Directional antennas with embedded single photon emitters

N. Verellen,[1,2] S. Philips,[1,2] J. Li,[1,2] and P. Van Dorpe[1,2]

[1] KU Leuven, Dept. of Physics and Astronomy, Celestijnenlaan 200D, B-3001 Leuven, Belgium
[2] imec, Kapeldreef 75, B-3001 Leuven, Belgium

In nanophotonics applications where every photon counts, one immediately benefits from directed photon routing (wavefront engineering) for efficient photon collection. We present the design of all-dielectric antennas that enable unidirectional emission of embedded quantum emitters. These could be single photon sources such as the nitrogen, silicon or germanium vacancy centers in diamond. The extraordinary emission properties of these dielectric antennas are the result of clever phase control of interfering electric and magnetic multipoles. Application can be found in solid-state quantum information processing and optical quantum sensing.

Introduction

Recently, color routers based on directional optical antennas were developed. These antennas are made either of a noble metal supporting plasmonic resonances [1], or dielectric material such as amorphous silicon [2]. Efficient directional emission of photons into well-defined modes with tailored angular scattering is enabled. In the current work, the aim is to improve the readout speed and readout fidelity of single photon emitters by embedding them in such antennas. These can for instance be nitrogen, silicon or germanium vacancy centers in diamond, but also defect centers in silicon carbite [6]. The high refractive index n = 2.4 of diamond is an ideally suited material for dielectric antennas. Here, we investigate directional diamond antennas based on previous designs for amorphous silicon [2]. These antennas redistribute the emission in a fundamentally different way than the conventional solid immersion lenses (SIL) [3], nanoengineered diamond waveguides [4], and circular bullseye gratings [5]. Compared to their plasmonic alternative, the dielectric antennas have lower absorption losses while maintaining very high scattering cross-sections.

The antenna that we investigate has a V-shaped, asymmetric geometry as illustrated in Figure 1a. The total antenna length is approximately 800 nm. The red sphere in the middle represents the quantum emitter which is embedded into the antenna host material and excited by an external laser. The red fluorescent light is unidirectionally scattered by the antenna. At the origin of this effect is the interference of several electromagnetic multipole modes supported by the V-shaped dielectric antenna. Previous studies for silicon antennas revealed that strong and sharp electric and magnetic dipole resonances arise in the visible range, as well as a pronounced electric quadrupole. Figure 1b shows the radiation patters for respectively the electric dipole (ED_y), magnetic dipole (MD_z) and electric quadrupole (EQ_{xy}). Panel c illustrates how with the proper phase alignment (indicated by the arrows) of these modes their combined far field interference (green dashed line) gives rise to directional emission in the x-y plane.

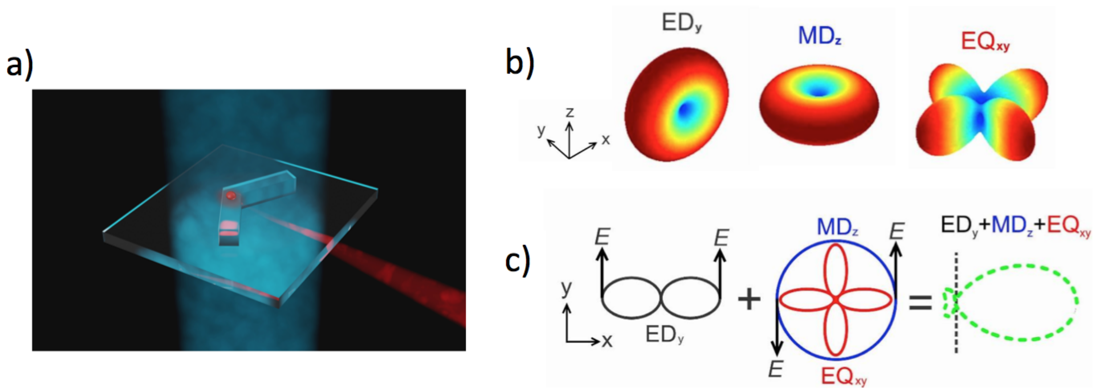

Figure 1: a) Conceptual illustration of a directional antenna with embedded single photon emitter. The directional emission can be reconstructed by considering the ED$_y$, MD$_z$ and EQ$_{xy}$ multipole modes supported by the antenna. b) 3D scattering patterns are shown. c) 2D cross-sections of panel b indicating the phase of the electric field. In-phase field oscillation of the modes on the right results in constructive interference while out-of-phase oscillation results in destructive interference to the left, leading to directional emission.

