Radiation-induced zero-resistance states: Possible dressed electronic structure effects

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Recent results on magnetoresistance in a two-dimensional electron gas under crossed magnetic and microwave fields show a new class of oscillations, suggesting a new kind of zero-resistance states. We consider the problem from the point of view of the electronic structure dressed by photons due to a in-plane linearly polarized ac field. The dressed electronic structure includes opening of radiation induced gaps that have been overlooked so far and could play a role in the recently observed oscillations in the transverse magnetoresistance.

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I. INTRODUCTION

A new class of low temperature nonequilibrium zero-resistance states (ZRS) have recently been identified by Mani and co-workers in irradiated quantum Hall systems based on GaAs/AlGaAs heterostructures[1]. The effect was confirmed in ultrahigh mobility GaAs/AlGaAs quantum wells by Zudov *et al.*, [2] who cited the phenomena as evidence for a new dissipationless effect in 2D electronic transport. Such ZRS are induced in the two-dimensional electron gas (2DEG) by electromagnetic-wave excitation with the ac electric field parallel to 2DEG, in a weak, static, perpendicular magnetic field. Oscillations of the resistance induced by microwave excitation, in low mobility specimens, had been reported previously.[3,4] There is strong experimental evidence that the ZRS coincide with a gap in the electronic spectrum, although the positions of the extrema remain controversial. Mani and co-workers [1,5] find resistance minima (maxima) at $\omega/\omega_c=\epsilon=j+1/4(j+3/4)$, where ω is the ac field frequency, ω_c the cyclotron frequency, and $j=1,2,3,\ldots$ is the difference between the indexes of the participating Landau levels (LLs). Zudov *et al.*[2] report different periodicities for the maxima and minima, with maxima at $\epsilon=j$ and minima on the high field side of $\epsilon=j+1/2$. Very recent results confirm the radiation induced longitudinal magneto-oscillations, but revealing also correlated oscillations in the transverse resistance.[6,7] These results also support that the density of states must to show pronounced modulation,[6] although the Shubnikov-de Haas oscillations are not resolved anymore at the low magnetic fields considered. Interest in this ZRS has produced an extensive list of preliminary results, which aim to establish a theory for understanding this remarkable effect.[8–21] A theoretical framework, based on current instabilities due to local negative resistivity for high filling factors, has been established[22] and seem to capture the essential features in order to explain the new oscillatory phenomena.

The experimental parameters reveal a rich physical scenario: the quantum Hall effects are observed at high magnetic fields $(B>0.4)$ T, while for low magnetic fields $(B<0.4$ T) new oscillations in the magnetoresistance are observed under radiation. Indeed, the resistance vanishes, in a given data collection at $B\approx 0.2$ T, for a radiation frequency of $\nu\approx 100$ GHz. At $B\approx 0.2$ T the LL separation is $\hbar\omega_c\approx 0.35$ meV, while the microwave photons have energy of the same order, namely $h\nu\approx 0.4$ meV. At the measurement temperature $T=1.5$ K, LLs are still resolved, since Shubnikov-de Haas oscillations are still seen below $B=0.2$ T in absence of radiation. On the other hand, these new oscillations are observable down to $B\approx 0.02$ T,[5] corresponding to a magnetic length $l_c\approx 0.18$ μm and a classical cyclotron radius up to $R_c\approx 4.5$ μm,[1] still small compared to a mean free path of $l_0\approx 140$ μm. Besides that, the used microwaves have frequencies down to $\nu=30$ GHz,[2] corresponding to a wavelength up to $\lambda=10$ mm, approximately a factor of 2 or 3 larger than the linear dimensions of the sample, w. Indeed, oscillations have been reported at frequencies down to 3 GHz ($\lambda=10$ cm).[23] A ratio $\lambda/w\approx 10$ validates a dipole approximation for the radiation-sample coupling. More important is that the estimated power level is of $\leqslant 1$ mW, over a cross sectional area of $\leqslant 135$ mm^2 in the vicinity of the sample.[1] This represents a field intensity of $I=7.4$ W/m^2, which can be related to the associated electric field by $I=E_{\rm rms}^2/(c\mu_0)$:[24] $E_{\rm rms}\approx 50$ V/m. Considering the classical cyclotron radius as the relevant length scale[25] and a frequency of 100 GHz, this leads to a ratio $eR_cE_{\rm rms}/(h\nu)\approx 0.35$ at $B=0.2$ T. Such ratio, between the energy gained from the ac field over a distance corresponding to the cyclotron radius and the photon energy, represents already a field intensity that cannot be considered perturbatively.[26]

