Theoretical study of plasmonic propagation on a chain array

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Abstract *- A chain of gold nanoparticles embedded in a dielectric waveguide is proposed to locally transfer energy from a guided optical mode into a nearby absorbing medium through the excitation of surface plasmon modes. The energy transfer is evaluated placing different absorbers at the end of the chain.*

Introduction

The purpose of this work is to investigate a way to locally transfer energy from a guided optical mode into an absorbing medium using a metallic nanodevice. Plasmonic properties of metallic particles provide both confinement and enhancement of the light, offering the potential for efficient energy transfer [1]. The idea is to use a chain of closely packed gold nanoparticles in order to produce a hot spot at the end of the chain, in a similar way to what was proposed by Ghenuche et al in [2]. For this purpose, a strong coupling between each gold particle is important. This can be achieved in the near-field coupling regime, which occurs when the metallic objects are coupled together through the evanescent waves they scatter under illumination. The interspace between the particles must then be only a few tens of nanometers. We consider a system made of a number N of gold nanoparticles placed inside a dielectric waveguide (Fig. 1). In the following simulations the size of the particles is chosen to be $100 \times 100 \times 20$ nm^3. The period of the chain is 120 nm, which means that the gap between two adjacent particles is 20 nm. The chain is excited by the first TE mode supported by the slab, with the electric field directs as shown in Fig. 1. This can excite a surface plasmon mode which results from the combination of the individual localized surface plasmon mode of each particle.

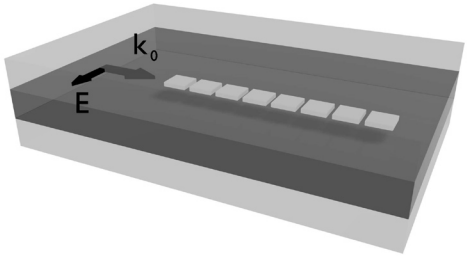
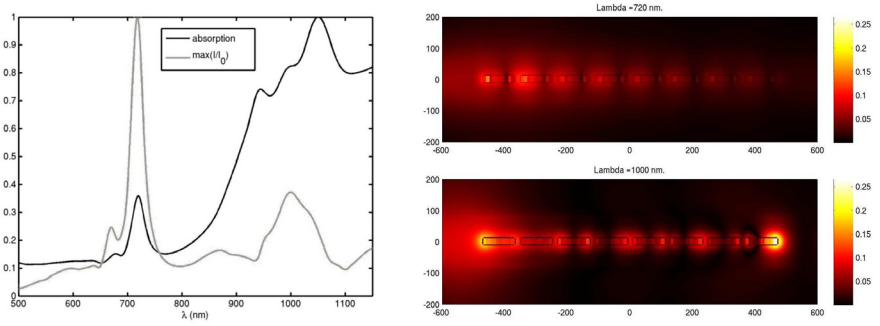


Figure 1: A chain of eight gold particles embedded in a dielectric waveguide and illuminated by a TE-polarized mode.

The electromagnetic field is computed using the Green's tensor formalism. A detailed description of the method can be found in the literature, see for example references [3, 4]. The data for gold susceptibility were taken from Palik [5].

Spectroscopy

As first example, we consider a structure where the waveguide is 150 nm thick, and the refractive index is equal to 2.1. The effective index of the incoming guided TE mode evolves from 1.7 ($\lambda = 720$ nm) to 1.4 ($\lambda = 1000$ nm). Several methods are possible to characterize the response of the structure. Two parameters are plotted in Fig. 2(a): the absorption per volume unit and the maximum of the electric field amplitude inside the gold structure. Absorption is calculated based on the time-averaged Joule power per volume unit ; by electric field amplitude we mean the square root of the time-averaged intensity.



(a) (b)

Figure 2: (a) Absorption and electric-field maximal-amplitude spectra, normalized to their maximum ; (b) Distribution of the electric-field amplitude in the plane perpendicular to the middle of the chain, for the two resonances of the maximal-intensity spectrum.

Both quantities have been normalized to their maximum for easier comparison. The absorption (black curve) and the field maximum (gray curve) show similar responses in the position and number of peaks. Two sets of resonances are observed, respectively around $\lambda = 700$ nm and $\lambda = 1000$ nm. Two peaks are visible around $\lambda = 700$ nm, whereas the broad resonance around $\lambda = 1000$ nm is composed of several different peaks, sometimes hidden in the wings of the main resonance (see $\lambda = 870$ nm). We note that the maximum for the field intensity, around 1000 nm, is not reached at the same wavelength as the one for maximal absorption, around 1050 nm. Figure 2(b) shows the distribution of the time-averaged electric-field amplitude on the plane crossing the middle of the chain, for the two resonance wavelengths of the maximum intensity spectrum (Fig. 2(a), gray curve). At 720 nm, the field amplitude drops rapidly along the chain direction, and is almost zero inside the last gold particle: the energy is completely absorbed and scattered by the chain while the incident guided mode propagates inside the system.
The resonance at 1000 nm has a completely different structure, as both ends of the chain show a strong field enhancement. This results from the coupling between the incident field and the collective mode of the chain. Indeed, as the effective wavelength of the mode supported by the dielectric waveguide is $1000/1.43 \approx 700$ nm, the chain length is about 1.5 times the wavelength. Hence the gold system resonates, and the electric field at the two ends oscillates in phase opposition. In the present case, the maximum is at

the forward end, which is interesting to optimize the energy transfer. The electric field intensity at this location is 26 times the intensity of the incoming electric field at the middle of the waveguide.

