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Citation: Applied Physics Letters 107, 031109 (2015); doi: 10.1063/1.4927401
View online: http://dx.doi.org/10.1063/1.4927401
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(Received 20 May 2015; accepted 14 July 2015; published online 22 July 2015)

Dielectric nanoantennas have generated much interest in recent years owing to their low loss and optically induced electric and magnetic resonances. In this paper, we investigate the coupling between a single emitter and dielectric patch nanoantennas. For the coupled system involving non-spherical structures, analytical Mie theory is no longer applicable. A semi-analytical model is proposed instead to interpret the coupling mechanism and the radiation characteristics of the system. Based on the presented model, we demonstrate that the angular emission of the single emitter can be not only enhanced but also rotated using the dielectric patch nanoantennas.

The ability to control and manipulate the radiation of nanoscale emitters is the cornerstone for a variety of applications, ranging from integrated optical nanocircuits to quantum communication.1–5 Metallic nanoantennas support resonant plasmon modes and mediate the interaction between nearby emitters and the far-field radiation, opening up exciting possibilities for modification of angular emission.3–6 However, their efficiency is limited by the high intrinsic loss of the metal. When complex plasmonic devices with large amounts of metal are involved, the efficiency is even further exacerbated. To circumvent this drawback, increasing attention is paid to high-index dielectric particles, which have been demonstrated to exhibit low loss and support both electric and magnetic resonances at optical frequencies.7–22 In this context, several different types of all-dielectric and hybrid metallo-dielectric nanoantennas have been devised to enhance the directional emission from a single emitter.14–21 Nevertheless, since the analytical Mie theory is strictly restricted to spherical particles, most of the designs are based on spherical nanostructures,14–19 and only a few efforts have been made to address the issue of coupling between nanoscale emitters and non-spherical structures.20–22

In this letter, given the ease of fabrication and integration, we consider using thin dielectric patch nanoantennas (DPAs) to tailor the angular radiation of a single emitter. To this end, we first study the electric and magnetic resonances supported by the thin dielectric patch and the impacts of geometric parameters. Then, we focus on the angular emission of the system comprised of a DPA and a single emitter placed in its proximity. For the coupled system containing non-spherical structures, which is not suitable for applying analytical Mie theory, we propose a semi-analytical model to interpret its radiation characteristics. Following the guideline provided by the semi-analytical model, we finally show the control over the angular radiation from single emitters. In particular, we demonstrate that the emission of a single emitter can be rotated by 90° utilizing the magnetic nature of the DPAs, which has not been shown before.

Fig. 1(a) shows the schematic diagram and the coordinate system. An x-oriented nanoscale emitter such as a molecule, a quantum dot, or a nitrogen-vacancy (NV) center is approximately characterized as a pure electric dipole \( \mathbf{p}_0 \) without any intrinsic loss. The emitter is in vicinity of a silicon (optical constants for single-crystalline silicon taken from Ref. 23) square patch with side length \( L \) and height \( H \). The distance between the emitter and the antenna is \( d_0 \). A homogeneous dielectric medium of relative permittivity \( \varepsilon_r = 2.10 \) contains the whole system. Numerical calculations are performed using the finite difference time domain (FDTD) method (Lumerical Solutions, FDTD Solutions). Perfectly matched layers (PMLs) are applied on every boundary of the simulation region and a refined mesh of 1 nm is used around the emitter and the dielectric patch.

We first analyze the radiative properties of the single emitter coupled to the DPA with \( L = 135 \) nm and \( H = 40 \) nm. The distance \( d_0 \) is 10 nm. A relevant figure of merit to describe the radiative properties is the well-known Purcell factor \( F_p \). \( F_p \) can be calculated as \( F_p = P/P_r \) where \( P \) and \( P_r \) are the power radiated by the emitter in the presence and absence of the DPA, respectively.24 We can also have the radiation efficiency \( \eta = P_r/P \), by comparing the radiated power \( P_r \) and the total power \( P \) of the system. The Purcell factor \( F_p \) and the radiation efficiency \( \eta \) of the system are plotted in Fig. 1(b). Two clear peaks in the curve of the Purcell factor correspond to the electric and magnetic resonances supported by the high-index dielectric particle, which has been verified both theoretically and experimentally by the previous reports.7–10 The lowest-order (i.e., lowest frequency) resonance at \( \lambda_0 = 540 \) nm is dominated by a magnetic dipolar (MD) mode, while the next higher-order resonance at \( \lambda_0 = 440 \) nm is an electric dipolar (ED) mode. The radiation efficiency first increases and then keeps relatively high around 90% at longer wavelengths due to the low.