We address the problem of dressed electronic states in a scenario that can be scaled down to the regime of the ZRS. This is achieved within a tight-binding approach, considering nonperturbatively the two main ingredients of the problem: Landau quantization and dressing of the electronic states by means of a coupling with the ac fields. The dressed electronic structure shows nontrivial features which are clear signatures of the newly observed resistance oscillations. The present model is a finite tight-binding lattice coupled nonperturbatively to an ac field by means of the Floquet method.[27] The time-independent infinite matrix Hamiltonian obtained

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from transforming the time-dependent Schrödinger equation, describes entirely these processes without any further *ad hoc* hypothesis. Therefore, the effects of an intense ac field on the electronic spectra must be described by a very large truncated matrix Hamiltonian.

This numerical endeavour is possible by means of a renormalization procedure, providing the spectral modulation as function of field intensity, revealing that higher photon replicas become relevant only for higher field intensities.[28]

II. NUMERICAL MODEL

The bare energy spectrum is the one of a tight-binding square lattice of *s*-like orbitals, considering only nearest neighbors interaction. The magnetic field is introduced by means of a Peierls substitution in the Landau gauge $\mathbf{A}=(0,l_1aB,0)$.[29] An ac field will be considered parallel to one of the square sides. Hence, the model for the bare electronic system coupled to an ac field is $H=H_0+H_{\text{int}}$, where

$$H_0=\sum_{l_1,l_2}\epsilon_{l_1,l_2}\sigma_{l_1,l_2}\sigma^\dagger_{l_1,l_2}+\frac{V}{2}\sum_{l_1,l_2}[\sigma_{l_1,l_2}\sigma^\dagger_{l_1+1,l_2}\sigma_{l_1+1,l_2}\sigma^\dagger_{l_1,l_2} + e^{i2\pi\alpha l_1}(\sigma_{l_1,l_2}\sigma^\dagger_{l_1,l_2+1}+\sigma_{l_1,l_2+1}\sigma^\dagger_{l_1,l_2})] \qquad (1)$$

and

$$H_{\text{int}}=eaF\cos\omega t\sum_{l_1,l_2}\sigma_{l_1,l_2}l_1\sigma^\dagger_{l_1,l_2}. \qquad (2)$$

Here $\sigma_{l_1,l_2}=|l_1,l_2\rangle$, $\sigma^\dagger_{l_1,l_2}=\langle l_1,l_2|$, where (l_1,l_2) are the (x,y) coordinates of the sites. The phase factor α is defined as $\alpha=\Phi/\Phi_e$, where $\Phi_e=h/e$ is the magnetic flux quantum, and $\mathbf{\Phi}=a^2B$ is the magnetic flux per unit cell of the square lattice. The atomic energy will be taken constant, $\epsilon_{l_1,l_2}=4|V|$, for all sites. The hopping parameter can emulate the electronic effective mass for the GaAs bottom of the conduction band, $m^*=0.067m_0$. Since $V=-\hbar^2/(2m^*a^2)$, $V=-0.142$ eV for a lattice parameter of $a=20$ Å.

