Enhancement of single-photon emission rate by plasmon induced transparency in metal-insulator-metal waveguides

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Abstract

In this paper, we propose a structure that realizes the plasmon induced transparency (PIT) effect through metal-insulator- metal waveguide and T-shaped resonator. PIT is a quantum interference effect, which can lead to a sharp transparency window in the wide absorption spectrum. By changing the coupling strength between the light and dark states of PIT effect, the distribution of electromagnetic field around the quantum-dot nanowire can be affected. Theoretical analysis showed the Purcell effect caused by the T-shaped resonator increases the emission rate of quantum dots by nearly 900 times. This ultrafast single-photon source has great potential in quantum communication and optical interconnection.

Model of T-shaped cavity

The schematic diagram of PIT realization through T- shaped resonator coupling proposed in this paper is shown in the Figure 1. The background material is silver whose permittivity is described by Drude model with:

$$\varepsilon_{Ag}(\omega)=\varepsilon_{\infty}-\omega_p^2/[\omega(\omega+i\gamma\omega)]$$

Where ε_{∞}=3.7, $\omega_p=1.38\times10^{16}rad/s$, and $\gamma=2.73\times10^{13}rad/s$.

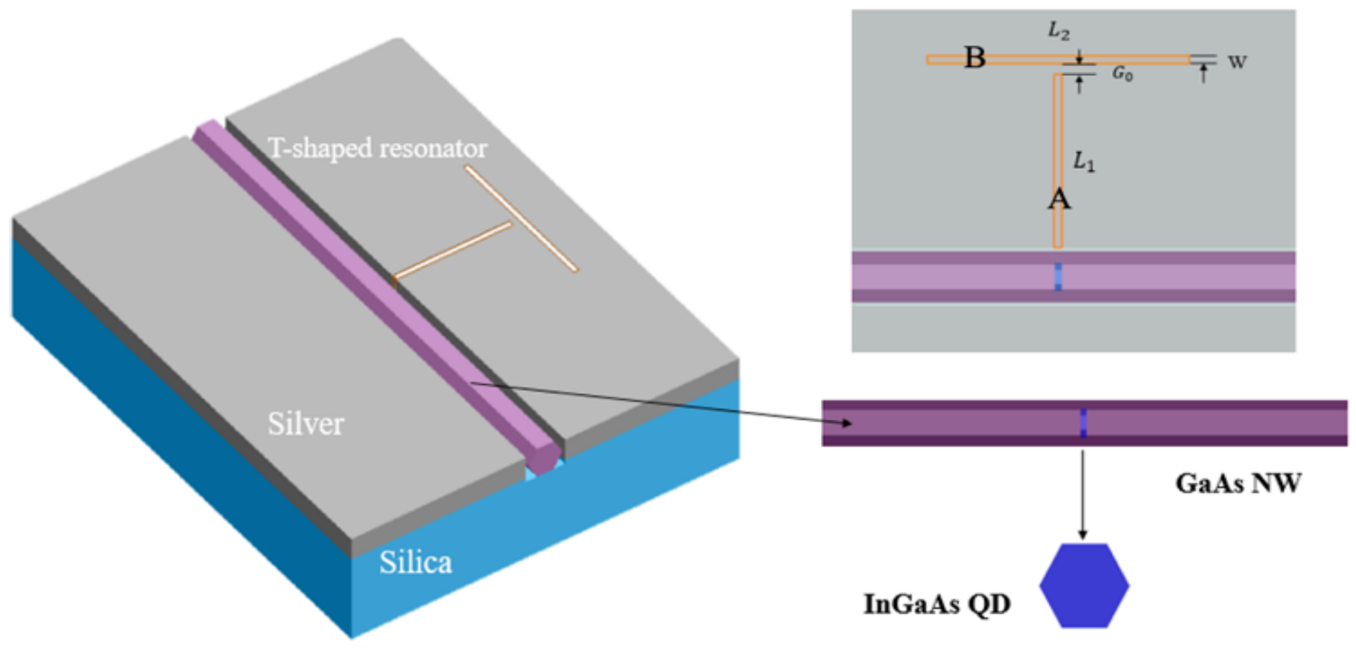

Figure 1. 3D schematic diagrams of InGaAs/GaAs QDNW heterostructure.

