Optik 152 (2018) 100–105

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Original research article

Light emission via surface plasmon modes in metal semi-shell cavity shaped antennas and film coupled structure

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ARTICLE INFO

Article history:
Received 17 May 2017
Received in revised form 4 September 2017
Accepted 25 September 2017

Keywords:
Surface plasmon
Nanoantenna
Light emission

ABSTRACT

The dipole emission into surface plasmon in a semi-shell cavity shaped metal antenna and metal film coupled structure is investigated numerically. The decay rate of the dipole emitter is found to be greatly enhanced at certain wavelength of surface plasmon resonance mode. Noradiative decay shows a near-field (~10 nm) effect, and radiative decay dependence on the emitter-antenna distance is determined by the dipole emitter location. In particular, light emission in metal antenna-metal film coupled structures have shown a further accelerated radiative decay and a directional far-field radiation pattern due to the surface plasmon mode coupling in complex structures.

1. Introduction

The past two decades have seen that solid state light emitters are rapidly gaining importance in a number of applications such as room lighting, traffic lights, and displays. Reasons for their success are compactness, spectral and spatial control of emission, high efficiency, and relatively inexpensive fabrication routes. More importance is gaining in the control of the radiative rate of light emitters. Advances in nano-opitcs have shown that metal nanoparticles can modify the spontaneous emission rate [1–9]. A small metallic nanoparticle can be considered as a subwavelength antenna that modifies both the radiative decay rates and excitation rate via their strong near-fields [10–12]. The concept of optical nanoantennas has been indeed coined to stress the ability of metal nanoparticles to convert light into localized electromagnetic energy and vice versa.

Although limited by the intrinsic loss of the metals in optical frequency range, advances in nanofabrication techniques recent years have made feasible a great variety of nanoparticle configurations, which have in turn fueled interest in metal nanoantenna coupled light emission. In this regard, if the nanoparticles present complex shapes and/or form optically coupled structures, surface plasmon (SP) resonances may be tuned, and extremely large near-field enhancements will arises at resonance. Experimental and theoretical reports have shown that by using various single metal nanoantennas (nanowires, nanoparticles, nanoprisms, etc.) or their combinations [10–20], spontaneous emission enhancement, changes in the fluorescence spectra shape and direction etc. were observed.

In this letter, we investigated the spontaneous emission of a dipole emitter coupled to surface plasmons in silver semishell cavity shaped nanoantennas, which has been fabricated by nanosphere lithography [21]. The purpose of this work is to theoretically determine the plasmon coupled emission of light emitters such as molecules or nanodots embedded in such semishell cavity. In particular, semishell cavity-film coupled structure was considered in modifying light emission. It is well

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https://doi.org/10.1016/j.ijleo.2017.09.089
0030-4026/

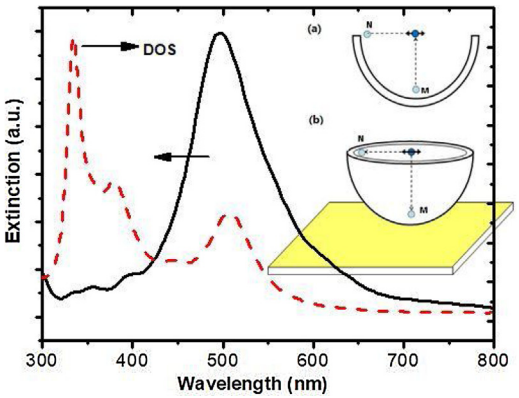

Fig 1. Extinction spectrum of the Ag antenna (solid line) and the localized density of state at position *N* with different excitation wavelength (broken line). Inset: Schematic diagram of Ag metal antenna in cross-section view (a) and antenna-metal film coupled structure in 3d view (b). *M* and *N* indicate two positions that light emitter situates with a distance of 5 nm to metal antenna.

known that in metal antenna-film coupled structure, localized SP mode of the metal antennas will be modified by mode hybridization with SP at metal films [22–24]. The effect of mode hybridization in metal antenna-film coupled strucutre on light emission has seldom been reported. Our calculation results show that light emitter in metal semishell cavity-film structure exhibits distinct radiative decay rate increase and unique far-field radiation distribution modification.