Here it should be noticed that lattice models must be used very carefully: one must know how lattice and size effects may hinder valid conclusions for the continuum limit (which should be described by the effective mass approximation), where the actual physical situation takes place.[28] In the presence of magnetic fields, this can only be warranted for low magnetic flux values $\Phi/\Phi_e<0.2$ through the lattice unit cell and for the lowest few Landau levels, which constitutes, indeed, the continuum limit of the Hofstadter spectrum.[30]

The ac field is defined by its frequency and amplitude, ω and F, respectively. The treatment of the time-dependent problem is based on Floquet states $|l_1,l_2,m\rangle$ where m is the photon index. We follow the procedure developed by Shirley, [27] which consists in a transformation of the time-dependent Hamiltonian into a time-independent infinite matrix. The elements of this infinite matrix are

$$\Big[(\mathcal{E}-m\hbar\omega-\epsilon_{l_1,l_2})\delta_{l_1'l_1}\delta_{l_2'l_2}-\frac{V}{2}\Big\{(\delta_{l_1',l_1-1}+\delta_{l_1',l_1+1})\delta_{l_2'l_2} + e^{i2\pi\alpha l_1}(\delta_{l_2',l_2-1}+\delta_{l_2',l_2+1})\delta_{l_1'l_1}\Big\}\Big]\delta_{m'm} = F_1l_1\delta_{l_1'l_1}\delta_{l_2'l_2}(\delta_{m',m-1}+\delta_{m',m+1}), \qquad (3)$$

where $F_1=\frac{1}{2}eaF$. The energy eigenvalues, $\mathcal{E}-m\hbar\omega$, are quasienergies of a system dressed by photons, shifted by multiples of the photon energy, usually called the mth "photon replica" of the system, which are coupled by the ac field. Diagonalization of a truncated Floquet matrix involves dimensions given by $L^2(2M+1)$. L is the lateral size of the square lattice in a number of atomic sites, while M is the maximum photon index. Since the ac field couples a Floquet state defined by m photons to states with $m-1$ or $m+1$ photons, multiple photon processes become relevant with increasing field intensity. As a consequence, M, which determines how many "photon replicas" are taken into account, increases with field intensity.

A truncated Floquet matrix is a tridiagonal block matrix which contains $L\times L$ diagonal blocks given by $\mathsf{E}^M=(\mathcal{E}-m\hbar\omega)\mathsf{I}+\mathsf{H}_0$ representing a photon replica with the matrix elements given by the left-hand side of Eq. (3). The coupling of the system with the intense ac electric field is represented by the off-diagonal blocks $\mathcal{F}$, which are diagonal block matrices, with the elements given by $\mathcal{F}=F_1l_1\delta_{l_1'l_1}\delta_{l_2'l_2}$. The dimension of the problem can be reduced to L^2 by means of a renormalization procedure, based on the definition of the associated Green's function, G, where $\mathsf{FG}=\mathsf{I}$. A detailed discussion of this method is given in previous work.[28] The final result of this renormalization of the Floquet matrix is the dressed Green's function for one of the photon replicas, say $M=0$, and a quasidensity of Floquet states, $\rho(\mathcal{E}+i\eta)$ can then be obtained,

$$\rho(\mathcal{E}+i\eta)=-\frac{1}{\pi}\text{Im}[\text{Tr }G_{MM}]. \qquad (4)$$

The trace of the Green's operator is taken over the atomic sites basis. We initially apply the present approach to investigate the ac field effect on a well-known problem.

