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Dielectric Yagi-Uda nanoantennas driven by electron-hole plasma photoexcitation

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Abstract. All-dielectric nanophotonics based on high-index dielectric nanoparticles became a powerful platform for modern light science, providing many fascinating applications, including high-efficient nanoantennas and metamaterials. High-index dielectric nanostructures are of a special interest for nonlinear nanophotonics, where they demonstrate special types of optical nonlinearity, such as electron-hole plasma photoexcitation, which are not inherent to plasmonic nanostructures. Here, we propose a novel type of highly tunable all-dielectric Yagi-Uda nanoantennas, consisting of a chain of Si nanoparticles exciting by an electric dipole source, which allow tuning of their radiating properties via electron-hole plasma photoexcitation. We theoretically and numerically demonstrate the tuning of radiation power patterns and the Purcell effect by additional pumping of several boundary nanoparticles with relatively low peak intensities of fs-laser.

1. Introduction

In the last several years high-index dielectric nanoparticles and nanostructures [1] proved to be a promising platform for various nanophotonic applications, in particular for the design of functional nanoantennas [2], enhanced spontaneous emission [3], photovoltaics [4], frequency conversion [5], Raman scattering [6], and sensing [7]. The great interest in such nanostructures is caused mainly by their ability to control the electric and magnetic components of light at the nanoscale [1], while exhibiting low dissipative losses inherent to the materials with a negligible concentration of free charges [7]. In particular, it has been demonstrated that nanoantennas composed of high-index nanoparticles have the ability to realize directional scattering of the incident light and to effectively transform the near field of feeding quantum sources into propagating electromagnetic waves [2].

Modification of the spontaneous emission rate of a quantum emitter induced by its environment, known as the Purcell effect [8], is not so pronounced in all-dielectric structures [9], as in microcavities [10] or plasmonic nanoantennas [11]. This is due to the fact that optical resonances of high-index nanoparticles are characterized by relatively low-quality factors and large mode volumes, which results in low efficiency of light-matter interaction. However, it was recently shown that this disadvantage can be overcome by relying on the *Van Hove singularity* of a chain of high-index nanoparticles [12]. Such approach allows to substantially enhance the local density of optical states (LDOS) at the location of a quantum source and thus achieve high values of the Purcell factor with relatively small dielectric nanostructures while leaving unaltered all their other advantages.

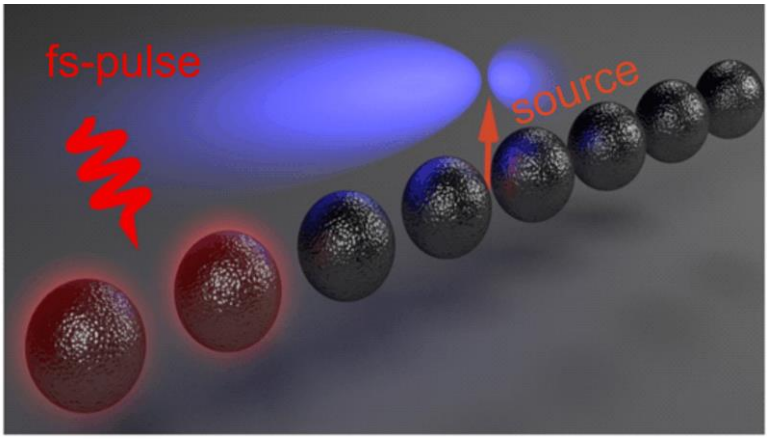

Figure 1. General view of the considered all-dielectric nanoantenna driven by the dipole source (orange arrow).

High-index dielectric nanostructures are also of a special interest for nonlinear nanophotonics, because they exhibit strong nonlinear responses. It was recently predicted and experimentally demonstrated that photoexcitation of dense electron-hole plasma (EHP) in silicon (Si) nanoparticles [13] and nanodimers [14] by femtosecond laser (fs-laser) pulses is accompanied by a dramatic modification of the radiation properties, whereas generation of EHP in germanium nanoantennas can even turn them into plasmonic ones in the mid-IR region [15]. Here, we propose a highly tunable all-dielectric nanoantenna, consisting of a chain of Si nanoparticles excited by an electric dipole source, which allows for tuning its radiation properties via electron-hole plasma photoexcitation. We theoretically and numerically demonstrate the tuning of radiation power patterns and Purcell factor by pumping several boundary nanoparticles in the chain with relatively low peak intensities of fs-laser pulses.

