Nanorice Chain Waveguides Based on Low and High Order Mode Coupling

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Abstract *– We investigate the optical properties of a plasmonic chain waveguide consisting of a linear array of elongated nanoshell particles (i.e. nanorice), where the interaction is based on low and high order mode coupling. Research shows that the propagation length can be improved by this kind of nanorice structures when compared to solid metallic structures with elongated (elliptical) shapes. Furthermore, at high order resonances, the propagation, as well as the energy transfer can be enhanced compared to the propagation at low order mode interactions. These findings allow the design of highly efficient waveguides for guiding light on the nanoscale.*

Introduction

Waveguiding at nanoscale dimensions using metallo-dielectric structures become an active research topic of increasing interest [1]. One promising candidate is the so-called plasmonic chain waveguide made of orderly arranged nanoparticles, which can provide strong 3D mode confinement at still moderate propagation lengths [1]. By changing the building blocks of the chain, the performance of the waveguide can be further improved, when using a more complex geometry for the nanoparticles [2], such as e.g. elliptical nanoparticles similar to a nanoscopic grain of rice [3]. Nanorice chains are essentially set up from a specific kind of (elongated) nanoshells, which consist of a dielectric core and metallic cladding material. The underlying nanorice particles show a wide tuning range of the surface plasmon resonances, reaching from ultraviolet to the near-infrared [3]. Moreover, the modes existing in nanorice particles can be either of low or high order provided the geometric parameters are properly selected. In the following we shall discuss the advantages of plasmonic chain waveguides when consisting of nanorice particles. We investigate energy propagation in the framework of low and high order mode coupling. This study complements our previous research on spherical nanoshell chain waveguides [2].

Numerical modeling considerations

In this paper, we use full wave simulations based on the Finite Element Method (FEM) [4], which is capable to handle the complex geometries, as well as the strong dispersive nature of the materials involved with reasonably small numerical errors. For simplicity, only two dimensional structures are considered in this paper. Since the surface plasmon resonances of most noble metals occur at ultraviolet or optical frequencies, our calculation is then carried our in the wavelength range from 300 nm – 900 nm. Considering the polarization dependence of such 2D structures, only *H*-polarization is used here, where the magnetic field (i.e. the H_z component) is oriented out of the plane as depicted in Fig.1.

Results and discussion

The nanoshell chains under consideration are shown in Fig.1. First, the resonances of an isolated nanorice particle are detected while calculating its scattering cross section (SCS). The wavelengths related to the peaks in the SCS's spectral response correspond to the resonance wavelengths, where the interaction of light at an angular frequency ω with the metal nanoparticle is strongest if ω lies in close vicinity to the particle's localized surface plasmon frequency.

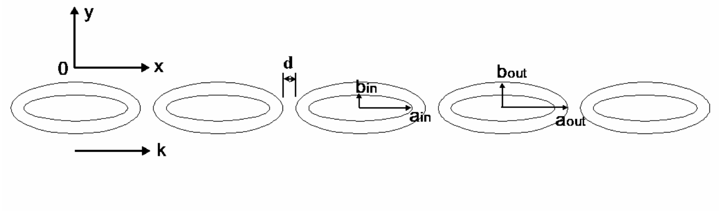


Fig.1. A schematics of the chain waveguide under calculation. The nanorice particle consists of a dielectric core ($n = 1.5$) and a silver shell [5], the overall structure is embedded in air. The coordinate system is indicated in the figure and the wave is incident from the $-x$ direction. The geometric parameters of the nanorice are $a_{\mathrm{in}} = 40$ nm, $b_{\mathrm{in}} = 10$ nm, $a_{\mathrm{out}} = 50$ nm, and $b_{\mathrm{out}} = 20$ nm, with a particle separation of $d = 10$ nm.

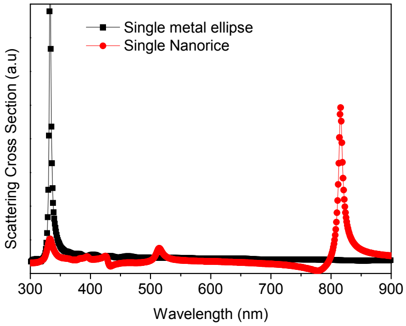
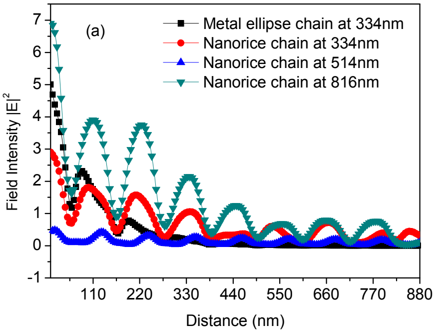


Fig.2. Scattering cross sections of a single nanorice and a solid metallic elliptical particle.

