Purcell effect control in active silicon dielectric nanoantenna for the near-IR wavelength range

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Abstract. Nowadays active light-emitting dielectric nanophotonics is one of the most rapidly developing research field. These nanosystems make possible to direct emission of a light source placed inside nanoantenna in the specific direction with low-losses. Here we study the application of silicon for the creation of active all-dielectric nanoantenna emitting at the telecommunication wavelength (1540 nm). We numerically calculate Purcell factor in silicon nanoparticles (spherical and cylindrical) and demonstrate that in these nanostructures Purcell factor value can be enhanced by two orders of magnitude for this wavelength. The obtained data can be applied for the creation of active silicon nanoantenna doped with erbium for perspective light emitting metasurfaces.

Introduction
Active dielectric nanoantenna with controllable optical properties and directivity represents special interests in nanophotonics [1]. Such nanoantenna is a promising device which can find its application in future communication lines. Recently several works about active dielectric nanoantenna made of different materials (perovskite [2], nanodiamonds [3] and silicon with quantum dots [4]) have been published. These works have clearly demonstrated the potential of the nanoantenna concept for the visible range. Creation of active dielectric nanoantenna for the telecommunication range is also attractive especially in terms of application.

Here we consider a concept of active silicon nanoantenna doped with erbium. Silicon is one of the most perspective material for the creation of dielectric devices for the near-IR range [5]. In turn, erbium has several very thin transitions on different wavelengths: 660 nm, 800 nm, 940 nm and 1540 nm [6]. The most interesting is the transition $^4I_{13/2} \rightarrow ^4I_{15/2}$ on wavelength of 1540 nm since it is the standard telecommunication wavelength [7]. We study scattering cross section for spherical and cylindrical silicon nanoantennas as well as Purcell factor in this system to estimate the possibility of lifetime control due to Mie-resonances.

Results and discussion
Increasing efficiency of the emitter can be estimated by calculating of Purcell factor. For estimation of Purcell factor, we take a nanoparticle made of silicon and put a point dipole source in the center of the nanoparticle. The experimentally measured refractive index of silicon has been chosen to perform numerical simulations [8]. Influence of erbium on the refractive index is negligible since it has a very small concentration in the particle and could be omitted.
Figure 1. (a) Simulated scattering cross section for the spherical silicon nanoparticles. Numerically calculated Purcell factor for: (b) perpendicular and (c) parallel orientations of dipole relative to the substrate as functions of wavelength and sphere diameter; Insets: upper - directivity of ED resonance nanoparticle on the wavelength of 1540 nm, lower - orientation of a dipole inside of nanoparticle; red dashed line is the standard telecommunication wavelength.

in calculations. We study two types of nanoparticles: spherical and cylindrical. We perform the calculation of scattering cross section, numerically calculate Purcell factor and directivity on the standard telecommunication wavelength. All calculations have been performed in commercially available software CST Studio Suite 2017 in time domain solver which based on finite integral technique (FIT) to solve Maxwell equations.

Firstly, we consider a spherical nanoparticle since it has central symmetry and scattering cross section does not depend on the incident angle of the plane wave. We make an analyze of

Figure 2. Simulated scattering cross section for the cylindrical silicon nanoparticles corresponds to polarization of electric field: (a) parallel and (c) perpendicular to the axes of cylinder. Numerically calculated Purcell factor for: (b) perpendicular and (d) parallel orientations of dipole relative to the substrate as functions of wavelength and sphere diameter. Insets: upper - directivity of ED resonance nanoparticle on the wavelength of 1540 nm, lower - orientation of a dipole inside of nanoparticle; red dashed line is the standard telecommunication wavelength.
the dimension of the sphere and get electric dipole (ED) resonance on the wavelength of 1540 nm when the nanoparticle diameter is approximately 600 nm (see Fig.1a).

For the estimation of Purcell factor, we put nanoparticles on a substrate made of glass (refractive index $n_{sub} = 1.5$) and calculate it using known technique [9]. We put 10 nm dipole in the center of the nanoparticle and perform calculation for two orientations (perpendicular and parallel relative to the substrate). For the spherical nanoparticle due to its central symmetry and a small refractive index of glass, we observe a small difference of Purcell factor between two orientations of the dipole. For the ED resonance on the wavelength of 1540 nm we predict Purcell factor of approximately 155 and 160 for perpendicular and parallel dipole orientations, respectively (see Fig.1b, c). Since the electric dipole transition is stronger than magnetic dipole transition we consider higher Purcell for ED resonance nanoparticles [10].

For the cylindrical nanoparticle we fixed its height ($h_{cyl} = 300$ nm). Since scattering cross section depends on the incident angle of the plane wave we perform numerical calculation for two cases, when the electric field vector is parallel to the cylinder axes (see Fig.2a) and perpendicular (see Fig.2c), corresponding to the orientation of the dipole inside of the cylinder along the axes and perpendicular to the axes, respectively. Then we repeat the same steps as for the spherical nanoparticle.

If the dipole is oriented along the axes of the cylinder we observe ED resonance on the wavelength of 1540 nm when the diameter is about 590 nm (see Fig.2a) and the value of Purcell factor equals to approximately 150 (see Fig.2b). When dipole perpendicular to the axes of the cylinder the diameter should be about 700 nm (see Fig.2c) and the Purcell Factor value is about 170 (see Fig.2d). For the same orientations of the dipole (see Fig.1b and Fig.2b for perpendicular and Fig.1c and Fig.2d for parallel orientations relative to the substrate) inside of spherical and cylindrical nanoparticles we observe the close forms of directivities.

**Conclusion**

In this work, we represent the results of the numerical investigation of active silicon nanoantenna for the telecommunication wavelength. We consider two types of nanoparticle, estimate scattering cross sections and calculate the value of Purcell factor. We specify the geometrical parameters of the nanostructures to tune ED resonance to the telecommunication wavelength. We demonstrate that for the cylindrical nanoparticle with the dipole orientation perpendicular to the cylindrical axes we observe the highest Purcell factor value of about 175. For another orientation, we observe the smallest Purcell factor value of 110 and for the spherical nanoparticle for both orientation of dipole Purcell factor is close to 157 with ED resonance on the wavelength of 1540 nm. We also demonstrate, that in such nanostructures power pattern diagram can be controlled by changing the orientation of the dipole inside of the nanoparticle. Numerically obtained data could be used for the experimental realization of active silicon-based nanoantenna. This nanoantenna can be applied for the creation of metadevices operating in the telecommunication range and compatible with existing telecommunication networks.

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