In our study, A and B are taken as PIT units, filled by air and arranged in the cladding of metal silver. As a branch of the core, the A can be directly excited by input waves. Therefore, A can be considered as a bright resonator. The B can be regarded as a dark cavity in the structure through near-field coupling with A line slot. In order to reduce the mode volume of the resonator, A and B are very narrow in width of only 10nm. The InGaAs/GaAs quantum dot nanowires (QDNW) was placed in the main resonator, the diameter of the nanowire is 70 nm and A is perpendicular to QDNW and connected to the center of the channel. We set the diameter and thickness of QD to be 40 nm and 8 nm, respectively, and embed it in the center of GaAs NW.

Results and Discussion

Spontaneous radiation is generated due to the interaction between the material and its local electromagnetic environment. As shown in Figure 2. The low refractive index air gap makes the photon mode and the plasma mode mix to form the mixed plasma mode. Therefore, the photons emitted by the QD can be coupled into the slot, and propagate and reflect in the slot nanocavity.

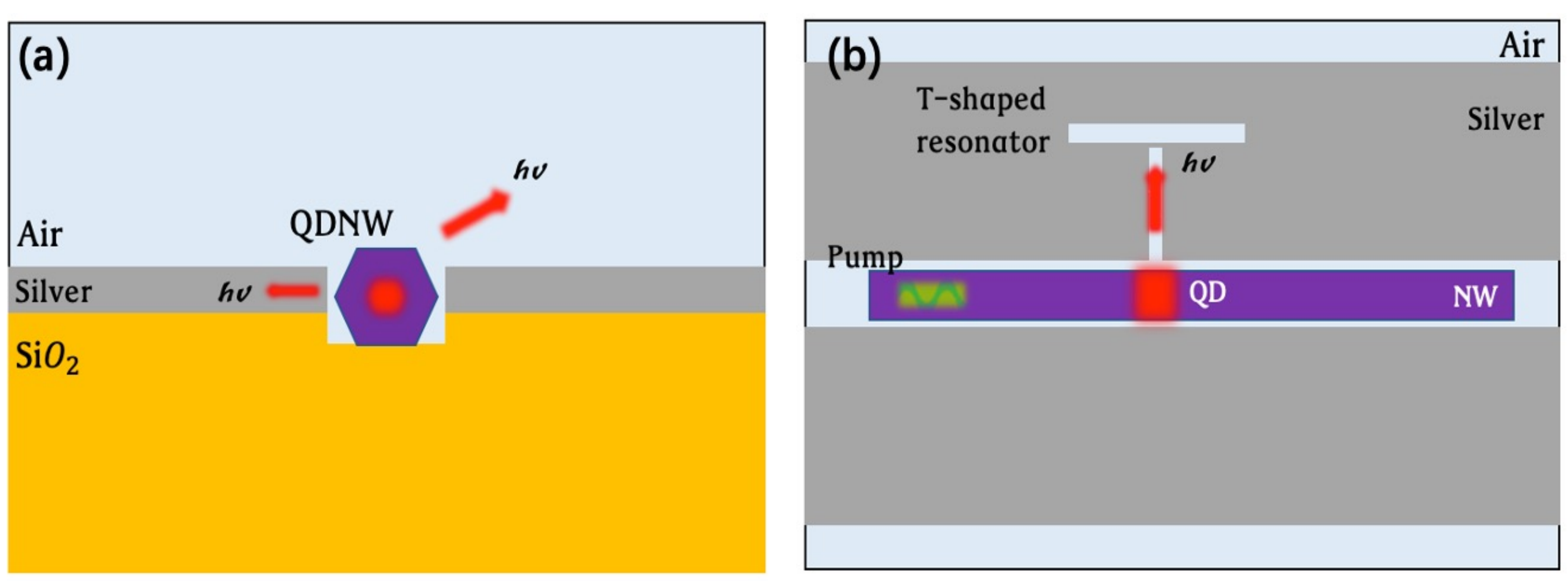

Figure 2. Diagram of light propagation in a resonator.

Figure 3. depicts the transmission spectrum and electromagnetic field distribution of a single cavity ($L_2=0$) and a T-shaped cavity ($L_1=240$ nm, $L_2=325$ nm).

