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Ultrastrong light-matter coupling at terahertz frequencies with split ring resonators and inter-Landau level transitions

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We study strong light-matter coupling at terahertz frequencies employing a system based on an array of deeply subwavelength split ring resonators deposited on top of an ensemble of modulation-doped quantum wells. By applying a magnetic field parallel to the epitaxial growth axis, at low temperatures, Landau Levels are formed. We probe the interaction of the inter-Landau level transitions with the resonators modes, measuring a normalized coupling ratio $\frac{\Omega}{\omega_c} = 0.58$ between the inter-Landau level frequency ω_c and the Rabi frequency Ω of the system. The physics of the system is studied as a function of the metasurface composition and of the number of quantum wells. We demonstrate that the light-matter coupling strength is basically independent from the metamaterial lattice spacing. © *2013 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4795543]

I. INTRODUCTION

The possibility to enhance and tune light-matter interaction results instrumental for fundamental studies of cavity quantum electrodynamics (QED) and for applied realizations of both classical and quantum devices.[1–4] The vacuum Rabi frequency Ω quantifies the coupling strength between the light part (cavity photons) and the matter part (elementary electronic excitation). The strong light-matter coupling regime can be attained when Ω results larger than the dephasing rates of the photons and electronic excitations. In the past few years, a considerable research effort has been devoted to the study of the the *ultrastrong* light-matter coupling regime.[5–17] This regime is realized when the vacuum Rabi frequency becomes an appreciable fraction of the unperturbed frequency of the system ω. In such a regime, theory predicts modifications of the ground and excited state properties due to the relevance of the counter-rotating terms of the Hamiltonian, resulting in non-adiabatic cavity QED effects.[5] We recently demonstrated ultrastrong coupling regime in a new system, namely, a high-mobility two-dimensional electron gas (2DEG) coupled to terahertz (THz) metamaterial resonators.[18] The photonic modes of an array of split ring resonators are coupled to the inter-Landau level transition of the 2DEG, obtained by applying a magnetic field perpendicular to the plane of the quantum wells (QWs). This highly controllable system is ideal for the study of strong coupling because the material excitation can be continuously tuned by changing the value of the applied magnetic field. The dependence of the optical dipole moment d on the cyclotron orbit length results critical in achieving very large coupling ratios. The dipole d scales as $d \sim el_0\sqrt{\nu}$, where $l_0 = \sqrt{\hbar/eB}$ is the magnetic length and $\nu = \rho_{2DEG} 2\pi l_0^2$ is the filling factor of the 2DEG, where ρ_{2DEG} is the electron areal density.[19] As soon as the cyclotron transition can be resolved, i.e., as soon as the condition $\mu B > 1$ is fulfilled, where $\mu = \frac{e\tau}{m^*}$ is the electron mobility and τ is the Drude scattering time, the system will have a gigantic dipole moment. With our previous work,[18] we demonstrated that the coupling ratio for this system scales as $\frac{\Omega}{\omega_c} \sim \sqrt{\alpha n_{QW} \nu}$, where α is the fine structure constant and n_{QW} is the number of 2DEGs.[19] In the present paper, we concentrate our study on a metasurface having a resonance at 500 GHz, and we study the dependence of the coupling ratio from the areal density of meta-atoms constituting the metasurface using two different heterostructures, with one and four quantum wells.

II. EXPERIMENTAL SETUP

The sample transmission is investigated in the 0.1–3 THz range by means of a THz-time domain spectrometer (THz-TDS).[20] A schematic of the experiment is presented in Fig. 1(a). THz pulses of 2 ps length are produced by illuminating an interdigitated photoconductive switch biased to an electric field of 30 kV/cm with 75 fs-wide pulses centered at 800 nm from a mode-locked Ti:sapphire laser (80 MHz repetition rate) at an average power of 300 mW. The switch is modulated at 15.5 KHz with a 50% duty cycle. Detection of THz radiation is performed via coherent electro-optic sampling employing a 200 μm thick ZnTe (110)-oriented crystal in optical contact with a 6 mm thick (100)-oriented ZnTe crystal (to minimize echoes) and a differential detection scheme. The resulting bandwidth of the system spans 0.1−3 THz. All THz beam path is purged with nitrogen. Two pairs of 90° off-axis parabolic mirrors of 2 in. diameter collect and refocus the THz signal in and out from a cryostat equipped with a superconducting magnet in a split-coil configuration. The THz spot size at the center of the magnet coils is about 2.5 mm in diameter, corresponding to the probed surface of the sample.

