

Spectrum of plasma excitations in a plasmonic crystal fabricated in an AlGaAs/GaAs heterostructure

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We report on the experimental study of the spectrum of plasma excitations in a plasmonic crystal fabricated from the two-dimensional electron system in an AlGaAs/GaAs semiconductor heterostructure. We perform a comprehensive research on the mode frequency and relaxation as a function of the gate width across different plasmonic crystal periods. Importantly, we develop an analytical approach that accurately describes the behavior of plasma excitations in plasmonic crystals, providing insights into the fundamental physics of plasmonic systems.

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I. INTRODUCTION

A plasmonic crystal represents a two-dimensional electron system (2DES) with a periodic gate deposited on the crystal surface over the 2DES. Pioneering experiments on plasma waves in semiconductor two-dimensional systems have been conducted using plasmonic crystals more than 40 years ago [1–3]. Since then, this system has become a platform for discovering numerous physical phenomena. These include observation of minigaps in the plasmon spectrum [4,5], 2D plasmons in layered materials [6,7], plasmonic crystal Tamm states [8,9], and various plasmonic crystal phases [10–12]. Moreover, most of the currently developed plasmonic devices rely on the concept of plasmonic crystals. Examples include terahertz (THz) radiation detectors [13–15], THz oscillators and amplifiers [16–18], and THz phase shifters [19,20].

The currently prevailing theoretical model suggests that an incident electromagnetic wave excites two types of plasma waves in the plasmonic crystal. When the distance from the gate to the 2DES is relatively small, this model is analogous to the tight-binding limit of the Kronig-Penney model, which describes the particle behavior in a periodic potential [21–25]. The plasma wave in the ungated region, which is excited in the gap between the gates, is described by the spectrum [26]

$$\omega_u(q) = \sqrt{\frac{n_s e^2}{2m^* \varepsilon(q) \varepsilon_0}} q_u, \quad (1)$$

where n_s is the 2D electron density, m^* is the effective electron mass, q_u is the unscreened plasmon wave vector, and $\varepsilon(q)$ is the effective dielectric permittivity of the medium surrounding the 2DES. In the region directly underneath the gate, the plasma wave is the screened plasmon with the linear spectrum [27]

$$\omega_g(q) = \sqrt{\frac{n_s e^2 h}{m^* \varepsilon \varepsilon_0}} q_g \quad (q_g h \ll 1). \quad (2)$$

Here, h is the distance between the gate and the 2DES, q_g is the screened plasmon wave vector, and ε is the dielectric permittivity of the semiconductor crystal, specifically $\varepsilon_{\text{GaAs}} = 12.8$. Then, the existing theoretical models make several assumptions. The plasmon dispersion relation for the system is obtained by (1) plane-wave expansion of the plasma wave electric potential in each region, (2) matching of the potential and electric current at the gated-ungated boundaries, and (3) imposing Bloch periodicity conditions for the fields in the neighboring gratings. These assumptions lead to Kronig-Penney-type dispersion of the optically active modes [21–25]:

$$q_u \sin\left(\frac{q_g l_g}{2}\right) \cos\left(\frac{q_u l_u}{2}\right) + q_g \cos\left(\frac{q_g l_g}{2}\right) \sin\left(\frac{q_u l_u}{2}\right) = 0, \quad (3)$$

where l_g is the gate strip's width and l_u is the width of the ungated 2DES area between the strips.