Methods

We performed finite difference time (FDTD) domain simulations using Lumerical FDTD Solutions solver to investigate the diamond antenna with embedded emitter. The emitter was modeled as a y-polarized point dipole source. To accurately evaluate the radiation pattern of the dipole source and the antenna, the Poynting vector was calculated over the surface of a large monitor box surrounding the antenna, similar to our previous work [1]. The refractive index of diamond was taken as n = 2.4, and quartz or glass as 1.52.

Results

A single emitter in an homogeneous medium presents the typical omni-directional dipole radiation pattern, as shown in Figure 2a for a y-polarized dipole in diamond. Panel b shows the case for the same emitter placed at a distance of 150 nm underneath the surface of a diamond crystal substrate. The radiation pattern is strongly modified by the inhomogeneous environment [7]. The output radiation is substantially enhanced along the critical-angle direction and almost no light can leave the diamond. In the next configuration, panel c, a V-antenna is etched in the diamond, leaving the emitter in the center position of the antenna. Interestingly, the resulting emission strongly deviates from the case of the plane film in panel b. The emission is now directional in the direction of the opening of the V-shape. Additionally, the critical angle has been reduced.

Stronger directional emission away from the normal to the substrate, can be achieved by increasing the refractive index contrast between the antenna and its environment. This results in stronger confinement of the modes. Panel d) shows the emission of a rod-shaped diamond antenna on top of a glass substrate. A symmetric emission pattern is restored. By switching to the V-antenna, again a strongly directional emission is obtained. The angle of maximum emission, has been pushed towards the substrate/air interface, as compared to the configuration of panel c.

The radiation patterns in Figure 2 correspond to a wavelength of 750 nm. Inherently,

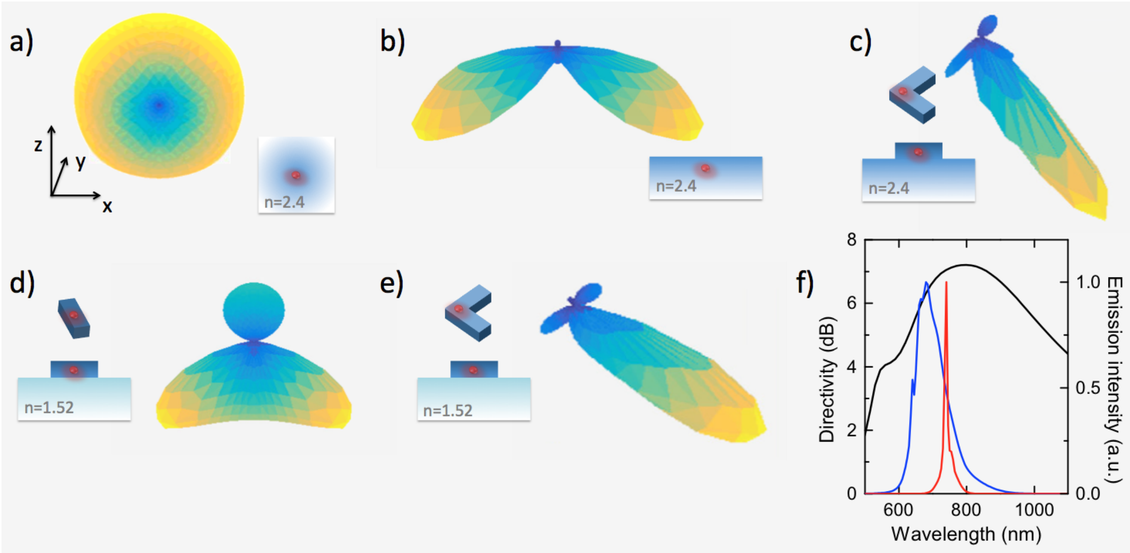

Figure 2: The effect of different environments on the radiation pattern of a y-polarized dipole. 3D radiation patterns are shown for a wavelength of 750 nm. a) Emitter in diamond medium. b) Emitter 150 nm below diamond/air interface. c) Emitter in the center of a diamond V-shaped antenna on top of a diamond substrate, resulting in directional emission. d) Emitter in a rod-shaped antenna on top of a glass substrate, resulting in symmetric emission—comparable to panel b. e) Emitter in a V-shaped diamond antenna on top of a glass substrate, resulting in shallow strongly directional emission. f) The spectral dependence of the directivity of the antenna in panel e (left axis) shown together with the emission spectra of the nitrogen (blue) and silicon vacancy (red) centers (right axis).

a wavelength dependent emission distribution is expected as it is based on constructive and destructive mode interference. Panel f shows the spectral dependence of the directivity of the V-antenna in panel e. The directivity of the antenna is calculated as $10\ log_{10}$ (P_r/P_l), with P_r the power radiated into the right hemisphere along the positive x-direction (antenna opening) and P_l the power radiated in the left hemisphere along the negative x-direction (antenna tip). A maximum directivity of 7 dB is obtained around 800 nm. For comparison, the normalized emission spectra of the diamond NV and SiV center at room temperature are shown in, resp., blue and red. The broad directivity peak has a good spectral overlap with these spectra, which would result in an efficient directional manipulation of the quantum emitters. By further tuning the antenna geometry the optimum directivity can be matched with, e.g. the zero phonon line of the NV center at 637 nm.

