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FDTD Studies of Metallic Cylinder Arrays: Plasmon Waveguide and Y-Splitter *

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The plasmon waveguide based on double chain of gold cylinders is studied using the finite-difference time-domain method (FDTD). The wavelength of the incident Gaussian beam ranges from 650 to 1200 nm, and the corresponding attenuation factors are calculated. We also present a Y-splitter with 90° splitting angle, each branch in the form of double chains. The transmission efficiencies for different wavelengths are evaluated.

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Surface plasmons (SPs) are coupled oscillations of electrons and electromagnetic fields which propagate along the metallic surfaces. It has attracted great attention in the last ten years due to its potential applications in subwavelength optics.[1−3]

In contrast to the conventional dielectric waveguide, the surface plasmons can be used to transport energy below the diffraction limit. Quinten *et al.*[4] theoretically suggested the possibility of propagating energy along a chain of metallic nanospheres. Then Maier *et al.*[5−8] and Brongersma *et al.*[9] studied this type of structure further both in theory and experiments.[5−9]

The 2D structure corresponding to spheres is the infinitely long cylinders. When a cylinder is much longer than the wavelength of incident light, it can be considered infinitely long, and then the Maxwell equations reduce into TE mode and TM mode. Since the fields with magnetic component parallel to the axis of the metallic cylinder (TM mode) can stimulate the SPs, arrays of such cylinders can be used to construct the 2D plasmon waveguides.[10−12]

In this Letter, we investigate two types of structures. First, we study a 2D plasmon waveguide made of double chain of nanocylinders, which is firstly presented by Gray and Kupka.[10] In Gray's work, the double chain silver cylinder array is studied for wavelength 300–500 nm, here we use much longer wavelength 650–1200 nm, and study their propagation properties in gold arrays. We also design our cone-shaped coupler which plays the same role as Gray's V-shaped one to guide energy into the waveguide. Motivated by Gray's statement that double chain of cylinders performed a more promising result to guide energy than the single one, so in the second case we propose a Y-splitter based on double chain of cylinders, which is different from the single chain Y-splitter presented by Panoiu and Osgood.[12]

All the results in this study are obtained from the FDTD simulations.[13,14] The grid size is 5 nm for simulations of plasmon waveguide, and 2 nm for the Y-splitter. The uniaxial perfectly matched layer (UPML) is used as absorbing boundary conditions. We employ the Drude model to describe the optical properties of gold,

$$\varepsilon(\omega) = \varepsilon_\infty - \omega_p^2[\omega(\omega + i\Gamma)]^{-1},$$

where the parameters $\varepsilon_\infty = 9.0685$, $\omega_p = 8.9269\,\text{eV}$, $\Gamma = 0.076\,\text{eV}$.[15] Figure 1 shows the difference between the Drude model and the experimental data for energies 1.02–2.01 eV obtained by Johnson and Christy.[16] For wavelength 650–1200 nm, the Drude model fits quite well with the experimental data.

Figure 2 shows a cross section of the double chain waveguide. Without loss of generality, the parameters used in our calculation are listed as follows: the radius of each cylinder is 50 nm, and the distance between the centres of the upper and lower cylinders in the double chain is 200 nm, while the centre-centre distance of the adjacent cylinders is 120 nm along each chain. Similar to Gray's V-shaped coupler, we devise a cone-shaped cylinder array coupler, which consists of 9 cylinders, each one has a radius 50 nm, and the centre-centre distance is 200 nm. A Gaussian beam with a waist of 600 nm and wavelength ranging form 650 nm to 1200 nm irradiates from the left side. Then it is guided into the double chain waveguide by the cone-shaped coupler as shown in Fig. 3.

In the calculation of the transmission loss, we follow Quinten's method while the energy flux but not the field intensity is considered. We calculate the time-averaged Poynting vector component S_x along

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the centre of each pair of cylinders in the double chain (see the open circles in Fig. 2). Each chain contains 100 cylinders which are long enough to neglect the contribution of the energy reflections from the end.

