Predicting Purcell Enhancement of quasi-Bound States in the Continuum with Spectral Parameters

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1. Introduction

The Purcell effect describes the enhancement of spontaneous emission of quantum emitters inside an optical cavity.[1] Optical cavities function to both increase the local density of states (LDOS) for enhanced spontaneous emission rate and redirect the emitted photons to specific out-coupling channels.[2,3] The Purcell enhancement is proportional to Q/V, i.e. the quality factor Q divided by the effective modal volume V, which represents the temporal and spatial confinement of the optical cavity respectively. While Q is straightforward to measure, V was known to be difficult to determine experimentally or analytically.

Bound states in the continuum (BIC) are optical resonances that are energetically compatible with free space but de-coupled from free space due to symmetry mismatch. The structures that support BIC can be detuned slightly to break the symmetry mismatch and create quasi-BIC that exhibit extraordinarily high Q. In this work, we analyzed the Purcell effect from quasi-BIC utilizing our analytical model that predicts the photoluminescence enhancement (PLE) with spectral parameters. We also explored the dependency of the PLE on different resonance characteristics of the quasi-BIC that significantly modulates the effectiveness of the quasi-BIC for enhancing luminescent processes.

2. Analytical Modelling of Purcell Enhancement

We recently reported about our new analytical model that predicted the averaged Purcell enhancement factor of the optical cavity with parameters fitted from spectral measurements.[4] In particular, the PLE was given by:

$$PLE(\omega_0) = \frac{c\Gamma_{rad}}{\omega_0 t {\Gamma_{tot}}^2}\frac{\Gamma_{abs,dye}}{\kappa}$$

where ω_0 is the resonant frequency, t is the dye layer thickness, κ is the extinction coefficient of the dye layer, and c is the speed of light in vacuum. $\Gamma_{tot} = \Gamma_{rad} + \Gamma_{abs,dye} + \Gamma_{abs,NP}$ is the total decay rate where Γ_{rad} is the radiative decay rate, $\Gamma_{abs,dye}$ and $\Gamma_{abs,NP}$ are the absorptive decay rates contributed by the dye layer and the nanoparticles. This model was subsequently verified by numerical simulations and photoluminescence measurement results.

3. Purcell Enhancement of quasi-BIC

We apply our analytical model to analyze the Purcell effect and the out-coupling of the enhanced luminescence. We simulated the quasi-BIC modes on bipartite silicon nanoparticle arrays with the finite-difference time-domain (FDTD) method. As shown in Fig. 1, the PLE first increased sharply as the detuning d was introduced, but as d further increases, the PLE reached a maximum and decreases for larger d. The initial increase was due to the increase in out-coupling efficiency while the decrease in Q reduced the PLE for larger d.

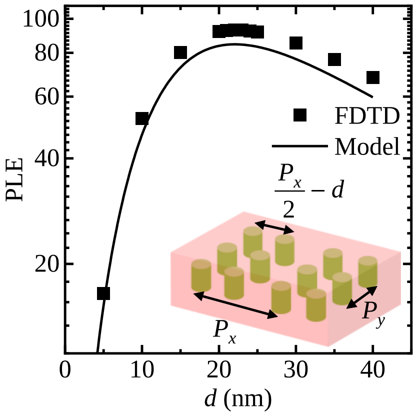

Figure 1. The FDTD simulated PLE and the PLE predicted by the analytical model was plotted against the detuning d. The inset illustrates the bipartite nanoparticle array that supports the quasi-BIC mode.

We also analyzed the quasi-BIC modes supported on asymmetric metasurfaces fabricated with glancing angle deposition. Due to the asymmetric shape of the nanoparticles in the metasurface, asymmetry was induced in Γ_{rad} about x-axis, and the BIC condition was also shifted from normal incident to 0.9°.

4. Conclusions

In conclusion, we developed an analytical model that describes the Purcell effect on quasi-BIC cavities and predicted the PLE that can be observed from the quasi-BIC modes. The spectral parameters were also analyzed to reveal the influence of Γ_{rad} on the PLE. This result presents a useful analytical framework for optimizing quasi-BICs for luminescence applications.

References

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