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loss of the dielectric material itself. Normalized near-field distributions at \( \lambda_0 = 540 \) nm in a cut plane through the center of the DPA are depicted in Figs. 1(c) and 1(d). For the electric field, we observe two dents along the \( x \) direction, indicating that the electric response of the DPA resembles an induced \( x \)-polarized electric dipole. For the magnetic field, we observe a confined \( |H_z| \) inside the DPA, mimicking a \( z \)-oriented magnetic dipole. The effects of geometric parameters are also studied, as shown in Fig. 2. By varying the geometric parameters, the resonances of the DPA could be tuned over a broad spectral range. Larger sizes of the DPAs result in redshifts of the resonant wavelengths and higher-order resonances gradually appear with the increasing sizes. Furthermore, since the absorption loss of the silicon is not negligible in the visible range, the radiation efficiency of the DPAs is also affected by the geometric parameters, especially for \( \lambda_0 < 550 \) nm. From a practical and experimental perspective, to maximum the Purcell factor as well as the radiation efficiency at a certain wavelength, the side length \( L \) has a larger impact than the height \( H \). Meanwhile, careful considerations and choices of the height \( H \) are also important for certain applications, for instance, DPAs with smaller heights (thus smaller footprints) would have advantages in photonic integrated circuits.

Next, we concentrate on the angular emission of the system. For simplicity, we fix the vacuum wavelength of the emitter at 540 nm and the geometric parameters of the DPA as \( L = 135 \) nm and \( H = 40 \) nm to optimize the Purcell factor.
The performance of the system is investigated in terms of the directivity \( D(\theta, \varphi) \), which is defined as \( D(\theta, \varphi) = 4\pi P(\theta, \varphi)/P_\text{r} \), where \( P(\theta, \varphi) \) is the angular radiated power. The 3D radiation patterns (in linear scale) and radiation patterns in three major planes are obtained numerically, as plotted in Figs. 3(b) and 3(d)–3(f). In order to reveal the underlying physics of the radiative properties of the system, we consider to use two dipoles (an electric and a magnetic) as the equivalent of the DPA, since both electric and magnetic responses of the DPA exhibit dipole-like behaviors as mentioned in Fig. 1. The presented equivalent model consists of three dipoles and is sketched in Fig. 3(a). The induced electric dipole \( \mathbf{p}_1 \) and magnetic dipole \( \mathbf{m}_1 \) are set at the middle center of the DPA as well as the origin of the coordinate system. The electric dipole moment \( \mathbf{p}_0 \) of the single emitter is initially set as \( \mathbf{p}_0 = 2.46 \times 10^{-31} \) Cm, which generates a radiated power of 1 fW in the homogeneous dielectric background without the DPA. The distance between the original single emitter and the induced dipoles is \( d \), which is \( d = d_0 + L/2 \). The far-field electric fields at any arbitrary point \( P(x, y, z) \) produced by the three individual dipoles of the system are given in the following expressions:

\[
\mathbf{E}_p = \frac{k^2 e^{ikr_0}}{4\pi\varepsilon_0 \varepsilon_r} (\mathbf{n}_0 \times \mathbf{p}_0) \times \mathbf{n}_0, \tag{1}
\]

\[
\mathbf{E}_p = \frac{k^2 e^{ikr_1}}{4\pi\varepsilon_0 \varepsilon_r} (\mathbf{n}_1 \times \mathbf{p}_1) \times \mathbf{n}_1, \tag{2}
\]

\[
\mathbf{E}_m = -\frac{Z k^2 e^{ikr_1}}{4\pi r_1} (\mathbf{n}_1 \times \mathbf{m}_1), \tag{3}
\]

where \( \mathbf{E}_p, \mathbf{E}_p, \) and \( \mathbf{E}_m \) represent the electric fields at point \( P \) produced by the original single emitter \( \mathbf{p}_0 \), the induced electric dipole \( \mathbf{p}_1 \), and the induced magnetic dipole \( \mathbf{m}_1 \), respectively; \( k \) is the wave number; \( \varepsilon_0 \) is the permittivity of the vacuum; \( r_0 \) and \( r_1 \) are, respectively, the distances between the point \( P \) and the original emitter as well as the induced dipoles; and \( \mathbf{n}_0 \) and \( \mathbf{n}_1 \) are the corresponding unit vectors in the direction of the distances \( r_0 \) and \( r_1 \). The electric field \( \mathbf{E}_p \) at point \( P \) thus can be calculated as \( \mathbf{E}_p = \mathbf{E}_{p0} + \mathbf{E}_{p1} + \mathbf{E}_{m1} \).