In the present work, we investigate the THz spectrum and relaxation of plasma excitations in a plasmonic crystal fabricated from an AlGaAs/GaAs heterostructure. Our experimental data reveal that the plasmonic crystal supports a series of resonant plasmon modes. We directly trace how the fundamental plasmon mode evolves from an unscreened plasmon [Eq. (1)] for narrow gates to a screened plasmon [Eq. (2)] for wider gates. Importantly, we have developed an analytical model that accurately describes the dispersion and relaxation

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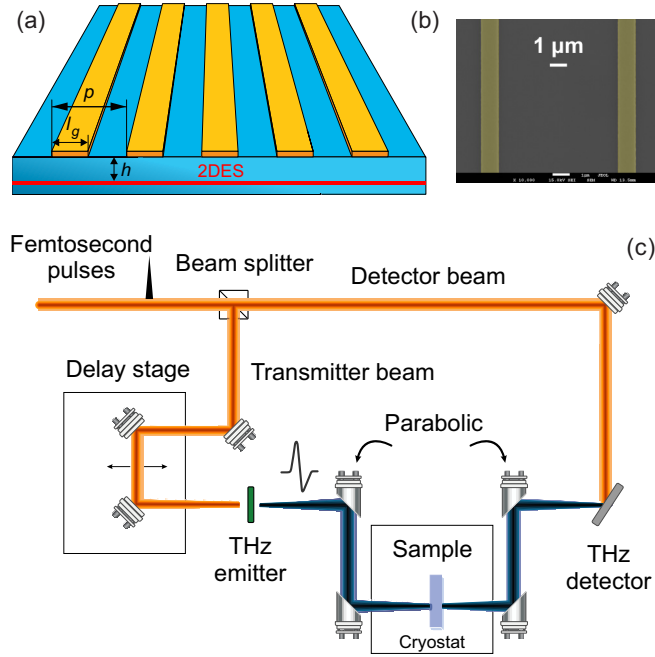


FIG. 1. (a) Sketch of the plasmonic crystal. (b) Scanning electron-beam microscope image of the grid-shaped gate. (c) Schematic diagram of the experimental TDS setup, highlighting the key elements of the apparatus.

of plasma waves propagating through the plasmonic crystal. The theory convincingly establishes that plasma excitations excited in the plasmonic crystal possess a delocalized superlattice nature. Our results hold promise for the engineering of THz plasmonic devices.

II. METHOD AND SAMPLES

In our study, we have explored the samples that were fabricated from the $\text{Al}_{0.24}\text{Ga}_{0.76}\text{As}/\text{GaAs}/\text{Al}_{0.24}\text{Ga}_{0.76}\text{As}$ heterostructure grown by the molecular beam epitaxy with a GaAs quantum well of 20 nm thickness situated at 210 nm beneath the crystal surface. Throughout the paper, we used the distance from the center of the quantum well to the crystal surface, $h = 220$ nm. The density of two-dimensional electrons in the quantum well was $n_s = 1.47 \times 10^{12} \text{ cm}^{-2}$ with mobility $\mu = 101\,000 \text{ cm}^2/(\text{V s})$, derived from the high-frequency data. A Cr (24 nm)/Au (200 nm) grid-shaped gate is evaporated on the top surface of the sample [Figs. 1(a) and 1(b)]. The samples made using electron-beam lithography have Cr (5 nm)/Au (95 nm). The grid strips have a width from $l_g = 0.8$ up to $10 \mu\text{m}$. We fabricated two sets of samples with two fixed grid periods of $p = 8$ and $12 \mu\text{m}$. A detailed table of all measured samples is listed in the Supplemental Material [28]. The experiments were conducted using the time-domain spectroscopy (TDS) setup, which covers a frequency range from 0.15 to 2 THz [see Fig. 1(c)]. The spectrometer is equipped with a continuous-flow liquid helium cryostat with transparent windows. All measurements are performed at the base sample temperature of $T = 5 \text{ K}$. To minimize noise from water absorption lines in the air, the THz beam path is enclosed in an evacuated chamber. Spectroscopy measurements are carried

