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Plasmonic Core-Shell Nanocones for Enhancing Spontaneous Emission

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Abstract: We employ the boundary integral method to compute the enhancement of spontaneous emission and the antenna efficiency for a quantum emitter coupled to a plasmonic core-shell nanocone. We consider the classical model of a dipole in the vicinity of a nanostructure and solve Maxwell's equations to study the effect of shell thickness and core refractive index on the total decay rate and the antenna efficiency. We also investigate the influence of position and orientation of the emitter, which are not easy to control from a practical point of view, in order to achieve a better understanding between experimental results and theoretical calculations. It is shown that by adjusting all mentioned parameters, the spontaneous emission rate is considerably enhanced. Moreover, one can easily tune the localized surface plasmon resonance in the visible and near-infrared region, where absorption in gold is smaller, by changing the shell thickness or the core refractive index.

Keywords: Core-shell nanocone; spontaneous emission rate; boundary integral method; nanoantenna; surface plasmon

Introduction

Optical nanostructures have recently attracted much interest in quantum optics for controlling light-matter interaction at the single-emitter level. The effect that a quantum emitter near a metal nanoparticle exhibits a strong modification of the spontaneous emission rate and of its quantum yield can be further explored by nanofabricated structures with a well defined geometry. In this work we focus on core-shell nanocones, that can be obtained by coating a dielectric core with a thin gold film [1]. We consider the variation of selected parameters and theoretically investigate how this affects the nano-cone performances.

We employ the boundary integral method (BIM) [2] to calculate the total decay rate and quantum efficiency and investigate the effect of various parameters on decay rates and quantum efficiency. As compared to body-of-revolution (BOR) finite-difference time-domain (FDTD) [3], the main advantage of BIM is that it is not limited to axially symmetric problems. Therefore, one can consider the situations where the emitter is moved around the nanocone tip.

Materials and method

As shown in Fig. 1, a quantum emitter is located in the vicinity of a nanoantenna made of a core-shell nanocone. The nanostructure is composed of a dielectric core, covered by a gold shell and embedded in air. We employ the boundary integral method to calculate the decay rate enhancement of the emitter due to coupling to the nanoantenna. We model the quantum emitter as a classical dipole and calculate the radiated power when the emitter is in the vicinity of the metallic nanostructure and divide it by radiated power in the free space to obtain the normalized total decay rate.

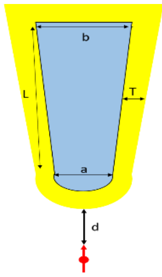

Fig. 1. An emitter in the vicinity of a core-shell nanocone. The base diameter is b, tip diameter is a, height is L, the thickness of shell is T. The emitter is located at a distance d from the nanocone tip.

The normalized total decay rate of the dipole and the antenna efficiency, η_a, are expressed as

$$\frac{\Gamma_t}{\Gamma_r^0} = \frac{P_t}{P_r^0} \qquad \eta_a = \frac{P_r}{P_t} \tag{1}$$

where P_r is the radiated power to the far field, P_t is the total emitted power and P_r^0 is instead the radiated power in free space [3].

Results and Discussion

In the following, the influence of various parameters such as refractive index of the dielectric core, thickness of the metallic shell, orientation and position of the emitter are analyzed and discussed. The normalized total decay rate versus wavelength for nano-cones with difference shell thickness (T = 15 nm, 20 nm, 25 nm) is depicted in Fig. 2. The nanocone is 100 nm long, it has a base diameter of 100 nm and a tip diameter of 20 nm. The emitter is always at 10 nm from the sharp end of the nanocone. As observed, the decay rate depends on the thickness of the gold shell. By reducing the thickness of shell the decay rate is increased and the peak red-shifts. Moreover, as shown in Fig. 3, when the thickness of shell is reduced the antenna efficiency is decreased.

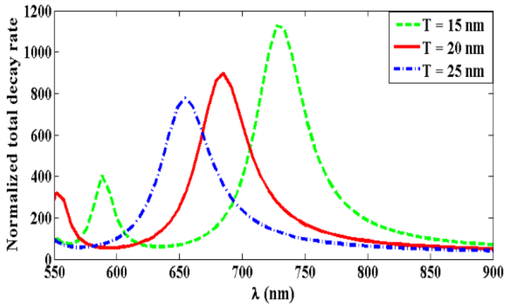

Fig. 2. Normalized total decay rate enhancement versus wavelength for an emitter coupled to a core-shell nanocone for various shell thickness.

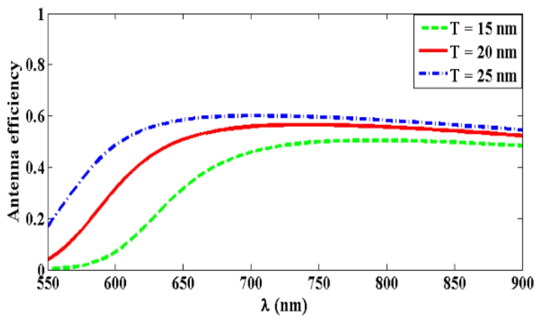

Fig. 3. Antenna efficiency versus wavelength for shell various thickness.