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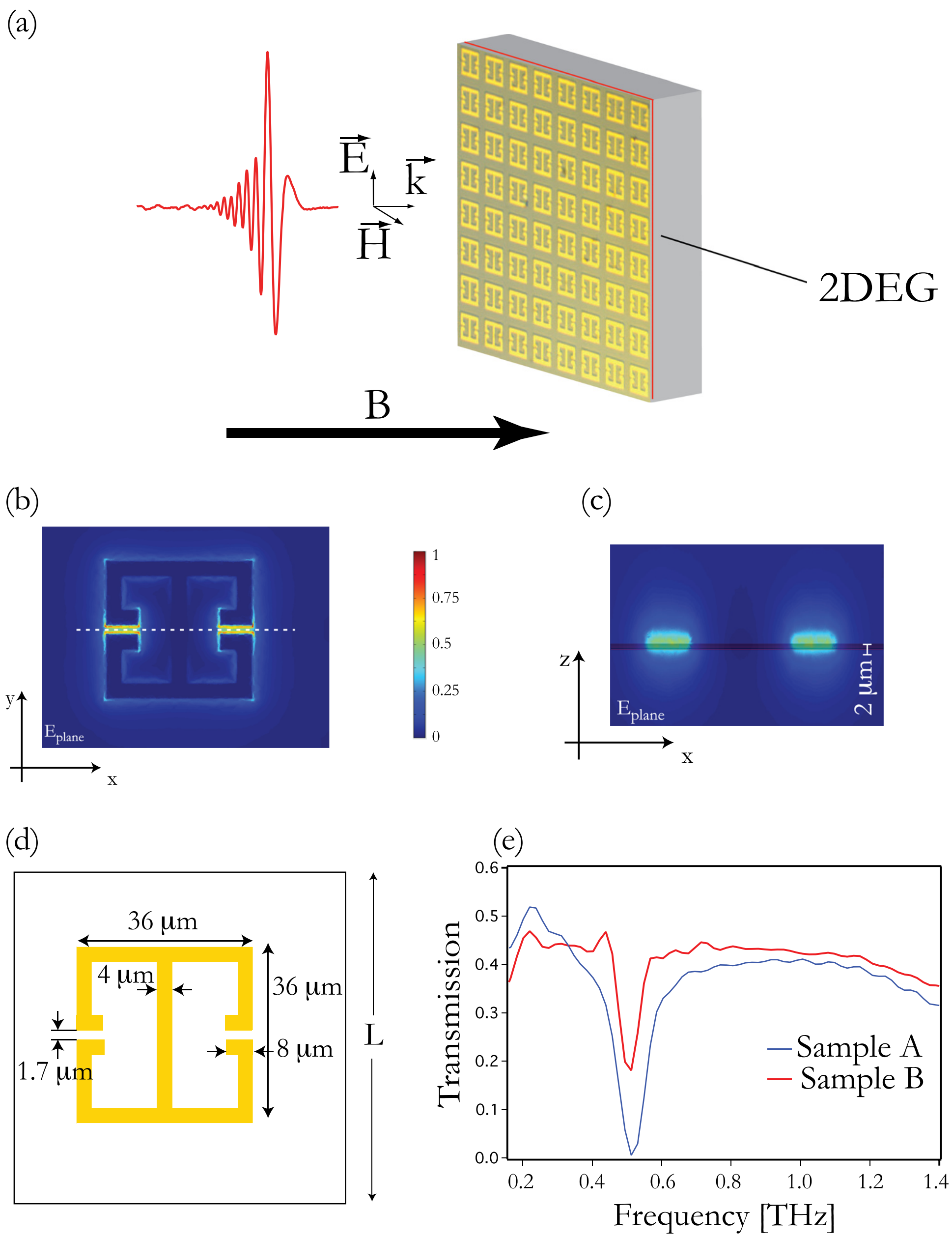

FIG. 1. (a) Schematic of the experimental arrangement which includes a 2-ps long broadband THz pulse probing the transmission of a metamaterial based on split-ring resonators deposited on top of an GaAs/AlGaAs heterostructure. (b) and (c) in-plane electric field intensity $\left(\sqrt{E_x^2 + E_y^2}\right)$ calculated at the resonance of 500 GHz. (d) Geometrical details of the employed unit cell containing a meta-atom. (e) Transmission spectra for the two metasurfaces A and B deposited on top of a semi-insulating GaAs wafer.

