Enhanced directional excitation and emission of single emitters by a nano-optical Yagi-Uda antenna.

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Abstract: We demonstrate by 3D numerical calculations that the interaction of a single quantum emitter with the electromagnetic field is both enhanced and directed by a nano-optical Yagi-Uda antenna. The single emitter is coupled in the near field to the resonant plasmon mode of the feed element, enhancing both excitation and emission rates. The angular emission of the coupled system is highly directed and determined by the antenna mode. Arbitrary control over the main direction of emission is obtained, regardless of the orientation of the emitter. The directivity is even more increased by the presence of a dielectric substrate, making such antennas a promising candidate for compact easy-to-address planar sensors.

OCIS codes: Optical antennas; (350.4238) Nanophotonics; (240.6680) surface plasmons; (280.5110) Phased-array radar; (260.3910) metal optics; (180.4243) Near-field microscopy.

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1. Introduction

Metallic nano-particles support resonant plasmon modes that couple strongly to the optical radiation field. Such particles function, in analogy to resonant radio antennas, as optical antennas [1-6]. If a quantum emitter is coupled to the antenna mode, the antenna acts as a resonator mediating the interaction between the emitter and the radiation field [1, 7]. Under suitable illumination the local field is enhanced, increasing the excitation rate. In emission, the decay rate, spectrum and angular emission are modified. The situation is analogous to the modification of spontaneous emission by coupling to, for example, cavity [8, 9] or photonic crystal [10] modes. The main advantage of nano-particles over such systems is their size: both the antenna dimensions and the volume of interaction are smaller than the wavelength, allowing manipulation on the nano-scale.

Optical dipole [3, 11, 12], monopole [6, 13] and several types of "gap" antennas [4, 5, 14, 15] have been demonstrated to enhance transition rates [3, 14-16] and, only recently, to modify angular emission [7]. All these antennas have an approximately dipolar angular emission; their modes both radiate and are excited with a dipolar angular dependence. Ideally an optical antenna has a high directivity; this enhances the interaction with a set of directed radiation modes, facilitating efficient excitation and the detection of emission. The common Yagi-Uda antenna achieves a high directivity by placing several passive scatterers around a resonant feed element [17, 18]. On one side of the feed, the scaterers are slightly capacitive detuned, these are called the directors. The elements on the other side, the reflectors, are detuned inductively. The resulting interference creates a beam directed towards the side of the directors. To use this principle of directed emission in optics, it has been suggested to place an emitter in an array of properly tuned particles [19, 20]. In those schemes the active feed element of the Yagi-Uda is replaced by a dipolar optical emitter and the other elements are approximated as induced point dipoles. Although a directed beam is indeed obtained, the prime advantage of optical antennas, the strong modification of transition rates by a near-field coupling to a resonant element, is totally forgone. In fact such arrangements resemble more an emitter in proximity of a grating than an emitter coupled to an antenna.

Here we show by numerical calculations that a complete nano-optical Yagi-Uda antenna, including a resonant feed element, simultaneously enhances transition rates and achieves high directionality. By near-field coupling a single optical emitter to the feed element, both the excitation and emission rates are enhanced, while the angular emission is determined by the total antenna mode and is highly directed. The near-field nature of the interaction makes coupling possible for all emitter orientations, leading to arbitrary control of the main emission direction. Finally, we show that the directivity is further increased when placing the antenna on a dielectric substrate, as is typically the case for applications of optical antennas.

