

A generalized model for the transport properties of dressed quantum Hall systems

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A generalized mathematical model for the transport properties of quantum systems exposed to a stationary magnetic and a strong electromagnetic field is presented. The new formulation, which applies to the two-dimensional dressed quantum Hall systems, is based on Landau quantization theory and Floquet-Drude conductivity approach. We model our system as a two-dimensional electron gas (2DEG) that interacts with two external fields. To analyze the strong light coupling with the 2DEG, we utilize the Floquet theory as a nonperturbative procedure. Moreover, the Floquet Fermi golden rule is adopted to explore the scattering effects against Floquet states in disordered quantum Hall systems. Based on our fully analytical expression and particular graphical representations, we demonstrate that the characteristics of conductivities in two-dimensional quantum Hall systems can be manipulated using a strong light. The outcomes align with the theoretical descriptions which are already well-suited with experimental results and at the same time our theory provides a more generalized analysis on the characteristics of conductivity of quantum Hall systems. Thus, this model more realistically describes that how to employ external strong radiation as a tool to utilize transport properties in various 2D nanostructures which serve as a basis for nano-scale quantum devices.

I. INTRODUCTION

Manipulating physical systems as a consequence of light engagements introduced an astonishing scope of twentieth-century physics namely quantum optics [1]. Quantum optics have dragged research attention in the disciplines of optoelectronics [2–4], sensing [5–7], energy harvesting [8, 9], quantum computing [10–12], bio-information [13, 14], and abundant affiliates of recent technologies [15]. The studies on quantum optics of nanostructures were centered on metamaterials [16, 17], quantum plasmonic effects [18, 19], lasers and amplifiers [20, 21], quantum cavity physics [22, 23]. However, over the past few years, the foremost aims for examining nanostructures under external radiation were focused on understanding the transport characteristics [24–31]. The significance of describing fundamental mechanisms taking place in charge transport is that they will pave the way to invent new nanoelectronic devices and optimize their performance [32]. Among these works, most studies have considered the driving field as a perturbation field [27, 28] that is not applicable for systems under high-intensity illumination [31, 33]. When the external electromagnetic field account with a perturbation method and it gets high intensive, the number of higher-order interaction terms need to be considered gets increase. Then a more accurate and powerful concept need to be adopted and we need to treat the interacting fermion system and the radiation as a one unique quantum system (dressed system) [28, 34, 35]. On account of the transport characteristics of dressed nanostructures, they are still expecting extensive analysis. Theoretical analyses of the transport properties of dressed fermions systems were recently reported in Ref. [26, 28, 31] where a general expression for Floquet-Drude conductivity has been derived

in a fully closed analytical form in Ref. [31], introducing a novel type of Green's functions namely four-times Green's functions. As a consequence, the established formalism introduces a novel approach to manipulate the transport characteristics of nanostructures by an intense dressing field.

On the other hand, quantum Hall effect [36] observed for two-dimensional fermions systems at low temperatures under strong stationary magnetic field manifest remarkable magneto-transport behaviors and transport properties of these systems attracted many researches attention in experimentally [37–39] and theoretically [40–46]. Akira Endo et al. [46] previously presented calculations of longitudinal and transverse conductivity tensor components and their relationship in a quantum Hall system and these theoretical calculations are well-suited with the experimental observations while other former studies [46] yields a semi-elliptical broadening for Landau levels and gives less fitting interpretations for the empirical results [46].

In contrast, more fascinating transport phenomena can be achieved by creating a quantum Hall system using a stationary magnetic field and simultaneously applying a dressing field. Whilst there exist a number of leading theories devoted to the calculation of conductivity tensor elements in quantum Hall systems [41, 45, 46], they have not been utilized to describe the optical manipulation of the transport properties of the quantum Hall systems. Furthermore, K. Dini et al. [30] have recently investigated the one-directional conductivity behavior of dressed quantum Hall systems, and they have not adopted the state-of-the-art model to describe the conductivity in a quantum Hall system. In their study, they used the conductivity models from T. Ando et al. [41, 45] and as mentioned in A. Endo et al. work [46] those models yields a semi-elliptical broadening for Lan-

dau levels and gives less fitting illustrations for the experimental results.