2. Result and Discussion

It is known that in periodic one-dimensional it is possible to observe Van Hove singularity, which is occurring at zero group velocity leading to infinite factor Purcell according to Ref. [16]:

$$F \cong \frac{1}{\pi}\left(\frac{\lambda}{2}\right)^2 \frac{c}{A_{\mathrm{eff}} V_{\mathrm{gr}}}, \tag{1}$$

with A_{eff} being the effective area of the resonant guided mode, λ the free space wavelength, V_{gr} the group velocity of the mode, and c is the speed of light. Here, we consider a chain of N spherical dielectric nanoparticles excited by an electric dipole (orange arrow), placed in the center of the chain and perpendicularly oriented to the chain axis, Figure 1. Crystalline silicon (c-Si) can be used as a material of the nanoantenna, with the real part of the dielectric constant being 16 in the considered frequency range [17]. All nanoparticles have the same radius r and center-to-center distance between neighboring particles is a.

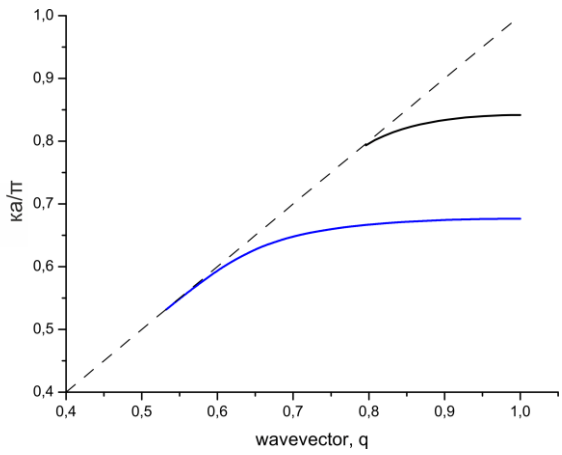

Figure 2. Dispersion curves of the eigenmodes in an infinite dielectric chain.

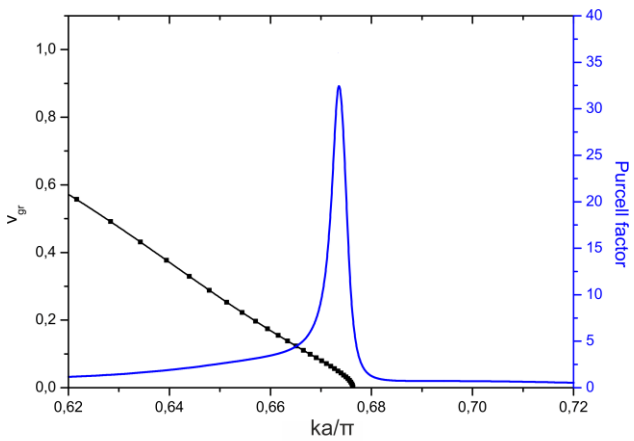

Figure 3. Spectral dependence of the Purcell factor (blue curve) and group velocity (black curve) for 8 dielectric nanoparticles.

To show existence of Van Hove singularity, we start by calculating dispersion of waveguide eigenmodes *ω(k)* in infinite chain of nanoparticles. For this we use well-known coupled-dipole model, where each particle is modeled as a combination of magnetic ***m*** and electric ***p*** dipoles oscillating with frequency ω. In the CGS system we can get the linear system of equations:

$$\mathbf{p}_i = \alpha_{ei} \sum_{j \neq i} (\hat{C}_{ij} \boldsymbol{p}_j - \hat{G}_{ij} \boldsymbol{m}_j), \tag{2}$$

$$\boldsymbol{m}_i = \alpha_{mi} \sum_{j \neq i} (\hat{C}_{ij} \boldsymbol{m}_j - \hat{G}_{ij} \boldsymbol{p}_j),$$

where, $\hat{C}_{ij} = A_{ij}\hat{I} + B_{ij}(\hat{r}_{ij} \otimes \hat{r}_{ij})$, $\hat{G}_{ij} = -D_{ij}\hat{r}_{ij} \times \hat{I}$, $\otimes$ is the dyadic product, $\hat{I}$ is the unit 3x3 tensor, $\hat{r}_{ij}$ is the unit vector in the direction from i-th to j-th sphere, and

$$A_{ij} = \frac{\exp(ik_h r_{ij})}{r_{ij}} \left(k_h^2 - \frac{1}{r_{ij}^2} + \frac{ik_h}{r_{ij}} \right), \tag{3}$$

