Optics Communications ■ (■■■■) ■■■–■■■

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Unidirectional enhanced spontaneous emission with metallo-dielectric optical antenna

Hongming Shen [a], Guowei Lu [a,b,*], Yingbo He [a], Yuqing Cheng [a], Qihuang Gong [a,b]

[a] State Key Laboratory for Mesoscopic Physics, Department of Physics, Peking University, Beijing 100871, China
[b] Collaborative Innovation Center of Quantum Matter, Beijing 100871, China

ARTICLE INFO

Article history:
Received 15 June 2015
Received in revised form
21 August 2015
Accepted 24 August 2015

Keywords:
Spontaneous emission
Unidirectional
Metallo-dielectric antenna
Plasmonic enhanced

ABSTRACT

A metallo-dielectric system consisted of two coupled metallic nanoparticles embedded in a planar dielectric antenna is proposed to control the light emission from a localized emitter. Such design integrates the advantages of planar dielectric antenna and plasmonic antenna such as highly localized excitation enhancement, emission direction control, and high collection efficiency. For specific configurations, the antenna can achieve unidirectional and plasmon-enhanced emission from single emitters, simultaneously presenting remarkable collection efficiency up to 96%. We show that the unidirectional effect is mainly determined by the plasmon coupling effect of the plasmonic dimer. The dependences of directivity property on the antenna geometry and emitter's position are also discussed in detail. These findings provide a promising route to realize novel optical devices involving directional and surface enhanced spontaneous emission, e.g. bright single-photon sources with high collection efficiency.

© 2015 Elsevier B.V. All rights reserved.

1. Introduction

Metallic nanostructures provide new conceptual routes to locally enhance and direct spontaneous emission with major applications in molecular biology, chemistry, nonlinear optics and quantum computation, etc. The nanostructures can generate strong localized surface plasmon resonances (LSPRs) to tailor the fluorescence process, e.g., increasing excitation rate, shortening fluorescence lifetime and shaping emission spectrum [1–4]. In the past decades, the "enhancement effect" has been thoroughly studied in many contexts [5,6]. Recently, tailoring angular emission pattern of single emitters attracts much attention [7]. Improved directivity has been confirmed to reciprocally enhance the excitation rate, playing an important role in efficient excitation and detection process [8]. In general, the angular emission of a single emitter in free space exhibits a typical 'doughnut' pattern, which is inefficient to collect photons by microscope objectives or couple within photonic chip. To control radiation directivity, researchers have investigated various kinds of optical antennas, such as Yagi-Uda antenna [9], bull's eyes aperture [10], metallic tip [11], plasmonic dimer [12–14] or single particles [15–17], dielectric antenna [18–20], and metallo-dielectric antenna [21–23]. However, despite much progress, the realization of high collection efficiency, unidirectional, and surface enhanced radiative rate simultaneously with the same optical antenna is still a challenging task.

In this study, we propose a metallo-dielectric antenna that consists of two neighboring metallic nanoparticles embedded in a planar dielectric antenna. By employing finite-difference time-domain method, it is found that the metallo-dielectric system can enhance and concentrate single-molecule emission in specific direction with remarkable collection efficiency up to 96%. A detailed insight into the directional emission process is demonstrated by using a simple 'two dipole' model. Taking into account practical applications, we also explored the dependence of the emission directivities from single emitters on the positions, orientations, and antenna geometrical parameters. These findings make a promising route to the development of spontaneous emission manipulation.

2. Simulation model and methods

Fig. 1(a) illustrates the schematic of our proposed antenna configuration. For comparisons, we consider three cases: (1) planar dielectric antenna (DA), (2) single gold nanoparticle embedded in the dielectric antenna (SDA), and (3) double gold nanoparticles embedded in the dielectric antenna (DDA). The DA structure consists of three dielectric layers and requires the refractive index $n_3 > n_2 > n_1$ to form the quasi-waveguide. The emitted radiation of single molecules would be channeled into the quasi-waveguide modes, and then drawn towards the denser substrate for ultrahigh

* Corresponding author at: State Key Laboratory for Mesoscopic Physics, Department of Physics, Peking University, Beijing 100871, China.
E-mail address: guowei.lu@pku.edu.cn (G. Lu).

http://dx.doi.org/10.1016/j.optcom.2015.08.068
0030-4018/© 2015 Elsevier B.V. All rights reserved.