2. Directional emission of single emitters

To solve the electromagnetic field, full-3D Finite Integration Technique [21, 22] calculations are performed. To make results generally valid, the transition of the quantum emitter is approximated as a pure electric dipole transition and represented by a classical point dipole, oscillating at a single frequency with fixed oscillator strength. In this way transition rates relative to a reference situation (here: vacuum) are obtained. The transition energy is chosen to match a vacuum wavelength of 570 nm. For emission calculations, the dipolar emitter is the source. For excitation, the antenna and emitter are illuminated by plane waves.
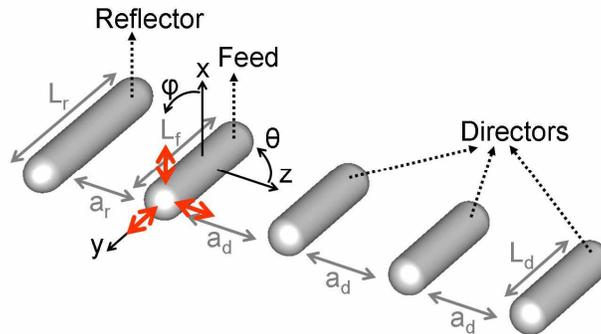

Fig. 1. Overview of the nano-optical Yagi-Uda antenna. For an operating wavelength of 570 nm and an aluminum antenna ($\varepsilon = -38.0 + i10.9$), the feed element is resonant for $L_f = 160$ nm. The director length (L_d) is $0.9L_f$, the reflector length (L_r) is $1.25L_f$. The director spacing (a_d) is $\lambda/4$, the reflector spacing (a_r) is $\lambda/4.4$. Red arrows represent x-, y- and z-oriented dipolar emitters and are placed at the location of efficient coupling to the feed element.

Figure 1 shows a nano-optical Yagi-Uda antenna. The antenna consists of 5 cylindrical elements (1 feed, 1 reflector and 3 directors) with hemispherical ends and all with a radius of 20 nm. These values are well within reach of current nano-fabrication methods [23]. The antenna is made of aluminum ($\varepsilon = -38.0 + i10.9$ at 570 nm [24]). Depending on the operation wavelength, using other materials, such as gold or silver, can give quantitatively different results, but does not change the qualitative behavior of the results presented or the principles derived here. The nano-optical Yagi-Uda is designed as follows. First, standard parameters for a 5-element Yagi-Uda antenna consisting of thin elements of a perfect electrical conductor (PEC) material are taken [17]. Next, the change in the dipolar resonance length of the feed element for realistic radius (20 nm) and material (aluminum) is calculated. Then, all element lengths are adjusted by the same scaling factor while keeping the spacing constant. Finally it is certified that the new parameters are indeed a (local) optimum.

The emitter is coupled to the feed element by placing it at a point of high electric mode density, for a dipolar resonance at the extremes of the antenna elements. Differently-oriented emitters couple most efficiently to the antenna at different positions. The respective positions for x-, y- and z-oriented emitters are shown in Fig. 1.

First the angular dependence of the emission is studied. The angular directivity $D(\varphi,\theta)$ is defined as [17]:

$$D(\varphi,\theta) = \frac{4\pi P(\varphi,\theta)}{\iint P(\varphi,\theta)d\Omega} \tag{1}$$

Where $P(\varphi,\theta)$ is the angular radiated power and the integral is over all angles. The maximum of $D(\varphi,\theta)$ is denoted as D and referred to as the directivity. An isotropic radiator would have a directivity of 1, whereas for a Hertzian dipole $D=1.5$.
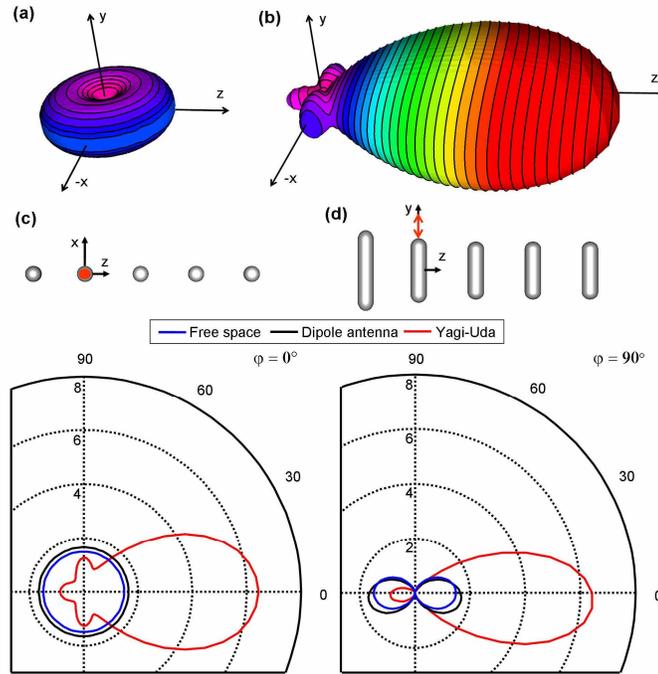

