Highly Directive All-Dielectric Nanoantenna

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Abstract. A highly directive dielectric nanoantenna in an integrated chip may enable faster communication as their low losses and small size overcome the limitation of temperature enhancement and low data transfer rate. We optimize nanoantenna consist of Si-nanoblock in the near-infrared region to efficiently transfer a point dipole light to a highly directive light in the far-field region. We engineer the intrinsic electric and magnetic resonances of a Si-block nanoantenna by modifying and reducing its geometrical symmetry. We realize a pronounced enhancement of directivity by systematically inducing perturbation in the Silicon block so that both its reflection and rotational symmetries are broken. Finally, we retain the traditional method to increase resonance’s coupling to outer space by introducing substrate with an increasing refractive index. We find that the directivity has boosted rapidly.

The study of the nanoantenna has been one of the hottest areas in the optical range due to their application in integrated optoelectronic semiconductor chips\cite{1,2}. Currently, semiconductor chips are limited by high enhancement of temperature which results in a low data transfer rate\cite{3}. The surface-plasmon-polariton wave can overcome the limitation as they are highly localized near the metal/dielectric interface\cite{4}. However, a metal nanostructure possesses high ohmic losses which limit the propagation distance\cite{5}. Therefore, integrating the all-dielectric optical nanoantenna in a semiconductor chip is one of the most promising for the integrated chip. It will not only increase the data transfer rate but also reduce the size of a chip.

A nanoantenna has the ability to bridge the size and impedance mismatch between nano-emitters and free-space radiation. It must have high radiation efficiency and be highly directive for wireless optical communication in photonic chips. But, existing optical nanoantennas usually do not radiate efficiently and have low directivity if they are far from their self-resonance. An all-dielectric nanoantenna with a high refractive index has the ability to excite both electric and magnetic dipole resonances, thus adding an extra degree of freedom to tailor those resonances at a certain wavelength\cite{6}. Such all-dielectric nanoantenna could have high radiation efficiency with low dissipative losses and high magnetic response. Forward and backward scattering characteristics of individual nanoparticles could be controlled by engineering the electric and magnetic resonance\cite{7-11}.

Because of the large refractive index and negligible absorption losses in the visible spectrum region, dielectric nanoantenna (Si or Ge-nanoparticle) has been investigated for various shapes\cite{12-15}. Over the last few decades, several all-dielectric metasurfaces have been designed to manipulate the light for possible applications in polarization, absorbance, optical nanoantenna, transmission, and many others\cite{16-21}. In order to achieve high directive, several studies combined plasmonic and dielectric
nanostructures to use their respective advantages [22,23]. However, high directive all-dielectric nanoantenna excited by point dipole in the near-infrared region was not much explored.

With this motivation, here we study the directivity of an all-dielectric nanoantenna in the near-infrared region. First, we demonstrate how the directivity of a Si-block nanoantenna is tailored when the nanostructure is excited by the point dipole. Next, we reveal that directivity of the such type of nanoantenna can be controlled by engineering symmetry breaking, as well as making a cluster of them. Finally, we demonstrate the nanoantenna with substrate providing very high directivity. Our main goal is to show how one can change the directivity of nanoantenna by engineering its structure.

1. High Directive Nanoantenna
The Directivity of an antenna is a measure of the concentration of the maximum radiated power in a particular direction $(\theta, \phi)$, that is, $D_{\text{max}} = (4\pi U(\theta, \phi)_{\text{max}})/P_{\text{rad}}$, where $\theta$ and $\phi$ are the polar and azimuthal angles in a spherical coordinate system, respectively. $U(\theta, \phi)_{\text{max}}$ is the maximum radiation intensity (power per unit solid angle) in $(\theta, \phi)$ direction and $P_{\text{rad}}$ is the total radiated power. The directivity is investigated numerically based on the COMSOL by the finite-element method for the geometry shown in Fig. 1. We consider several dielectric nanoantennas shown schematically in Figure 1a—c, composed of Si-nanoblock ($n = 3.5$). For all numerical results presented here, we choose $l = 380$ nm, which is much smaller than the operating wavelength.

