Gap Surface Plasmon and Plasmonic Waveguide based Single Photon Source

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***Abstract*- An integrated single photon source structure that based on gap surface plasmon and plasmonic waveguide is proposed. The gap surface plasmon generated in the structure can greatly increase the photon emission rate, while the plasmonic waveguide can effectively collect the photons generated by the single photon source. The highest Purcell factor of this device structure is 3320 at wavelength of 680nm. The highest coupling efficiency from the single photon source to the plasmonic waveguide is 41.45%, while the cross section of the waveguide is only 240×240nm^2. Directional excitation of surface plasmon polaritons in the waveguide is also realized by adjusting the position of the single photon source. The optical power ratio in the two opposite directions of the plasmonic waveguide is 1:16.**

I. INTRODUCTION

Single photon source (SPS) is a fundamental resource for quantum information, quantum computing, high precision measurement and micro-nano photonics [1, 2]. Various types of materials are utilized to generate single photon including fluorescent molecules, diamond nitrogen-vacancy centers and quantum dots [2, 3]. Generally, the photon emission rate and collection efficiency of single photon sources in free space are low, which limit their actual applications. Based on the Purcell effect, i. e., the modification of the density of states of the electromagnetic field to enhance the spontaneous emission rate [4], photonic crystals [5-7] and dielectric micro-cavities [8] are designed to increase the photon emission rate and single photon collection efficiency. Moreover, by designing nanostructures, the emission direction of SPS can be modulated to increase the collection efficiency [9-11]. However, the Purcell factor of photon crystals and dielectric micro-cavities are usually only ten to several tens. In another way, due to the field enhancement and confinement, plasmonic nanostructures can greatly increase the decay rate of SPS [10]. In this work, we propose a gap surface plasmon and plasmonic waveguide based SPS, which can effectively increase the decay rate and collection efficiency.

II. NUMERICAL MODEL AND SIMULATION RESULTS

The proposed integrated SPS is schematically shown in Fig. 1. A SiO$_2$ strip is placed on a gold film top surface to construct a plasmonic waveguide named dielectric loaded surface plasmon polariton (DLSPP) waveguide. The width and height of the DLSPP waveguide are both 240nm. In the DLSPP waveguide, a gold nanorod is placed at a distance of $d = 10\text{nm}$ above the gold film top surface. The nanorod compose of a cylinder of length a and two semi-spheres with diameter of $D = 45\text{nm}$. The gap between the gold nanorod and the gold film supports the gap surface plasmons that have strong field enhancement and confinement. A quantum emitter is placed in the gap with a distance of $d/2$ from the gold nanorod.

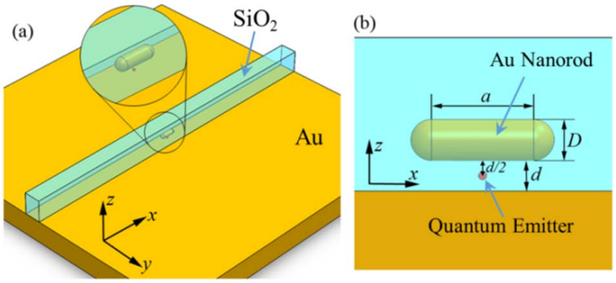

Fig. 1. Schematic of the integrated single photon source.

Numerical simulations by finite element method (FEM) using the COMSOL Multiphysics software are performed to explore the emission and collection properties of the proposed SPS. In the simulation, the quantum emitter is simulated as an electric dipole. The wavelength of radiated single photons is 680nm. The total decay rates γ_{total} of the electric dipole can be divided into four contributions: decay into nonradiative channels γ_{nr}, radiate decay into free space γ_{r}, decay into SPP channels γ_{SPP}, and decay into DLSPP modes in the waveguide γ_{DLSPP}. The Purcell factor of the SPS is the ratio between the total decay rates γ_{total} and the decay rate of the dipole in a vacuum γ_0. The normalized decay rates can be obtained by calculating the radiated power of the dipole in different decay ways [10].

The normalized decay rates for dipole emitter at the middle of the gap versus the length of the nanorod are shown in Fig. 2(a). When the length of the nanorod changing from 10nm to 160nm, all the normalized decay rates have only one peak at $a = 100\text{nm}$. This corresponds to the excitation of the quadrupolar gap plasma [10], with the electric field pattern on xz plane shown in Fig. 2(b). At this point, the Purcell factor of the SPS is maximum as 3320. The maximum normalized decay rate into DLSPP modes is $\gamma_{\text{DLSPP}}/\gamma_0 = 1376$, which corresponds to the collection efficiency of 44.45%.