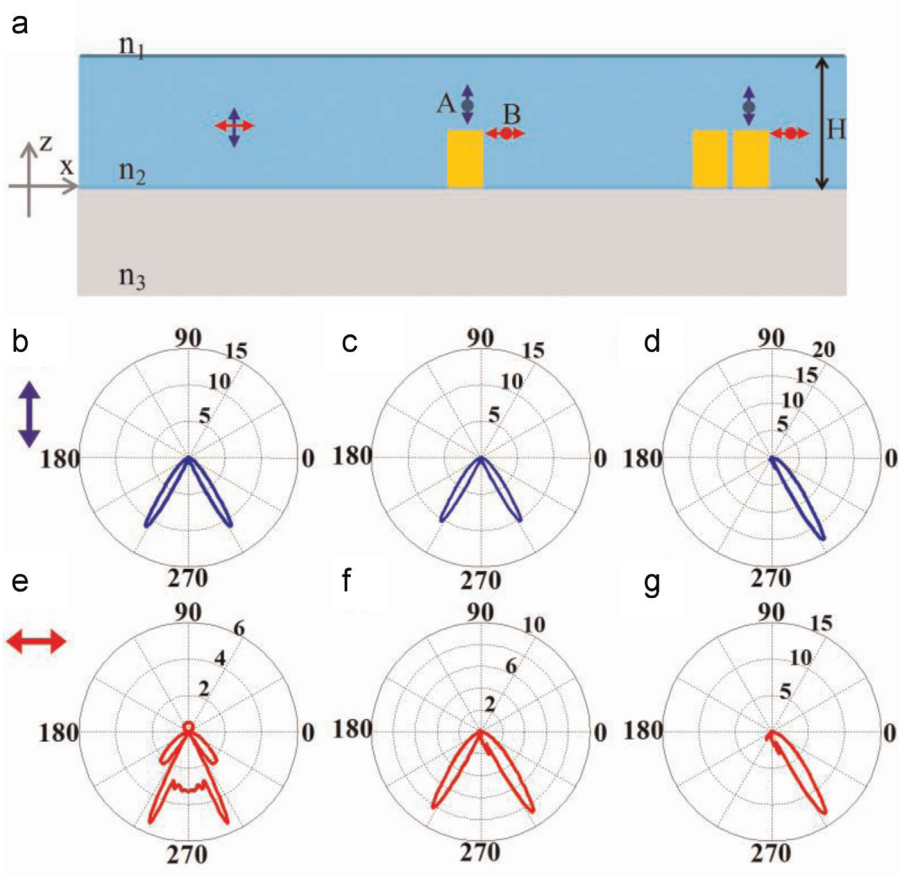

Fig. 1. Schematic of three antenna structures and the calculated far-field directivities in the x–z plane of an oriented dipole ($\lambda \sim 670$ nm) based on NFTFF method. (a) Schematic of three antenna structures: DA structure (left), SDA structure (middle) and DDA structure (right). (b)–(d) demonstrate the corresponding emission patterns for a V-dipole at 39 nm (Position A) above the polymer/substrate interface, while (e)–(f) for an H-dipole at 35 nm above the polymer/substrate interface (Position B), respectively.

collection efficiency [19]. We choose the refractive index $n_3 = 2.5$ for the high-index substrate and the top layer is air ($n_1 = 1.0$). As for the middle layer, a thin transparent polymer film is used with thickness $H = 180$ nm and $n_2 = 1.5$ to form a planar dielectric antenna. Then, an oriented emitter at emission wavelength of 670 nm is placed within the middle layer.

The finite-difference time-domain (FDTD) method is performed to calculate the local electromagnetic fields, spectral response, and charge density distribution. FDTD is a powerful tool to simulate the emission process of a single dipole source near metallic nanostructures [24,25]. The basic principle of FDTD is to numerically solve the Maxwell's differential equations, where both the space and time are divided into discrete segments. In our calculation, a classical point current source is implemented in the FDTD calculations (here we use the free-software MEEP for electromagnetic simulations) [26], referred to as a single quantum emitter. The emitter orientation is thus determined by the components of the current dipole source. Perfectly matched layer (PML) absorption boundary conditions are used and the mesh size is set to 1 nm in all cases. (1) For the calculation of far-field radiation patterns based on near-field-to-far-field (NFTFF) transformation, we first recorded the near-field electromagnetic data [$\boldsymbol{E}(t)$, $\boldsymbol{H}(t)$] at two sufficiently large surfaces (~ 4 μm wide) above air/polymer interface ~ 50 nm and beneath the polymer/substrate interface ~ 100 nm by performing 2D FDTD simulations in the Cartesian coordinates. Then we performed Fourier transform on the fields ($\boldsymbol{E}$, $\boldsymbol{H}$) and calculated the surface electric ($\boldsymbol{J}_s$) and magnetic ($\boldsymbol{M}_s$) currents, respectively. According to the surface equivalence theorem, we finally derived the angular directivity $D(\theta) = 2\pi P(\theta)/\int P(\theta)d\theta$ in our 2D geometry, where $P(\theta)$ is the angular radiation power density [24]. The NFTFF transformation method has been successfully applied in the photonic crystal resonators and plasmonic nanoantennas [11,27,28]. (2) For the calculation of spectral response, a temporal Gaussian point dipole source is implemented in the FDTD. The radiative enhancement factor is defined as $S_F = P_{rad}/P^0_{rad}$, where P_{rad} is obtained by integrating the Poynting vector over a closed surface that contain the dipolar source and the dimer resonator. P^0_{rad} is the power radiated to the far-field without metallic particles. (3) For the 'two-dipole' model method [15], we treated the dimer resonator as two coherent electric dipoles oscillating in the z direction. Here, the field radiated in the $\pm x$ direction is proportional to $\cos[(\Delta\phi \pm kl)/2]$, with $\Delta\phi$ the phase difference between the two dipoles, $k = 2n\pi/\lambda$ the wavelength vector and l the dipole–dipole separation distance (actually k should be the wave-number of the waveguide and here we approximately treat effective index n as a constant n_2 for simplicity since l is much smaller than the wavelength λ). From the charge density distribution, the total dipole moment $P = Pe^{i\phi}$ can be obtained by $P_i(\lambda) = \iint \rho_i(x, z, \lambda) z dz dx$, where $i = 1, 2$ represents the left/right dipole and ρ is the complex charge density. Then we can evaluate the phase difference $\Delta\phi = \phi_2 - \phi_1$ and the relative magnitude of dipole moment P_1/P_2 of the two dipoles. The charge density distribution is obtained from the Poisson equation by calculating complex local electric fields.

Please cite this article as: H. Shen, et al., Optics Communications (2015), http://dx.doi.org/10.1016/j.optcom.2015.08.068

Download English Version:

https://daneshyari.com/en/article/5449543

Download Persian Version:

https://daneshyari.com/article/5449543

Daneshyari.com