THz Ultrastrong Coupling in an Engineered Fabry–Perot Cavity

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ABSTRACT: We report a monolithic THz planar Fabry–Perot cavity fabricated with wafer bonding and provided with metallic mirrors with subwavelength apertures. We demonstrate its coupling to the cyclotron resonance of a high-mobility, two-dimensional electron gas. Q factors up to 89 are observed for the first mode at approximately 300 GHz, with cooperativity $C = 56.4$ and a normalized coupling ratio $\Omega/\omega$ in the first mode of up to 17.5% and the third mode of up to 6.4%.

KEYWORDS: THz, Fabry–Perot cavity, compact, ultrastrong coupling, Q factor, multiple modes

In the last few decades there has been a surge of interest in terahertz (THz) science and technology. The THz spectral region has been attracting considerable attention for a wide range of applications from quantum cascade lasers and imaging to the area of cavity quantum electrodynamics (QED). Cavity QED experiments play a crucial role in the study of light–matter interaction. The parameters describing the light–matter interaction are the normalized coupling strength ratio $\Omega/\omega$, where $\Omega$ and $\omega$ are the vacuum Rabi frequency and the cavity frequency respectively, the non-radiative matter decay rate $\gamma$, and the photon decay rate $\kappa$; these time scales can define different coupling regimes for the coupled systems, from weak to deep strong coupling. When the coupling strength ratio is $0.1 < \Omega/\omega < 1$, we enter the so-called ultrastrong coupling regime. In the THz frequency range, strong and ultrastrong coupling has been observed in different experimental systems; particularly interesting is the one where the Landau level (LL) transitions in a two-dimensional electron gas (2DEG) are coupled to optical modes of cavities such as THz metamaterial split-ring resonators forming Landau polaritons. Ultrasharp coupling in the THz regime with Landau polaritons was first demonstrated experimentally by Scalari with a coupling ratio $\Omega/\omega = 0.58$. Deep strong coupling ($\Omega/\omega > 1$) also has been observed with a cavity based on THz metamaterial resonators, which is the starting point for the study of a new regime of light–matter interactions. A great deal of previous research on light–matter interactions in the ultrastrong coupling regime is focused on metallic or superconducting THz metamaterial-based cavities with semiconductor quantum wells. Recently, photonic rather than electronic THz cavities have been proposed and already enabled the investigation of a fundamental phenomena in the area of the condensed matter physics and quantum optics, such as the vacuum Bloch–Siegert shift. Photonic crystal cavities demonstrated high quality (Q) factors, allowing the study of ultrastrong coupling in several cavity modes simultaneously and demonstrating cooperativities (C) as high as C = 3513 in the THz range.

In this work, we describe the design and implementation of a monolithic, engineered Fabry–Perot (FP) cavity for observing ultrastrong coupling in the THz regime. We show the simulations, fabrication, and measurements of FP cavities with a higher Q factor than the metamaterial-based cavities (typically $Q < 10$). The FP cavity consists of a slab of wafer-bonded semiconductor material terminated by high reflectivity gold mirrors based on subwavelength hole apertures. The finite element simulation of the cavity was obtained using the CST Microwave studio, and the fabrication techniques and results

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are shown. We achieve Q factors up to \( Q \approx 89 \), ultrastrong coupling ratios with a single QW up to \( \frac{\Delta k}{k_0} = 17.5\% \) in the first mode and a cooperativity of \( C = 56.4 \). Using a single QW, we focused on the studying of the alternative design and the compact geometry of the FP cavity. This study is setting out to explore advanced phenomena and be adopted in the different systems, such as the ones studied with chiral optical cavities.26

Although some research has been carried out on ultrastrong coupling in the THz range, no study exists yet that demonstrates a compact, monolithic FP cavity, as it was originally suggested by Hagenmüller et al.12 An interesting aspect of FP cavities is that the different modes present significantly higher Q factors with respect to the ones usually achieved with planar metamaterials. In such a cavity, the coupling ratio is \( \frac{\Delta k}{k_0} \sim \sqrt{\alpha n_{QW} l_0} \), where \( \alpha \) is the fine structure constant, \( n_{QW} \) is the number of the quantum wells, and \( l_0 \) is the electron areal density and \( l_0 \) is the magnetic length.