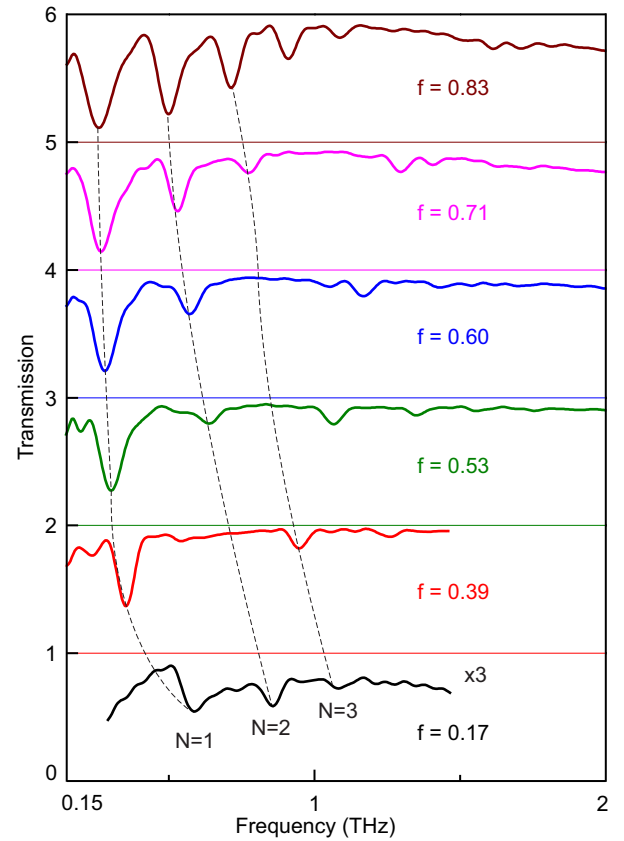


FIG. 2. Transmission spectra measured for the plasmonic crystal with different grid filling factors $f = 0.17, 0.39, 0.53, 0.60, 0.71$, and 0.83 . These filling factors correspond to gate widths of $l_g = 2.0, 4.7, 6.3, 7.2, 8.5$, and $9.9 \mu\text{m}$. The dotted lines are a guide to the eye, connecting the frequency positions of the fundamental, $N = 1$, and harmonic, $N = 2, 3$, plasma resonances. The polarization of the electromagnetic wave is perpendicular to the grids.

out using a 6-mm aperture positioned close to the sample to ensure that the electromagnetic radiation passes only through the grating-gate active region of the plasmonic crystal. The polarization of the electromagnetic radiation is directed perpendicular to the grids.

III. EXPERIMENTAL RESULTS

Figure 2 shows the transmission through a series of samples with varying gate widths, keeping the grid period constant at $p = 12 \mu\text{m}$. We refer to the Supplemental Material for the analogous set of curves recorded for the plasmonic crystal with a period of $p = 8 \mu\text{m}$ [28]. For clarity, the curves are shifted along the vertical axis. Each sample exhibits several plasma resonances in the transmission spectrum. The dotted line marks the frequency position of the fundamental plasma resonance, $N = 1$, as well as harmonic, $N = 2, 3$, modes. As the gate width decreases, the frequency of the fundamental plasma mode increases. Figure 3 summarizes the frequency positions of the fundamental plasma mode versus the grid filling factor $f = l_g/p$ measured for the plasmonic crystal with $p = 12 \mu\text{m}$ [panel (a)] and $8 \mu\text{m}$ [panel (b)]. The dashed black lines in Fig. 3 depict the frequency of the plasmon

