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Influence of the Metamaterial Geometry on Ultra-Strong Light-Matter Interaction

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Abstract: We present a comprehensive study on the influence of the metamaterial geometry on ultra-strong coupling to intersubband transitions. The spatial overlap of a metamaterial cavity mode and quantum-well region shows the strongest effect.

OCIS codes: (160.3918) Metamaterials; (130.4110) Modulators; (130.3060) Infrared

1. Introduction

Optical metamaterials in the mid-infrared (MIR) spectral range have attracted tremendous research interest. Their effective permittivity and permeability are defined by material properties and by geometry. The latter new degree of freedom in design is used to explore effects like negative refraction [1], super-resolution [2] and cloaking [3]. Furthermore, metamaterials also show strong field enhancement in the near-field making them very attractive to study light-matter interaction.

Here, we present a comprehensive study of ultra-strong coupling between an intersubband transition (IST) in a semiconductor quantum-well and different metamaterial geometries. In the ultra-strong interaction regime the Rabi frequency (the rate at which energy is exchanged between the cavity field and the matter states) becomes comparable to the fundamental system resonance. In other words, the energy exchange happens on the same time-scale as the fundamental system oscillation itself. The metamaterial geometry affects the cavity near-field and thereby the coupling to the ISTs. We have fabricated four conventional and three complementary metamaterials and we have found similar Rabi frequency values. The fundamental IST is set to 12 µm (100 meV, or 24 THz).

2. Experimental results and discussion

Experimentally, we study the ultra-strong light-matter interaction by performing optical transmission experiments. The energy exchange between the cavity mode and the matter system leads to a splitting of a bare cavity resonance into the two polariton branches. On resonance, this splitting is exactly twice the Rabi frequency Ω_R. For the present system, we can express it in a very instructive way as

$$\Omega_R = \frac{\sqrt{f_W}\omega_p}{2}, \tag{1}$$

where ω_p describes the quantum-well plasma frequency and f_W is the geometrical overlap parameter. This notation instantly separates the influence of the semiconductor from the cavity. The plasma frequency is defined exclusively by the quantum-wells and kept constant at 5.6 THz for this study. The geometry parameter f_W describes the spatial overlap of the optical mode with the quantum-wells and can be altered with different metamaterial designs.

The parameters that change most with metamaterial geometry are radiative losses, field-enhancement and decay length of the cavity mode into the semiconductor. As an example we show the transmission spectra for a conventional split-ring resonator (SRR) and a dumbbell resonator [4] in Fig. 1. The metamaterial resonance is varied by geometric scaling and swept across the IST. The splitting from the single cavity resonance into the two polariton branches is clearly visible for both resonator types.

Simulations show that the SRR-based metamaterial has a stronger *z*-polarized field enhancement and smaller radiative losses than the dumbbell-based one. The frequency and spatially resolved near-field for both resonators is presented in Fig. 2. In the case of the SRR, the cavity mode decay length is 160 nm. For the dumbbell it extends to about 200 nm from the semiconductor surface. Nevertheless, both samples show a splitting of 15% of their center frequencies in the experiment. In other words, the shorter decay length of the SRR is offset by its higher field enhancement resulting in the same splitting. The radiative losses have no effect on the splitting strength.