III. SAMPLES AND RESONATORS EMPLOYED

Our THz metamaterial integrates the 2DEG with a metasurface composed of meta-atoms (electronic split-ring resonators[21–23]), which display electric field enhancement on length scales which are strongly subwavelength, making them very appealing in reaching extreme light-matter couplings in the Mid-Ir and THz range where long wavelength radiation (0.1-3 mm) has to interact with quantum well systems typically extending over length of some micrometers.[24,25] In our case, the in-plane electric field couples efficiently to the TE-polarized cyclotron transition when the magnetic field is applied perpendicularly to the plane of the layers and parallel to the wavevector of the incident THz pulse (see Figs. 1(b) and 1(c)). Metasurfaces composed of meta-atoms of the kind described in Ref. 26 and displaying an LC resonance at 500 GHz are deposited in a square array with a unit cell side of $L = 50\,\mu$m (metasurface A, approximately 2000 meta-atoms probed) and $L = 100\,\mu$m (metasurface B, approximately 500 meta-atoms probed), respectively.

Conventional photolitography and Ti/Au (5/250 nm) e-gun metallization were used to realize the resonators. Two series of samples were realized, employing the two metasurfaces A and B deposited onto heterostructures containing a single modulation-doped triangular quantum well and four symmetrically modulation-doped square wells. A control sample was realized depositing the metasurfaces on top of a semi-insulating (SI) GaAs substrate. The measured transmission $|T|$ for the metasurfaces A and B on SI GaAs are displayed in Fig. 1(e). The expected resonance at 500 GHz is clearly observed. The structures present also a broad dipolar mode around 2 THz which will not be considered in the present study, and which is known to be strongly affected from the meta-atoms density.[27] The simulated transmission characteristic for a single resonator predicts a resonance at 500 GHz, in excellent agreement with what was measured on both control samples. A strong difference in the absorption among the different metasurface is expected and indeed observed, yielding a ratio of 3.3 between the integrated absorptions of samples A and B with respect to a difference of a factor of 4 in the resonator's density. The slight mismatch is compensated by the difference in absorption in the other resonance at 2 THz. It is important to highlight that the Q factor is changing from $Q_A = 5.2$ to $Q_B = 10$, i.e., when reducing the resonator density, but the resonance frequency remains basically unaffected. The dependence of the quality factor and of the resonance frequency from the metamaterial packing density has been investigated in detail by Singh *et al.*,[28] The quality factor of the LC mode has been observed to increase as a function of the meta-atom separation and saturate in correspondence of a first order resonance condition which favors radiative coupling in the metamaterial plane. Our results are fully consistent with those reported in Ref. 28. In our case, it would be inconvenient to push the system towards the highest quality factor that would correspond to a very low density of meta-atoms ($L = 166\,\mu$m, approximately 200 meta-atoms probed) and the signal contrast would decrease excessively with respect to the uncoupled cyclotron resonance line. A possibility, currently under study, would be offered by the selective removal of the quantum well material in-between the resonators; this would reduce strongly the uncoupled cyclotron resonance but would introduce another periodic pattern in the system.

IV. EXPERIMENTAL RESULTS: ULTRASTRONG AS A FUNCTION OF METASURFACE DENSITY

In Fig. 2, we show the transmission $|t|$ as a function of the applied magnetic field for samples constituted by one triangular quantum well with a sheet density $n_s^{1QW} = 3.2 \times 10^{11}$ cm^{-2} with the two different meta-atom distributions described in Sec. III. We first examine the data reported in Fig. 2(a), relative to the metasurface A; as the magnetic field is swept through the metasurface resonance, a clear anticrossing is observed. We can identify the upper and lower branches of the cavity magnetopolariton originating from the strong coupling of the electron residing in the last occupied Landau level to the cavity photons of the meta-atoms which constitute the metasurface. Cyclotron signal is also present because of the 2DEG which is present in-between the meta-atoms and which contributes to the total transmission. In the case of sample B, the contrast of the signal is very low (as pointed out in Sec. III this is expected from the different metasurface composition); for this reason together with the color plot, we present the