Fig. 2. Directivity for a y-oriented dipolar emitter in (a) free space and (b) coupled to a Yagi-Uda antenna. (c), (d) the directivity in the two major planes. As a reference the emitter coupled to a dipole antenna is added. The schematics show the location of the emitter and the orientation of the emitter and Yagi-Uda antenna relative to the image plane. The distance between the emitter and the antenna element is 4 nm. The emission of the emitter coupled to the Yagi-Uda antenna is highly directed.

Figure 2 shows $D(\varphi,\theta)$ of a dipolar emitter oriented along the y-axis in 3D and in the two major planes. Three situations are considered: the emitter in free space (no antenna, Fig. 2(a)), coupled to a dipole antenna and coupled to the Yagi-Uda antenna (Fig. 2(b)). The emitter is placed 4 nm from the antenna element. The dipole antenna is simply the feed element alone and is added as a reference situation. The radiation pattern for the dipole antenna is similar to the free-space dipole. The directivity is slightly higher (1.7 compared to 1.5) and the pattern slightly asymmetric due to the relative position of the emitter and the antenna. In contrast, the angular emission of the emitter coupled to the Yagi-Uda is strongly directed along the +z-axis. The maximum directivity is 6.4, 3.8 times higher than for the dipole antenna. For an ideal lossless antenna D is an additional factor 2 higher (not shown) and in accordance with typical values for radiowave 5-element Yagi-Uda antennas [17]. Clearly, the Yagi-Uda concept is valid for realistic dimensions in the optical domain. These results are in agreement with results obtained by coupled-dipole theory under a point-dipole approximation in Ref. [19],

confirming that such an approximation is justified for the far-field emission. More importantly, our calculations include a resonant feed element and allow to explore the antenna near field and the effects of the emitter-antenna coupling.
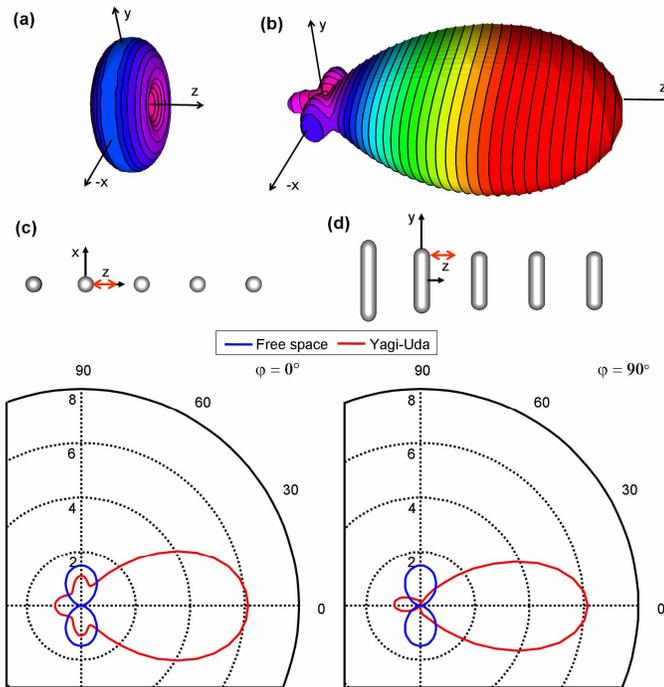

Fig. 3. Directivity for a z-oriented emitter in (a) free space and (b) coupled to a Yagi-Uda antenna (distance 3 nm). (c), (d) directivity in the major planes. The schematics show the position of the emitter and the orientation of the emitter and antenna relative to the image plane. The emission of the coupled system is highly directed and rotated by 90 degrees.

