Non-locality and single meta-atom spectroscopy in THz Landau polaritons

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Abstract. We will discuss, theoretically and experimentally, the existence of a limit to the possibility of arbitrarily increasing electromagnetic confinement in polaritonic systems, where strongly sub-wavelength fields can excite a continuum of high-momenta propagative magnetoplasmons. This leads to peculiar nonlocal polaritonic effects, as certain polaritonic features disappear and the system enters in the regime of discrete-to-continuum strong coupling. We will as well present experiments reporting spectroscopy of a single, ultrastrongly coupled, highly subwavelength resonator operating at 300 GHz.

INTRODUCTION

Sub-wavelength electromagnetic field localization is a central theme in photonic research, as it allows sensing capabilities as well as increasing the light-matter coupling strength. Recently, the strong and ultrastrong light-matter coupling regime [1] in the THz range with split-ring resonators coupled to magnetoplasmons [2] has been widely investigated, achieving successive world-records for the largest light-matter coupling ever achieved. Ever-shrinking resonators have allowed to approach the regime of few electrons strong coupling, in which single-dipole properties can be modified by the vacuum field [3].

We will discuss, theoretically and experimentally, the existence of a limit to the possibility of arbitrarily increasing electromagnetic confinement in polaritonic systems. Strongly sub-wavelength fields can excite a continuum of high-momenta propagative magnetoplasmons [4]. This leads to peculiar nonlocal polaritonic effects, as certain polaritonic features disappear and the system enters in the regime of discrete-to-continuum strong coupling. We will as well discuss experiments reporting spectroscopy of a single, ultrastrongly coupled, highly subwavelength resonator operating at 300 GHz. By using a combination of immersion lenses we unravel the linewidth dependence of planar metamaterials as a function of the meta-atom number indicating quenching of the superradiance. On these grounds, we investigate ultrastrongly coupled Landau polaritons at the single resonator level [5], measuring a normalized coupling ratio $\frac{\Omega}{\omega} = 0.6$.

Polaritonic non-locality

Nanophotonic structures confine electromagnetic radiation below the Abbe diffraction limit by storing part of the electromagnetic energy into the kinetic energy of moving charges. Primarily relying on metals as charge reservoirs, plasmon- ics has mainly targeted the visible portion of the electromagnetic spectrum. The possibility of extending plasmonic excitation to low frequencies (mid-infrared and terahertz)by employing semiconductors and two-dimensional (2D) systems with plasma frequency tunable via the carrier concentration has allowed extreme electro-magnetic field confinements in nanostructures. An important question arises on the physical limitations to reducing the cavity volume and the subsequent increase of light–matter coupling. We show theoretically that the nonlocal effects are driven by the confinement of the resonator's electromagnetic field coupling to a continuum of propa- gating magnetoplasma excitations.

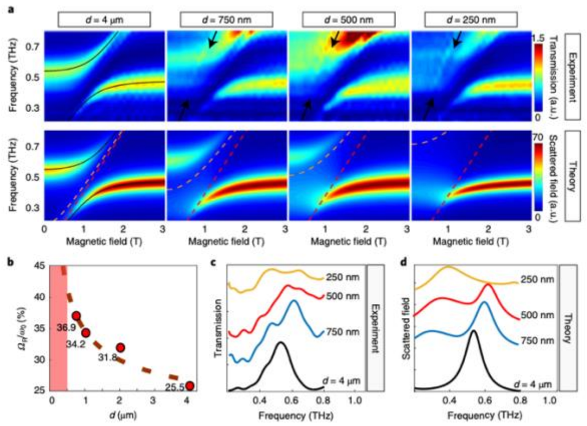

Fig. 1. a) Top row: transmission of cSrrs coupled to the Landau level transition in 2DEG versus magnetic field for four different gap sizes, *d*. . bottom row: the calculated scattered field for different gap feature sizes, *d* (same as the gap sizes of the experiment results). **b**, Normalized coupling versus *d*. The red-shaded region corresponds to where the large broadening of UP does not allow a measurement of the coupling. **c**,**d**, Sections (offset for clarity) of the colour plots in **a** at zero magnetic field for the experimental result (**c**) and the theoretical calculation (**d**) [4].

We experimentally observed such a physics using Landau polaritons at sub-terahertz frequencies by employing nanometre-sized resonators. First, we show that, when

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nonlocal effects are not relevant (gap size d>750nm), the normalized coupling ratio between light and matter scales as √1d, increasing by ~50% from d = 4 μm to 750 nm, and reaching 37% (Fig.1 (b)). For smaller gap values, nonlocal effects become dominant and the sys- tem is no longer well described by a standard Hopfield model. As predicted by our multimode dissipative bosonic Hamiltonian, we observe a broadening of the UP branch and partial disappearance on the lower one (Fig.1a,c)

2 A single, ultrastrongly coupled THZ meta-atom

Free-space coupling to subwavelength individual optical elements is a central theme in quantum optics, as it allows the control over individual quantum systems. In this second experiment we show that, by combining an asymmetric immersion lens setup and a complementary resonating meta-surface we are able to perform terahertz time-domain spectroscopy of an individual, strongly subwavelength (50 um wide) meta-atom oscillating at 300 GHz, corresponding to a free space wavelength of 1 mm. We show that the linewidth of the metasurface scales as 1/N where N is the number of the meta- atoms, indicating quenching of the superradiant coupling. We propose an explanation of the observed signals based on a Fourier optics argument (Fig.2(a-c)).

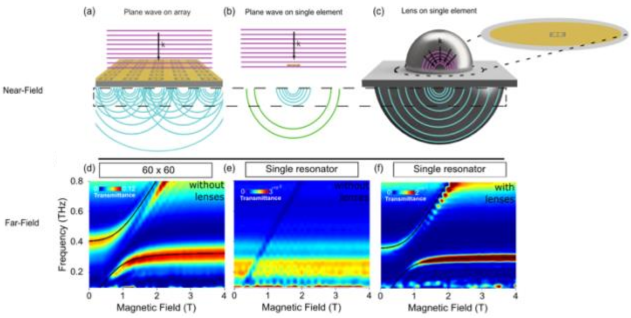

Fig. 2. Schematic views of the near field interaction between the THz field and (a) an array of cSRRs (b) a single cSRR without lenses, and (c) a single cSRR with lenses. (d)-(f) show the colormaps corresponding to the normalized transmittances of cSRRs on top of a GaAs quantum well measured under a varying B-field from 0-4T with the same lens configurations.

We successively investigate ultrastrongly coupled Landau polaritons at the single resonator level. We clearly show how the lens system allows the measurements of the polaritonic branches that are completely lost in the case of the single resonator excited by a plane wave, whose radiation is collected without an immersion lens. In this case, we do not measure signs of ultrastrong coupling since the correct resonant LC mode cannot be excited and detected. In Fig.2 f we report a single-resonator ultrastrong coupling measurement yielding a coupling ratio $\Omega/\omega=0.33$ with a single resonator cooperativity C = 94. Employing a more doped 2DEG we could measure a coupling ratio of $\Omega/\omega=0.6$ [5].

Our findings pave the way towards the control of ultrastrong light-matter interaction at the single electron/ resonator level. The proposed technique is way more general and can be useful to char- acterize the complex conductivity of micron-sized samples in the terahertz domain.

References

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