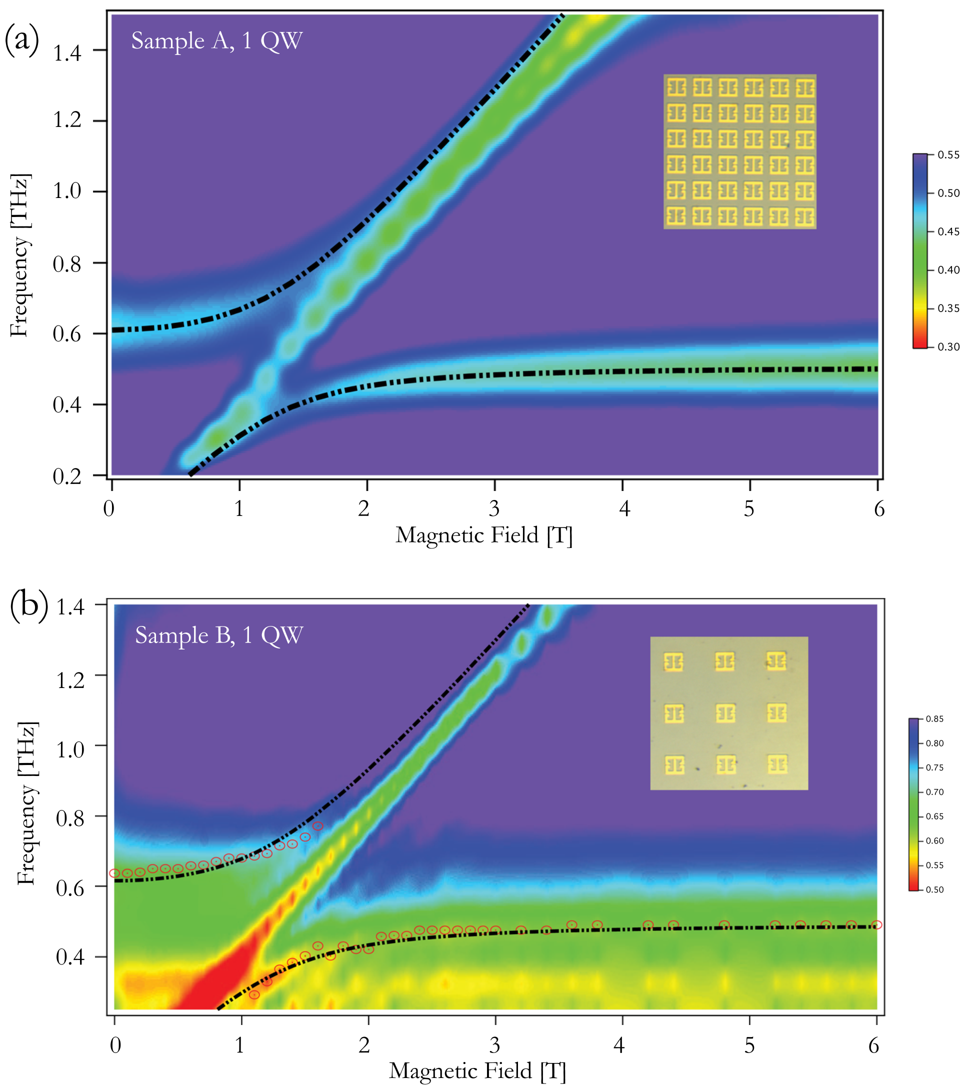

FIG. 2. (a) Color plot representing the transmission $|t|$ as a function of the applied magnetic field for the metasurface A deposited on top of a single quantum well sample. The black dashed line is the fit to the extracted transmission minima. The regular intensity modulation of the cyclotron absorption is an artifact of the interpolation procedure due to the discrete sampling on the magnetic field axis. Values of the field where there is no corresponding measurement result in an artificially lower value for the cyclotron absorption. Inset: photograph of the sample surface showing the arrangement of the meta-atoms. (b) Color plot representing the transmission as a function of the applied magnetic field for metasurface B deposited on top of the single quantum well sample together with the transmission minima (red circles). The black dashed line is the best fit to the data. Inset: photograph of the sample surface showing the arrangement of the meta-atoms. All the measurements are performed at T = 10 K.

