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Intersubband Polaritonics in Dielectric Metasurfaces

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Abstract: We experimentally demonstrate tailorable polaritons resulting due to strong coupling between Mie modes of dielectric nanoresonators in a metasurface and intersubband transitions in semiconductor quantum wells that are embedded inside the resonator.

OCIS codes: (240.5420) Polaritons; (160.3918) Metamaterials; (230.5590) Quantum-well, -wire and –dot devices

1. Introduction

Quasiparticles known as polaritons, which form due to strong light-matter interaction, have been a topic of intense research for decades for both fundamental and practical applications ranging from optoelectronics, quantum information to nonlinear optics. Among different types of polaritons, intersubband (ISB) polaritons resulting due to strong coupling between a photonic mode and intersubband transitions (ISBT) in semiconductor quantum wells (QWs) are particularly interesting as they have shown potential for numerous applications ranging from tunable filers, modulators, light-emitting diodes to ultrathin nonlinear optical devices [1-4].

To date, ISB polaritons have been achieved using only plasmonic nanoresonators [5]. This is because plasmonic nanoresonators can be very compact and offer strong near field enhancement of the optical fields. Plasmonic nanoresonators however are intrinsically lossy at optical frequencies and have low optical damage thresholds. This poses serious limitations to applications such as nonlinear optics where the fundamental beams need to be intense. The ability to achieve strong light-matter interaction using an all-dielectric platform would remove these limitations and would therefore create exciting new opportunities. In this work, we demonstrate for the first time, strong coupling between ISTs and Mie modes in hybrid dielectric metasurfaces. Furthermore, using our flexible all-dielectric platform, we demonstrate the ability to tailor the strength of the light-matter interaction and generate polaritons with Rabi splitting ranging from 2 % to 10 % by either engineering the semiconductor heterostructure or by coupling ISB transitions to different photonic modes of the Mie resonators with different mode profiles.

2. Design and Fabrication of Hybrid Dielectric Metasurface

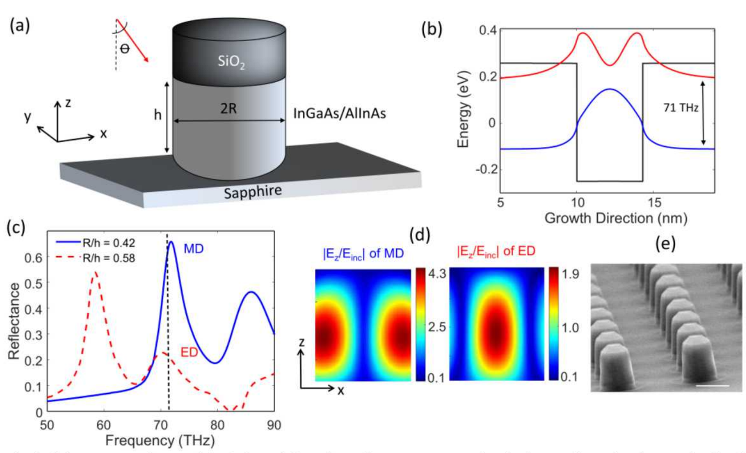

Fig. 1 (a) Schematic of the hybrid metasurface. (b) 8 band k.p band structure calculation of a single period of the $In_{0.53}Ga_{0.47}As/Al_{0.52}In_{0.48}As$ heterostructure embedded inside the Mie resonator. It is optimized to have an ISBT at 71 THz. (c) Finite-difference-time domain calculation of reflectance from metasurfaces with cylinders of radius/height (R/h) = 0.42 (blue solid) and 0.58 (red dashed). The 0.42 (0.58) scale factor aligns MD (ED) resonance with the ISBT shown by black dashed line. (d) Numerically calculated magnitude of field enhancement of MD and ED resonances. (e) Top view scanning electron micrographs of the fabricated hybrid Mie resonators. The white scale bar corresponds to 1 μm.

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To demonstrate strong coupling, we fabricated hybrid dielectric metasurfaces comprising of Mie resonators made from III-V semiconductors with *n*-doped QWs embedded inside the individual resonators (Fig. 1(a)). The approach involved transferring of engineered $In_{0.53}Ga_{0.47}As/Al_{0.52}In_{0.48}As$ quantum heterostructures which support an ISBT at 71 THz (Fig. 1(b)) to a lower refractive index transparent substrate and then following that by fabrication of cylindrical Mie resonators using electron beam lithography and etching. Resonators of different radii were fabricated to spectrally scale either the magnetic dipole (MD) or the out-of-plane electric dipole (ED) Mie resonance (Fig 1(c)). We chose the first two lowest order dipole modes as it allowed us to make the resonators as small as possible. Furthermore, since only photonic modes with strong E_z components can couple to the ISBTs due to selection rules, we chose out-of-plane ED instead of the standard in-plane ED resonance (Fig. 1(d)). We excited the out-of-plane ED by optimizing the size of the resonator along with using an off-normal incidence (Fig. 1(a)). Finally, metasurfaces with resonators containing different number of QWs and doping were also fabricated to demonstrate variable strong-coupling (Fig. 1(e)).