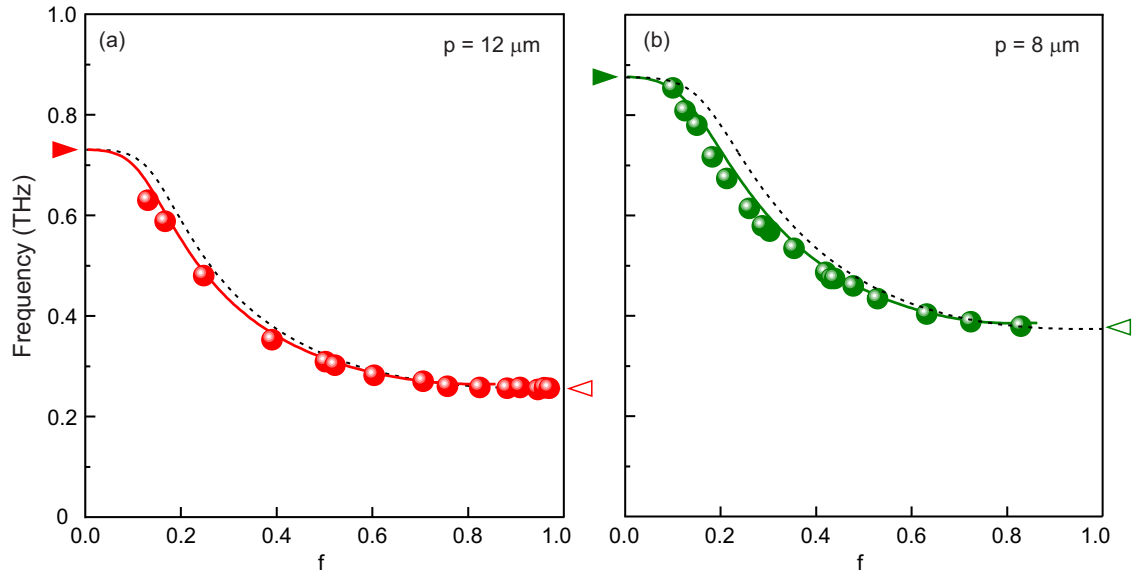


FIG. 3. The frequency of the fundamental plasma mode in the plasmonic crystal as a function of the filling factor $f = l_g/p$. The period of the plasmonic crystal is fixed at $p = 12 \mu\text{m}$ (a) and $p = 8 \mu\text{m}$ (b). Solid lines show the result of our theoretical model (5). Dashed line represents the prediction from the Kronig-Penney plasmonic model, Eq. (3) [28]. The filled arrows point to the frequency of the unscreened plasmon from Eq. (1) with wave vector $q = 2\pi/p$. The empty arrows point to the frequency of the screened plasmon from Eq. (2) with the same wave vector $q = 2\pi/p$.

modes predicted from the Kronig-Penney model, Eq. (3) [28]. In computations, we take $m^* = (0.076 \pm 0.001)m_0$ due to the nonparabolicity of the electron conduction band occurring at such high 2D electron densities of $n_s = 1.47 \times 10^{12} \text{ cm}^{-2}$ [29–31]. The results from model (3) show a reasonable agreement with the experimental data. However, since model (3) is phenomenological in nature, the accuracy of the found resonant frequencies and ways for improvement are unclear. In addition, the model does not account for the linewidth of the plasmon resonances, including the radiative contribution, nor does it provide information on the final line shape.

In order to find a better way to describe the behavior of plasmon modes in the plasmonic crystal, we develop a method based on the solution of Maxwell's equations for space harmonics of the electric and magnetic fields:

$$\begin{aligned} E_{x,z}(x, z, t) &= \sum_{k=-\infty}^{\infty} E_{x,z}^k(z) e^{iq_k x - i\omega t}, \\ H_y(x, z, t) &= \sum_{k=-\infty}^{\infty} H_y^k(z) e^{iq_k x - i\omega t}, \end{aligned} \quad (4)$$

where $q_k = 2\pi k/p$ is the k th space harmonic of the grating, z axis is oriented perpendicular to the 2DES, y axis is oriented along the grating, and x axis is perpendicular to the grating. The detailed derivation of the dispersion equation below can be found in the Supplemental Material [28]. When describing the plasmons, we consider the gates to be ideal metals and assume that currents are negligible at the edges. Additionally, we note that the wavelength of the THz radiation is significantly larger than the period of the plasmonic crystal, which substantially simplifies our analysis. Finally, given that the plasmon decay rate, caused by collisions with impurities, phonons, and the emission of electromagnetic waves, is mini-

