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Highly Tunable Dielectric Nano Antenna Consisting Chain of Silicon Particles by Dipole Emitter

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ABSTRACT

The study of a highly tunable dielectric nano antennas consisting of a chain of silicon nanoparticles excited by a quantum emitter was made. This allowed radiation properties tuned through hole plasma photo excitation. The tuning of radiation power patterns and the Purcell effect by pumping of boundary nanoparticles with relatively low peak intensities were demonstrated. This was also found that these effects were valid for the nano antenna situated on a dielectric surface. It was found that nano antennas were allowed for the tunable unidirectional lending of surface plasmon waves. The high index dielectric nanostructures for nonlinear nano photonics was produced due to their strong nonlinear response. The modification of the spontaneous emission rate of a quantum emitter induced by its environment was not so pronounced for single dielectric nanoparticles. This was due to low quality factor and large mode volumes which produced low efficiency of the light matter interaction. This was removed by relying on slowly guided modes in chain nanostructures. The Van Hove singularities associated with infinite structures in the high Purcell factor was enhanced due to use of eigen mode analysis. These modes made the structure very sensitive to any change in geometrical shape which created highly tunable devices. The combination of Van Hove singularity and electron-hole plasmon excitation produced a highly tunable dielectric nanoantennas, consisting of a silicon nanoparticles chain excited by and electric dipole emitters. The obtained results were found in good agreement with previously obtained results.

KEYWORDS

Tunable, Dielectric Antenna, Nanoparticles, Nanostructure, Quantum Emitter, Plasma Photo Excitation, Purcell Effect, Spontaneous Emission, Nonlinear Nano Photonics, Quality Factor, Van Hove Singularity, Excitation.

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INTRODUCTION

Krasnok et al. [1] and Alex et al. [2] studied that dielectric nano antennas allowed directional scattering of an incident light and effective transformation of the near field of feeding quantum emitters into propagating electromagnetic waves. Makarov et al. [3], Shcherbakov et al. [4] and Baranov et al.[5] studied experimentally that photo excitation of dense electron hole plasma in single silicon nanoparticles and silicon nanodimers [6] by femto second laser pulses was accompanied by a modification of the radiation properties. Fischer et al. [7] presented the generation of electron hole plasma in germanium nanoantennas turned them into plasmonic in the mid infrared region. Kuznetsov et al. [8] and Juhani et al. [9] studied dielectric nanoparticles and nanostructures made of materials with large positive dielectric permittivity such as, Silicon Gallium Phosphide and Gallium arsenide were platforms for various nanophotonic applications. Functional nanoantennas [10-12] enhanced spontaneous emission [13-16], Photovoltaics [17] and frequency conversion [18-20] and sensing [21] were studied. Some investigators [22-25] established approaches to unidirectional surface plasmon polariton wave excitation, nonlinear wave guiding systems with quantum emitters as a source and applied it for many applications in nanophotonics and quantum optics. Manga Rao and Hughes [26] presented generic periodic on dimensional system supporting a set of guided modes using Green's tensor into a series of eigen modes and calculated the Purcell factor in such a system. Koenderink [27] and Alu et al. [28] studied the optical properties of nanoparticles based nanoantenna considering the finite chain model dispersion. Alexander et al. [29] calculated the Purcell factor using the method based on the input impedance of a small dipole antenna.

METHOD

The nanoantennas possessed slowly guided modes corresponding to the Van Hove singularity in a infinite chain. These modes are very sensitive to the nanoparticles permittivity and the radiation properties of the nanoantennas became extremely sensitive to electron-hole plasma photoexcitation. It was theoretically and numerically studied tuning of the radiation power patterns and the Purcell factor by pumping several boundary nanoparticles in the chain with relatively low intensities of femto second laser pulses. We have considered a generic periodic one dimensional system consisting of a set of guided modes. Green's tensor into a series of eigen modes were used to calculate the Purcell factor using the relation