transmission minima extracted from the measurements performed at different magnetic fields. The lower contrast is also due to the relative increase of the cyclotron signal because there is more surface nonoccupied by the resonators. The physics of the system is modeled employing a full quantum treatment described in Refs. 18 and 19; we report the best fit to the transmission minima extracted from the data. For sample A, we measure a coupling ratio $(\frac{\Omega}{\omega_c})_{1QWA} = 0.34 \pm 0.01$ and for sample B, we obtain $(\frac{\Omega}{\omega_c})_{1QWB} = 0.38 \pm 0.03$. In this case, we see that within the error given by the mean square deviation we measure the same value for the strong light-matter coupling ratio in the two samples. The magnetic field of $B = 1.2$ T corresponds in this case to a fill factor of $\nu_{1QW}(1.2) \simeq 11$.

We then examine the data relative to the experiments performed with the two metasurfaces A (Fig. 3(a)) and B (Fig. 3(b)) deposited on top of a heterostructure containing four quantum wells each containing an average sheet density of $n_s^{4QW} = 4.5 \times 10^{11}$ cm^{-2}. In this case, the filling factor of the 2DEG at the anticrossing magnetic field $B = 1.2$ T is $\nu = 15$. The difference in the absorption signal between the samples is clear, and the difference is even more dramatic if compared to the cyclotron signal which comes, in the case of sample B, from a larger portion of surface unoccupied from the resonators. The theoretical model measures a coupling ratio of $(\frac{\Omega}{\omega_c})_{4QWA} = 0.58 \pm 0.02$ for sample A, where the extraction of the transmission minima is straightforward. If we compare this value to what was obtained in the case of the single quantum well, we see that there is an increase of 1.7 times in the coupling ratio. This is expected and is attributed to the increased filling factor and to the increased number of quantum wells; by employing the relation $\frac{\Omega}{\omega_c} \sim \sqrt{\alpha n_{\mathrm{QW}} \nu}$ (derived in the ideal case where all the QWs are identically coupled to the electric field[19]), we would expect an increase in the coupling ratio by a factor $\sqrt{\frac{15\times4}{11}} \simeq 2.3$, which results in good agreement with the measured value 1.7. The small discrepancy can be ascribed to the different coupling of the quantum wells to the electric field in the case of the 4 quantum well sample and to eventual inhomogeneities of the electron distribution on the large samples. In the case of sample B, the identification of the upper branch features is especially difficult due to reduced signal; we then extracted the transmission minima for the lower branch only and applied the model. The result is plot on top of the transmission data in Fig. 3. The agreement with the lower branch dispersion is excellent and the model gives a value of $(\frac{\Omega}{\omega_c})_{4QWB} = 0.54 \pm 0.02$ for the coupling ratio. We report also sections of the two transmission graphs at the anticrossing points corresponding to a field value of $B = 1.2$ T. We can note the difference in the quality factor of the two different metasurfaces by inspecting the lower branch of both samples A and B for high values of the applied magnetic field. In this regime, the resonance recovers the shape and the frequency of the metasurface without any

