methods of computational electrodynamics, such as finite difference time domain (FDTD), finite volume time domain (FVTD), finite element time domain (FETD), can be adopted. We choose FDTD to solve the equations[6,7]. In order to eliminate the influence of interface reflection on calculation results, a layer of vacuum area should be added to the solving area and a suitable absorbing layer should be putted on the outskirt of the vacuum area. According to the standard Yee algorithm of FDTD, the various components of electromagnetic field can be obtained. Then the poynting vector is

$$\vec{P} = \vec{E} \times \vec{H}. \tag{5}$$

According to Eq. (5) we can analyze the power transmission properties of silver nanoparticles arrays.

We simulate two cases, one is 90° coner arrays in vacuum and the other is Y structure on the dielectric material with $n = 1.414$. The parameters of the silver arrays are that the radius of particles is 25 nm and the space between particles is 75 nm. The exciting source is plane wave with a wavelength of 410 nm and width of 50 nm. The spatial sampling step is $\Delta x = \Delta z = 2$ nm, the time sampling step is $\Delta t = 4.45 \times 10^{-3}$ fs and the lasting time is $t = 8.9$ fs used in the FDTD algorithm. The results are shown in Figs. 1 and 2.

The simulations indicate that due to the near-field nature of the coupling, signals can be guided around 90° corner and split via Y structures (120° corners) at the discontinuity. But we can see plasmon waveguides suffer losses caused by internal damping. Internal damping of the surface plasmon mode results from resistive heating and is shown to induce transmission

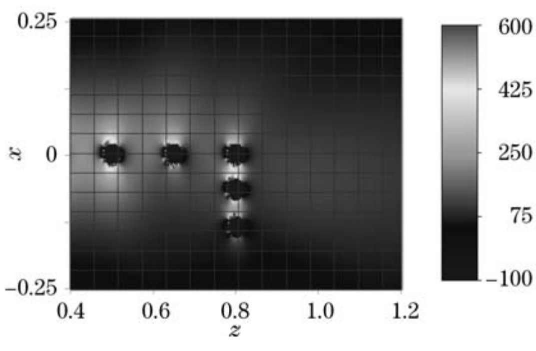

Fig. 1. The xz cross section distribution of the poynting vector along the chain of silver nanoparticles in vacuum, bending corner is 90°.

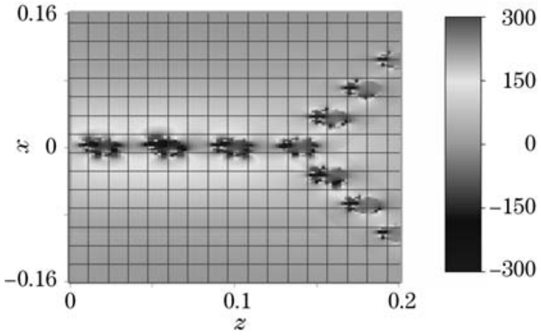

Fig. 2. The xz cross section distribution of the poynting vector along the chain of silver nanoparticles in dielectric material of $n = 1.414$, bending corner is 120°.

loss of about 0.01 dB/nm. While this is a high loss per length, the possibility of creating an entire device smaller than 1 μm^2 implies that the loss per function may be comparable with other integrated photonic devices. And the unique property of the Y structures is that it can split light along the silver chains below the diffraction limit at the discontinuity.

In conclusion, we have presented simulation analyses of the transport of optical energy along nonperiodic nanoparticle arrays, in which electromagnetic energy can be transported and split below the diffraction limit. These properties are of considerable interest in the applications of future electronic and optical integrated device.

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