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

Where A_{eff} is the effective are of the resonant guided mode, λ is the free space wavelength, V_{gr} is the group velocity of the mode, c is the speed of light. The analytical approach based on the coupled dipole model was used for the study. Each particle was modeled as a combination of magnetic and electric dipoles with magnetic moments (m) and electric momentum (p), oscillating with frequency $\omega\left[\alpha \exp\left(-\mathrm{i}\,\omega t\right)\right]$. The magnetic polarizability α_m and electric polarizability α_e of a spherical particle was calculated by the relation

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

Where a_1 is the electric Mie coefficient b_1 is the magnetic Mie coefficient. Symmetry of the electric dipole source was matched with the symmetry of the transverse magnetic staggered mode for obtaining enhancement of the Purcell factor for a finite system the following equation was utilized

$$F = \frac{3}{2k_h^3} z.\mathrm{Im}\left[G\left(0,0;\omega\right)\right].z\,,$$

Where $G\left(0,0;\omega\right)$ is the Green's tensor of the electric dipole in the centre of a chain, z is the unit vector pointing in the z-direction, $\mathrm{Im}\left[G\left(0,0;\omega\right)\right]$ was found by solving the scattering problem with the dipolar quantum emitter. The electron hole plasma induced tuning of the nanoantennas, the analytical approach was developed using the dynamics of

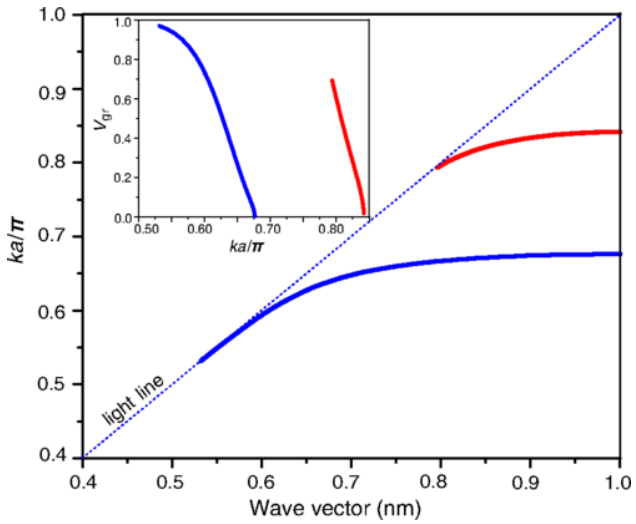
volume averaged electron-hole plasma density ρ_{eh} was modified through rate equation

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

Where W_1 and W_2 are the volume averaged absorption rates due to one and two photon processes, Γ is the electron-hole plasma recombination rate and dependent on electron-hole plasma density. The switching of the nanoantennas properties, the nonlinear response caused by electron-hole plasma photo excitation in boundary particles of the silicon nanoantennas was utilized. The obtained results were compared with previously obtained results of theoretical and experimental works.