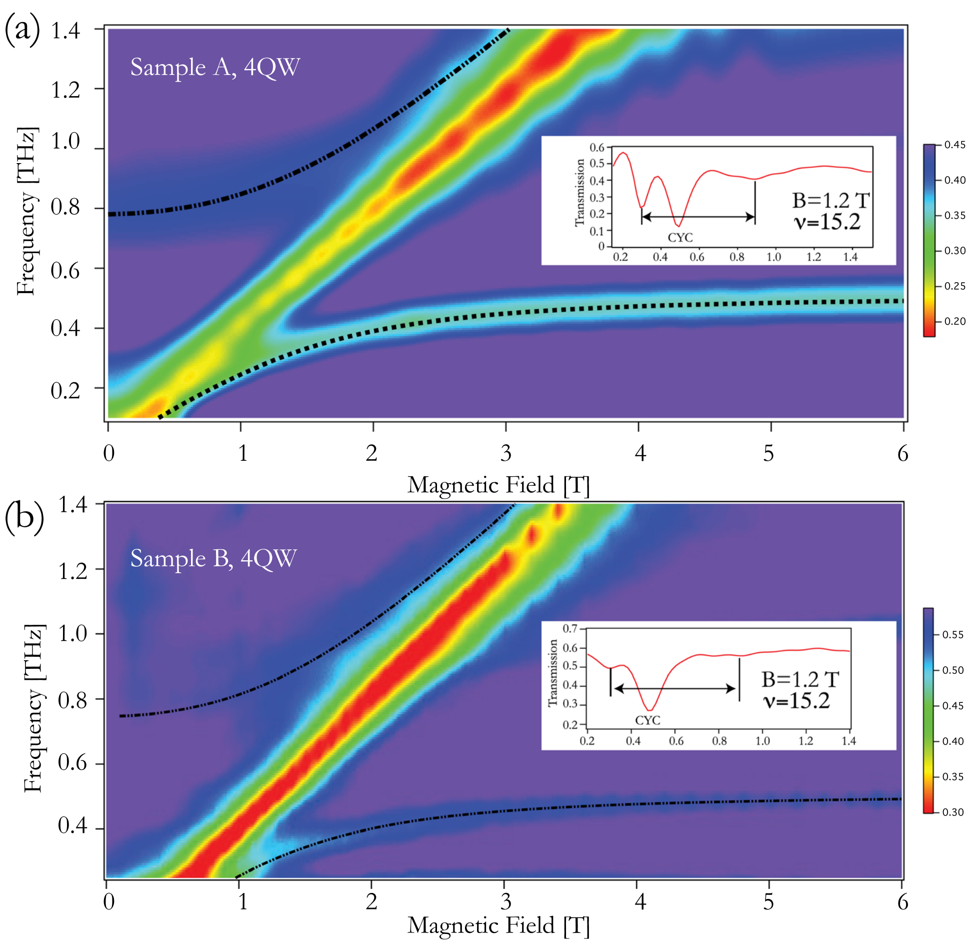

FIG. 3. (a) Transmission as a function of the applied magnetic field for the metasurface A deposited on top of a 4 quantum well sample. Inset: section of the previous graph representing the transmission at $B = 1.2$ T corresponding to the anticrossing point. (b) Transmission minima for metasurface B deposited on top of the single quantum well sample. Inset: section of the previous graph representing the transmission at $B = 1.2$ T corresponding to the anticrossing point. The dashed lines are the best fit to the data employing the model described in Refs. 18 and 19. All the measurements are performed at $T = 10$ K.

quantum well (as in the case of Fig. 1(e)). We indeed use the high magnetic field value of the metasurface resonance in the fitting procedure as the cold cavity resonance value.

From the analysis of the four investigated samples, we can conclude that a change of a factor of four in the density of the meta-atoms comprising our metasurfaces does not affect significantly the light-matter coupling strength. As expected, the strength of the absorption signal is significantly weaker in the case of the less dense metasurface, justifying the adoption of closely spaced metasurfaces in order to increase the signal-to-noise ratio.

V. CONCLUSIONS

We studied strong light-matter coupling in the THz range by employing metasurfaces of metallic split-ring resonators coupled to the inter-Landau level transition of a 2DEG immersed in strong magnetic field. We demonstrated a normalized value of the coupling ratio of $\frac{\Omega}{\omega_c} = 0.58$ and we experimentally proved that the coupling ratio is basically independent from the meta-atom density of the metasurface. Extension of the present system to the microwave range employing multiple quantum wells should yield even larger coupling ratios.