Subsequently, combining the numerical simulations, we propose a simple retrieval method to derive the magnitude and the phase of the induced dipoles \( \mathbf{p}_1 \) and \( \mathbf{m}_1 \). Using the near-to-far-field transformation, we first numerically obtain the electric field at point \( P1(0, 0, 1) \) \((z = 1 \) m\) as \( \mathbf{E}_{p1} = 1.52 e^{0.35i} \times 10^{-7} \) V/m. For the point \( P1 \), the induced magnetic dipole \( \mathbf{m}_1 \) has no contribution to the electric field \( \mathbf{E}_{p1} \). Therefore, the electric field \( \mathbf{E}_{p1} \) is only the sum of \( \mathbf{E}_{p0} \) and the known \( \mathbf{E}_{p1} \). By applying Eq. (2), we can derive the induced electric dipole as \( \mathbf{p}_1 = 1.60 e^{0.99i} \times 10^{-31} \) Cm. Similarly, the electric field \( \mathbf{E}_{p2} \) at point \( P2(0, 1, 0) \) can also be numerically obtained as \( \mathbf{E}_{p2} = 4.37 e^{0.12i} \times 10^{-7} \) V/m. Thus, we can get the induced magnetic dipole \( \mathbf{m}_1 = 7.26 e^{0.99i} \times 10^{-23} \) Am\(^2\). We compare the radiation patterns of the equivalent semi-analytical model and the numerical results in Figs. 3(d)–3(f). The results are in good agreement with each other. The slight differences are probably due to the neglect of higher-order responses. Our semi-analytical model provides a guideline for how to shape the emission of the single emitter as well. For example, since the distance \( d \) has impacts on both the phases and the magnitudes of the induced dipoles, it creates the possibility for us to tailor the radiation by varying the distance \( d \). Radiation patterns for \( d_0 = 70 \) nm (i.e., \( d = 137.5 \) nm) are depicted in Figs. 3(c) and 3(g)–3(i). The radiation in \(-y\) direction is remarkably enhanced compared
with the case when $d_0 = 10$ nm. Furthermore, the results obtained by the semi-analytical model and the numerical simulations are still in good accordance with each other, proving the validity of the equivalent model.

It is also worth noting that the radiation pattern shown in Fig. 3(f) is particularly interesting: while for the isolated single emitter, there is almost no emission along the $x$ direction at all; the emission of the coupled system is mainly along the $x$ direction. The radiation of the single emitter seems to be highly redirected and rotated by $90^\circ$. This is due to the induced electric dipole $\mathbf{p}_1$ and magnetic dipole $\mathbf{m}_1$, both oscillate nearly out-of-phase compared to the original single emitter $\mathbf{P}_0$ when $d_0 = 10$ nm. A destructive interference thus occurs between the far-field radiation of the two electric dipoles. For this reason, the radiation in $x-z$ plane is dominated by the magnetic dipole. This unique property indicates the possibilities for using the magnetic nature of the dielectric nanoantennas to modulate the polarization and the direction of the far-field radiation from nanoscale emitters. As an example, we consider to use an array of the DPAs, as illustrated in Fig. 4(a). Several DPAs are placed along the $-x$ direction and the distance between the DPAs is $d_x$. Here, we simply choose $d_x = 30$ nm, which is well within reach of present nanofabrication technique. Fig. 4(b) shows the radiation in $x-z$ plane of the single emitter and with different numbers $N$ of the DPAs. It is evident that the radiation of the single emitter is rotated by $90^\circ$ by applying the array of DPAs. The near-field distributions in Fig. 4(c) reveal that the DPAs resemble a Yagi-Uda-like or a linear array of induced magnetic dipoles, resulting in the rotation and the enhancement of the directivity. Moreover, owing to the low loss of the dielectric material, the increase in the number of the DPAs would not lead to a significant decline in the radiation efficiency, as plotted in Fig. 4(d). An additional DPA only brings a decrease of roughly $2\%$ in the efficiency. Future optimization of the array or applying other designs such as introducing hybrid nanoantennas might help to further improve the performance of the system.

In conclusion, we study the coupling between a single emitter and the DPAs. By combining numerical calculations and a retrieval method, we propose a semi-analytical model to interpret the radiation characteristics of the system involving non-spherical dielectric nanoantennas. We also demonstrate that by employing the DPAs, we can not only enhance but also control the angular emission of a single emitter. In particular, we show how to rotate the emission of a single emitter by employing the magnetic nature of the DPAs. These unique properties, combining the ease in fabrication and integration as well as the tunable resonances, make the DPAs promising for a variety of applications such as sensing and optical communication.

This work was supported by the National Natural Science Foundation of China (Grant Nos. 61235007, 61205030, 61425023, and 61275030), the Qianjiang River Fellow Fund of Zhejiang Province, the Scientific Research Foundation for the Returned Overseas Chinese Scholars from the State Education Ministry, the Opened Fund of State Key Laboratory of Advanced Optical Communication Systems and Networks, the Fundamental Research Funds for the Central Universities (2014QNA5020), the Doctoral Fund of Ministry of Education of China (Grant No. 2012011120128), and the Swedish Research Council (VR).

Y. Yang thanks L. Meng, J. Tian, and X. Chen for useful discussions.