2. Methods

The silver nanoantenna with a shape of semi-shell cavity is illustrated schematically in the inset of Fig. 1. Fig. 1(a) shows a cross-section view scheme of the nanoantenna, and Fig. 1(b) shows shematically the nanoantenna-metal film coupled system in 3d view. The size of the antenna is depicted using the inner (r_2) and outer radius (r_1) of the semi-shell which are assumed to be 30 nm and 50 nm respectively. Thus the thickness of the semi-shell (r_1-r_2) is 20 nm. The distance dependent emission of the dipole near metal antenna was investigated by moving the dipole from the semi-shell center *O* closer to the metal cavity inner surface in two directions, vertically and horizontally. *M* and *N* denoted the two nearest positions to the inner surface with a distance of 5 nm. For the nanoantenna-metal film coupled structure shown in Fig. 1(b) (inset), the thickness of the metal film is set at 100 nm, which can be regarded as a metal substrate with an infinite thickness. The gap between the nanoantenna and the metal film is assumed to be 5 nm to obtain effective plasmon hybridization.

We apply three-dimensional finite-difference time-domain (FDTD) calculations to simulate the light emission. The refractive indexes of the metal (Ag) used in the computation were theoretical fitting results done by Lumerical software using Lorentz-Drude model to the experimental values from reference [25]. The dipole decay rates including nonradiative γ_{non} and radiative γ_r are calculated and normalized to the dipole decay rate in free space γ_0. The dipole emission wavelength is centered at 550 nm with a band width of 500 nm. The analysis of the FDTD results rely on the fact that, for an atomic dipole transition that can only occur through radiation, the quantum mechanical decay rate in an inhomogeneous environment can be related to the classical power radiated by the dipole in the same environment [26]. Specifically, it has the relation $\frac{\gamma_r}{\gamma_0} = \frac{P}{P_0}$, where γ_r and P are the decay rate and radiated power of a dipole near metal nanoantennas, γ_0 and P_0 are the decay rate and power radiated in free-space.

3. Results and discussions

The black solid curve in Fig. 1 shows the Ag antenna extinction efficiency (usually referred to as its localized surface plasmon spectrum) calculated for a plane wave illumination. Two SP resonance maximum were observed at 500 nm and 360 nm, which has been ascribed to dipole oscillation mode and high order multipole mode respectively.

Let us begin by examining the emitter coupled to Ag nanoantenna. First, the emitter was placed at position *M* with a separation of 5 nm. The polarization direction is assumed to be parallel to *ON*. The solid and dashed curves in Fig. 2(a) display the wavelength dependence of modified radiative decay rates $\gamma_r$and nonradiative decay rates γ_{non} normalized to the unperturbed dipole decay rate respectively. As shown, both γ_r and γ_{non} are enhanced, but γ_{non} clearly dominates. The maximum enhancement of γ_{non} at 340 nm wavelength reaches about 700 fold. The maximum enhancement occurs exactly at a well-defined wavelength around high-order multipole plasmon resonance. E-field distribution at this emission wavelength is shown in Fig. 2(a), which demonstrates a multipole mode pattern. Thus, it confirmed that nonradiative decay was accelerated through higher-order multipole resonance of Ag antennas. The maximum enhancement of γ_r occurs near 500 nm, which is coincide with the dipole mode shown in Fig. 1. Not surprisingly, the emission field distribution at 500 nm shown in Fig. 2(b) demonstrates a dipole pattern. So it can be concluded the radiative decay enhancement is mainly benefit from coupling to the dipole plasmon resonance mode of the Ag nanoantenna. It is known that the presence of metal antennas