III. RESULTS AND DISCUSSION

The present model can handle nonperturbatively the coupling of the system to the ac field, irrespective of the frequency ω. The magnetic field introduces a further energy scale to the problem, namely the separation between Landau levels, ω_c. We address two limits of the energy ratio ω/ω_c that are of interest. The second one, $\omega/\omega_c\approx1$, is related to the microwave induced magneto-oscillations regime.[1,2]

A. $\omega\ll\omega_c$

A finite square lattice in the presence of a perpendicular magnetic field shows a rich "quantum dotlike" spectrum with a low magnetic flux region dominated by finite sample size quantization (cyclotron radius, large compared with the lin-

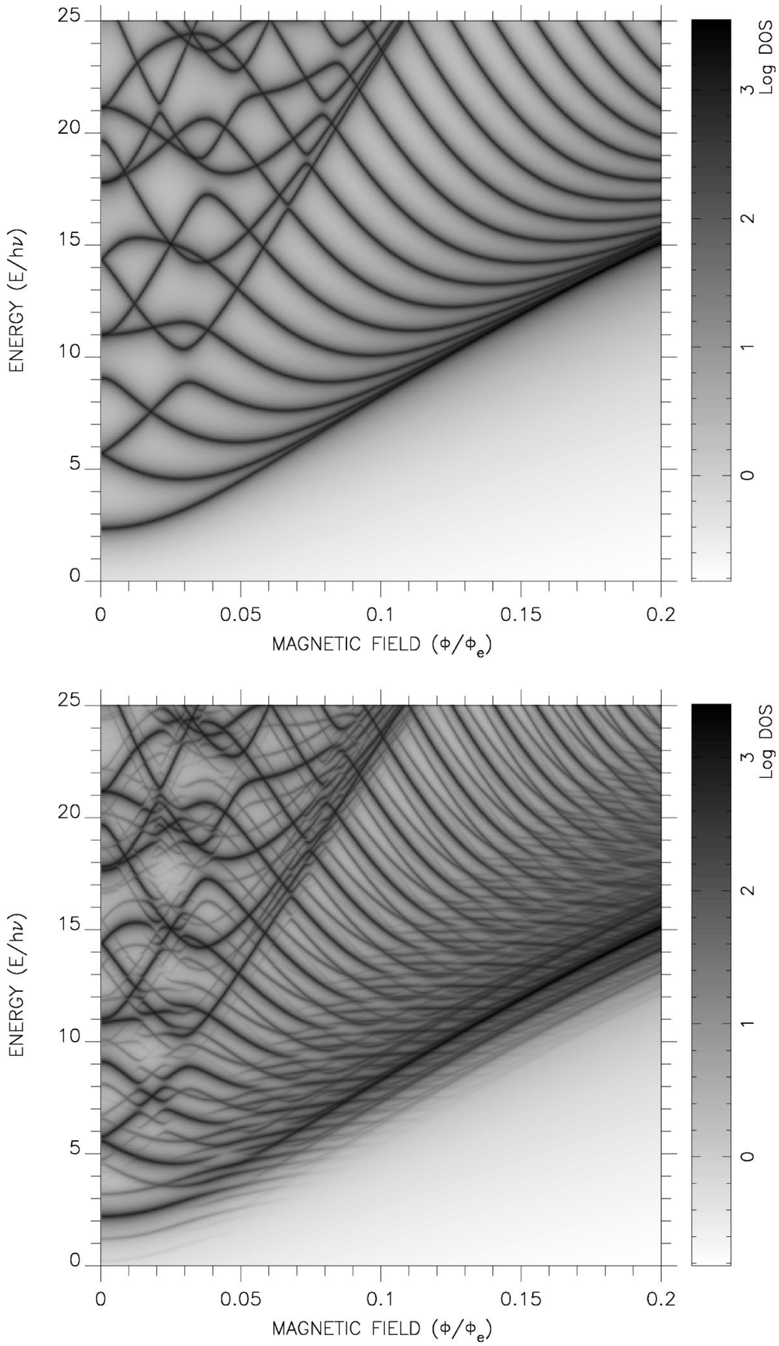

FIG. 1. Spectra of the density of states as a function of magnetic flux. Black (white) stands for highest (lowest) density of states. (Top) Spectrum for a square lattice with $L=10a$ (see text) in absence of an ac field. (Bottom) Spectrum for the same system with an ac field with $h\nu=10$ meV and $eaF=5$ meV.

ear dimensions of the sample), as well as bulk LLs and edge states, well defined for intermediate magnetic fluxes ($\Phi/\Phi_e \leqslant 0.2$), as clearly discussed already 15 years ago.[29] Here we also consider a rather small $10a\times 10a$ square lattice, focusing on the low magnetic flux range as illustrated in Fig. 1 (top). The presence of edge states could hinder the interpretation of the ac fields on the bulk LLs. Nevertheless, ac field effects on bulk LLs and edge states can be distinguished, as shown below.

