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Silicon nanoantenna for controlling the polarization direction of radiation from standalone quantum light source

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Abstract. The emission control of standalone quantum sources has recently attracted the interest of the scientific community due to the growing technological capabilities for fabrication and on-demand positioning of these emitters. Here we report on simulation of silicon-on-insulator prismatic nanoantenna possessing resonantly induced bianisotropy that provides a strong dependence of its emission on the location of the quantum emitter inside the system. Obtained results could potentially be used in sensing, nanoscale light control, and quantum computing applications.

Keywords: quantum islands, silicon nanoantenna, radiation pattern, numerical simulation, nanophotonics

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Кремниевая наноантенна для контроля поляризации излучения одиночного квантового источника света

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Аннотация. В последнее время управление эмиссией одиночных источников излучения привлекает интерес научного сообщества в связи с ростом технологических возможностей по созданию и позиционированию таких излучателей. В этой работе мы сообщаем о моделировании наноантенны в виде призмы на базе кремния-на-изоляторе, поддерживающей резонансно возбуждаемый бианизотропный отклик и обеспечивающей сильную зависимость характеристик излучения от положения квантового излучателя внутри наноструктуры. Полученные результаты могут применяться в области зондирования, управления светом на наномасштабе и, в перспективе, для создания квантовых компьютеров.

Ключевые слова: квантовые островки, кремниевая наноантенна, диаграмма направленности, поляризация, численное моделирование, нанофотоника

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Introduction

The creation of efficient compact photon emission sources has a wide range of potential applications, primarily in optical communication lines and information processing systems, including quantum computers. To increase variability of procedures that can be performed on a single chip, the number of independently controlled emitters should be reduced – at best to unity. Only recently it became possible to create standalone emitter, located on demand, in silicon wafer [1]. Herewith, silicon-on-insulator-based nanostructures attract great scientific interest due to the possibility of efficient light control at the nanoscale via excitation of both electric and magnetic Mie-type resonances [2, 3, 4].

Here we study silicon nanoresonators placed on an insulator substrate with an individual emitter precisely located inside and focus on the effect how polarization in the far field zone depends on the light source position. It is favorable for developing efficient emission sources with controllable polarization in the measurable zone [5–6].

We have previously studied the effects of induced bianisotropy in asymmetric nanoresonators and nanoclusters in [7, 8], and have shown that the coupling between electric and magnetic multipoles in such structures results in interesting effects, including polarizability-dependent modes excitation and directional scattering. These concepts can be applied and developed to control the emission from the quantum islands in silicon nanostructures. Based on our discussions with colleagues, proposed designs can be manufactured with accuracy ±10 nm by the methods of electron beam lithography and plasma etching from a bare layer with controllable positioned emitters. The last one can be obtained via techniques discussed in [1] which can be briefly represented as follows: the structure is grown at 600 °C using molecular-beam epitaxy on a SOI substrate with buffer layer and contain several layers of Ge(Si) QDs interspersed with intermediate Si layers.

Materials and Methods

Different polarizations of incident electromagnetic wave can excite different modes inside the prismatic nanoparticle at the same frequency. Moreover, degenerated modes have completely different field distribution, corresponding to the transverse electric and transverse magnetic types (see Fig. 1,*c*). It becomes possible due to bianisotropy induced in the nanoresonator. Bianisotropy appears in resonators with a lack of the inversion symmetry and manifests itself in the excitation of multipoles inside a resonator which are not presented in the incident plane wave [9]. In the case when the resonator's optical size is comparable with the incident wavelength, bianisotropic response can be easily presented in the following form:

$$\begin{aligned} \vec{p} &= \varepsilon_0 \hat{\alpha}^{EE} \vec{E} + \frac{1}{c} \hat{\alpha}^{EH} \vec{H}, \\ \vec{m} &= \varepsilon_0 \hat{\alpha}^{HH} \vec{H} + \frac{1}{Z_0} \hat{\alpha}^{HE} \vec{E}, \end{aligned} \tag{1}$$

where $\vec{E}$ and $\vec{H}$ are the electric and magnetic fields of the incident wave at the dipoles coordinates, c is the speed of light, Z_0 is the free space impedance, ε_0 is the vacuum permittivity, and $\hat{\alpha}^{EE}, \hat{\alpha}^{EH}, \hat{\alpha}^{HE}, \hat{\alpha}^{HH}$ are the second rank polarizability tensors.

