Surface-mediated transmission efficiency of optical signals through linear chains of metal nano-particles

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Abstract

We show that the transmission efficiency of optical signals through a linear chain of spherical silver metal nanoparticles can be substantially changed by placing the array close to a reflecting interface. We discuss the polarization and spectral dependence of the transmission efficiency in the presence of different reflectors.

1. Introduction

Metal nano-particles (MNPs) are known to have absorption cross sections that can exceed the MNP's geometrical cross section by more than an order of magnitude, if the excitation is close to the plasmon resonance [1]. This property makes MNPs very usefull for scaling down optical components to the nano-scale. For guiding light at these subwavelength scales, it was suggested to use arrays of closely spaced MNPs [2]. In this research, we theoretically study the transmission efficiency of optical signals through a linear array of MNPs, i.e., the ratio of the modulus squared of the dipole moments of the first and last MNPs, in the presence of a reflecting interface.

2. Theory

Excitation of a spherical MNP induces a dipole moment $\mathbf{p}$ in the particle with a direction parallel to the polarization of the excitation field $\mathbf{E_0}$. The amplitude of the dipole moment will depend on the amplitude and frequency ω of the applied field. The proportionality coefficient between the dipole moment and the field amplitude is called the polarizability α, which is given by

$$\frac{1}{\alpha(\omega)} = \frac{1}{\alpha^{(0)}} - \frac{k^2}{a} - \frac{2i}{3}k^3, \quad \text{where} \quad \alpha^{(0)} = \frac{\epsilon(\omega) - \epsilon_b}{\epsilon(\omega) + 2\epsilon_b}a^3 \quad \text{and} \quad k = \frac{\omega}{c}\sqrt{\epsilon_b}. \tag{1}$$

The equation for the bare polarizability $\alpha^{(0)}$ is derived in the quasi-static limit (ϵ_b is the permittivity of the background medium and a is the radius of the MNP), while the k-dependent corrections to $\alpha^{(0)}$ result from the depolarization field in the particle [3]. The frequency dependence of $\alpha(\omega)$ comes from the dielectric function of the metal $\epsilon(\omega)$. The polarizability exhibits a resonance at the frequency for which the denominator of α is minimized. This corresponds to the so-called surface plasmon resonance, originating from the collective oscillation of the free electrons in the particle.

When an array of MNPs is considered, the dipole moment that will be induced in each particle results from the incoming field and the electric field produced by all other MNPs. In a homogeneous environment, the electric field at a position $\mathbf{r}$ produced by an oscillating point dipole located at $\mathbf{r}'$ is represented by the Green's tensor $\hat{\mathbf{G}}^H$ [4]

$$\hat{\mathbf{G}}^H(\mathbf{r},\mathbf{r}') = \frac{1}{\epsilon_b}\Big(k^2\mathbf{1} + \nabla\nabla\Big)\frac{e^{ik|\mathbf{r}-\mathbf{r}'|}}{|\mathbf{r}-\mathbf{r}'|}. \tag{2}$$

In the presence of an interface, the field that is reflected from the interface will also contribute to the dipole moments in the array. To account for this effect, we define a Green's tensor $\hat{\mathbf{G}}^S$ that describes the reflected field, and write the full tensor as $\hat{\mathbf{G}} = \hat{\mathbf{G}}^H + \hat{\mathbf{G}}^S$. The components of $\hat{\mathbf{G}}^S$ can be calculated within the framework of Sommerfeld's treatment of a dipole oscillating close to a partially reflecting interface (see ref. [4] and references therein). Using this approach, the dipole moments induced in an array of N MNPs placed near a dielectric-metal interface (Fig. 1) can be calculated from the following system of equations:

$$\sum_m \Big[\frac{1}{\alpha}\delta_{n,m} + (G^H_{n,m} + G^S_{n,m})\Big]\mathbf{p}_m = \mathbf{E}_m \Leftrightarrow \hat{\mathbf{M}}\mathbf{p} = \mathbf{E} \tag{3}$$

where $\delta_{n,m}$ is the Kronecker delta, $\hat{\mathbf{M}}$ is a $3N$-by-$3N$ matrix and $\mathbf{p}$ and $\mathbf{E}$ are $3N$-component vectors that represent the dipole vector and applied electric fields on each MNP. The dipole moments can now be computed after calculating the inverse matrix $\hat{\mathbf{M}}^{-\mathbf{1}}$.

