Dielectric metasurface for emission control of magnetic dipole in the near-IR wavelength range

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Abstract. Developing active dielectric systems is in high demand due to growing the internet of things. Such systems can control the optical properties of nanoemitters which leads to an increase in the performance of the telecommunication networks. Here we numerically investigate metasurface consists of all-dielectric erbium-doped silicon nanocylinders. We demonstrate that such a structure can effectively control and enhance 320-folds spontaneous emission in the near-IR wavelength range. The results of this paper can be used for creating new telecommunication systems.

1. Introduction
All-dielectric nanostructures can enhance and control the directivity of spontaneous emission[1, 2]. Recently, it was demonstrated that active dielectric nanoantennas[3, 4, 5] and metasurface[6] can work in the visible wavelength range. Hereby the development of nanostructures working in the optical telecommunication wavelength range is very promising and attractive.

Here we offer a conceptual design of metasurface consists of all-dielectric erbium-doped silicon nanocylinders. This material attracts attention due to several reasons. The first one is that silicon is lossless in the wavelength region higher than 1300 nm[7]. The second one is due to erbium has a transition at the wavelength of 1540 nm which corresponds to the standard telecommunication wavelength[8]. Mentioned above reasons make silicon doped by erbium a very prospective material in optical telecommunication wavelength.

In this work, we numerically study all-dielectric erbium-doped silicon metasurface for the near-IR wavelength range. We compute reflection and transmission spectra, estimate Purcell factor and directivity patterns of metasurfaces.

2. Results and discussion
In Figure 1, the designs of finite metasurfaces consisted of 5x5, 9x9, 15x15, and 31x31 unit cells are shown. The unite cell is represented by a silicon cylinder in a vacuum. We carry out numerical simulations to compute geometrical parameters of metasurface with magnetic dipole (MD) resonance at the wavelength of 1540 nm.

Firstly, we calculate the scattering of the single cylinder to tune the MD response at the wavelength of 1540 nm, using commercially available software CST Studio Suite and frequency-domain solver. In Figure 2 the scattering cross-section spectrum for the silicon nanocylinder with equal diameter and height of 380 nm is demonstrated. The electric and magnetic dipole...
responses are observed at wavelengths of 1220 nm and 1540 nm, respectively. Highly important to notice that the concentration of erbium is negligibly low and has no influence on the optical properties of silicon.

Next, we perform the numerical simulation for the infinite metasurface using Floquet periodic ports and calculate the unit cell period. The transmission(T) and reflection(R) spectra are shown in Figure 2b. For the unit cell period of 1300 nm, the MD response is set up at the wavelength of 1540 nm, the ed response shifts to 1400 nm due to the near-field interaction.

Finally, we consider the finite metasurface, estimate the Purcell factor and compute directivity patterns. The electric dipole with a length of 10 nm is placed in the center of the central nanocylinder of the finite metasurface along y-axes (see Fig.1). Since the emission of erbium at the wavelength of 1540 nm described by magnetic dipole transition [9], we apply the duality of Maxwell’s equations[10]. Using this technique, we replace the permeability by the permittivity and simulate the magnetic dipole by the electric dipole. Due to silicon is lossless in the wavelength range from 1400 to 2000 nm[7] we calculate only the radiative Purcell factor by the following equation[11]:

\[ F_p = \frac{P}{P_0} \]  

where P is the power radiated by a dipole in the presence of the metasurface and P_0 - in a vacuum.

In Figure 2c calculated Purcell factor is shown. One can see that the Purcell factor achieves the value of about 340 and does not depend on the number of unit cells in the finite metasurface. However, the directivity patterns have some dependence on the number of unit cells. In Figure 3
the directivity pattern only in the upper-hemisphere is represented since the considered system is symmetrical relative to the z-axis (also to x- and y-axes). For the case of 5x5 unit cells (see Fig.3a) more power emits in x-direction compare to other cases (see Fig.3b-d). We observe an increase of the power radiated in z-direction for 9x9 unit cells (see Fig.3b) and patterns stay quite the same for 15x15 and 31x31 unit cell cases (see Fig.3c and d). Consequently, if dipoles are placed in each unit cells the directivity will have quite the same pattern and the emitters will radiate more power perpendicularly to the surface along the z-axis.

3. Conclusion
In this work, we demonstrate the results of a numerical study of all-dielectric metasurface consists of silicon nanoparticles doped by erbium. We compute the Purcell factor for finite metasurfaces and its value can be up to 320. We show that the emission of the dipole placed in the center of the central unite cell in the finite metasurface radiates mostly along the z-axis and an increasing number of the unit cell leads to decreasing of the emission in the plane of the metasurface.

The results presented in this paper can be useful in developing modern telecommunication systems and can improve the performance of existing ones.
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