The spectrum of the system depicted in Fig. 1 (top), modified by an ac field, is shown in Fig. 1 (bottom), for a photon energy $\hbar\omega=10$ meV, which is lower than the quantum-dotlike states separation at very low magnetic fluxes and much lower than the LL separation at values of Φ/Φ_e where the LLs start to be well defined. In Fig. 1 (bottom) the field intensity is $eaF=5$ meV and $a\approx l_c$ at $\Phi/\Phi_e\approx 0.1$.[31]

This represents already a nonperturbative field intensity $eaF/\hbar\omega=0.5$. A dramatic change in the quasidensity of states can be observed, with a coupling between different photon replicas leading to a flattening of the states and opening of gaps in the lower part of the spectrum induced by the ac field. In the energy scale of the figure, $E/h\nu=1$ is the separation between successive photon replicas. At higher magnetic fluxes, photon replicas of the lowest bulk LL can be clearly followed. Increasing the field intensity leads to the formation of higher order photon replicas of the lowest LLs, as well as new periodic structure (as a function of magnetic flux) in the quasienergy spectrum (not shown here).

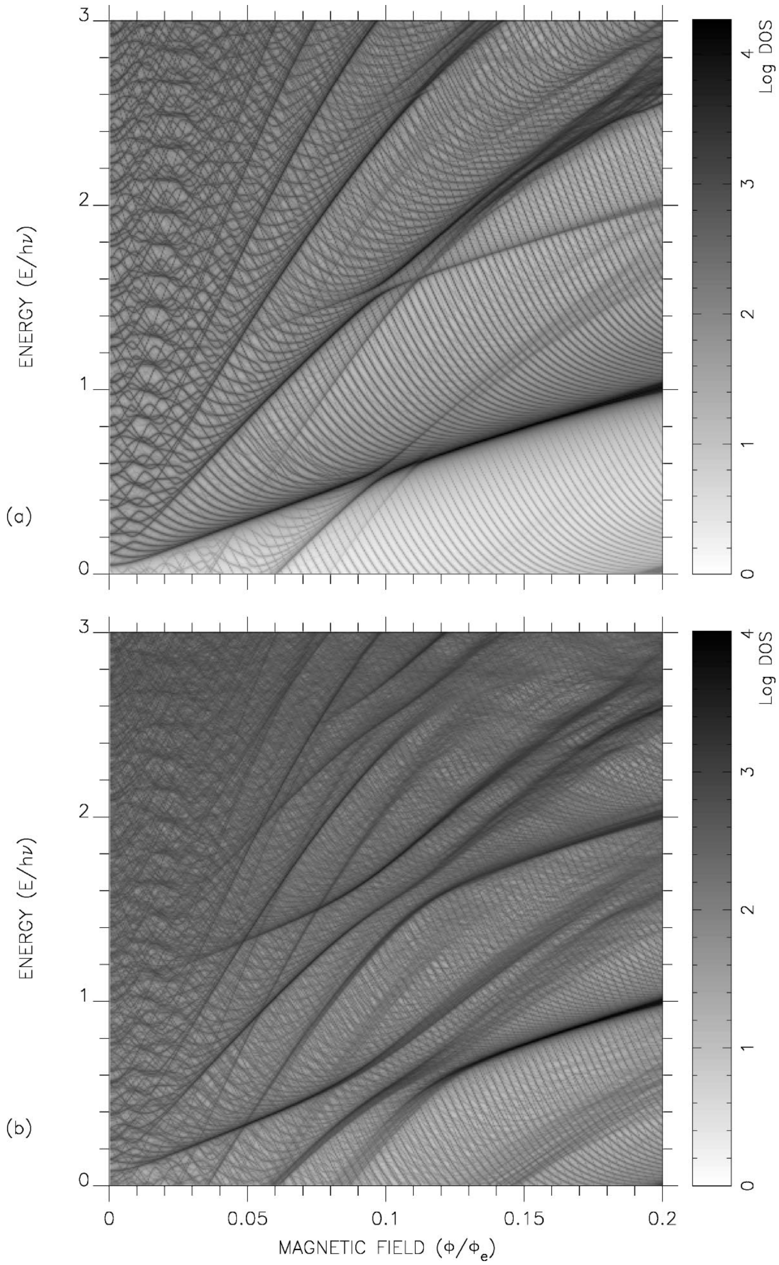

FIG. 2. (Top) Spectrum for a square lattice with $L=20a$ (see text) with an ac field with $h\nu=150$ meV and $eaF=10$ meV. (Bottom) Spectrum for a square lattice with $L=20a$ (see text) with an ac field with $h\nu=150$ meV and $eaF=40$ meV.

B. $\omega \approx \omega_c$

