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Magnetic hot-spots in hollow silicon cylinders

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Abstract. Silicon nanoparticles can possess magnetic Mie-resonant response in the visible and near infrared wavelength ranges. In this paper, we consider numerically the features of magnetic hot-spots realized inside silicon nanocylinders at the conditions of the optical magnetic resonances, and show that the intensity of the magnetic field inside nanoparticles with a coaxial through hole can be much stronger than the intensity of incident light waves.

1. Introductions

Last decades all-dielectric high-index nanostructures (consisting of, e.g., silicon or germanium) attract great attention in the field of nanophotonics and related areas [1, 2]. Despite the non-magnetic nature, nanostructures composed of silicon, germanium etc. can possess magnetic response [3, 4], which is following from the Mie theory [5]. Conductive currents inside such high-index semiconductor nanoparticles are almost zero [6] while the displacement currents can have special circular distribution, which corresponds to the excitation of magnetic dipole and high-order magnetic multipoles [7, 8]. Magnetic dipole mode in the high-index structures was considered previously [8, 9] with respect to the light scattering problem, while magnetic field distributions and magnetic field localization effects were not studied in details. At the same time, the resonant enhancement of magnetic field or, by other words, the magnetic hot-spots (MHSs) in the nanoparticles can be used in large amount of applications, such as, e.g., optomechanics, optical trapping, sensing of magnetic particles etc [8]. In this paper we investigate in details resonant MHSs inside silicon nanocylinders. Moreover, as it is shown that a coaxial through cavity in the nanoparticle (such holes can be produced by focused ion-beam milling or electron beam lithography and reactive ion etching [10]) does not lead to the total destroying of the MHSs, providing possibility for practical applications of MHSs.

Note that several approaches to get the MHSs in free space have been proposed in literature including the hot-spots in the gap between silicon nanoparticles [11, 12] and indirect magnetic field enhancement in plasmonic nanostructures [13, 14]. However, there are principal limitations, for example, very small region of magnetic field enhancement between two nanoparticles and strong electromagnetic field absorption inside metal material. Scattering of light by high-index dielectric nanoparticles with cavities has been considered previously [10, 15], however, without investigation of the MHSs.

2. Eigen modes of nanocylinders
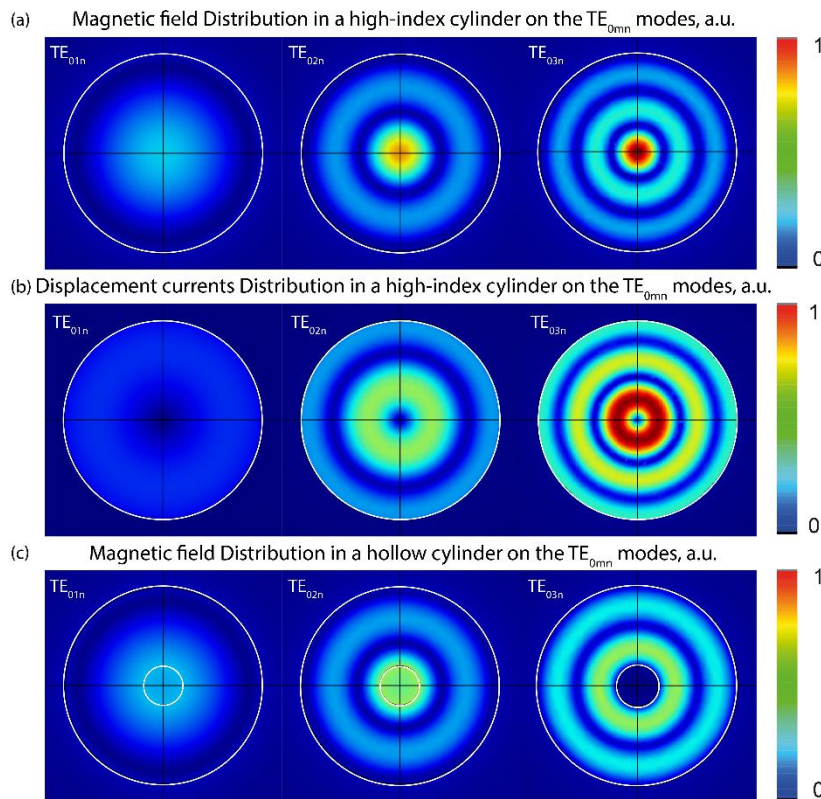
Figure 1 (a) Magnetic field distribution (a), and displacement currents distribution (b) in the dielectric cylinder on the TE_{0mn} eigen modes, m=1, 2, 3. (c) Magnetic field distribution in the hollow dielectric cylinder on the TE_{0mn} eigen modes, m=1, 2, 3. White contours highlight boundaries of cylinder (a-c) and hollow (c).