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[1] J. Raimond, M. Brune, and S. Haroche, Rev. Mod. Phys. **73**, 565 (2001).
[2] A. Wallraff, D. I. Schuster, A. Blais, L. Frunzio, R.-S. Huang, J. Majer, S. Kumar, S. M. Girvin, and R. J. Schoelkopf, Nature **431**, 162 (2004).
[3] S. Christopoulos, G. B. H. von Högersthal, A. Grundy, P. Lagoudakis, A. Kavokin, J. Baumberg, G. Christmann, R. Butté, E. Feltin, J.-F. Carlin *et al.*, Phys. Rev. Lett. **98**, 126405 (2007).
[4] K. Hennessy, A. Badolato, M. Winger, D. Gerace, M. Atatuere, S. Gulde, S. Faelt, E. L. Hu, and A. Imamoglu, Nature **445**, 896 (2007).
[5] C. Ciuti, G. Bastard, and I. Carusotto, Phys. Rev. B **72**, 115303 (2005).
[6] C. Ciuti and I. Carusotto, Phys. Rev. A **74**, 033811 (2006).
[7] S. DeLiberato, C. Ciuti, and I. Carusotto, Phys. Rev. Lett. **98**, 103602 (2007).
[8] M. H. Devoret, S. M. Girvin, and R. J. Schoelkopf, Ann. Phys. **16**, 767 (2007).
[9] J. Bourassa, J. M. Gambetta, A. A. Abdumalikov, O. Astafiev, Y. Nakamura, and A. Blais, Phys. Rev. A **80**, 032109 (2009).
[10] Y. Todorov, A. M. Andrews, R. Colombelli, S. DeLiberato, C. Ciuti, P. Klang, G. Strasser, and C. Sirtori, Phys. Rev. Lett. **105**, 196402 (2010).
[11] M. Geiser, F. Castellano, G. Scalari, M. Beck, L. Nevou, and J. Fais, Phys. Rev. Lett. **108**, 106402 (2012).
[12] V. M. Muravev, I. V. Andreev, I. V. Kukushkin, S. Schmult, and W. Dietsche, Phys. Rev. B **83**, 075309 (2011).
[13] T. Schwartz, J. A. Hutchison, C. Genet, and T. W. Ebbesen, Phys. Rev. Lett. **106**, 196405 (2011).
[14] P. Nataf and C. Ciuti, Phys. Rev. Lett. **104**, 023601 (2010).
[15] A. Anappara, S. Liberato, A. Tredicucci, C. Ciuti, G. Biasiol, L. Sorba, and F. Beltram, Phys. Rev. B **79**, 201303 (2009).
[16] G. Guenter, A. A. Anappara, J. Hees, A. Sell, G. Biasiol, L. Sorba, S. DeLiberato, C. Ciuti, A. Tredicucci, A. Leitenstorfer *et al.*, Nature **458**, 178 (2009).
[17] T. Niemczyk, F. Deppe, H. Huebl, E. P. Menzel, F. Hocke, M. J. Schwarz, J. J. Garcia-Ripoll, D. Zueco, T. Hmmer, E. Solano *et al.*, Nat. Phys. **6**, 772–776 (2010).
[18] G. Scalari, C. Maissen, D. Turcinkova, D. Hagenmuller, S. Liberato, C. Ciuti, C. Reichl, D. Schuh, W. Wegscheider, M. Beck *et al.*, Science **335**, 1323 (2012).
[19] D. Hagenmüller, S. DeLiberato, and C. Ciuti, Phys. Rev. B **81**, 235303 (2010).
[20] D. Grischkowsky, S. Keiding, M. van Exter, and C. Fattinger, JOSA B **7**, 2006 (1990).
[21] D. Schurig, J. J. Mock, B. J. Justice, S. A. Cummer, J. B. Pendry, A. F. Starr, and D. R. Smith, Science **314**, 977 (2006).
[22] H.-T. Chen, W. J. Padilla, J. Zide, A. Gossard, A. Taylor, and R. Averitt, Nature **444**, 597 (2006).
[23] W. J. Padilla, A. J. Taylor, C. Highstrete, M. Lee, and R. D. Averitt, Phys. Rev. Lett. **96**, 107401 (2006).
[24] D. Shelton, I. Brener, J. Ginn, M. Sinclair, D. Peters, K. Coffey, and G. Boreman, ACS Nano Lett. **11**, 2104 (2011).
[25] D. Dietze, A. Benz, G. Strasser, K. Unterrainer, and J. Darmo, Opt. Express **19**, 13700 (2011).
[26] H.-T. Chen, J. F. O'Hara, A. J. Taylor, R. D. Averitt, C. Highstrete, M. Lee, and W. Padilla, Opt. Express **15**, 1084 (2007).
[27] D. R. Chowdhury, R. Singh, A. J. Taylor, H. Chen, W. Zhang, and A. Azad, Int. J. Opt. (USA) **2012**, 148985 (2012).
[28] R. Singh, C. Rockstuhl, and W. Zhang, Appl. Phys. Lett. **97**, 241108 (2010).