The first step in the development of the FP cavity was the design of the cavity geometry and the simulation of its transmission characteristics. The three-dimensional FP cavity was numerically investigated using a series of full-wave, three-dimensional, finite element simulations using CST Microwave Studio (Figure 1). Once the wavelength \( \lambda \) of the lowest frequency mode is chosen, the thickness of the cavity is determined by

\[
L_{\text{cav}} = \frac{\lambda}{2n_{\text{GaAs}}}
\]

where \( L_{\text{cav}} \) is the thickness of the cavity and \( n_{\text{GaAs}} = 3.6 \) is the refractive index of gallium arsenide (GaAs). A cavity thickness of \( L_{\text{cav}} = 140 \mu m \) was chosen, corresponding to a frequency of \( \approx 300 \) GHz (\( \lambda \approx 1 \) mm in vacuum). The next step was to achieve higher reflectivity in the mirrors. We chose to use circular subwavelength apertures in a metallic layer. Thus, gold (Au) mirrors patterned with a two-dimensional (2D) array of circular holes were simulated on both sides of the FP cavity. For the simulation of the mirrors, we used lossy gold to include ohmic losses on the mirrors of the cavity.

High reflectivity was achieved using a parametric sweep on the hole radius (\( r \)) and the periodicity (\( L \)). For a given \( r \), as we increased the periodicity, due to the reduction of the radiative losses, the Q factor of the modes improved. Simultaneously, a larger \( L \) resulted in a lower transmission at low frequencies. We found a good trade off for \( L = 70 \mu m \) to both have a high Q factor and still a sizable transmission at low frequencies to ensure high signal-to-noise in the study of the strong coupling of the first mode (at \( f=270 \) GHz). This value resulted in being equal to half of the cavity thickness, \( L_{\text{cav}}/2 = 70 \mu m \) (Figure 3a). The simulation also showed the electric field enhancement in the middle of the FP cavity for the first mode (Figure 1a,b), third mode, and the following odd modes and not in the case of the second mode and the following even modes as it was expected (Figure 1c,d).12,27,28 The extracted frequencies and their corresponding Q factors for the first three modes of the simulated FP cavity with \( L = 70 \mu m \) and \( r = 25 \mu m \) are reported in Table 1. All the Q factors are calculated using the Breit–Wigner–Fano fitting of the cavity line shape.

As shown in Figure 2d, for the fabrication of the cavity with a QW in the center, we used a GaAs/Al_{0.3}Ga_{0.7}As heterostructure grown by molecular beam epitaxy, double delta-doped square well (EV2451), and an undoped semi insulating (SI) GaAs substrate. After etching the GaAs substrate surface with HCl to remove GaAs oxides,29 we used thermocompression wafer bonding to join the 2DEG to

Figure 1. Simulation of the THz electric field enhancement in the FP cavity, using CST Microwave Studio, with \( L_{\text{cav}} = 140 \mu m \), \( L = 70 \mu m \), and \( r = 25 \mu m \). The perspective view (a) and the side view (b) of the first mode of the cavity at frequency \( f = 0.278 \) THz and the perspective view (c) and the side view (d) of the second mode of the cavity at frequency \( f = 0.554 \) THz are shown.
the GaAs substrate. As a result, the QW is in the middle of the cavity, as it is shown in Figure 2b. After wafer bonding, one side was polished carefully to achieve a high quality surface and adjust the thickness of the substrate to the desired value of 70 μm. After this step, metallic mirrors consisting of circular apertures were defined, using standard UV-photolithography and titanium/Au (5/250 nm) metallization, followed by a lift-off step. Then, on the other side of the cavity, polishing followed to obtain a total thickness for the cavity $L_{\text{cav}} = (140 \pm 10)$ μm, and mirrors were deposited following the previously described method. A control cavity without QW was also fabricated with the same technique.