In order to design electromagnetic response of silicon nanoparticles, their modal structure should be analyzed. Among the number of high-index cylinder eigen modes there are some of them which correspond to the magnetic field concentration inside the cylinder. At the figure 1a magnetic field distributions on the TE_{0mn} modes, m=1, 2, 3, n=1, are shown. These distributions, for cylinder with height of 100 nm and radius of 200 nm and dielectric permittivity equals to 16, were obtained numerically (with help of Comsol Multiphysics [16]). Here modes with n>1 are not shown because for n>1 magnetic field distribution at the frontal cross section is repeated manually this for TE_{0m1} mode but number of magnetic field maxima on the cylinder axis are increasing (1 for TE_{0m1} mode, 2 for TE_{0m2} mode and so on). TE_{0mn} modes are of highest interest, because special circular distribution of displacement currents (see figure 1b), slightly depends on the defects on the cylinder axis.

Actually, in coaxial cylinders with a cavity the magnetic field concentration stays quite high for low-order modes but disappears for high-order modes (see figure 1c) because of overlapping between the cavity and the area of displacement currents maxima. In order to estimate the magnetic field enhancement in the cavity a full-wave simulations should be done. Results are presented in the next section.

3. Magnetic hot-spots in hollow cylinders under plane wave irradiation

In figure 2 results of numerical simulations for cylinder (radius is 200 nm, height is 100 nm) irradiated by linearly polarized plane wave are presented. Here we take into account dispersion of silicon dielectric function [3]. We consider two different propagation directions: along and perpendicular to the cylinder axis (see figure 2a, b). Results for third case, when propagation vector is perpendicular to