The local field at the apex of the feed element contains all field directions, indicating that emitters of all orientations can couple to the antenna mode. Figure 3 shows the angular emission for a dipolar emitter oriented along the z-axis, i.e. perpendicular to the one of Fig. 2, both in free space and when coupled to the Yagi-Uda. This is a particularly interesting example: while for the free emitter there is no emission along the z-axis at all, the emission for the coupled emitter-antenna is directed mainly along the z-axis. The emission is highly directed and rotated by 90° compared to the free dipole. Full control of the main direction of emission is thus obtained by the near-field nature of the coupling. Such a full redirection of emission is generally not obtained by far-field coupling to cavities or particle arrays. The angular emission of the antenna-emitter system is approximately the same as for the y-oriented emitter (Fig. 2), in agreement with the picture that the emitter couples to the antenna mode, which in turn couples to the radiation field and determines the angular emission [7].

3. Antenna enhanced excitation and emission rates

Next we concentrate on the influence of the nano-optical Yagi-Uda antenna on the emitter transition rates. The near-field coupling to the resonant mode of the feed element changes the excitation (K_{exc}), the radiative (K_{rad}) and the non-radiative (K_{nr}) transition rates of the emitter. The relative excitation rate, $K_{exc}(\varphi,\theta)$, for illumination by a plane wave is given by:

$$K_{exc}(\varphi,\theta) = \frac{\left(\boldsymbol{E}(\varphi,\theta)\cdot\boldsymbol{p}\right)^2}{\left(E_0 p\right)^2} \tag{2}$$

Where $\boldsymbol{E}(\varphi,\theta)$ is the absolute electric field vector at the emitter position for an incoming plane wave with a wave vector $\mathbf{k}$ along (φ,θ) and free-space amplitude E_0, $\boldsymbol{p}$ is the emitter dipole moment with magnitude p.

The relative radiative decay rate K_{rad} is obtained from:

$$K_{rad} = \frac{\iint P(\varphi,\theta)d\Omega}{\iint P_0(\varphi,\theta)d\Omega} \tag{3}$$

With P_0 the emitted power by the emitter in free space. The total dissipated power in the metal (relative to the free space radiative rate), the non-radiative rate (K_{nr}), gives rise to the radiation efficiency (or quantum efficiency) η:

$$\eta = \frac{K_{rad}}{K_{tot}} \tag{4}$$

With $K_{tot} = K_{rad} + K_{nr}$ the total decay rate. Note that here a perfect emitter with an intrinsic quantum efficiency of 1 is assumed. In the case of emitters with a lower intrinsic efficiency the radiation efficiency can be enhanced by the coupling to the antenna [14]. For the quantum mechanical dipole transition, the (relative) excited state lifetime is inversely proportional to K_{tot}.