mal, we can derive the following equation for the fundamental plasmon frequency ω_p :

$$g(f) + \sum_{k=1}^{+\infty} \frac{k^2(1 + \varkappa)e^{-4\pi hk/p}}{\omega_p^2/\omega_u^2 - k(1 + \varkappa)e^{-4\pi hk/p}} \left(\frac{\cos \pi k f}{1 - 4k^2 f^2} \right)^2 = 0, \quad (5)$$

where $\omega_u = \sqrt{2\pi n_s e^2 / 2m^* \varepsilon_{\text{GaAs}} \varepsilon_0 p}$ is the frequency of unscreened plasmon (1) at the wave vector $q_u = 2\pi/p$, $\varkappa = (\varepsilon_{\text{GaAs}} - 1)/(\varepsilon_{\text{GaAs}} + 1)$, and the function $g(f)$ is defined via the series

$$g(f) = \sum_{k=1}^{+\infty} k \left(\frac{\cos \pi k f}{1 - 4k^2 f^2} \right)^2 \quad (6)$$

and can be expressed through the special functions. It is important to note that each plasmon mode of the plasmonic crystal consists of a superposition of standing plasma waves with wave vectors $q_k = 2\pi k/p$ propagating through the plasmonic crystal. To achieve good convergence, we left a sufficiently large number of space harmonics (100) in the sum of Eq. (5), after which the desired plasmon frequency can be calculated numerically. The resulting frequencies of the fundamental plasmon mode, calculated from Eq. (5), are shown as solid curves in Fig. 3 for different filling factors. There is a remarkable agreement between theoretical predictions and experimental results, which supports the validity of our theoretical approach.

Several important observations can be made. It is particularly interesting that the plasmon frequency remains essentially constant, starting from the fully screened case of $f = 1.0$ and all the way down to $f = 0.6$. In this state, the frequency of the plasmon resonance stays close to the frequency of the screened plasmon [Eq. (2) with $q = 2\pi/p$ (the empty arrows in Fig. 3)]. Beyond this point, the plasmon