In order to investigate the effect of the core refractive index on the decay rate, we change this parameter (n=1.33, 1.5, 1.7, 2) and keep the other parameters fixed. The result is shown in Fig. 4. It shows that increasing the refractive index of the core makes a small red-shift in the resonance wavelength and reduces the enhancement of the total decay rate.

Another effective parameter is the position of the emitter with respect to the nanocone. As shown in the inset of Fig. 5, we displace the emitter by δ away from the nanocone axis and compare the result with an emitter placed in the center (δ=0). By increasing the distance from the axis, the total decay rate decreases, but by a small value if the displacement is smaller than the tip diameter.

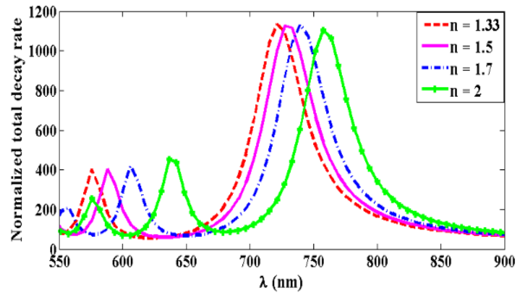

Fig. 4. Normalized total decay rate as a function of wavelength for different values of the core refractive index.

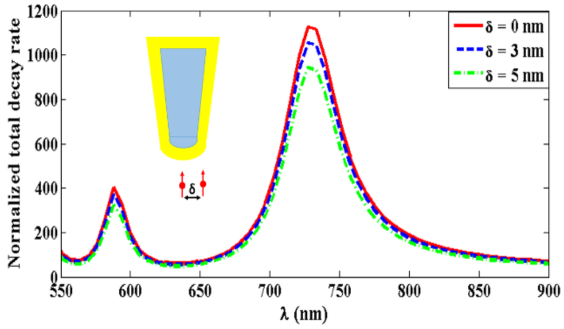

Fig. 5. Normalized total decay rate enhancement as a function of wavelength for an emitter coupled to core-shell nanocone for different lateral displacements of the emitter.

We finally investigate the effect of dipole orientation. Fig. 6 and Fig. 7 compare the results for vertical and horizontal dipole orientation, respectively.

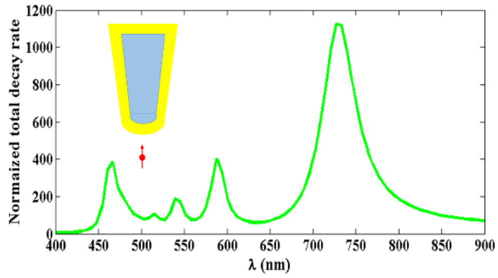

Fig. 6. Normalized total decay rates as a function of wavelength for a core-shell nanocone excited by an emitter parallel to the nanocone axis.

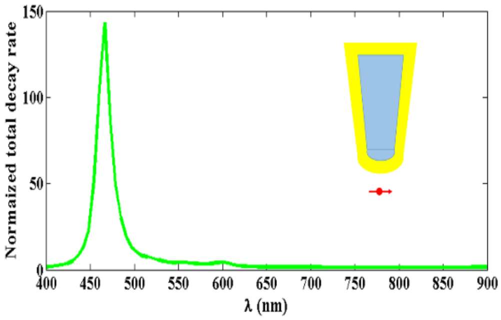

Fig. 7. Normalized total decay rates as a function of wavelength for a core-shell nanocone excited by an emitter perpendicular to the nanocone axis.

Conclusions

In this paper, we have employed the boundary integral method to investigate enhancement of the spontaneous emission rate and the antenna efficiency of a quantum emitter coupled to a core-shell nanocone. The results show how these quantities depend on parameters, like the shell thickness, the core refractive index, the dipole position and its orientation. The behavior as a function of the nanocone height and aspect ratio has been reported elsewhere for similar structures [3]. Altogether, these findings are useful for planning experiments on the modification of light-matter interaction with nanofabricated cones [1].

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References

[1] A. M. Flatae, F. Tantussi, G. C. Messina, A. Mohammadi, F. Angelis, M. Agio, “Plasmonic Gold Nanocones in the Near-Infrared for Quantum Nano-Optics”. *Advanced Optical Materials*, **5** (2017) 1700586.

[2] A. Firoozi, A. Mohammadi, “Investigating Molecular Spontaneous Emission Rate Enhancement Close to Elliptical Nanoparticles by Boundary Integral Method”. *Journal of Optoelectronical Nanostructures*, **1** (2016) 27-35.

[3] A. Mohammadi, V. Sandoghdar, M. Agio, “Gold nanorods and nanospheroids for enhancing spontaneous emission”, *New Journal of Physics*, **10** (2008) 105015.