Figure 2 shows the SCSs for single nanorice and a solid silver elliptical particle having the same shape and volume as the nanorice. The resonances for the nanorice are found at 334 nm, 514 nm, 816 nm within our wavelength of interest. The modes in the nanorice at 334 nm and 514 nm are characterized as multipolar modes due to mode hybridization [3, 6], whereas the mode at 816 nm and the mode in the solid elliptical counterpart at 334 nm are identified as low order modes. To investigate the propagation properties we use the resonant modes as an excitation field at the input of the particle chain. For comparison, energy propagation relying on other non-resonant modes will be demonstrated as well.

The chain waveguide under investigation consists of 12 nanorice particles (the spacing between two adjacent particles is 10 nm throughout the paper). In order to numerically estimate the power attenuation of the chain waveguide, first; the field intensity along the particle chain was computed at a line parallel to the propagation direction which is displaced to the outmost surfaces (*y*- direction) of the nanorice; second, the attenuation factors are then calculated referring to the Beer-Lambert law (exponential decay of the field intensity with respect to the propagation length). Here we will use the spatial averages of the field intensities. Note that the computed data from the first and the last nanorices in the chain will be excluded, in order to mask out interference effects stemming from impedance mismatch at the far and the near end of the chain waveguide.



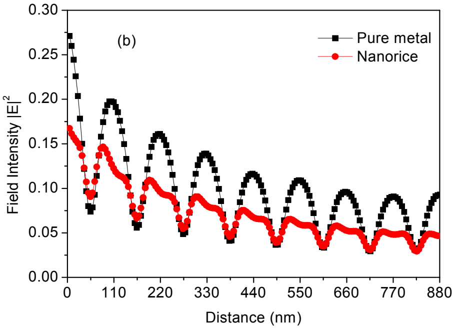


Fig.3. Total electric field intensities along the outer surfaces of the 12-nanorice chain. The starting point (0) is at the outmost surface of the second nanorice particle. (a) The chain waveguides are operated at the single resonance of the underlying particle, namely the nanorice or the solid metallic elliptical particle, including low and high order modes. (b) The chains operated at off-resonance of the structures (at 600 nm).

Figure 3(a) displays the results of the total electric field intensities along the outmost surfaces of a 12-nanorice chain under the operation of low order modes (816 nm) and high order modes of a single nanorice (334 nm, 514 nm). The result of a 12-elliptical solid particle chain is also shown for comparison. The power attenuation factors for the cases as given in Fig. 3(a) are $\alpha_1 = 0.0010488\,\mathrm{nm}^{-1}$(nanorice chain at 334 nm), $\alpha_2 = 0.0011834\,\mathrm{nm}^{-1}$ (nanorice chain at 514 nm), $\alpha_3 = 0.00455\,\mathrm{nm}^{-1}$ (nanorice chain at 816 nm), and $\alpha_4 = 0.0093\,\mathrm{nm}^{-1}$ (elliptical particle chain at 334 nm), which correspond to a 1/*e*-propagation length of $L_1 = 953$ nm, $L_2 = 845$ nm, $L_3 = 219$ nm, $L_4 = 107$ nm, respectively. As can be seen from these figures, the propagation length is dramatically enhanced by a factor of 8 when using such nanorice structures instead of the pure metal counterpart even when the structure is operated on the low order resonance of the single nanorice particle. Since the light matter interaction is strongest at low order resonances, the enhanced propagation of nanorice chain at low order mode arises likely from the large field enhancement in the interparticle space [cf. the behavior of the field intensities in Fig. 3(a)]. Whilst at high order mode resonances, the propagation lengths are generally larger although the light matter interaction is not as strong as before. The enhanced propagation at high order mode coupling is owing to the promising far-field radiation features of the high order modes in nanorice structures, which shows forward radiation features along the chain direction [2], and thus the interaction between particles is supported by far-field contributions. Figure 3(b) shows the results when the chains are operated at off-resonance either of the nanorice or of the solid metallic elliptical particle. As can be seen in Fig. 3(b), there is no big difference for the structure's propagation properties, and high-energy transfer is also possible at off resonances. This is due to the fact that at off-resonances, the nanoparticle acts as a weak dipole, where the weak coupling between adjacent particles leads to a considerable reduction of damping losses. However, there is a well-known trade-off between mode confinement and propagation length: The propagation length is smaller at resonant coupling which is associated to a strong field concentration; the propagation length is larger at off-resonances but with less tight field confinement. It should be noted that the local response of the chain is quite sensitive to the incident light due to interference effects. In particular, the mode coupling becomes more complicated when the nanoshell particle encompasses complex geometries. Under these circumstances mode hybridization is likely to give rise to a considerable amount of novel features that will be investigated in the near future.

Conclusions

In this paper, we investigate the optical properties of a plasmonic chain waveguide consisting of elongated nanoshells, i.e. nanorice. The propagation lengths under resonant and non-resonant conditions of single nanorice particles are analyzed. Studies show that the propagation, as well as energy transfer can be significantly improved by means of the proposed structure. Particularly, high order mode coupling provides enhanced propagation compared to low order mode coupling in the particle chain. This would inspire new design rules for light guiding in the nanoscale range.

References

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