Light manipulation with plasmonic nanoantennas

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***Abstract*— We explore the electromagneti properties of nanostructured plasmonic antenna and show that they can be effectively used fo light nano-confinement, field enhancement, an allow one to achieve left-handed response fro the nanoantenna composite.**

I. INTRODUCTION

Recent years have brought enormou progress to the field of material fabricatio leading to the increasing interest in th properties of nanostructured composites. The strategic positioning of such materials in between atoms (and similar-sized particles) and "macro-world" of continuous media causes promising and sometimes surprising electromagnetic properties. In this work we focus on the optical response of metallic nanowires and nanowire composites. Because nanowires and their composites can act as antennas in the rest of the paper we interchangeably use the terms "nanoantenna" and "nanowire".

We assume that the characteristic radius of individual nanowires b_2 is much smaller than the wavelength of the incident light λ, and is comparable with the skin-depth of the material. The length of the wire $2b_1$ should be at least comparable to the wavelength (see Fig.1). The properties of such nanostructures are somewhat similar to the properties of "conventional" antennas widely used in modern communications. However, the finite value of the dielectric constant of the metal in the optical range and typically low aspect ratio lead to the fundamental differences in the response of optical- and radio- antennas. Since the analytical solution for the problem of electromagnetic response of nanowires is hardly possible, we use the well-known coupled-dipole approximation[1], [2], [10] to find the response of our system.

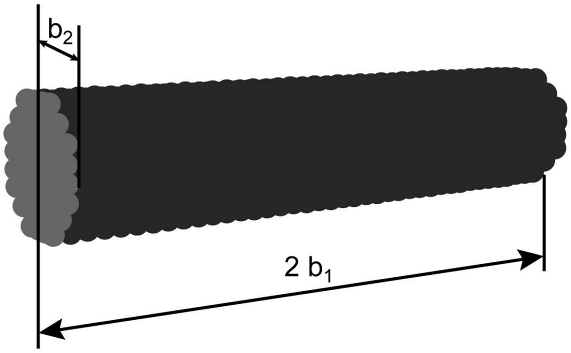

Fig. 1. A long nanowire represented by the array of point dipoles.

In this approach, a single nanowire is represented by an array of point dipoles. Each dipole is subjected to the field of an incident (plane) wave and to the field of all other dipoles. Thus, the dipole moments of all dipoles are coupled through the following *coupled-dipole equations* (CDEs):

$$\mathbf{d}_i = \alpha_0 \left[\mathbf{E}_{inc} + \sum_{j\neq i}^{N} \hat{G}(\mathbf{r}_i - \mathbf{r}_j)\mathbf{d}_j \right], \quad (1)$$

where E_{inc} represents the incident field at the location of i-th dipole, $\mathbf{r}_i$, $\hat{G}(\mathbf{r}_i - \mathbf{r}_j)\mathbf{d}_j$ represents the EM field scattered by the dipole j at this point, and $\hat{G}$ is a regular part of the free-space dyadic Green function defined as

$$\begin{aligned} G_{\alpha\beta} &= k^3[A(kr)\delta_{\alpha\beta} + B(kr)r_\alpha r_\beta], \\ A(x) &= [x^{-1} + ix^{-2} - x^{-3}]\exp(ix), \quad (2) \\ B(x) &= [-x^{-1} - 3ix^{-2} + 3x^{-3}]\exp(ix), \end{aligned}$$

with $\hat{G}\mathbf{d} = G_{\alpha\beta} d_\beta$. The Greek indices represent the Cartesian components of vectors and the summation over the repeated indices is implied.