All samples presented in this work were measured using a THz time-domain spectrometer (THz-TDS). For the generation of the THz electric field ($E_{\text{THz}}$), a photoconductive antenna (PCA) is illuminated with an ultrafast femtosecond laser at an average power of 500 mW on the PCA. For the detection of $E_{\text{THz}}$ through the samples, we used electro-optic sampling with a 3 mm long ZnTe (110) crystal. The bandwidth of the system is 0.1 to 2.5 THz. In order to produce a circular THz polarized beam, a silicon-based, broadband THz retarder (Hamamatsu) was used. All the measurements were conducted at temperature $T = 3$ K. First, we measured the bare cavity samples without any QW. We analyze the three first modes of the cavity in a frequency range of 0.2 to 1.2 THz. For the three modes with $L = 70$ μm and $r = 25$ μm, the Q factors measured as $Q_{\text{first mode}} = 30.0$, $Q_{\text{second mode}} = 21.5$, and $Q_{\text{third mode}} = 17.2$. The measured Q factor values are lower than the simulated due to the resolution limit of the THz-TDS and to fabrication uncertainties. The FP cavity’s performance is in fact very sensitive to the flatness and parallelism of the polished substrate surfaces.

Figure 3a shows a comparison between the simulated and the experimental results including the Breit–Wigner–Fano fitting of the Q factors for the first, second, and third modes. The simulations and the experimental results show quite a good agreement, especially for the central mode frequency. However, the transmittance is lower in the experimental case due to a nonperfect parallelism of the polished surfaces. Figure 3b–d shows a magnification of the comparison for the first three modes of the cavity. The Q factor of these modes are also presented in the Table 1.

The FP cavity can be a potential candidate for reaching high coupling rates with an high cooperativity in the THz range and for the investigation of the magnetic cyclotron transition of a 2DEG coupled to a THz electric field. In order to couple the modes of the FP cavity to the LL transitions in the QW positioned at the center of the cavity the magnetic field was applied perpendicularly to the plane of the QW and perpendicularly to $E_{\text{THz}}$ (Figure 2b). To apply the magnetic field, the THz–TDS system was coupled to a split-coil...
superconducting magnet. Magnetic fields between $B = -3 \text{T}$ and $B = 3 \text{T}$ that were applied as transmission spectra were recorded. In this case, the cavity was fabricated with a thickness $L_{\text{cav}} = (153 \pm 10) \mu\text{m}$, $L = 70 \mu\text{m}$, and $r = 30 \mu\text{m}$, and the frequencies of the first three modes are $f = 270.9 \text{GHz}$, $f = 543 \text{GHz}$, and $f = 811 \text{GHz}$ at $B = 0 \text{T}$. These frequencies were extracted from the asymptotic limit of the lower polariton branch at high magnetic field. The thickness of the cavity was calculated using eq 1. The frequencies of the first three modes of the FP cavity are in good agreement with the frequencies computed in the simulations.