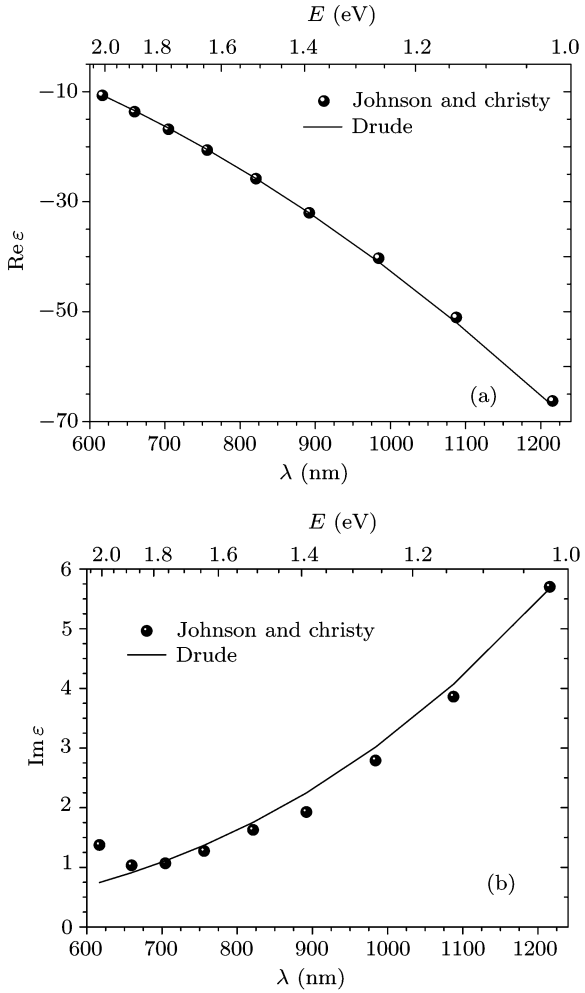


Fig. 1. (a) Real part of the permittivity of gold. (b) Imaginary part of the permittivity of gold.

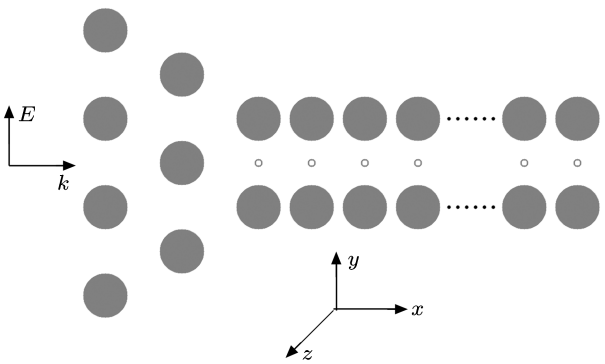


Fig. 2. Scheme of the double chain waveguide.

Figure 4(a) shows the propagation decay of energy flux for several wavelengths. The energy does not decrease constantly but reach its maximum after several hundreds of nanometres. This indicates that reflections still exist even after 12 μm transmission length. Another reason may be the impedance mismatch between the incident light and the waveguide. For wavelengths above 800 nm, the curve shows a linear decrease after 2 μm transmission length, or the energy flow decreases exponentially. This means that the waveguide mode has been fully excited for those wavelengths. However, for the wavelengths of

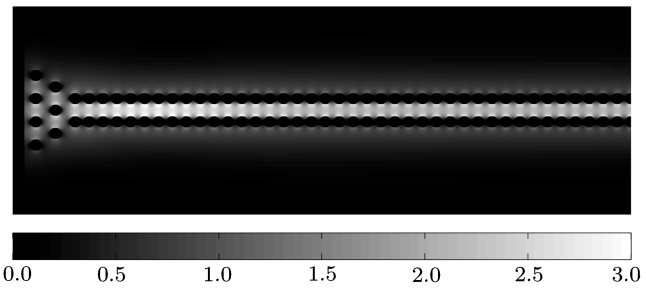


Fig. 3. Normal Poynting vector component S_x/S_0 distribution for the wavelength 1000 nm, S_0 is the Poynting vector component at the incident line. The waveguide contains 100 pairs of cylinders, only 40 pairs are demonstrated.