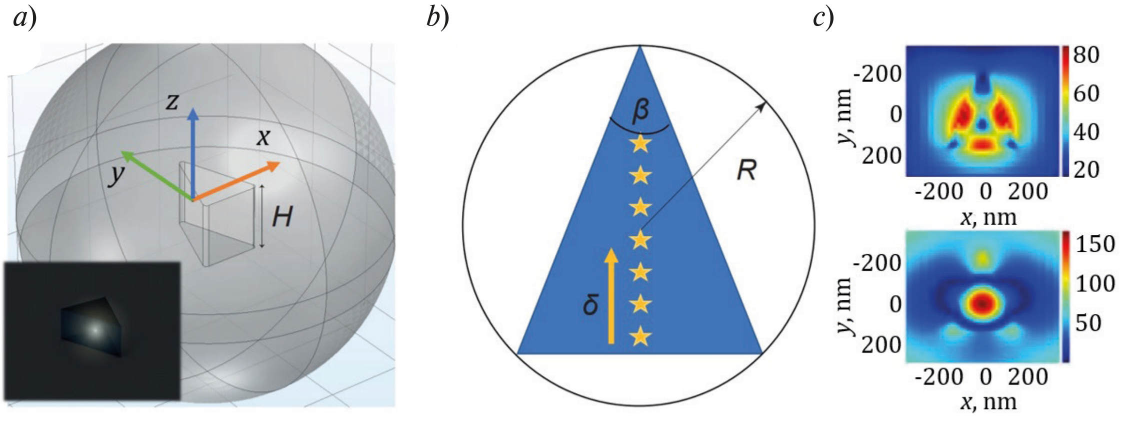

Fig. 1. Scheme of a silicon prismatic nanoresonator with an embedded point emitter: COMSOL model view (*a*); the inset shows a prismatic nanoparticle with a single emitter, artistic view; cut plane of the prism parallel to the substrate (*b*); the asterisks mark different positions of the emitter. Electric field distributions on the cut plane shown in Fig. 1,*b* excited in the prism illuminated by plane waves with two orthogonal polarizations (*c*)
The last figure was adopted with permission from [8]

By tuning the geometrical parameters, it is possible to create a structure where bianisotropic excitation of the magnetic dipole from the incident wave's electric field arises resonantly at the same frequency with the simple electric dipole resonance in the orthogonal polarization (see [8] for details). Due to the reciprocity principle, different modes excited in the nanoparticle have different polarization in the emitted far field. In order to enhance modes with different field distributions it is necessary to place the emitters differently inside the nanoresonators. In this case, the coupling between the emitter and the resonator modes strongly depends on its location and orientation, and the desired mode can be excited.

We carried out numerical calculations of the characteristics of the proposed nanosystem on a substrate in the COMSOL Multiphysics software. The emitter was modelled as a point dipole source oriented parallel to the substrate's surface and located inside the silicon nanoparticle at various positions. The material properties of crystalline silicon were emulated via refractive index equal to 3.5, which silicon has in the infrared range, and the refractive index of quartz substrate has taken to be 1.5. Particle's environment was air.

Results and Discussion

Fig. 1,*a*,*b* shows the scheme of a considered structure, a silicon triangular prism on a quartz substrate. Parameters of the structure were chosen in accordance with optimized geometry from [7]. Here, $H = 382$ nm, $R = 282$ nm, $\beta = 40^{\circ}$. Point dipole was located in a plane parallel to the substrate at a distance $H/2$ from it, different positions of the emitter along the triangle symmetry axis with different values of shift δ from the base side were modeled. The corners of the prism were smoothed in the simulation, as there will be no sharp corners in the fabricated samples.