Figure 4 shows K_{exc}, K_{rad}, K_{nr} and η for a y-oriented emitter a distance y from the apex of the feed of the Yagi-Uda and of a dipole antenna. K_{exc} is shown for illumination by a y-polarized plane wave with $\mathbf{k}$ in the negative z direction (φ=0, θ=0), the direction expected to be efficient for both the Yagi-Uda and dipole antenna. For the dipole antenna, $K_{exc}(0,0)$ is enhanced up to a factor 200 for very short distances, due to the locally enhanced field. K_{rad} follows nearly the same curve as $K_{exc}(0,0)$. For K_{nr}, there are two contributions: losses of the antenna mode and losses due to the field induced directly in the metal by the dipole. The latter causes the steep increase of K_{nr} and decrease of η for very short emitter-metal distances (quenching). The strong distance dependence of all rates demonstrates the local nature of the coupling to the dipole antenna or feed element.
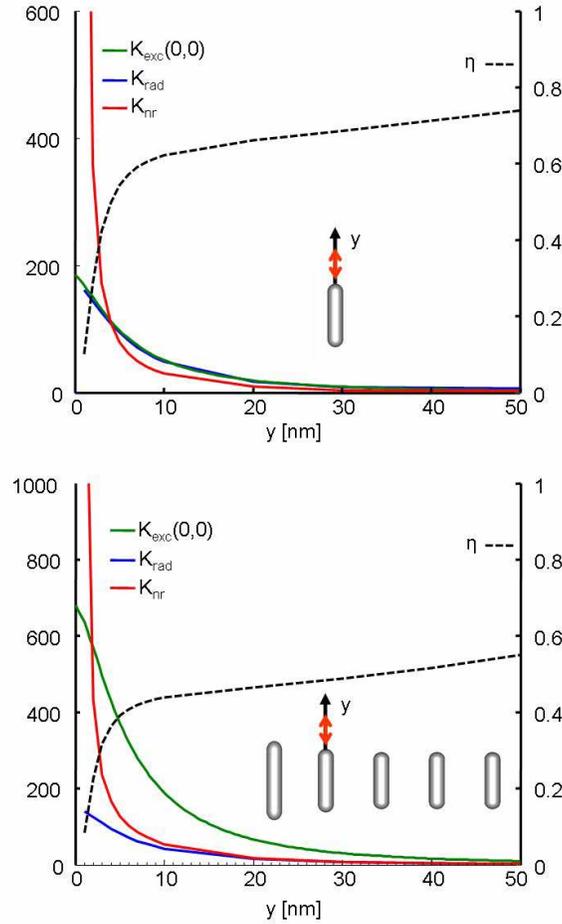
Fig. 4. The distance dependence of the excitation, $K_{exc}(0,0)$, radiative, K_{rad}, and non-radiative, K_{nr}, rates and the efficiency, η, for a y-oriented dipole coupled to a dipole and to a Yagi-Uda antenna. The insets show the position and orientation of the emitter relative to the dipole respectively Yagi-Uda antenna.

For the emitter coupled to the Yagi-Uda antenna (Fig. 4) an increase of K_{nr} and slight decrease K_{rad} are observed due to the extra losses in the added elements. This results in an overall decrease of η. However, the most striking difference to the reference dipole antenna is the strong enhancement of $K_{exc}(0,0)$, which now reaches a value over 600, an increase by more than a factor 3. This originates from the increased directivity, $D(0,0)$, of the Yagi-Uda antenna (Fig. 2(a).) and can be understood as follows. The emission and excitation are related by Lorentz reciprocity. For changes in the local environment, i.e. a constant refractive index of the far-field medium, the relative excitation rate for a plane wave incident from a certain direction is equal to the relative emitted power in that direction. $K_{exc}(\varphi,\theta)$ is thus related to K_{rad} by the directivity, $D(\varphi,\theta)$:

$$K_{exc}(\varphi,\theta) = \frac{D(\varphi,\theta)}{D_0} K_{rad} \qquad (5)$$

Where D_0 is the directivity of the free-space dipole (= 1.5). A high directivity thus enhances the excitation rate for specific illumination directions (Fig. 4 and Equation 5) and directs the emission (Fig. 2). The directivity clearly plays an important role in both efficient

detection and excitation. The nano-optical Yagi-Uda antenna combines strongly enhanced transition rates due to near-field coupling to a resonant element with a high directivity due to interference with several surrounding elements.