The key parameter in CDEs is the polarizability of a monomer, α_0, usually given by Clausius-Mossotti relation (see, for example [5]) with the radiative correction introduced by Draine [2]

$$\alpha_{LL} = R^3 \frac{\epsilon - 1}{\epsilon + 2}, \tag{3}$$

$$\alpha_0 = \frac{\alpha_{LL}}{1 - i(2k^3/3)\alpha_{LL}}, \tag{4}$$

where ϵ is the dielectric permittivity of the material and α_{LL} is the Lorentz-Lorenz polarizability without the radiation correction. The magnitude of this polarizability, controlled by the parameter R serves as a fitting parameter, and is determined by the condition that the system response in the quasi-static limit should yield the correct depolarization factors. The fitting parameter R may be visualized as a radius of an imaginary sphere, centered over the position of a point dipole.

II. ENHANCED LOCAL FIELDS IN NANOANTENNA ARRAYS

The properties of a single metallic nanowire, as the properties of any metallic nanostructure are governed by its geometry and by the plasma-like response of a free electron gas inside it. Special kind of surface wave, known as plasmon polariton, can propagate on a metal-air interface of an infinitely long wire. The magnitude of such wave has its maximum at the interface and exponentially decays inside and outside the wire, so it effectively confines the optical light down to the “nanoscale”. In a finite-length nanowire the plasmon polariton conserves its surface nature, but becomes “leaky”, effectively coupling with the incident plane wave [10].

This surprising coupling between the plane and polariton waves, absent in the case of infinite media [11], opens a possibility to propagate the optical light through the array of nanoantennas, using them as wires in all-optical computers and telecommunication systems. It also opens the possibility of resonant light amplification on the nanoscale due to resonant excitation of polariton waves.

The local intensity in this case could exceed the intensity of the incident field by three or more orders of magnitude (Fig. 2). Such high local fields are beneficial for enhanced spectroscopy, lithography, absorption, nonlinear processes and all related applications. Note that high local fields at the resonance are usually accompanied by the narrow frequency band where the resonance exists [10]. The resonant frequency itself is controlled by the length of the nanowire and its material.

While the area of the enhanced local field is concentrated near the nanoantenna surface, the collective resonance of several antennas can lead to the enhancement of the *average* intensity in the antenna composite. The response of the equally separated parallel nanowires resembles the behavior of an isolated antenna (Fig. 2 a), exhibiting huge intensity enhancement in the narrow frequency ranges corresponding to the “eigen” frequencies of the plasmon polariton waves in the individual wires.

The situation changes dramatically when the antennas are randomly deposited on a dielectric substrate, and a surface metal concentration reaches the value when the composite starts to conduct a DC current (known as the percolation threshold). At this point the composite contains nanowire clusters of all possible sizes and configurations, each having its own resonance frequency, and generating at this frequency high local fields. The collective effect of all the clusters leads to the extremely broadband intensity enhancement, as shown in Fig. 2 (b). This effect is similar to the broadband field excitation in a conventional percolation film [3], [4]. However, in contrast to the percolation film, where the percolation threshold concentration is fixed and is equal to 50%, the percolation threshold in a nanowire composite is inversely proportional to the aspect ratio of the individual nanowires and can be made arbitrary small, making it possible to fabricate a “transparent nanoresonator”.

III. RADIATION BY NANOANTENNAS

The radiation properties of an isolated nanoantenna are well-described by its dipole moment (Fig. 3). The induced polarization in a substantially long and thin wire close to its first resonance ($2b_1 = \lambda_p/2$, where λ_p is the wavelength of the plasmon polariton) can be represented by the following relation [6]:

$$d_E = \frac{2b_1 b_2^2 f(\Delta) E \epsilon_m}{3(1 + f(\Delta)\epsilon_m (b_1/b_2)^2 \ln(1 + b_1/b_2)\cos\Omega)}, \tag{5}$$

where the dimensionless frequency Ω is given by $\Omega^2 = (b_1 k)^2 \frac{\ln(b_1/b_2) + ikb_1}{\ln(1+b_1/b_2)}$. The function