![Figure 1: Perspective and side view of the nanoantenna composed of Si and excited by the point dipole which is placed at a distance $d$ from the top surface of the nanostructure: (a) consist of a nanoblock of sides $l$; (b) an asymmetric block created by removing the bricks of size $l/2 \times l/2 \times h$ from the block top surface; (c) cluster of asymmetric blocks having gap $g$ from each other.](image)

![Figure 2: The dependency of the directivity on wavelength and (a) the distance between the dipole source and top surface of the block; (b) the height of the bricks ($h$) removed from the top surface of the block. The three-dimension radiation pattern for maximum directivity is also shown.](image)

In Figure 2, we study the directivity of the nanoantenna for the schematic shown in Fig. 1(a) and (b). It can be seen in Fig. 2(a) that the directivity of the nanoantenna can be tailored by the position of the dipole (d). Higher directivity is obtained when the dipole is placed near the nanoantenna. Maximum directivity $D_{\text{max}} = 7.7$ is observed at a wavelength $\lambda = 830$ nm when $d = 5$ nm. Now, we break the symmetry of the block by removing the bricks of size $l/2 \times l/2 \times h$ from the top surface of the block
as shown in Fig. 1(b). The dependency of the directivity on the height of the brick \(h\) is shown in Fig. 2(b). Maximum directivity \(D_{\text{max}} = 9.6\) is achieved at a wavelength \(\lambda = 805\) nm when \(h = 85\) nm. The radiation pattern corresponds to \(D_{\text{max}} = 7.7\) and 9.6 are also shown in Fig. 2(a) and (b), respectively.

Here, the directivity is higher than the directivity of the point dipole (1.5) because when a local source (electric or magnetic emitter) is placed close to the antenna, the near-field coupling between the emitter and the dipole resonance (ED and MD) inside the antenna offers the highly unidirectional emission. It is important to note that, a higher directivity is obtained when we introduced the asymmetricity in the block. By introducing the asymmetricity, significant higher-order multipole is excited which results in more contribution in scattering.

Next, we assume that nanoantenna showed in Fig. 1(a) and (b) are placed on a substrate \(n_{\text{sub}}\). Figure 3 shows the variation of directivity with the refractive index of the substrate \(n_{\text{sub}}\). As observed from Fig. 3, directivity increases sharply when the nanoblock is placed on the substrate which is due to the coupling of the light into the substrate when the nanoblock embedded on a substrate and excited by the local source such as dipole emitters. The coupling mechanism plays an important role in achieving directional light scattering and emission using nanoantenna.

![Figure 3](image1.png)

**Figure 3.** Directivity of the nanoantenna tailored by the refractive index of the substrate: (a) simple block on substrate leads to maximum directivity of 14.4 with \(n_{\text{sub}} = 1.6\) at \(\lambda = 840\) nm when \(d = 5\) nm; (b) asymmetric block on substrate gives maximum directivity of 20.8 with \(n_{\text{sub}} = 2.0\) at \(\lambda = 820\) nm when \(d = 5\) nm and \(h = 85\) nm. The three-dimension radiation pattern for maximum directivity is also shown.

Finally, we demonstrate how the directivity is affected by the cluster of the nanoblock. We consider an arrangement of two asymmetric blocks having a gap \(g\) excited by the point dipole (see Fig. 1(c)). The variation of the directivity with the wavelength and the gap \(g\) is shown in Fig. 4. While comparing Fig. 2(b) and Fig. 4, we found higher directivity for the cluster of nanoblocks due to the enhance in the amplitude of higher-order multipole moments, which is not achievable with a single nanoblock. When the cluster of blocks is placed at the optimal distance, the external field is so inhomogeneous that the magnetic and electric dipole components of the polarization current in the cylinder are no longer dominant, as they would be for the case of a single block.

![Figure 4](image2.png)

**Figure 4.** Directivity of the nanoantenna tailored by the gap between the two asymmetric blocks (cluster). Maximum directivity of 14.7 is observed with \(g=160\) nm at \(\lambda=820\) nm when \(d=5\) nm, and \(h=120\) nm. The three-dimension radiation pattern for maximum directivity is also shown.
2. Conclusions
In summary, we have studied the high directive all-dielectric nanoantenna in the near-infrared region for several nanoparticles consist of Si-nanoblock. We demonstrated that the directivity of the nanoantenna can be controlled by the position of the point dipole and it was maximum when the dipole was placed near to the nanoblock. An enhancement in the directivity has been observed when we break the symmetry by removing the brick shape from the Si-nanoblock. The directivity of the nanoantenna has been further increased due to the coupling of light into the substrate when the nanoblock was embedded on the substrate. Finally, to observed the effect of a cluster on directivity, we considered two asymmetric nanoblock. We showed that the cluster of the nanoblock enhances the directivity by increasing the amplitude of the higher-order multipole moment.