RESULTS AND DISCUSSION

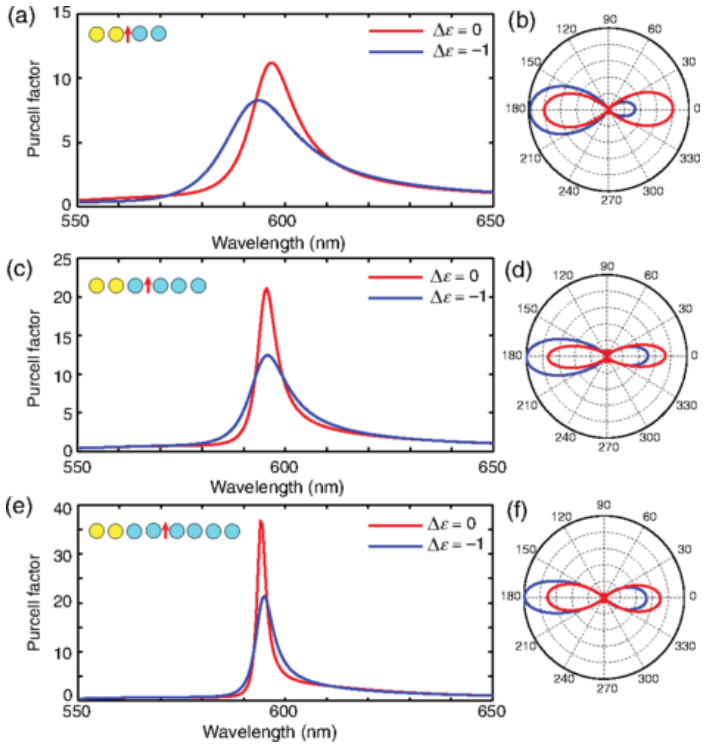
High index dielectric nano structures for nonlinear nanophotonics due to strong nonlinear response was studied. It was found that photo excitation of dense electron hole plasma in single nanoparticles and silicon nanodimer by laser pulses was accompanied by a modification of radiation properties and production of electron-hole plasma in germanium nano antennas turned into plasmonics. Graph (1) shows the plot of dispersion of an infinite chain of dielectric nano particles with different radius and periods. The transverse magnetic and transverse electric modes were found excited by the dipole quantum emitter with selected orientation. These modes are characterized by the induced magnetic and electric moments. The spectral separation of resonances of the single particle, the magnetic moments were dominant in the first branch of transverse magnetic mode and it was also found the electric moments dominated in the second branch of transverse electric mode.



Graph 1: Plot of dispersion of an infinite chain of dielectric nanoparticles with radius.

Graph (1) also shows the calculated group velocities of the waveguide modes as a function of frequency. It was found that the group velocity V_{rg} droped to zero at the band edge. The symmetry of the electric dipole source matched the symmetry of the transverse magnetic mode and significant enhancement of the Purcell factor for a finite system around $\frac{ka}{\pi} \approx 0.675$. Graph (2) shows the plot of spectral dependence of the Purcell factor for the chains of dielectric nanoparticles for different number of nanoparticles. Graph (2) (a) and (2) (c) and show the decrease of the Purcell

factor by a factor of 2 in all cases and spectral broadening caused by symmetry breaking of the chain and corresponding decrease of the quality factor of the Van Hove singularity mode. Graph (2) (b), (2) (d) and (2) (f) shows the electron-hole plasma photo excitation modified the radiation pattern of the nanoantennas. The radiation pattern exhibited two symmetric lobes directed along the chain axis in the forward and backward directions. It was found that the degree of modification of the radiation pattern grown with an increasing number of particle. The directivity in the left direction was found nearly 2 times larger than that in the right direction. The tuning of the radiation pattern was caused by the Van Hove singularity regime of the initially unaffected nanoantennas. The nanoantennas exhibited a quantum emitter position tolerance of about 30nm which is useful for practical realization with existing technologies of quantum dot positioning. In nanoantennas realizations the substrate substantially affected the nanoantennas characteristics. The obtained results were compared with previously obtained results of theoretical and experimental works and were found in good agreement.



Graph 2: The plot of spectral dependence of the Purcell factor for the chains of dielectric nanoparticles for different number of nanoparticles.

CONCLUSION

We have studied the properties and characteristics of highly tunable dielectric antenna having chain of silicon nanoparticles. The nanoantennas exhibited slow group velocity guided mode which corresponded to Van Hove singularity in an infinite structure and created large Purcell factor and were found sensitive to the nanoparticles permittivity. It was found that sensitivity produced nanoantennas tuning through electron hole plasma excitation. The modification of the spontaneous emission rate of a quantum emitter induced by its environment called Purcell effect for single dielectric nanoparticles. The presentation of unidirectional surface plasmon polaritons launched with

electron hole plasma excitation in the nanoantennas. These effects remained valid for the nanoantennas situated on a dielectric surface. The results obtained were found in good agreement with previously obtained results.

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