Dielectric nanoresonator for enhancement of 2D material photoluminescence

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Abstract. Nowadays the volume of transmitted information exponentially grows and requires the development of new telecommunication systems. Dielectric nanoresonators can be considered as a basic part of such systems to control the emission of the nanoscale source. Here we numerically investigated resonant dielectric nanoresonators for emission enhancements of 2D nanomaterials. We show that the radiative Purcell factor can achieve the value of up to 21 and 12 for the magnetic quadrupole and dipole responses, respectively. Also, we compare the directivity patterns for magnetic dipole and quadrupole resonances. The results obtained in this work can be applied in the development of optical chips and interfaces.

1. Introduction

The development of dielectric resonators as a basic element of optical interfaces and chips to control the emission of nanoscale sources is on-high demand due to the increasing volume of transmitted information in the last decade[1]. Such interfaces can find their applications in optical information and telecommunication systems. One of the most important requirements for nanoscale sources is the ability to operate at room temperature[2]. Therefore two-dimensional material such as hexagonal boron nitride(hBN) is considered to satisfy this requirement.

The emitters based on defects of hBN have such optical properties as an optical readout of the electron spin state[3] and single photon emission at room temperature[4]. It should be noted that the zero-phonon line (ZPL) of hBN is characterized by rather narrow emission lines at room temperature[5]. At the same time, ZPL wavelength various from deep ultraviolet to near-infrared due to the presence of various defects[6]. According to the above-mentioned reasons, hBN is a very promising candidate for the nanoscale emitter.

To control the emission of nanoscale emitters plasmonic and dielectric structures can be used. However, plasmonic systems have several problems such as complex directivity patterns and high dissipative losses in the visible range[7]. Otherwise, dielectric systems are devoid of these drawbacks and have both electrical and magnetic responses (Mie resonances) which lead to the rapid growth of emission control by all-dielectric nanophotonics[8].

In this paper, we offer and numerically investigate dielectric nanoresonator for enhancement of the spontaneous emission of the hBN flake. We study and compare the impact of the magnetic dipole and quadrupole resonances on the total and radiative Purcell factors.
2. Results and discussion
The dielectric nanoresonator consists of the silicon nanosphere placed on the glass substrate with the hBN flake. The diameter of the nanosphere depends on the excitation wavelength of defects and the resonance responses of the nanoparticle. It varies from 140 nm to 286 nm. The thickness of the hBN flake is 1 nm, which corresponds to several layers [4].

We start our consideration from the plane wave scattering on the silicon nanosphere placed on the infinite glass substrate. Using commercially available software CST Studio Suite and integral equation solver we calculate the diameters (see fig. 2 legends) of the nanosphere which corresponds to the magnetic dipole (MD) and quadrupole (MQ) tuned to the three (min, mean and max) experimentally measured wavelengths [4]: 576 nm, 652 nm and 762 nm. The dispersions of silicon and hBN are taken from references [9] and [10], respectively. The refractive index of glass is constant and equals 1.45.

Next, we put 10 nm dipole in the center of the hBN flake along the x-axis precisely under...
the silicon nanosphere to estimate the Purcell factor. Since silicon has losses in the considered wavelength range (500-900 nm) the total and radiative Purcell factors are calculated using the following equations[11]:

\[
F_{pp}^{\text{Tot}} = \frac{\text{Re}(Z)}{\text{Re}(Z_0)} = \frac{P_{\text{rad}} + P_{\text{nonrad}}}{P_0}
\]

(1)

\[
F_{pp}^{\text{rad}} = \frac{P_{\text{rad}}}{P_0}
\]

(2)

where \(Z\) is the impedance of the dipole in the presence of the system, \(Z_0\) – the impedance of the dipole in a vacuum, \(P_{\text{rad}}\) – the power radiated by the dipole in the presence of the system, \(P_{\text{nonrad}}\) – the power dissipated in the system and \(P_0\) – in a vacuum. We numerically computed radiated powers and impedances using a frequency-domain solver. On the figure 3 calculated total and radiative Purcell factors for MD and MQ tuned at the chosen excitation wavelengths of hBN are represented. Considering the MD case the total Purcell factor achieves the values of about 15 for all considered cases (see fig.3a, dashed curves). For the radiative Purcell factor we observe a slow increase from 10 at the wavelength of 576 nm to 12 at 762 nm (see fig.3a, solid curves). At the same moment for the MQ case, the total and radiative Purcell factors increase from 22 to 24 and from 14 to 21, respectively (see fig.3b). One can see that the radiative Purcell

**Figure 3.** The total(dashed lines) and radiative(solid lines) Purcell factors for the silicon nanosphere on the glass substrate for (a) the magnetic dipole (MD) and (b) the quadrupole (MQ) tuned on the hBN emission wavelengths. The legend shows the diameter of the silicon nanosphere.

**Figure 4.** Directivity patterns for the excitation at the wavelengths tuned on (a) magnetic dipole (MD) and (b) magnetic quadrupole.
factor increases faster than the total one due to decreasing losses in silicon with increasing the wavelength.

The directivity patterns are calculated for the dipole emission in the considered system. It is important to stress out at the point that directivities differ for MD and MQ cases but do not depend on the tuned wavelength. Therefore in both cases, the emission mostly radiated in the substrate (see fig.4).

3. Conclusion

In this paper, we demonstrate the results of the numerical investigation of the silicon nanoparticle for enhancement of the hBN flake emission. We compare Purcell factors for MD and MQ resonance nanospheres. We show that for the MD case the radiative Purcell factors vary from 10 to 12, but the total one remains almost the same and equals 15 in the considered wavelength range. However, for the MQ case, we observe a fast increase of radiative Purcell factor from 14 to 21 and a slow increase of total Purcell factor from 22 to 24. For both cases, power radiates mostly in the substrate.

Investigated dielectric nanoresonator can find its application and telecommunication interfaces as a basic part of all-optical chips.

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