$$B_{ij} = \frac{\exp(ik_h r_{ij})}{r_{ij}} \left(-k_h^2 + \frac{3}{r_{ij}^2} - \frac{3ik_h}{r_{ij}} \right),$$

$$D_{ij} = \frac{\exp(ik_h r_{ij})}{r_{ij}} \left(k_h^2 + \frac{ik_h}{r_{ij}} \right),$$

where, r_{ij} is the distance between the centers of i-th and j-th spheres, ε_h is the permittivity of the host medium, $k_h = \sqrt{\varepsilon_h}\, {}^{\omega}/_{c}$ is the host wavenumber, $\omega = 2\pi\nu$, ν is the frequency. The quantities α_e and α_m are the magnetic and electric polarizabilities of a spherical particle [18]:

$$\alpha_e = i\frac{3\varepsilon_h a_1}{2k_h^3}, \qquad \alpha_m = i\frac{3b_1}{2k_h^3}, \tag{4}$$

where a_1 and b_1 are electric and magnetic Mie coefficients.

Dispersion of infinite chain with r = 70 nm and a = 200 nm in free space is presented on Figure 2. Here, we use the dimensionless wavenumber $q = {}^{\beta a}/_{\pi}$, where β is the Bloch propagation constant. One can observe two modes in this frequency range. To characterize this mode, we calculate electric and magnetic moments and field distribution inside of nanoparticles. It turns out that blue and black curves correspond to TM-mode and TE-mode, respectively. In case of transverse magnetic mode, magnetic moments of each nanoparticles oscillating with π phase difference, which matches to magnetic field of dipole, orientated in the z direction. For this reason, we may expect significant enhancement of the Purcell factor for a finite system around the frequency, where group velocity of TM vanishes.

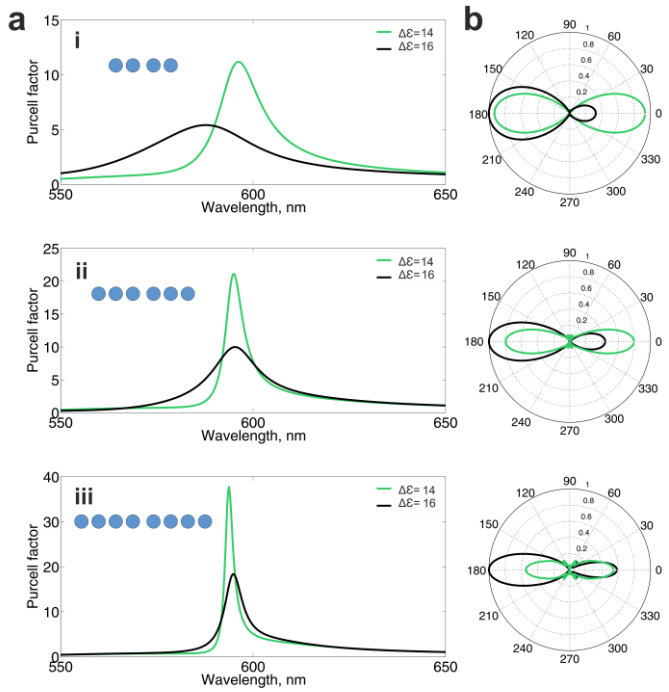

Figure 4. (a) Spectral dependence of the Purcell factor for the chains of dielectric nanoparticles for different number of nanoparticles N: (i) N = 4; (ii) N = 6; (iii) N = 8. (b) Radiation power patterns (E-plane) of the electric dipole source at the radiation wavelength of 600 nm. Green curves correspond to the unaffected chains Δε=0, whereas the black ones correspond to the chains with photo-excited boundary particles (Δε=-2).

To confirm this expectation, we calculate the Purcell factor using the Green's tensor approach [19]:

$$F = \frac{3}{2k_h^3}\boldsymbol{z}\cdot \mathrm{Im}[\boldsymbol{G}(0,0,\omega)]\cdot \boldsymbol{z}, \tag{5}$$

with *G(0; 0; ω)* being Green's tensor of an electric dipole in the center of chain (point of the dipole source localization) and ***z*** being the unit vector pointing in the z direction (Figure 1). Figure 3 shows the group velocity (black line) of TM-mode and calculated Purcell factor (blue line) as a function of wavelength for finite chain consisting of 8 nanoparticles with r = 70 nm and a = 200. We can observe a maximum of factor Purcell around the Van Hove singularity.