the cylinder axis, and electric field oscillations are along cylinder axis, are similar to the case of frontal excitation and, therefore, are omitted.
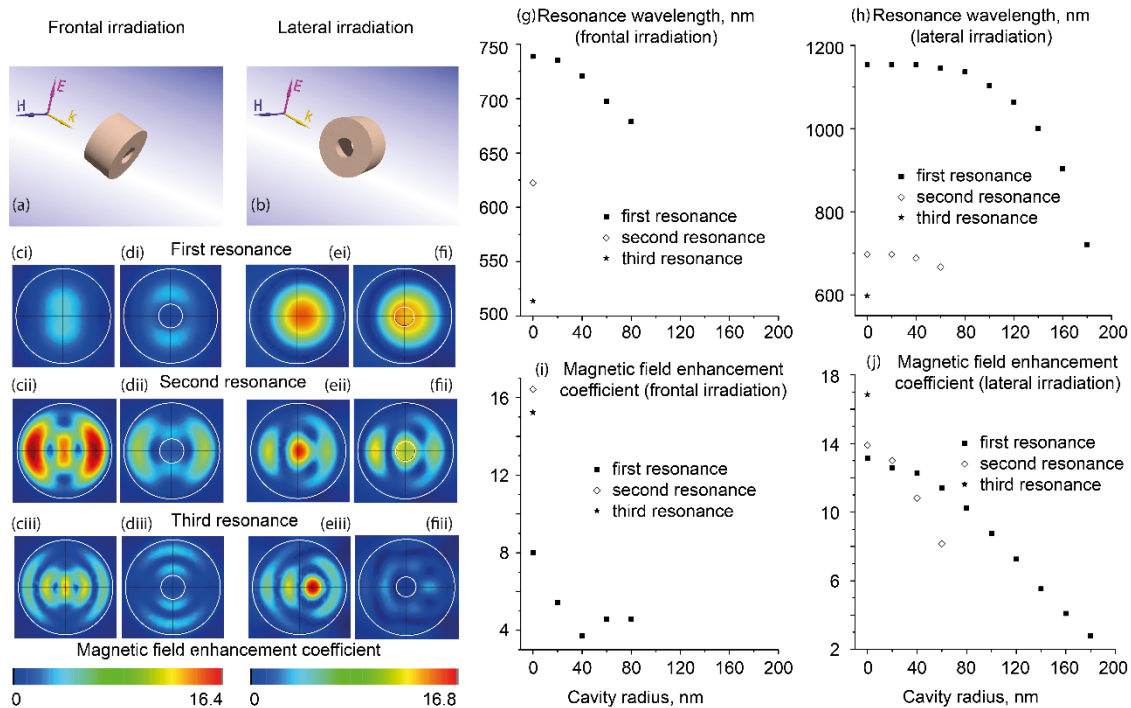
Figure 2 (a, b) Frontal (a) and lateral (b) excitation of cylinder with radius 200 nm and height 100 nm with a coaxial through hole. (ci-fi) Distributions of normalized (with respect to the magnetic field of incident light waves) magnetic field for the first resonance: (ci) cylinder without cavity, frontal irradiation, wavelength 739 nm; (di) with coaxial cavity of 40 nm radius, frontal irradiation, wavelength 721 nm; (ei) cylinder without cavity, lateral irradiation, wavelength 1154 nm; (fi) with coaxial cavity of 40 nm radius, lateral irradiation, wavelength 1154 nm. (cii-fii) Distributions of normalized magnetic field on the second resonance: (cii) cylinder without cavity, frontal irradiation, wavelength 622 nm; (dii) with coaxial cavity of 40 nm radius, frontal irradiation, wavelength 622 nm; (eii) cylinder without cavity, lateral irradiation, wavelength 698 nm; (fii) with coaxial cavity of 40 nm radius, lateral irradiation, wavelength 688 nm. (ciii-fiii) Distributions of normalized magnetic field on the third resonance: (ciii) cylinder without cavity, frontal irradiation, wavelength 514 nm; (diii) with coaxial cavity of 40 nm radius, frontal irradiation, wavelength 514 nm; (eiii) cylinder without cavity, lateral irradiation, wavelength 598 nm; (fiii) with coaxial cavity of 40 nm radius, lateral irradiation, wavelength 598 nm. (giii) Resonance wavelength as a function of cavity radius, frontal irradiation. (hiii) Resonance wavelength as a function of cavity radius, lateral irradiation. (i) Maximal normalized magnetic field in the cavity as a function of cavity radius, frontal irradiation. (j) Maximal normalized magnetic field in the cavity as a function of cavity radius, lateral irradiation.

Distribution of electromagnetic field for the first resonance (corresponding to the TE_{011} mode) in particles with relatively small cavity and without the cavity is similar (figure 2ci-fi). Inside the cylinders without cavity magnetic field is quite homogeneous and have a Lorentz-like maximum near the middle of cylinder axis, and for cylinders with void core maximum is shifted to the cavity boundary. Maximal magnetic field in the cavity decreases when cavity size enlarges. Interestingly, for lateral irradiation case (figure 2b) the magnetic field in the cavity is 2 times higher than the magnetic field of the incident wave even in the case of very thin silicon shell. For all the resonances the lateral excitation of cylinder is more prospective than the frontal one from the application point of view. This

is a consequence of the circular character of displacement currents, which are not changed significantly for the lateral irradiation. The wavelength of resonance decreases monotonically when the size of cavity goes up in the both cases of excitation (figure 2g, h). Note the following important feature of the MHSs for the first resonance: it is a large region (up to 80% of overall cylinder radius) where the enhancement coefficient exceeds the factor 4. The obtained dependencies of frequency and enhancement factor on the cavity size can be used allow for the construction of systems with required level of magnetic field enhancement at the certain frequency.

Higher-order hybrid modes excited in the cylinder can also provide the magnetic field enhancement. In figure 2cii-fii, ciii-fiii distributions of the magnetic field for the second and third resonance are shown for both irradiation cases, respectively. Note that the high-order resonances give stronger magnetic field enhancement (see figure 2i, j). However, the influence of cavity size on the high-order resonances is more considerable because the regions of magnetic field concentration decrease with the increase of the resonant order.

As a conclusion, we investigated the magnetic field distributions inside the silicon cylinders with and without coaxial through holes (cavities) at the resonant optical conditions using the full-wave numerical simulations. Obtained results can be used for development of new optical components and devices for management, trapping and detection of magnetic nanoparticles and molecules with magnetic transitions.

Acknowledgements

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