Influence of the waveguide parameters

The proposed system has a very large parameter space, as all the dimensions and materials can be modified in order to optimize a chosen property. In the following we focus on the effect of the waveguide thickness. Moreover, we also change the waveguide material to SiO_2 in order to demonstrate that the previous effects can be shifted to different wavelengths ($n = 1.5$).

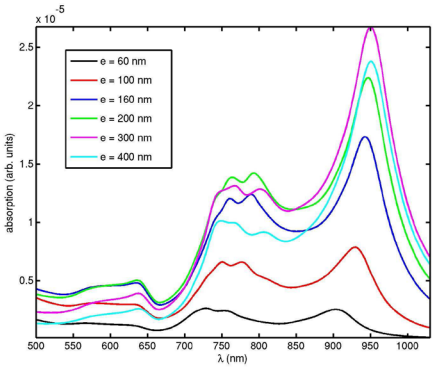
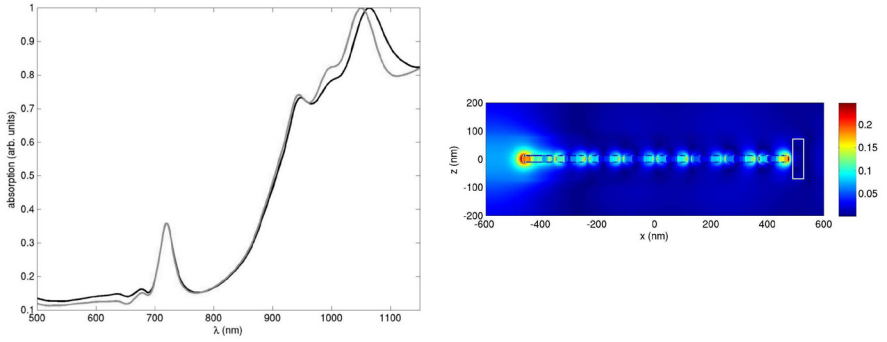


Figure 3: Evolution of the absorption spectra with the thickness of the silica waveguide.

Figure 3 shows the absorption spectra of a chain composed of 10 gold particles, placed in a $n = 1.5$ waveguide of variable thickness e. As in the previous paragraph, two broad peaks are observed. An increase of the waveguide thickness results in a red-shift of the different resonance wavelengths. The longer wavelength peak corresponds here to absorption of the incoming wave by the chain. Similarly, the light intensity decays all along the system (not shown). The shorter wavelength group of resonances corresponds to the excitation of cavity modes: the evaluation of the effective wavelength of the incident guided mode shows that the light couples in this case to the $L = 2\lambda$ cavity mode of the chain. The electric-field distribution (not shown) indicates that the balance between the electric field amplitude at the end and the beginning of the gold chain can be modified by varying on e. Moreover the enhancement in intensity at the end of the chain is about 40 times the incoming intensity in the middle of the waveguide from $e = 60$ nm to $e = 300$ nm.

Effect of an absorbing element

In order to study the energy transfer to a nearby absorbing medium, several geometries and materials has been considered. In the following example, a chromium pad is added 20 nm away from the last gold particle. The block is chosen to be $150 \times 150 \times 30$ nm^3, with the shortest side being set parallel to the chain axis.



(a) (b)

Figure 4: (a) Absorption spectra of the eight-particle chain without (black) and with (gray) chromium block placed 20 nm away from the last particle ; (b) Amplitude of the electric field along the middle of the chain, with the chromium block.

As expected, the absorption spectra computed with and without the absorber are almost identical around the short wavelength resonance, as the incoming wave does not reach the last particle (Fig. 4(a)). The shapes differ somewhat for the wavelengths around 1000 nm, as the last gold particle is then strongly excited: the mode is then more sensitive to the presence of the chromium particle. A shift of 20 nm in the position of the maximum is observed. The distribution of the electric field amplitude (Fig. 4(b)) shows unfortunately that the presence of the chromium particle is unfavorable since it tends to expel the field, which prevents the energy from being transferred efficiently from the guided mode to the substrate. It will be shown that we can change the material of the particle and add an air layer between the chain and the absorbing part to influence the energy transfer.

References

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