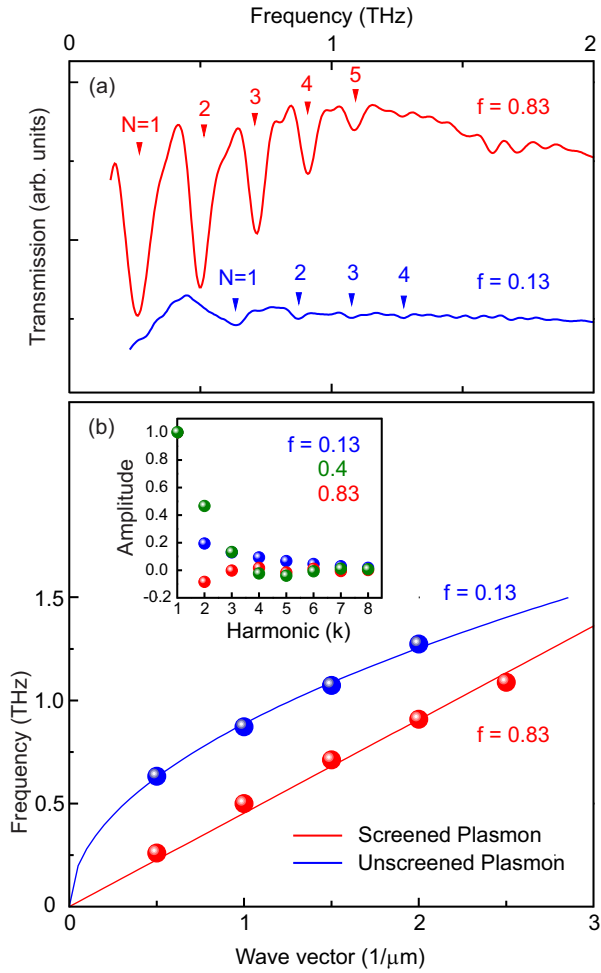


FIG. 4. (a) The transmission spectra recorded for the plasmonic crystal samples with a period of $p = 12 \mu\text{m}$ and different filling factors $f = 0.83$ (red curve) and $f = 0.13$ (blue curve). For each of the curves, the frequency positions of the successive plasma resonances are labeled as $N = 1, 2, 3, \dots$ (b) The dispersions of the plasma excitations obtained under the assumption of $q = N \times 2\pi/p$. The red line shows a linear dispersion law according to Eq. (2), which is characteristic of the screened plasmon. The blue line presents a square-root dispersion law according to Eq. (1), which is characteristic of the unscreened plasmon. The inset shows the normalized intensity of the k th space harmonic of the fundamental plasmon mode calculated using our theory for $f = 0.13, 0.4$, and 0.83 .

frequency increases sharply and eventually saturates near the filling factor of $f = 0.1$, aligning with the frequency of the unscreened plasmon with $q = 2\pi/p$ [Eq. (1)], and the dielectric permittivity $\epsilon(q) = 7.7$ for $p = 12 \mu\text{m}$ and $\epsilon(q) = 8.0$ for $p = 8 \mu\text{m}$ (arrows in Fig. 3). Notably, the calculated values of the effective dielectric permittivity are slightly larger than the average value of $(1 + \epsilon_{\text{GaAs}})/2 = 6.9$. This difference arises due to the $0.22 \mu\text{m}$ GaAs top layer covering the 2DES [28].

To further illustrate the superlattice nature of the plasmon modes excited in the plasmonic crystal, we plot the normalized intensity of the calculated k th space harmonic of the fundamental plasmon mode for $f = 0.13, 0.4$, and 0.83 (inset of Fig. 4). The normalization is done with respect to the intensity of the $k = 1$ fundamental harmonic. For small ($f = 0.13$)

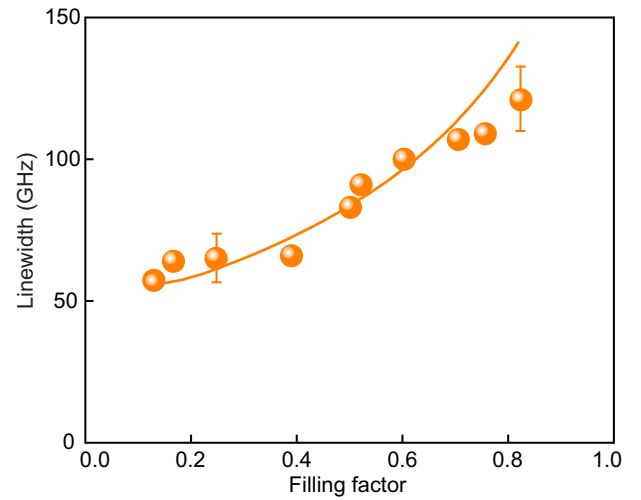


FIG. 5. The linewidth of the fundamental plasma mode vs the filling factor $f = l_g/p$. The sample with the period of the plasmonic crystal $p = 12 \mu\text{m}$. The orange line shows the result of our theoretical analysis [28].