The results discussed above are intrinsically interesting, but we should focus on the experimental conditions,[1,2] i.e., frequencies of the order of the LL separation. Now we consider a larger system: $20a \times 20a$ square lattice. In Fig. 2 (top) we choose $\hbar\omega=150$ meV, namely the LL separation for $\Phi/\Phi_e \approx 0.1$, a flux for which the lowest LLs are already well defined. The main feature for the present discussion is the avoided crossing between the second LL and the first photon replica of the lowest LL (plus one photon). An avoided crossing can also be seen between the lowest LL and a first photon replica of the second Landau level (minus 1 photon in this case). An important point is that the field intensity for the case illustrated in Fig. 2 (top) is $eaF=10$ meV, corresponding to a ratio $eaF/\hbar\omega=0.07$, a value far below the estimative for experimental conditions, as discussed in the Introduction $[eR_cE_{\mathrm{rms}}/(h\nu) \approx 0.35$ at $B=0.2$ T]. In Fig. 2 (bottom) we show a similar spectrum but for a higher field intensity, $eaF=40$ meV, i.e., $eaF/\hbar\omega=0.27$. The quasienergy spectrum has qualitatively changed for a ratio $eaF/\hbar\omega$ still below the estimative for the field intensity in actual experimental conditions.

In Fig. 3 we sketch a few photon replicas of LLs showing crossings in absence of ac field coupling. The energies are $E_{n,m}=e_n \pm mh\nu$, where $e_n=(n+1/2)\hbar\omega_c$, while $\pm m$ are the replicas obtained by adding/subtracting m photons. We consider $n,m \leqslant 2$ for the sake of clarity.

The magnetic flux scale in Fig. 2 (top) corresponds roughly to the cyclotron frequency scale in Fig. 3, therefore a direct comparison is possible and useful. The strongest anticrossings in Fig. 2 (top) correspond to crossings at $\omega/\omega_c=1$ in Fig. 3. Further crossings occur at this point, which indeed evolve into anticrossings between $n=0, m=0$