To get insight into the spectral dependence of the transmission efficiency, it is very useful to know the normal modes and eigen frequencies of the array (see below). These can by calculated by solving equation (3) for $\mathbf{E}$ equal to the zero-vector, which implies that the frequencies at which det($\hat{\mathbf{M}}$)= 0 have to be found.

In an isolated linear chain of MNPs, there are two different types of modes: those with dipole moments parallel to the chain axis (longitudinal) or perpendicular to the chain axis (transverse). It has been shown that for transverse modes an anti-crossing occurs at the light line, indicating polariton behaviour, and that for an infinite array modes situated below the light line do not suffer from radiative losses. Furthermore, the slope in the dispersion relation, i.e., the groupvelocity, is maximized close to the light line [5].

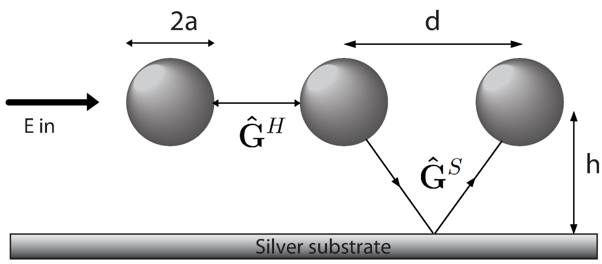

Fig. 1: Schematics of the system under study.

3. Results and Discussion

In this research, we consider and compare three different cases: the transmission through an isolated array, through an array above a perfectly reflecting substrate, and through an array above a silver substrate. In this abstract we present the results for longitudinal excitation of an array consisting of 10 silver MNPs under CW excitation of the first particle (shown in Fig. 2). The parameters of the array are given in the caption of the figure.

For the longitudinal geometry, the interaction between the dipoles is negative, implying that the normal modes with high k-values correspond to high frequencies. Since those modes suffer less from radiative losses, they are expected to be the most important for guiding purposes. Comparing the spectral position of the transmission efficiency of an isolated array with the plasmon resonance for single MNPs (dashed line), indeed a shift to smaller wavelengths (blueshift) is observed.

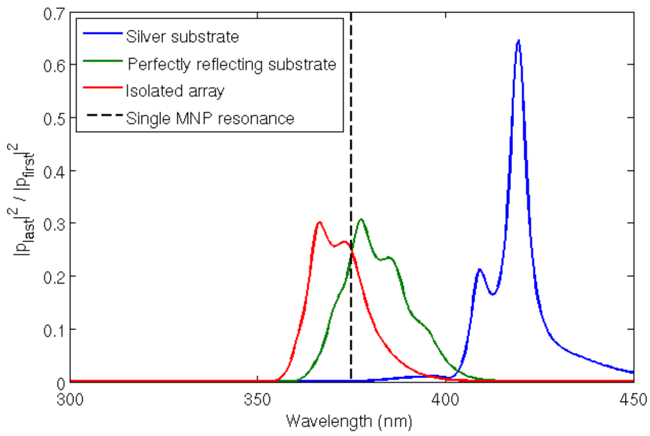

Fig. 2: Transmission efficiency $|\mathrm{p}_{\mathrm{last}}|^2/|\mathrm{p}_{\mathrm{first}}|^2$ of the signal as a function of the excitation wavelength for an array of 10 MNPs with a radius of 30 nm, interparticle spacing of 90 nm, and at a heigth of 45 nm above the substrate. The excitation is only on the first particle with polarization along the chain axis (longitudinal).

If we compare the transmission efficiency for an isolated array with that of an array on top of a perfectly reflecting interface, we observe that the latter is red-shifted. The reason for this is that the interaction of the dipoles in the array with the image dipoles induced in the substrate has a positive sign. Therefore, due to this interaction the modes that are dominant for transmission will reside at larger wavelengths. Furthermore, a part of the field that has been radiated by the array will be reflected from the interface and excite the array again. This will give rise to a mixing of the modes present in the isolated array and, because of this mixing, there is a difference between the spectral shape of the transmission efficiency of an array with and without an interface.

A non-perfect reflector, like silver, differs from a perfect reflector in the sense that several types of surface modes can be excited on the interface. For one of these modes, the surface plasmon polariton (SPP), the possibility of guiding these modes by arrays of MNPs has been shown [6]. Therefore, under some conditions, these SPPs can support transmission through the array and increase the transmission efficiency. Due to the exponential decay away from the surface, the influence of SPPs is most pronounced in close proximity to the interface.

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