References
[1] Dong, P, Chen, Y K, Duan, G H and Neilson, D T 2014 Nanophotonics 3 215-228.
[2] Bogaerts, W and Chrostowski, L 2018 Laser Photonics Rev. 12 1700237.
[3] Ozbay, E, 2006 Science 311 189-193.
[4] Agrahari, R, Lakhtakia, A and Jain, P K 2019 Sci. Rep. 9 1-9.
[5] Kostina, N, Petrov, M, Ivinskaya, A, Sukhov, S, Bogdanov, A, Toftul, I, Nieto-Vesperinas, M, Ginzburg, P and Shalin, A 2019 Phys. Rev. B 99 125416.
[6] Evlyukhin, A B, Fischer, T, Reinhardt, C and Chichkov, B N 2016 Phys. Rev. B 94 205434.
[7] Baryshnikova, K, Filonov, D, Simovski, C, Evlyukhin, A, Kadochkin, A, Nenasheva, E, Ginzburg, P and Shalin, A S 2018 Phys. Rev. B 98 165419.
[8] Kozlov, V, Filonov, D, Shalin, A S, Steinberg, B Z and Ginzburg, P 2016 Appl. Phys. Lett. 109 203503.
[9] Canos Valero, A, Kislov, D, Gurvitz, E A, Shamkhi, H K, Pavlov, A A, Redka, D, Yankin, S, Zemaine, P and Shalin, A S 2020 Adv. Sci. 7 1903049.
[10] Barhom, H, Machnev, A A, Noskov, R E, Goncharenko, A, Gurvitz, E A, Timin, A S, Shkoldin, V A, Koniaikhin, S V, Koval, O Y, Zyuzin, M V and Shalin, A S 2019 Nano Lett. 19 7062-71.
[11] Kozlov, V, Filonov, D, Shalin, A S, Steinberg, B Z and Ginzburg, P 2016 Appl. Phys. Lett. 109 203503.
[12] Krasnok, A E, Simovski, C R, Belov, P A and Kivshar, Y S 2014 Nanoscale 6 7354-61.
[13] Oe, H S, Kang, J H, Brongersma, M L and Seo, M K 2015 Nano Lett. 15, 1759-65.
[14] Moitra, P, Slavick, B A, Gang Yu, Z, Krishnamurthy, S and Valentine, J 2014 Appl. Phys. Lett. 104 171102.
[15] Forouzmand, A and Mosallaei, H 2017 Adv. Opt. Mater. 5 1700147.
[16] Kruk, S, Hopkins, B, Kravchenko, I I, Miroshnichenko, A, Neshov, D N and Kivshar, Y S 2016 APL Photonics 1 030801.
[17] Terekhov, P D, Baryshnikova, K V, Greenberg, Y, Fu, Y H, Evlyukhin, A B, Shalin, A S and Karabchevsky, A 2019 Sci. Rep. 9 1-9.
[18] Terekhov, P D, Shamkhli, H K, Gurvitz, E A, Baryshnikova, K V, Evlyukhin, A B, Shalin, A S and Karabchevsky, A 2019 Opt. Express 27 10924-35.
[19] Fu, Y H, Kuznetsov, A I, Miroshnichenko, A E, Yu, Y F and Luk’yanchuk, B 2013 Nat. Commun. 4 1-6.
[20] Shalin, A S 2010 JETP Lett. 91 636-642.
[21] Zhao, W, Jiang, H, Liu, B, Song, J, Jiang, Y, Tang, C and Li, J 2016 Sci. Rep. 6 1-7.
[22] Sugimoto, H, Hinamoto, T and Fuji, M 2019 Adv. Opt. Mater. 7 1900591.
[23] Rusak, E, Staude, I, Decker, M, Sautter, J, Miroshnichenko, A E, Powell, D A, Neshov, D N and Kivshar, Y S 2014 Appl. Phys. Lett. 105 221109.