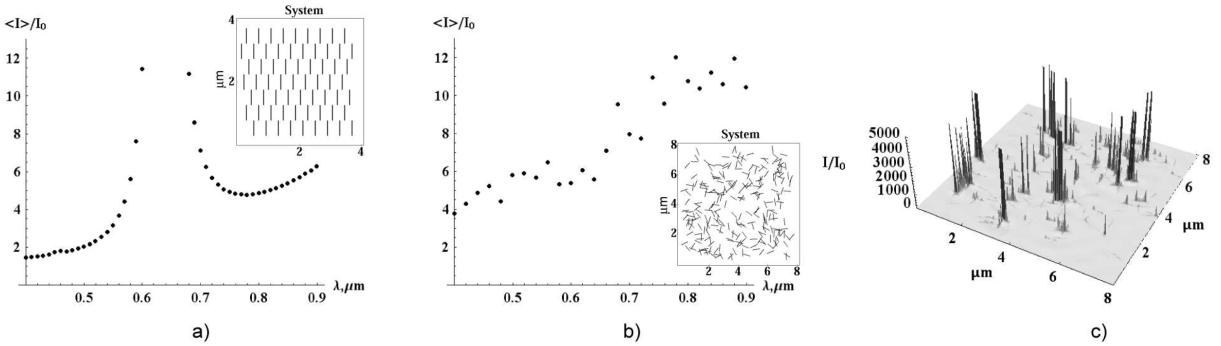

Fig. 2. (a) The average intensity enhancement over the parallel wire composite (inset) clearly shows a separated-resonance structure, an implicit property of single nanowire. (b) The random nanowire percolation composite (inset) exhibits a broadband intensity enhancement due to collective excitation of a large number of different resonant clusters. The intensity distribution over this composite for $\lambda = 800\ nm$ is shown in (c). The size of individual wire in both composites is $600 \times 20 \times 20$nm; surface concentration of metal is 4%.

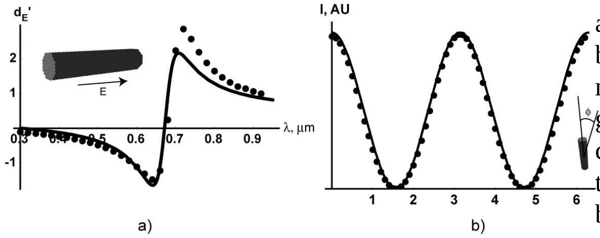

Fig. 3. (a) The comparison between the dipole moment found from numerical simulations (dots) and calculated using Eq.5 (line). The moments are normalized by unit volume. (b) Far-field intensity radiation pattern of a single nanowire in (a) is obtained from numerical simulations (dots) and calculated by approximating the antenna by a point dipole (solid line). The dimensions of the wire are $162 \times 32 \times 32$nm. The far field pattern is calculated for $\lambda = 560$nm.

$f(\Delta) = \frac{1-i}{\Delta}\frac{J_1[(1+i)\Delta]}{J_0[(1+i)\Delta]}$ is introduced to account for the skin effect; the parameter $\Delta = b_2\sqrt{2\pi\sigma_m\omega}/c$ represents the ratio of nanowire radius and the skin depth, and σ_m is the bulk metal conductivity.

However, the electromagnetic coupling between the different antennas in the composite may substantially change their optical response. As an example, we consider a system of two parallel nanowires positioned closely to each other. We consider the electric field of the incident plane wave to be parallel to the wires, and the magnetic field to be perpendicular to the common plane of the two wires (see Fig.4). The electric field excites the dipole moment in both wires. The magnetic field, on the other hand, excites the magnetic moment in the system through the excitation of circular current corresponding to the polariton waves traveling in opposite directions in different wires. The dipole and magnetic moments in the nanowire pair can be thought of as symmetric and anti-symmetric modes of coupled plasmon polaritons propagating on the nanowire surfaces. The polariton coupling is controlled by the distance between the wires. Similarly to the tunneling coupling between wavefunctions localized in different wells in the double-well potential, which causes the splitting between the energies of symmetric and anti-symmetric wavefunctions, the polariton coupling in nano-antenna system defines the frequency shift between the positions of dipole and magnetic resonances. By changing the geometry of the system we can shift the resonances to any region from the visible to near infrared frequency ranges [10], [12], [13].