Figure 4a displays the sample transmission as a function of the applied magnetic field, normalized to the electric field of the reference. For our measurements we used air as the reference, illuminating the same aperture as when the sample is mounted. The 2DEG is constituted by a single square QW ($n_{\text{QW}} = 1$) and the electron surface density is $\rho_{\text{2DEG}} = 2.93 \times 10^{11}/\text{cm}^2$. Using the cyclotron transition frequency $\omega_c = \frac{eB}{m^*}$, where $e$ is the electron charge and $m^*$ is the effective electron mass, the effective mass of the 2DEG was extracted from the measurement of the QW without mirrors, resulting in $m^* = 0.072m_e$ with $m_e$ being the electron mass. In Figure 4a, the polaritonic states are shown as the magnetic field is swept between $B = -3 \text{T}$ to $B = 3 \text{T}$. Anticrossing can be observed when the cyclotron energy matches the modes of the cavity with the correct field distribution. To determine the Q factor, two long scans (scan length = 400 ps) at $B = 0 \text{T}$ and $B = -3 \text{T}$ are taken. The transmittance of these two scans are shown in Figure 4b. The Q factor for the first and third modes is $Q_{\text{first\_mode}} = 89$ and $Q_{\text{third\_mode}} = 22$ at $B = 0 \text{T}$ and $Q_{\text{first\_mode}} = 70$ and $Q_{\text{third\_mode}} = 19$ at $B = -3 \text{T}$: those values are considerably higher than the ones measured in the cold cavity (cavity without QWs, measured at room temperature) case. The higher values in the FP cavity with QW are due to the improvements in the fabrication process of the new samples. With further improvement in the fabrication, even higher Q factors could be achieved in principle, as shown in the comparison with the simulation of Figure 3 that includes metallic losses. The line widths of the first and third modes at $B = -3 \text{T}$ were used to calculate the photon decay rate ($\kappa$). It is worth mentioning that the Q factor of the upper polaritonic mode in the absence of the magnetic field (at $B = 0 \text{T}$) is as good and even higher than the $Q$ factor of the low polariton mode at $B = -3 \text{T}$. This is an advantage of this type of cavity over the metamaterial-based ones, in which the upper polaritonic modes at low values of the magnetic field can be significantly broadened due to coupling to 2D plasmonic excitations, especially for highly subwavelength feature sizes. To estimate the coupling strength for the first and third modes, the maxima of the transmission spectra at each magnetic field are extracted. All the extracted maxima are then fitted to the polaritonic branches using the Hopfield model. The fittings for the first and third modes are shown in Figure 4c,d. For the first mode, the coupling strength is $\frac{\Delta \omega}{\omega_c} = 17.5\%$.
and for the third mode $\frac{\Delta \omega}{\omega_c} = 6.4\%$. The second mode of the FP cavity does not couple to LL transitions due to the node (minimum of the field) located at the center of the cavity where the QW is, as it was expected from the finite element electromagnetic simulations (Figure 1). In addition, the cooperativities for the first and third modes were calculated using the relation $C = \frac{4g^2}{\kappa \gamma y}$, where $g$ is half of the vacuum Rabi splitting at the anticrossing. For the first and third modes, the cooperativity was $C_{\text{first mode}} = 56.4$ and $C_{\text{third mode}} = 6.2$, respectively. It is worth mentioning that the weak intensity for the first mode is due to the fact that the lower frequencies (larger wavelengths) have lower transmission through the mirrors compared to the other modes at the higher frequencies. Furthermore, this mode is located at the frequencies close to the lower limit of the bandwidth (100 GHz) of our spectrometer.

The nonradiative matter decay rate ($\gamma$) is calculated using the direct measurement of the cyclotron decoherence time $\tau_{\text{cyc}}$. As it is explained in this reference, $\gamma$ is calculated by extracting the decay time from the time domain measurement at a magnetic field value of $B = 2\ T$. The coherent oscillation is fitted by a sinusoidal function with exponentially decaying amplitude to provide direct measure of the decay time and the oscillation frequency. The other important parameter for computing cooperativity is $\kappa$, the photon decay rate, that is calculated from the extracted line width of lower polariton at its asymptotic limit (at $B = -3\ T$). According to the Hopfield model, the lower polariton mode converges to the cavity mode at its asymptotic limit.

One of the aims of this work is the investigation of an alternative cavity design for observing ultrastrong coupling with long-lived polariton states. The high $Q$ factor, $Q = 89$, for the first mode, is a value higher than the second and the third modes. These values are considerably higher than $Q$ factors that are observed in metamaterials systems, but lower than the values of the photonic crystal cavities. Similarly, also, the coupling strength was higher for the first mode ($\frac{\Delta \omega}{\omega_c} = 17.5\%$) than the third mode ($\frac{\Delta \omega}{\omega_c} = 6.4\%$). The coupling strength in the FP system is higher in comparison with photonic cavities with 1 QW. In addition, we observed ultrastrong coupling for the first mode of the cavity when we added a QW in the center. The normalized coupling ratio for the first mode was $\frac{\Delta \omega}{\omega_c} = 17.5\%$ and $\frac{\Delta \omega}{\omega_c} = 6.4\%$ for the third mode. We also computed a cooperativity up to $C = 56.4$.
for the first mode of this FP cavity. The development of a THz FP cavity has important implications for the further investigation of light–matter interactions in the THz range. The FP naturally bridges the results obtained with metamaterial and photonic crystal cavities for the study of ultrastrong coupling because of its geometry. This cavity can be used for the investigation of new phenomena and mechanisms in the ultrastrong and deep–strong coupling regime. Further research should be undertaken to investigate the coupling ratio, while increasing the effective number of carriers using this type of FP cavity.

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Notes

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