On the next step we have shown that Van Hove singularity is very sensitive to electron-hole plasma (EHP) photoexcitation in boundary particles. Due to this excitation, one can control optical properties of the material and consequently the radiation properties (intensities of emission and power patterns) of the nanoantenna. To describe EHP-induced tuning of the nanoantenna, we employ the analytical

approach developed in Ref. [14]. The dynamics of volume-averaged EHP density ρ_{eh} is modeled via the rate equation:

$$\frac{d\rho_{\mathrm{eh}}}{dt} = -\Gamma\rho_{\mathrm{eh}} + \frac{W_1}{\hbar\omega} + \frac{W_2}{2\hbar\omega}, \tag{6}$$

where, $W_{1,2}$ are the volume-averaged absorption rates due to one- and two-photon processes, and Γ is the EHP recombination rate which depends on EHP density [20]. The absorption rates are written in the usual form as $W_1 = \frac{\omega}{8\pi}\langle|\tilde{E}_{\mathrm{in}}|^2\rangle \mathrm{Im}(\varepsilon)$ and $W_2 = \frac{\omega}{8\pi}\langle|\tilde{E}_{\mathrm{in}}|^4\rangle \mathrm{Im}\chi^{(3)}$ where angle brackets denote averaging over the nanoparticle volume, and $\mathrm{Im}(\chi^{(3)}) = \frac{\varepsilon c^2}{8}\beta$, with β being two photon absorption coefficient. The relaxation rate of EHP in c-Si is dominated by Auger recombination $\Gamma = \Gamma_{\mathrm{ag}}\rho_{\mathrm{eh}}^2$, $\Gamma_{\mathrm{ag}} = 4\cdot 10^{-31}\mathrm{s}^{-1}\mathrm{cm}^6$. Now the permittivity of photoexcited Si should be related to time dependent EHP density:

$$\varepsilon(\omega,\rho_{\mathrm{eh}}) = \varepsilon_0 + \Delta\varepsilon_{\mathrm{bgr}} + \Delta\varepsilon_{\mathrm{bf}} + \Delta\varepsilon_D, \tag{7}$$

where ε_0 is the permittivity of non-excited material, while $\Delta\varepsilon_{\mathrm{bgr}}$, $\Delta\varepsilon_{\mathrm{bf}}$, $\Delta\varepsilon_{\mathrm{D}}$ are the contributions from bandgap renormalization, band filling, and Drude term, respectively. The detailed expressions for all contributions in Eq. (7) can be found in Ref. [14].

We calculated Purcell factor for different number of particles N before and after EHP photoexcitation (Figure 4). The calculations are performed for the change of the real part of Si permittivity Δε=-2, where $\Delta\varepsilon = \varepsilon(\omega,\rho_{\mathrm{eh}}) - \varepsilon_0$, which is achieved at the wavelength of 600 nm upon excitation of EHP with density $\rho_{\mathrm{eh}} = 1.5\cdot 10^{21}\mathrm{cm}^{-3}$. The decrease of the Purcell factor approximately by a factor of 2 in all cases (i–iii), along with the spectral broadening, are caused by symmetry breaking of the chain and corresponding decrease of the quality factor of the Van Hove singularity mode. The EHP photoexcitation also modifies the radiation pattern of the nanoantenna, Figure 4(b). Before the plasma excitation ($\Delta\varepsilon = 0$) the radiation pattern has two symmetric lobes directed along the chain axis in forward and backward directions (green curves). In this case, the maximal value of directivity grows with increasing of *N*. After the plasma excitation ($\Delta\varepsilon = 2$), nanoantenna radiates mostly in the direction of the affected particles. We note that the degree of modification of the radiation pattern grows with increasing number of particles. For example, in the case of *N=8* [Figure 4(b)iii], the directivity in the left direction is two times larger than in the right one. Thus, the EHP photoexcitation can be applied for all-optical switching of radiation patterns. Such dramatic tuning of the radiation pattern is caused by the Van Hove singularity regime of the initially unaffected nanoantenna.

3. Conclusion

We have proposed highly tunable all-dielectric nanoantennas, consisting of a chain of Si nanoparticles excited by an electric dipole source, that allow tuning their radiation properties via electron-hole plasma photoexcitation. We have theoretically and numerically demonstrated the tuning of radiation power patterns and the Purcell effect by additional pumping several boundary nanoparticles with relatively low peak intensities.

Acknowledgments

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