4. A surface Yagi-Uda antenna: enhanced excitation-emission directivity

A further enhancement of the directivity is found when the Yagi-Uda antenna is placed on a dielectric substrate. Importantly, this is the typical experimental realization for optical antennas. The emitter is coupled to a lossless Yagi-Uda placed on a glass substrate ($\varepsilon = 2.25$).
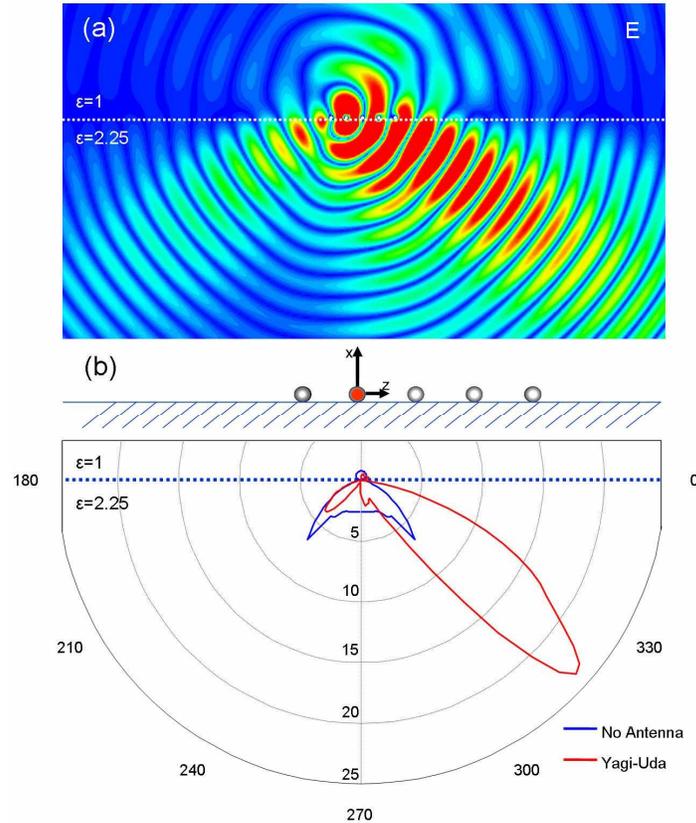

Fig. 5. A y-oriented emitter coupled to a lossless Yagi-Uda antenna (distance 4 nm, $L_f = 187$ nm) placed on a dielectric substrate ($\varepsilon = 2.25$). (a) Snapshot of the local field (xz plane). Movie of full cycle is available as supporting information. (b) The angular directivity. The substrate fills the half-space from $\theta = 180°$ to $360°$. The situation without antenna is shown as a reference. The emission is directed in a single lobe into the substrate.

Figure 5(a) demonstrates how a directed beam is formed by showing the local field at the antenna. Figure 5(b) shows the resulting angular far-field directivity. As a reference the directivity for the emitter without antenna, for which analytical solutions are available [25], is shown. While in both cases the emission is directed mainly into the substrate, the emission of the antenna-emitter system is concentrated in a single highly-directed lobe. The directivity is increased to above 20, noticeably above the 12 obtained for a lossless Yagi-Uda without the substrate. The highly directed single-lobe pattern of a Yagi-Uda on a substrate allows the antenna to be efficiently addressed, making such antennas a promising approach for planar sensors.

5. Conclusions

In summary, the nano-optical Yagi-Uda antenna combines enhanced excitation and emission rates with a high directivity in a compact system; the antenna occupies a volume as small as a single unit cell of a photonic crystal. The near-field coupling to the feed element provides the same high directivity for emitters of all orientations. These unique characteristics make the nano-optical Yagi-Uda antenna promising for bright nano-scale light sources with a directed emission. In a sensing or spectroscopy application, Yagi-Uda antennas on a substrate can be used to detect optical signals efficiently even with low NA objectives. An array of antennas occupies a small surface area and may be designed to probe different characteristics. The optical Yagi-Uda brings high directivity and enhancement to the nano-scale.

Supporting information available

The local field dynamics of a nano-optical Yagi-Uda antenna on a dielectric substrate.