and large (0.83) filling factors, the fundamental superlattice harmonic $k = 1$ dominates the plasmonic response. However, for intermediate f values, the $k = 2$ and 3 harmonics become significant. Indeed, Fig. 4(a) shows the spectrum of the plasma excitations observed for the sample with $l_g = 9.9 \mu\text{m}$ and period $p = 12 \mu\text{m}$ ($f = 0.83$). We now take the frequencies of the successive plasma peaks and assign them sequential wave vectors $q = N \times 2\pi/p$ ($N = 1, 2, 3, \dots$). Here, we assume that only $k = 1$ space harmonic contributes to the plasmonic response. The theoretical prediction, shown as a red line in Fig. 4(b), exhibits a linear form characteristic of the screened plasmon. The theory [Eq. (2)] shown by a red line in Fig. 4(b) adequately agrees with the experimental points. In the opposite limit of narrow gates, when $l_g = 1.6 \mu\text{m}$ ($f = 0.13$), the dispersion obtained using the same procedure has a square-root dependency on $q = N \times 2\pi/p$ [blue dots in Fig. 4(b)]. This behavior is typical of the unscreened plasmon, with its dispersion described by Eq. (1), represented by a blue line in Fig. 4(b). In the most common case of intermediate gate widths, the fundamental plasmon state arises from the hybridization of different superlattice space harmonics. Thus, a simple expression for the plasmon frequency cannot be provided.

Another matter of interest is associated with the relaxation dynamics of plasmons in the plasmonic crystal. Figure 5 shows the dependence of the fundamental plasma mode linewidth $\Delta\nu$ on the filling factor. For small filling factors f , the resonance linewidth is primarily influenced by a single-particle scattering. Indeed, a linewidth of $\Delta\nu = 54 \text{ GHz}$ corresponds to a relaxation time of $\tau = 1/(2\pi\Delta\nu) = 3 \text{ ps}$, which agrees with the electron mobility obtained from the transport measurements. However, as the filling factor increases, we observe a significant broadening of the resonance, accompanied by an increase in amplitude. This suggests that the plasmon linewidth is influenced by an additional mechanism beyond just single-particle scattering. The solid line in Fig. 5 shows the result of the theoretical analysis. 2D

plasmons on a homogeneous surface are nonradiative modes. Nevertheless, the gate grating used for the coupling process also couples electromagnetic radiation out of the plasmon excitation [3,16]. Such radiative damping is typical for plasmon excitations when the plasmon wavelength is comparable to the wavelength of the incident electromagnetic wave [32,33]. However, the observation of radiative effects for the plasmon excitations in the $p \ll \lambda$ limit is quite surprising.

To gain some feeling about the strength of the radiative decay in our system, we used the simplest expression for the linewidth of the plasmon resonance in 2DES [34,35]:

$$\Delta\omega = \frac{1}{\tau} + \Gamma_{\text{rad}} = \frac{1}{\tau} + \frac{n_s e^2}{m^* c \epsilon_0 (1 + \sqrt{\epsilon_{\text{GaAs}}})}. \quad (7)$$

This expression provides an estimate of the maximum radiative decay rate that we can expect for our plasmonic crystal, $\Delta\nu_{\text{rad}} = \Gamma_{\text{rad}}/2\pi = 65$ GHz. As illustrated in Fig. 5, the experimental data demonstrate an increase in radiative damping with an increase in filling factor f . The range of values extends from 60 GHz ($f = 0.13$) to a maximum of 120 GHz for a filling factor of $f = 0.83$. Therefore, the gate grating performs as an efficient radiative antenna.

IV. CONCLUSION

In conclusion, we have investigated the plasma excitations in the terahertz transmission of the plasmonic crystal made from 2DES in the AlGaAs/GaAs semiconductor het-

erostructure with a periodic metal grating deposited on the surface. Experiments have demonstrated that the plasmonic crystal supports a series of plasmon modes, which evolve from an unscreened state in a narrow-gate configuration to a screened state for wide gates. An analytical approach has been developed that has managed to accurately describe the fundamental plasma state in the plasmonic crystal. It has been established that plasmons in a plasmonic crystal have a delocalized superlattice nature, being the combination of both screened and unscreened plasmons. Moreover, they consist of a superposition of multiple harmonics with wave vectors $q_k = 2\pi k/p$ ($k = 1, 2, 3, \dots$). The obtained results establish a scientific foundation for engineering different plasmonic terahertz devices.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available because they contain commercially sensitive information. The data are available from the authors upon reasonable request.

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