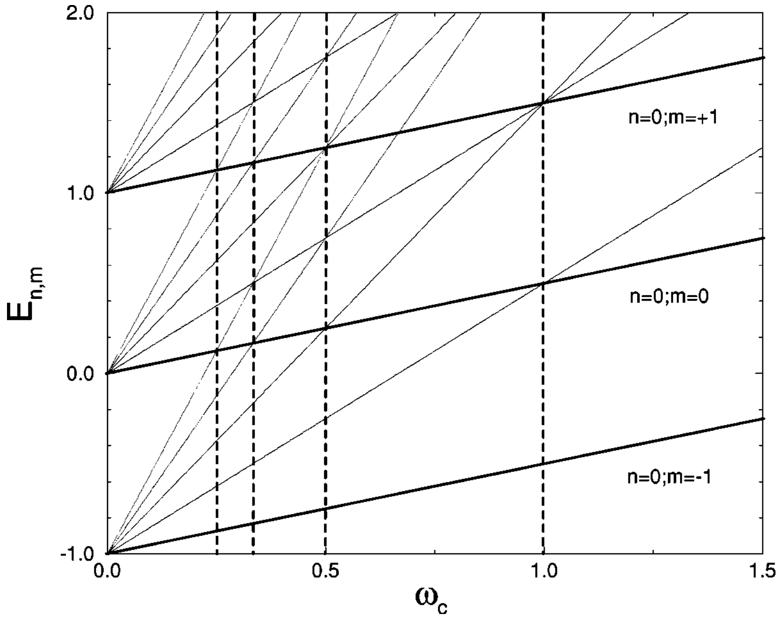

FIG. 3. $E_{n,m}=(n+1/2)\hbar\omega_c \pm mh\nu$ (see text), as a function of the cyclotron frequency, ω_c. Only $m=0$ (thick lines), $m\pm1$ (thin line), $m\pm2$ (dashed lines) photon replicas are considered. Vertical dashed lines represent $\omega/\omega_c=j$.

and $n=3,m=-2$ and $n=0,m=1$ and $n=3,m=-1$, i.e., for $\Delta m=\pm2$. Notice that these anticrossings are shifted in respect to the strongest ones. These are double photon effects that become more pronounced for increasing field intensities as can be seen in Fig. 2 (bottom). It is worth mentioning that higher order effects should lead to anticrossings for $\omega_c>\omega$. However, at this high magnetic flux limit, $\Phi/\Phi_e\approx0.2$, lattice effects become relevant[29] and LLs start to deviate from the linear behavior. It is also noteworthy that the coupling between photon replicas at lower magnetic fields, $\omega/\omega_c=2$, seem to be absent: actually the crossings at this magnetic field in Fig. 3 do not evolve into anticrossings in Fig. 2. One should keep in mind what we learn from the introductory example shown in Fig. 1: larger systems are necessary to show well-developed photon replicas of LLs at low magnetic fields. More important is the fact that selection rules prevent many of the crossings for $\omega/\omega_c\neq1$ to become avoided crossings. Here the disorder should play an important role by breaking down the selecting rules due to LL mixing.

IV. FINAL REMARKS

In summary, crossing of these LLs replicas become anticrossings by turning on the ac field with intensities compatible with those in actual experimental conditions.[1] These anticrossings could originate modulation of $E_{n,m}$ with a periodicity given by $\omega/\omega_c=j$. Such behavior resembles the spectrum of quantum rings and dots pierced by a magnetic flux. [32] Higher order effects could also play a role, since further photon replicas become relevant for increasing field intensity. The actual parameters in the present calculation are for high magnetic fields. Nevertheless, the results could be relevant to the experimental situation whenever $eaF/\hbar\omega<eR_cE_{\rm rms}/(h\nu)$.

It should be noticed that experimental observations are at magnetic field ranges at which the relevant LL index is above 50.[1] However, the ac field induced anticrossing effects should not be LL index sensitive. Besides, very recent results[6] point out that the modulation of the density of states is still resolved in the experiments, suggesting that the ac field induced gaps could be also experimentally seen. On the other hand, from the experimental point of view, investigations of microwave effects at higher magnetic fields (radiation induced changes in the Shubnikov-de Haas oscillations) begin to be reported.[33]

The present work suggests that effects related to the dressing of states by microwaves could be interesting and invite future work on the ZRS regime. The microwave induced gaps might be experimentally observable.

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