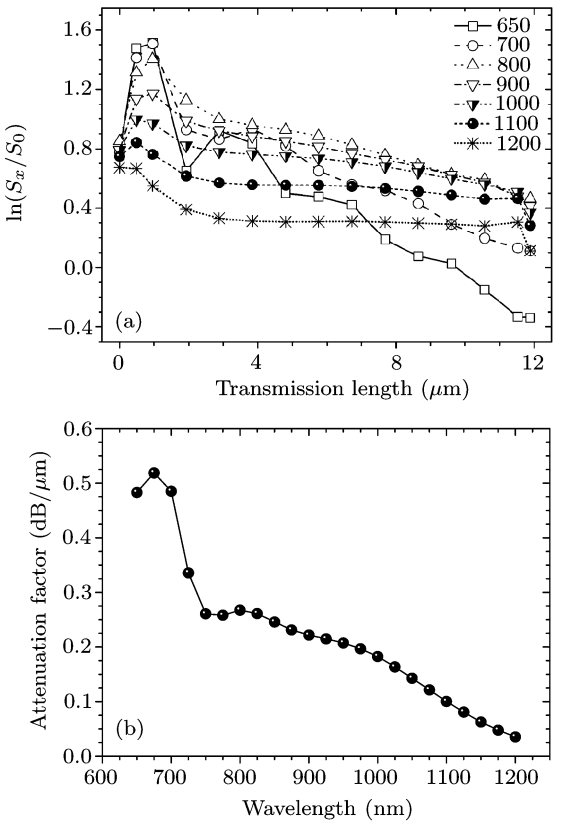


Fig. 4. (a) Decay of the Poynting vector component along the chain axis. (b) Attenuation factor of the double chain waveguide. The results are obtained from the linear fit of $\ln(S_x/S_0)$ between the 61st and 90th pair of cylinders.

650 nm and 700 nm, the situation is complicated. The curves decrease rapidly with some oscillations, which means that no waveguide mode can be excited.

Figure 4(b) shows the attenuation factor for wavelengths in the range 650–1200 nm. The results are obtained from the linear fit of $\ln(S_x/S_0)$ between the 61st and 90th pair of cylinders. The attenuation for wavelength below 750 nm is much greater than the wavelength above it. For wavelength above 800 nm, the longer wavelength corresponds to lower attenuation.

We also presented a Y-splitter as shown in Fig. 5. Both the input side and the splitter side are composed of two chains of cylinders with radius 50 nm. At the input side, each pair of cylinders vertical to the major axis has a centre-centre distance 200 nm, but at the splitter side the distance is correlated to the splitting angle, and can be easily calculated from the geometry relations. For our 90° splitting angle, this distance is 141 nm. The separation distance of the adjacent cylinders at the input side is 20 nm, and at the splitter side only 10 nm to reduce the energy leakage.

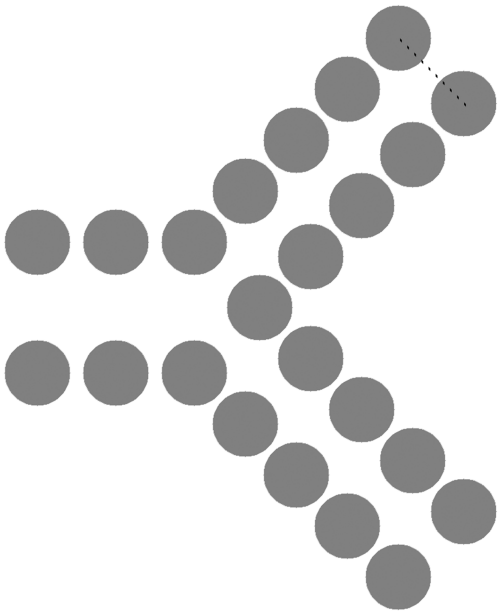


Fig. 5. Scheme of the double chain Y-splitter. The Poynting vector component normal to the dotted line is monitored.