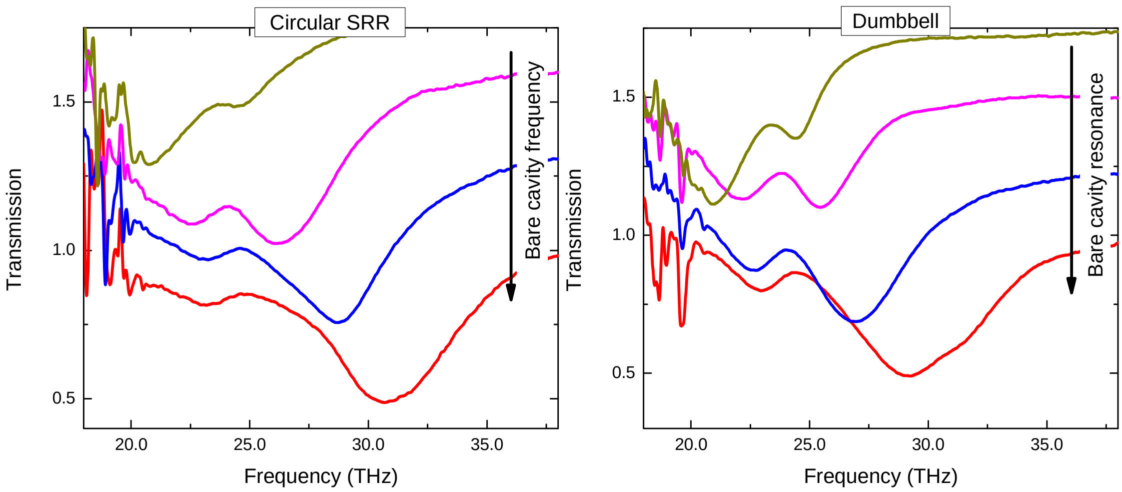

Fig. 1: Comparison of the ultra-strong light-matter interaction between a circular SRR (left) and a dumbbell resonator (right). Both metamaterials operate on the fundamental resonance. The noise below 20 THz is caused by the reduced sensitivity of our MCT detector. The individual curves are offset in the vertical direction by 0.2 for clarity.

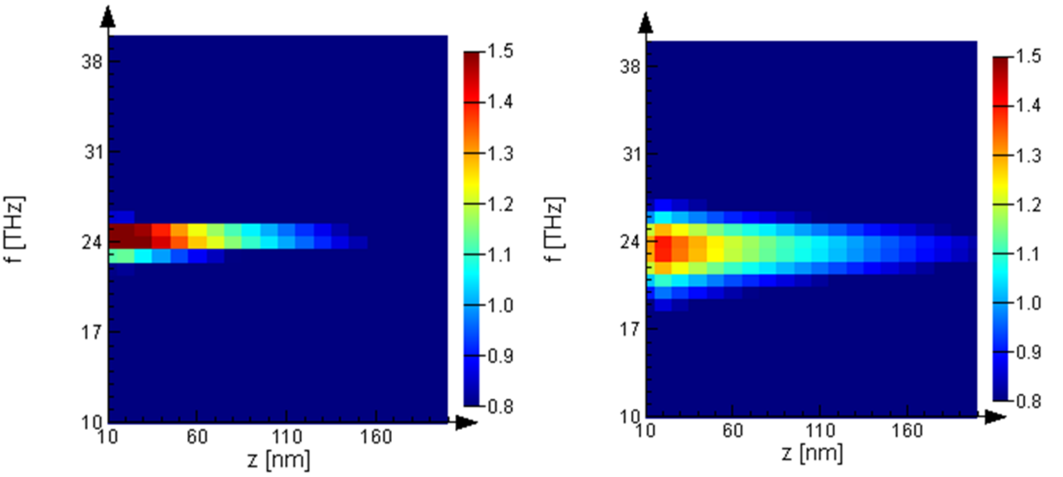

Fig. 2: Frequency and spatially resolved metamaterial near-field for the circular SRR (left) and the dumbbell (right). Both structures show a single resonance at 24 THz. The decay length is increased by 25% for the dumbbell compared to the SRR.

3. Conclusion

In conclusion, we have presented a comprehensive study on the influence of metamaterial geometry on ultra-strong light matter interaction. The resonator design affects the radiative losses, the field enhancement, and the decay of the near-field. The magnitude of the polariton anti-crossing is defined by the decay length (which defines the overlap between cavity mode and quantum-wells) as long as the quantum-wells are kept constant at a certain quantum-well plasma frequency ω_P.

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4. References

[1] R. A. Shelby, D. R. Smith and S. C. Schultz, "Experimental verification of a negative index of refraction," Science **292**, 77 (2001).
[2] J. B. Pendry, "Negative refraction makes a perfect lens," Phys. Rev. Lett. **85**, 3966 (2000).
[3] D. Schurig, J. J. Mock, B. J. Justice, S. A. Cummer, J. B. Pendry, A. F. Starr and D. R. Smith, "Metamaterial electromagnetic cloak at microwave frequencies," Science **314**, 977 (2006).
[4] C. Walther, G. Scalari, M. I. Amanti, M. Beck and J. Faist, "Microcavity Laser Oscillating in a Circuit-Based Resonator," Science **327**, 1495 (2010)