Abstract: Optical nano-antennas are nano-scaled metallic devices capable of manipulating and controlling visible light at sub-wavelength scales. Here we discuss the development of novel nanometric slot antennas and their complementary nanoparticle antennas.

1. Introduction

Antennas are well-known as devices for controlling the emission of radio-frequency electromagnetic radiation. There is considerable excitement surrounding the extension of antenna concepts down to the near-infrared and visible regions of the spectrum. This will open up the capacity to control the emission of light by emitters including fluorescence molecules, quantum dots and colour centre defects in materials. Most current investigations of optical antennas involve scaling conventional RF antenna designs down to the nanometric scale [1]. As a consequence, most optical antennas under consideration are isolated metallic nanostructures. Apertures in a metallic film can be considered to be ‘slot’ antennas. Such aperture cavities have the capacity to simultaneously enhance the radiative decay rate of adjacent or incorporated emitters as well as modifying the far-field radiation pattern. Furthermore, other concepts emerging from the new field of plasmonics can also be incorporated into an antenna design. For example, texturing the surface around the antenna can also provide further control of the radiated field. Consequently, ‘nanoslot’ antennas present considerable promise as platforms for the design of novel receiving and emitting systems.

It is well-known that certain apertures, such as slots, coaxial apertures and cross-apertures possess relatively high-Q resonances compared to lower capacitance apertures such as circular or square holes. As a consequence, they have the potential to produce considerable radiative decay enhancements. Furthermore, symmetric apertures such as symmetric cross- and coaxial apertures possess resonances that are independent of the transverse orientation of an embedded dipole. This provides flexibility in terms of device design and reduces constraints on the orientation of an emitter incorporated into the antenna.

Here, we explore strategies for enhancing the strength of electric fields within cross-shaped apertures (Fig. 1(c)) and their complementary structure, the cross-shaped nanoparticle (Fig. 1(b)), through the excitation of localized surface plasmon resonances (LSPRs) in the aperture cavity as well as controlling the far-field radiation pattern. When an emitter is introduced into an antennas structure, it couples to modes of the system and, hence, the resulting radiation pattern is determined by the antenna, rather than by the emitter itself. Furthermore, by modifying the surface surrounding the aperture cavity [2], it is possible to control the classical emission of EM waves from the surface to collimate, focus or otherwise shape the emission. In particular, a cross-aperture possessing distinct easily
tunable resonances [3, 4], can be considered in tandem with surface corrugations acting analogous to a distributed
brag reflector in micro-cavities, to confine and focus the far-field radiation.

2. Nanometric slot antennas

The basic element to be considered here is a cross-shaped structure, Fig. 1(a) with arms of length 250 nm and
armwidths of 50 nm. A cross-shaped aperture with these dimensions perforates a film of silver of thickness 50 nm
and we also consider a nanometric cross-shaped particle with the same dimensions in the next section. A point
dipole, horizontally oriented parallel to one of the cross-arms (Fig. 1(c)), is located at the centre of the aperture. The
Finite Element Method (FEM) as implemented in COMSOL Multiphysics, was used to simulate the far-field
radiation pattern and calculate the radiative decay rate enhancement produced by this structure (Fig. 2(a)). It is
apparent that there is a resonance at 1075 nm resulting in 95 times enhancement in the radiative decay rate. The
resulting radiation pattern (Fig. 2(b),(c)) appears as modified dipole radiation and corresponds to the radiation
pattern produced by excitation of the LSPR within the aperture.

![Image]

Fig. 2. (a) The enhancement in the radiative decay rate for a point dipole located in the centre of the aperture and oriented parallel to
one of the arms in the x-direction, (b) the far-field radiation pattern in z-x plane and (c) the far-field radiation pattern in y-x plane at
1075 nm.

![Image]

Fig. 3. (a) Far-field scattering cross-section for a silver cross with arm lengths of 250 nm, arm widths of 50 nm and a height of 50 nm
as a function of wavelength, (b) the scattered far-field radiation pattern and (c) the magnitude of the electric field at resonance on the
surface of the nanoparticle, where red denotes the maximum value.

3. Nanoparticle Antennas

Coherent excitation of surface conduction electrons in metallic nanostructures, referred to as Localized Surface
Plasmon Resonance (LSPR), enhances the scattering cross section of the metallic nanostructure by many orders of
magnitude larger than the physical cross section [5]. Any application relying on far-field excitation/near-field
detection, e.g. photodetection [6], sensing [7], and vice versa, e.g. emission [8], would benefit from this property. A
model whereby a silver cross-shaped particle having arm lengths of 250 nm, arms height and width of 50 nm
positioned in vacuum is examined. The scattering cross-section was studied using the Finite Element Method (FEM)
as implemented in COMSOL Multiphysics. The direction of the incident field was taken to be normal to the axes of the cross and the polarization parallel to one of the arms. The cross can be regarded as consisting of two orthogonal nanorods and as a consequence, has a response that is independent of the polarization of the incident field. The far-field scattering cross-section is given in Fig. 3(a). It is evident from Fig. 3(a) that the LSPR occurs at a free-space wavelength of 925 nm, i.e. a blue shift of 155nm in comparison to resonance of a cross-shaped aperture in having the same dimensions. The far-field scattered radiation pattern is shown in Fig. 3(b). It is apparent that the radiation pattern possesses a very strong resemblance to an electric dipole. Fig. 3(c) shows the magnitude of the electric field on the surface of the particle where the excitation of the dipole mode is evident clearly.

Finally, we propose a slot antenna that combines the benefits of enhancement in radiative decay rate with beam shaping [2], introduced by texturing one or both sides of the metal film. A schematic and a test structure fabricated using Focused Ion Beam milling are shown in Fig. 4.

4. References

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