3. Experimental Results

When the MD resonance did not spectrally overlap with the ISBT, as expected, changing the scale factor led to linear scaling of the resonant frequency (Fig. 2(a)). When the MD resonance spectrally overlaps with the ISBT, we observed Rabi splitting of the original resonance confirming the presence of strong coupling. Figure 2(b) shows reflectance spectrum of metasurfaces consisting of resonators of different scale factors in their radii, and we clearly observe an anti-crossing of the two resulting polariton branches. Fig. 2(c) shows reflectance spectrum of metasurfaces consisting of resonators of same scale factors as in 2(b) but with QWs with higher doping. The Rabi splitting observed is now much larger and is about 10 % of the unloaded resonance frequency which is comparable to what has been observed for plasmonic metasurfaces coupled to ISBTs. Finally, in comparison to MD, since the ED mode has lower field enhancement (defined as $|E_z/E_{inc}|$ as shown in Fig. 1(d)), a much less pronounced Rabi spitting of ~ 2 % was observed. Fig. 2(c, d) are reflectance spectrum of metasurfaces with the same heterostructure but in 2(c) MD is aligned to the ISBT and in 2(d) the ED is aligned to ISBT. To conclude, we demonstrate that in these all-dielectric hybrid metasurfaces, we can achieve strong coupling and can also tailor the strength of strong-coupling by either engineering the matter excitation or by coupling to different photonic modes of the resonators.

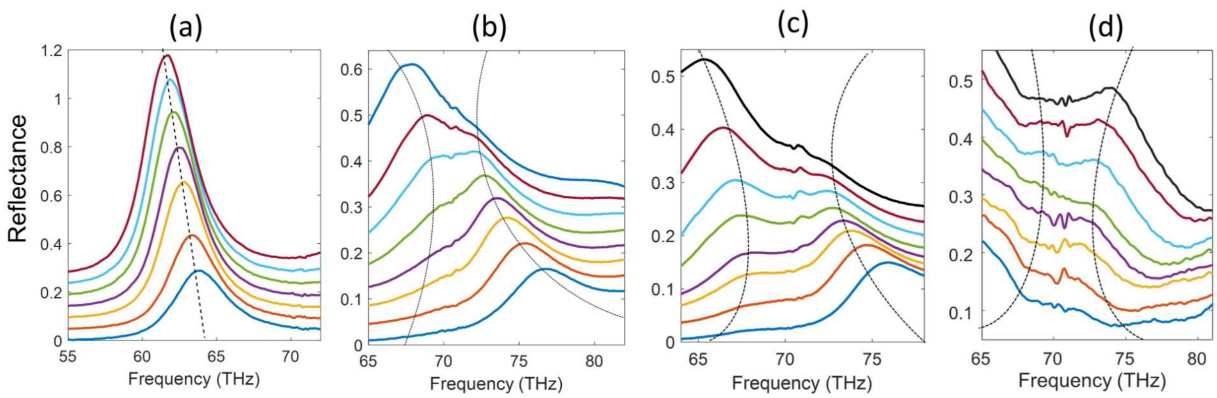

Fig. 2 (a) Experimentally measured reflectance spectrum of Mie resonators of different radii with MD resonances detuned from IST resonance. Reflectance curves are offset vertically for clarity. The dashed lines are shown as guide to eyes. Changing radii leads to linear scaling of the MD resonance. (b,c) Experimentally measured reflectance spectrum of Mie resonators of different radii with MD resonances spectrally overlapping with the ISBT. A clear anti-crossing behavior of the polariton branches is observed. The doping densities of the QWs inside the resonators are $8x10^{17}$ cm^{-3} for (c) and $3x10^{18}$ cm^{-3} for (d). (d) Experimentally measured reflectance spectrum of Mie resonators of different radii with ED resonances spectrally overlapping with the IST resonance. The doping density of QWs is same as in (c). A much smaller Rabi splitting compared to (c) is observed.

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