Simulations showed that the radiation from the structure goes predominantly into the substrate, however, the experimental setup, for which we developed the design of the nanostructure, collects the light from the ambient air side. Therefore, it is more important to analyze the radiation in the upward direction. Its features depend strongly on the location and orientation of the emitter. Thus, it is possible to find the location where emission in the upward direction has only y-polarization (e.g. along prism triangle's height), no matter how the emitting source is polarized. Fig. 2 shows emitted light polarization maps in the far field zone area above the investigated nanostructure for two positions of the source, 150 nm and 300 nm away from the short side of the triangle at the prism base and for different orientations of the emitter. As seen in the first row of Fig. 2, radiation in the considered area have both two polarizations in the observation direction upward from the substrate, along the triangle base and along its height. And the second row shows that for another emitter position both x- and z-oriented dipoles bring y-polarized contribution to the emitted light, while contribution of x-oriented dipole into the far field radiation is negligibly small. The

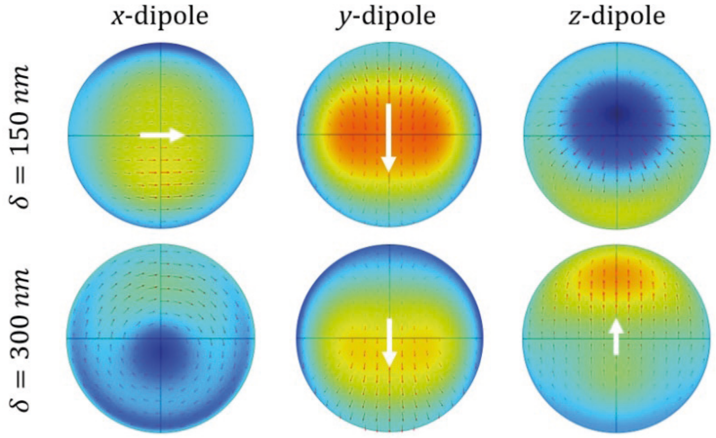

Fig. 2. Maps showing the electric field direction on the half-spherical surface above the structure in the far field wave zone. White arrows indicate direction and magnitude of the light's electric field in the upward direction. Two rows correspond to the two different emitter locations, three columns correspond to the three different emitter orientation directions

x-dipole radiation dominates over the y-dipole one, meanwhile in the second row the y-dipole dominates over the two other orientations. The z-dipole radiation in the upward direction is low in both considered cases.

The direction of the dipole moment of the electron transition in the experimentally fabricated nanoislands strongly depends on shape and geometry and, thus, can be assumed unknown, so we consider all three polarizations of quantum emitter. It means that x-, y- and z- dipoles are excited with the same probability. However, if radiation at a chosen angle can "choose" the orientation of the dipole depending on its location, and we can manipulate and control the emitter location inside the nanostructure, we can use this mechanism to obtain the photoluminescence polarized on demand. Moreover, the luminescence signal of Ge-Si nanoislands is characterized by a large width [1], which makes it possible to interact with non-degenerated nanoresonator modes depending on their location. It expands the scope of possible designs sufficiently and opens a new route to design active metadevices.

These results are of a big interest of author's collaborators and the first experiments with standalone quantum nano-islands have been already performed based on the designs shown in this paper.

Conclusion

We have demonstrated a prismatic nanoresonator on a substrate in which different electromagnetic modes can be excited depending on the location of the incorporated light emitter. Different modes radiate into the far field zone in a different manner, and the dominant polarization is strongly dependent on the emitter location. This result can be used for generation of a polarized luminescence signal as well as for determining the emitter location by analyzing the polarization of the radiation.

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