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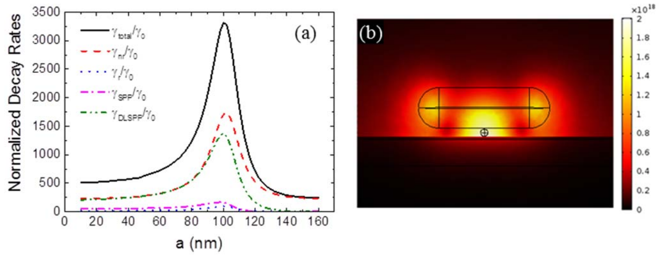

Fig. 2. (a) Normalized decay rates for a dipole emitter at the middle of the gap. (b) Electric field pattern on *xz* plane for *a*=100nm.

When placing the dipole emitter at the corner of the gap, directional excitation of the modes in the plasmonic waveguide can be realized. The simulation results are shown in Fig. 3 and Fig. 4. While the length of the nanorod varying from 10nm to 160nm, the normalized decay rates have two peaks at $a = 27$nm and 108nm, as shown in Fig. 3(a). The corresponding electric field patterns on *xz* plane are shown in Fig. 3(b) and (c), respectively. The Purcell factors for these two peaks are 1658 and 786nm, respectively, and the corresponding collection efficiency are 33.84% and 34.22%, respectively. The electric field patters $|E|$ and E_z on *xy* plane for a=27nm are shown in Fig. 4. Most of the radiated power is coupled into the waveguide, and the field in $+x$ and $-x$ directions are not the same. The power ratio between the two directions is 1:16. For $a = 108$nm, the powers coupled into the $\pm x$ directions are also unequal, and the ratio is 1:1.7.

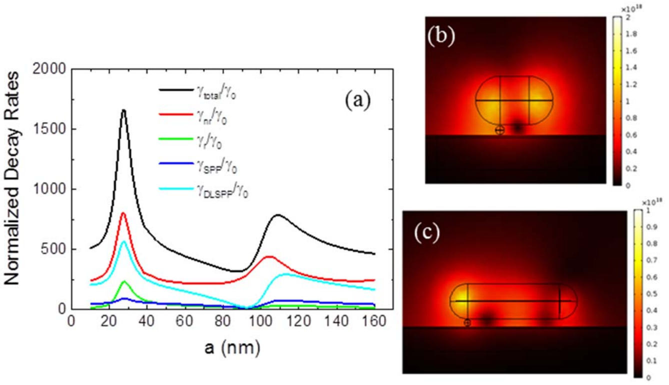

Fig. 3. (a) Normalized decay rates for a dipole emitter at the left corner of the gap with a varying of the length *a* of the Au nanorod. (b-c) Electric field patterns on *xz* plane for *a*=27nm (b) and 108nm (c), respectively.

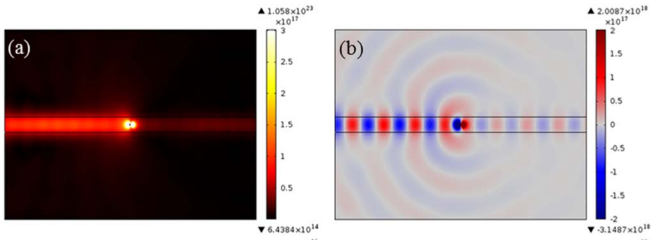

Fig. 4. (a-b) Electric field patterns $|E|$ (a) and E_z (b) on *xy* plane for a dipole emitter at the left corner of the gap while *a*=27nm.

III. CONCLUSION

In this report, we proposed and numerical simulated an integrated SPS structure that can greatly increase the photon emission rate with high collection efficiency. The highest Purcell factor of this device structure is 3320 at wavelength of 680nm. The highest coupling efficiency from the SPS to the waveguide is 41.45%, while the cross section of the waveguide is only 240×240nm^2. When changing the position of the dipole emitter in the SPS, directional excitation of surface plasmon polaritons in the plasmonic waveguide is realized. The optical power ratio in the two opposite directions of the waveguide is 1:16.

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