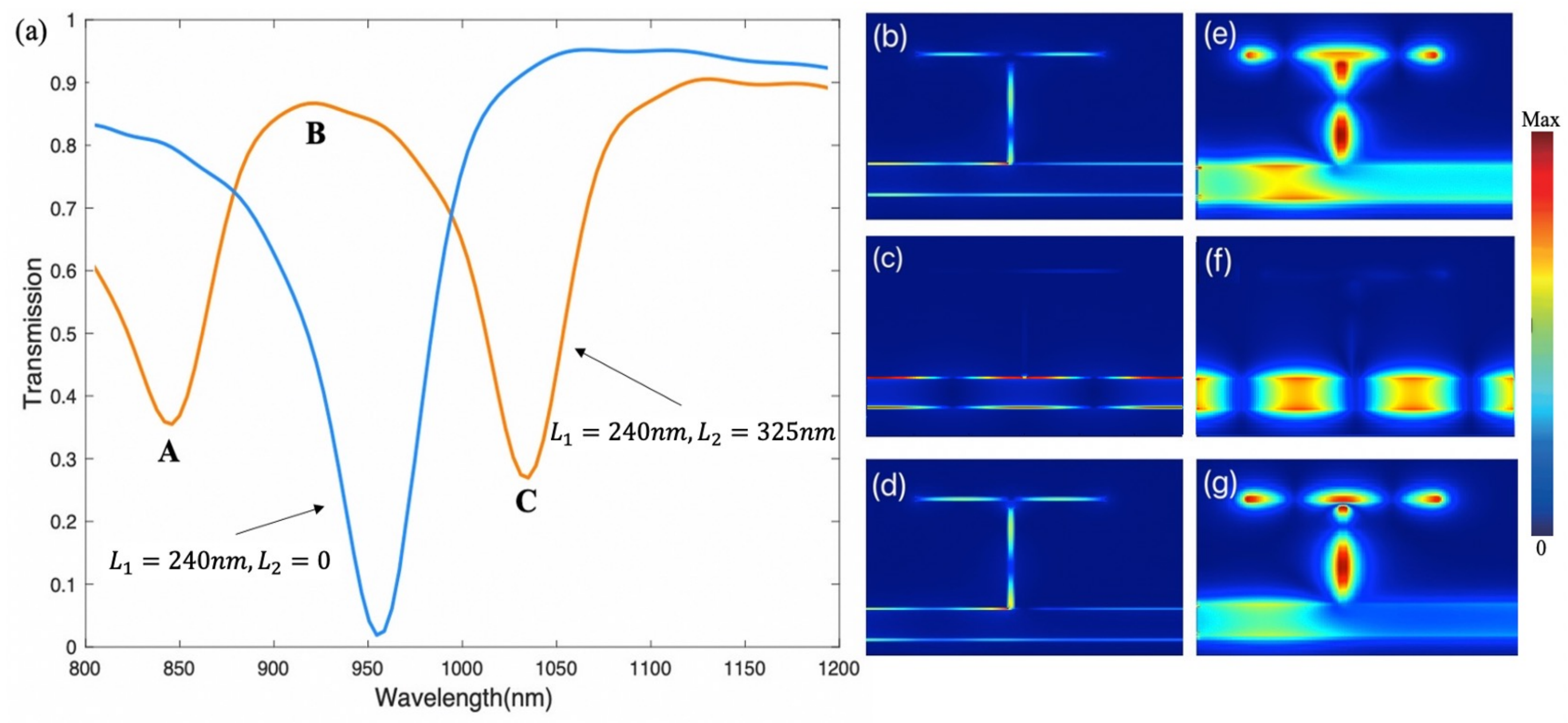

Figure 3. (a) System transmission spectra with or without A resonator. (b-g) Distributions of electric amplitude and magnetic amplitude corresponding to the three frequency values represented by f_A, f_B, and f_C, in (a).

The electromagnetic field density has a great influence on the spontaneous emission rate, so it can be modified by adjusting the spatial and spectral redistribution of the vacuum fluctuation. In this paper, QDNW is put into the channel and a T-shaped resonator is connected on one side to realize the enhancement effect of local field. Therefore, Purcell factor is defined as the ratio of the spontaneous radiation rate of artificial atom in a given mode to that in the bulk material. The specific expression is:

$$F_P=\frac{\gamma_{SE}}{\gamma_0}=\frac{3Q\lambda^3}{4\pi^2V}$$

The Purcell factor is mainly determined by Q factor and modal volume, but the influence of Q factor and modal volume is contradictory. It is difficult to obtain high Q factor due to the large loss of plasma strength. However, the mode effective volume can be effectively reduced beyond the diffraction limit. Although the Q factor is relatively small, due to the nanoscale structure and very small modal effective volume, the Purcell factor can still be very high.