The diamond antennas can be realized by standard diamond REI etching using, e.g., a silicon etch mask. The antennas on top of a glass substrate (Figure 2d and e) can be fabricated by thinning thick diamond membranes in a reactive ion etcher and subsequent transfer to a glass cover slip [8, 5]. Defect centers in diamond can be localized using electron beam irradiation within a region of a few 100 nm [9], or by implantation through high resolution masks defined by electron beam lithography to regions $<$100 nm. The number of NV centers can be controlled by the implantation ion fluence [10]. In practice, multiple NV centers can be present in the antenna. The position of the emitter within the antenna will affect the mode coupling (phase and amplitude) and consequently the resulting directional behavior [1]. Similarly, the polarization of the emitter has to be considered. For diamond NV centers, the polarization of the dipole emitter is along the axis of the defect center, which again depends on the crystal orientation. Experimentally, these parameters can be controlled to a certain degree. So far, here, we considered the ideal case of a single emitter located in the center of the antenna and with polarization parallel to the y-directions, *i.e.* with y-polarized emission. First results indicate that the directionality is maintained even for random distribution of emitter polarization and different emitter locations. Also our previous work on directional plasmonic antennas with dye doped PMMA supports this. Experimentally, the presented simulation results can be verified by means of back focal plane fluorescence imaging of the antenna emission. [1]

Conclusions

In conclusion, we have demonstrated by means of FDTD simulations that rational design of dielectric nanostructures with embedded quantum light sources can generate extraordinary emission patterns. Because of the absence of rotational symmetry around the emitter, directional side emission into planes that are diagonal to the substrate has been achieved. Here, we focused on NV and SiV centers in diamond, but the concept can easily be transfered to different materials. The effect on the localization and polarization of the emitters will be further investigated. The designs can be further optimized and new designs explored. A bi-directional color router, e.g., could separate the unabsorbed excitation laser light from the photoluminescence emission. As such, the requirements on, e.g., integrated filters in a quantum metrology device, would be less stringent [11, 12]. These directional optical antennas could also improve single photon coupling into waveguides by forcing emission above the critical angle for guiding light into the waveguide.

References

[1] D. Vercruysse et al., ”Directional Fluorescence Emission by a Single V-antenna Explained by Mode Expansion”, *ACS Nano* 8, 8232–8241, 2014.

[2] J. Li et al., ”All-Dielectric Antenna Wavelength Router with Bidirectional Scattering of Visible Light”, *Nano Lett.* 16(7), 2016.

[3] M. Jamali et al., ”High-Density Near-Field Readout Using a Diamond Solid Immersion Lens”, *Rev. Sci. Instrum.* 85, 123703, 2014.

[4] S. A. Momenzadeh et al., ”Nanoengineered Diamond Waveguide as a Robust Bright Platform for Nanomagnetometry Using Shallow Nitrogen Vacancy Centers”, *Nano Lett.*, 15 (1), 165–169, 2015.

[5] L. Li et al., ”Efficient Photon Collection from a Nitrogen Vacancy Center in a Circular Bullseye Grating” , *Nano Lett.*, 15, 1493–1497, 2015.

[6] I. Aharonovich et al., ”Solid-state single-photon emitters”, *Nature Photonics*, 10, 631–641, 2016.

[7] J. Mertz et al., ”Radiative absorption, fluorescence, and scattering of a classical dipole near a lossless interface: a unified description” *J. Opt. Soc. Am. B.*, 17(11), 2000.

[8] J. S. Hodges et al., ”Long-lived NV^- spin coherence in high-purity diamond membranes”, *New Journal of Physics* 14 093004, 2012.

[9] C. A. McLellan et al., ”Patterned Formation of Highly Coherent Nitrogen-Vacancy Centers Using a Focused Electron Irradiation Technique” *Nano Lett.*, 16, 2450–2454, 2016.

[10] S. Sangtawesin et al., ”Highly tunable formation of nitrogen-vacancy centers via ion implantation”, *Appl. Phys. Lett.* 105, 063107, 2014.

[11] L. Rondin et al. ”Magnetometry with nitrogen-vacancy defects in diamond”, *Rep. Prog. Phys.* 77, 056503, 2014.

[12] I. Lovchinsky et al. ”Nuclear magnetic resonance detection and spectroscopy of single proteins using quantum logic”, *Science* 351, 6275, 2016.