In the present analysis we report a robust mathematical model for dressed two-dimensional electron gas (2DEG) exposed to another stationary magnetic field. A stationary magnetic field is applied perpendicularly across the surface of 2DEG system and the orbital motion of electrons becomes completely quantized, and the energy spectrum becomes discrete by creating Landau levels [47]. Such a singular system is known as a two-dimensional quantum Hall system and in this study, we explicitly calculate the longitudinal (σ^{xx} , σ^{yy}) components of the conductivity tensor in the periodically driven quantum Hall systems by developing a generalized mathematical model to describe transport properties of dressed quantum Hall systems using Floquet-Drude conductivity [31]. Finally, we demonstrate that our generalized model is agreed with state-of-the-art conductivity model [46] already developed for specialized quantum Hall systems that have been considered without the external dressing field. Furthermore, the mechanism of optical manipulation can be used as a tool to utilize transport properties in various two-dimensional nanostructures which serve as a basis for nanoelectronic devices and, we believe that our theoretical analysis and visual depictions of results can be used to understand the basic structure and optimize the performance of optical manipulation of transport properties in a two-dimensional quantum Hall system.

II. SCHRODINGER PROBLEM FOR DRESSED QUANTUM HALL SYSTEM

Our system consist of a two-dimensional free electron gas (2DEG) confined in the (x, y) plane of the three-dimensional coordinate space. In our analysis, the 2DEG is subjected to a stationary magnetic field $\mathbf{B} = (0, 0, B)^T$ which is pointed towards the z axis. In addition a linearly polarized strong light is applied perpendicular to the 2DEG plane and we specially tune the frequency of the field ω such that the optical field behaves as a purely dressing field (nonabsorbable). Without limiting the generality we can choose y -polarized electric field $\mathbf{E} = (0, E \sin(\omega t), 0)^T$ for the dressing field configuration (Fig. 1). Here B and E represent the amplitude of the stationary magnetic field and oscillating electric field respectively.

Using Landau gauge for the stationary magnetic field, we can represent it using vector potential as $\mathbf{A}_s = (-By, 0, 0)^T$ and choosing Coulomb gauge, the vector potential of the dynamic dressing radiation can be presented as $\mathbf{A}_d(t) = (0, [E/\omega] \cos(\omega t), 0)^T$. These vector potentials are coupled to the momentum of 2DEG as kinetic momentum [48, 49] and this leads to the time-dependent Hamiltonian

$$\hat{H}_e(t) = \frac{1}{2m_e} \left[\hat{\mathbf{p}} - e(\mathbf{A}_s + \mathbf{A}_d(t)) \right]^2, \quad (1)$$

where m_e is the effective electron mass and e is the magnitude of the electron charge. $\hat{\mathbf{p}} = (\hat{p}_x, \hat{p}_y, 0)^T$ represents the canonical momentum operator for 2DEG with electron momentums $p_{x,y}$. The exact solutions for the time-dependent Schrödinger equation $i\hbar \frac{d}{dt} \psi = \hat{H}_e(t) \psi$ was already given by Refs. [30, 50, 51] and we can present them as a set of wave functions defined by two quantum numbers (n, m)

$$\begin{aligned} \psi_{n,m}(x, y, t) &= \frac{1}{\sqrt{L_x}} \chi_n [y - y_0 - \zeta(t)] \\ &\times \exp \left(\frac{i}{\hbar} \left[-\varepsilon_n t + p_x x + \frac{eE(y - y_0)}{\omega} \cos(\omega t) \right. \right. \\ &\left. \left. + m_e \dot{\zeta}(t) [y - y_0 - \zeta(t)] + \int_0^t dt' L(\zeta, \dot{\zeta}, t') \right] \right), \end{aligned} \quad (2)$$

where $n \in \mathbb{Z}_0^+$ and $m \in \mathbb{Z}$; see Appendix A. Here $L_{x,y}$ are dimension of the 2DEG surface, \hbar is the reduced Planck constant, and $y_0 = -p_x/eB$ is the center of the cyclotron orbit along y axis. χ_n are well known solutions for Schrödinger equation of a stationary quantum harmonic oscillator

$$\chi_n(x) \equiv \frac{\sqrt{\kappa}}{\sqrt{2^n n!}} e^{-\kappa^2 x^2/2} \mathcal{H}_n(\kappa x) \quad \text{with} \quad \kappa = \sqrt{\frac{m_e \omega_0}{\hbar}}, \quad (3)$$