Note that the system of coupled wires has a magnetic dipole moment comparable to its electric dipole moment and vanishing higher moments, so it exhibits highly-directional emission. This fact is illustrated in Fig.4, which shows excellent agreement between the far field obtained by direct calculation and by approximating the system by point electric and magnetic dipoles.

IV. NEGATIVE DIELECTRIC AND MAGNETIC RESPONSES OF A COUPLED NANOWIRE SYSTEM

The media with simultaneously negative dielectric permittivity and magnetic permeability, originally considered by Veselago [8] was predicted to have a negative refractive index and consequently exhibit a wide variety of surprising optical phenomena. Among them are the reversed Snell's law, Cherenkov radiation, and Doppler Effect. Due to its negative phase

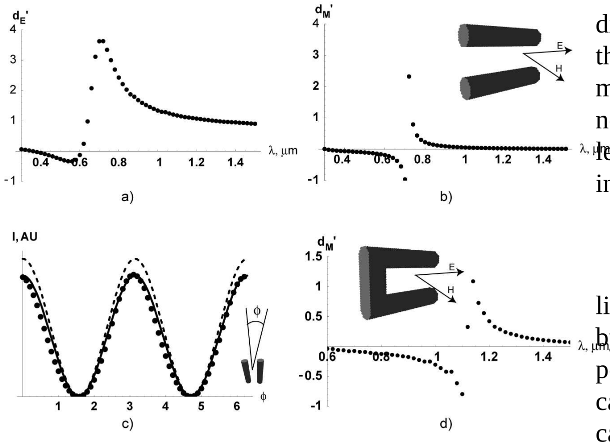

Fig. 4. (a) The dipole moment of the coupled nanowire system with dimensions 162 nm (antenna length) by 32 nm (antenna diameter) by 80 nm (distance between antennas). (b) The magnetic dipole moment of the system in (a). (c) Far field intensity distribution of system in (a-b) calculated using exact numerical simulations (dots), by approximating the system by point electric dipole (dashed line) and by approximating the system by point electric and magnetic dipoles (solid line). The far field pattern is calculated for $\lambda = 560$nm. (d) Connecting the coupled nanowires in (a-b) into a Π-structure drastically shifts the position of the magnetic resonance, leaving the dipole moment of the system practically unchanged (not shown). All moments are normalized by the unit volume.

velocity such media are often referred to as “left-handed”, meaning that the wavevector and the vectors of electric and magnetic fields form in such a material a left-handed trio in contrast to a conventional “right-handed” case.

One of the most promising phenomenon present in left-handed materials is so-called “superlensing”, where a slab of a medium with $\epsilon = \mu = -1$ is used to obtain an optically perfect image with subwavelength resolution in the far field [7].

While the left-handed materials were successfully fabricated in the microwave frequency range [9], direct “scale-down” of such media to the near infrared or optics is impossible. Moreover, any nontrivial magnetic response close to optical frequencies is often considered to be questionable[11]. However, as we showed above, the system of coupled nanoantennas does exhibit the magnetic response and may be used to prepare the optical composite with a negative refractive index.

When the wavelength of an incident light is below the polariton resonance in the coupled nanowire system, the excited moments are directed in opposite to the excitation field. Despite the shift between the positions of the dipole and magnetic resonances, there exists the frequency region where both dipole and magnetic moments are negative (Fig.4). Such negative responses may be used to implement a left-handed composite in the optical and near-infrared ranges[10], [12], [13].

V. CONCLUSION

The unique resonant characteristics of metallic nanoantennas could be precisely controlled by their geometry and material properties. The polariton resonance frequency in such devices can be tuned to any given range from the optical to the mid-infrared. Applications of plasmonic nanowire composites include narrow- and broadband nano-resonators, photonics, and left-handed media.

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