In order to calculate the efficiency of the splitter, we arranged 16 pairs of cylinders at each branch of the splitter and monitor the energy flux along the 5th pair (see the dotted line in Fig. 5). The Poynting vector component normal to the monitoring line is integrated, and then divided by the incident power to give the transmission efficiency. In our actual simulations, we also use the coupler discussed above to receive more energy of the incident Gaussian beam with waist 600 nm, and set an artificial perfect conductor screen to avoid the direct illumination from the incident beam on the splitter arrays. The transmission efficiencies are calculated for wavelength from 650 to 1200 nm, as shown in Fig. 6. For wavelength between 725 nm and 900 nm the splitter performs better, and each branch reaches about 20% of the incident power, much more than the value of 7% for wavelength 1200 nm. The electric field amplitude distribution for wavelength 800 nm is displayed in Fig. 7. Since the distance between the monitoring line and the input side is not long enough, the attenuation of the waveguide mode does not dominate, and the transmission efficiency for different wavelengths is mainly due to the match of impedance between the input side and the splitter side.

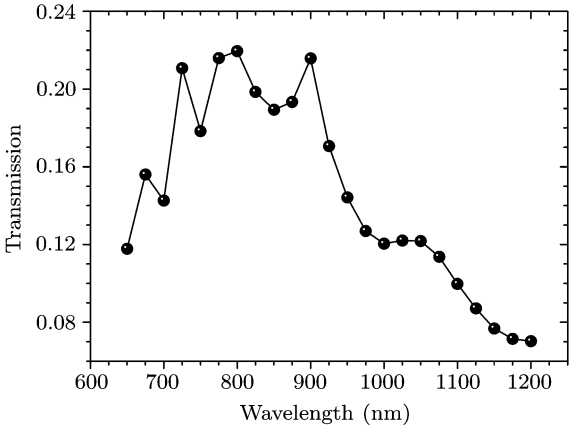


Fig. 6. Transmission efficiency of the Y-splitter with 90° splitting angle.

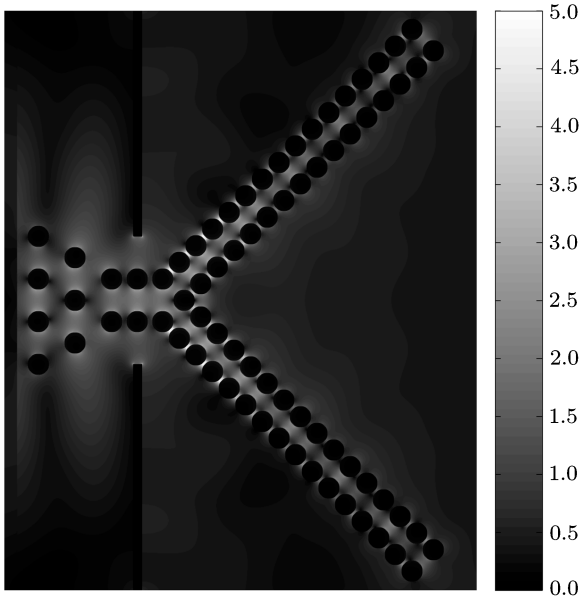


Fig. 7. Normal electric field amplitude $|E/E_0|$ distribution for light with 800 nm wavelength. The cone-shaped coupler is used at the input side, and an artificial perfect conductor screen is set between the splitter side and the input side.

We also simulate Panoiu's single chain Y-splitter with the same radius and splitting angle as our double ones. The transmission efficiency at the wavelength of 800 nm is estimated to be about 1% using the method applied above, the same order with Panoiu's calculation, which is lower than 21.9% of the present method. It is not surprising that the double ones perform better than the single ones, because the light not only propagates along each chain just as the single one, but also along the gap of each other, as shown in Fig. 7.

In conclusion, we have studied the 2D surface plasmons waveguide based on double chain nanocylinders using FDTD, and calculated the attenuation factor for wavelength 650–1200 nm. For wavelength longer than 750 nm the attenuation of the waveguide is low. We have also presented a Y-splitter based on double chain, and calculated the transmission efficiency for splitting angle 90°, which gives a quite well efficiency for wavelength range 725–900 nm. Lower attenuation and higher splitting efficiency may be obtained by optimizing the geometrical parameters and wavelength range.

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