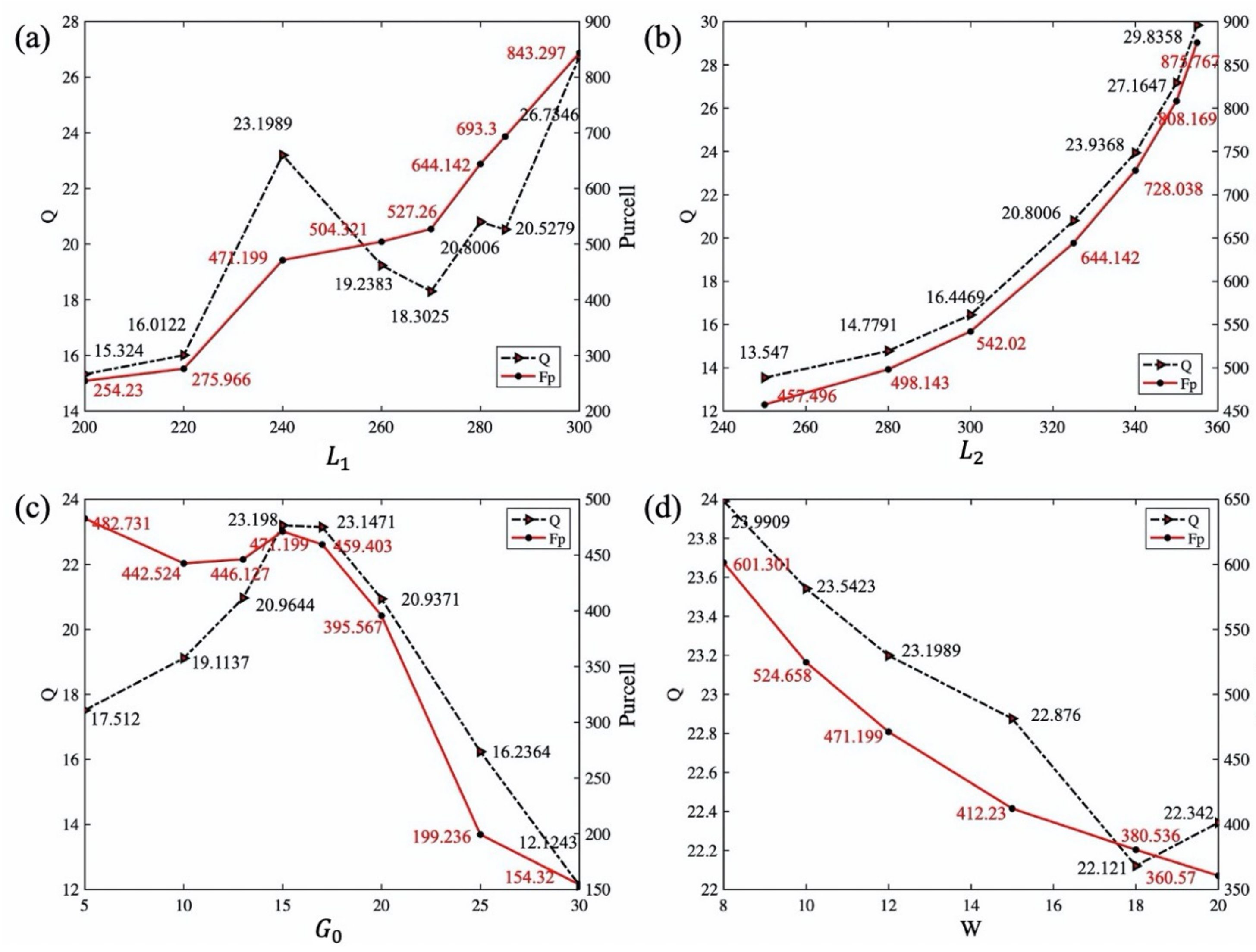

Figure 4. (a-d) Dependence of Q factor and Purcell value on the different parameters.

Conclusion

In summary, we realize PIT effect on-chip transmission by coupling the Fabry-Perot resonator on the MIM waveguide side. The QDNW offered site controllability for the QD single-photon emitter. By adjusting the length and width of the T-cavity and the coupling spacing, the plasmon induced transparency and peak adjustability are realized. Since PIT effect changes the electromagnetic environment around QD, the spontaneous emission rate of single photon was significantly enhanced to a maximum rate of more than 900 times. We believe that this new structure will have an important impact on the development of nano devices and quantum communication.

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