with eigenvalues given by $\varepsilon_n = \hbar \omega_0 (n + 1/2)$ and $\omega_0 = eB/m_e$ is the cyclotron frequency. Each n value defines the energy (ε_n) of the respective Landau level. The path shift of the driven classical oscillator $\zeta(t)$ is given by

$$\zeta(t) = \frac{eE}{m_e(\omega_0^2 - \omega^2)} \sin(\omega t), \quad (4)$$

while the Lagrangian of the classical oscillator $L(\zeta, \dot{\zeta}, t)$ can be identified as

$$L(\zeta, \dot{\zeta}, t) = \frac{1}{2} m_e \dot{\zeta}^2(t) - \frac{1}{2} m_e \omega_0^2 \zeta^2(t) + eE \zeta(t) \sin(\omega t). \quad (5)$$

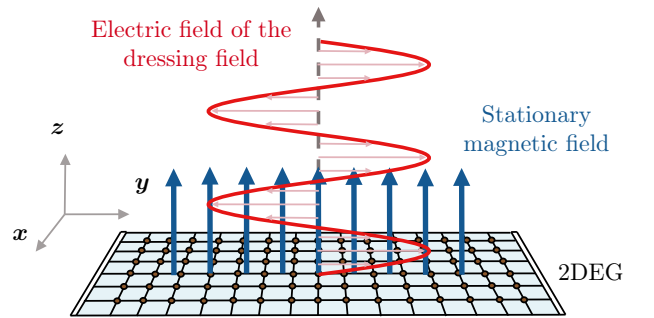


FIG. 1. Two dimensional electron gas (2DEG) confined in the (x, y) plane while both stationary magnetic field \mathbf{B} and strong dressing field with y -polarized electric field \mathbf{E} are being applied perpendicular to the surface of 2DEG.

The exponential phase shifts in Eq. (2) represent the influence done by the stationary magnetic field and strong dressing field. Therefore we can accept that magnetotransport properties of 2DEG will be renormalized by the magnetic field as well as the dressing field.

III. FLOQUET THEORY PERSPECTIVE

The general interpretations of physical systems are mostly derived using symmetry conditions in quantum theory. Famous Bloch analysis of electrons in quantum systems introduces a mathematical explanation of quantum systems occupying a discrete translational symmetry in configuration space. Floquet theory gives a mathematical formalism that can be used for translational symmetry in time rather than in space [33, 52, 53]. Examine the transport properties of systems exposed to strong radiation using the Floquet-Drude conductivity method introduced recently by M. Wackerl [31]. In their analysis they have presented more accurate results than previously existed theoretical descriptions for the conductivity in presence of a strong dressing field. Therefore, we are hoping to apply the Floquet-Drude conductivity method to analyse our 2DEG system which is subjected to both a stationary magnetic field and a strong dressing field.

First we need to identify the *quasienergies* and periodic *Floquet modes* for derived wavefunctions in Eq. (2). By factorizing the wavefunction into a linearly time dependent part and a periodic time dependent part, the quasienergies can be present as

$$\varepsilon_n = \hbar\omega_0 \left(n + \frac{1}{2} \right) - \Delta_\varepsilon, \quad (6)$$

which is only depend on single quantum number (n) and Floquet modes are given by

$$\begin{aligned} \phi_{n,m}(x, y, t) = & \frac{1}{\sqrt{L_x}} \chi_n [y - y_0 - \zeta(t)] \\ & \times \exp \left(\frac{i}{\hbar} \left[p_x x + \frac{eE(y - y_0)}{\omega} \cos(\omega t) \right. \right. \\ & \left. \left. + m_e \dot{\zeta}(t) [y - y_0 - \zeta(t)] + \xi \right] \right), \end{aligned} \quad (7)$$

with

$$\Delta_\varepsilon = \frac{(eE)^2}{4m_e(\omega_0^2 - \omega^2)} \text{ and } \xi = \frac{(eE)^2(3\omega^2 - \omega_0^2)}{8m_e\omega(\omega_0^2 - \omega^2)^2} \sin(2\omega t). \quad (8)$$

It is important to notice that these Floquet modes are time-periodic ($T = 2\pi/\omega$) functions. At the resonance $\omega = \omega_0$, the energy levels occupies a continuous form and the discrete quasienergies are not longer valid [54]. Therefore in this work we choose the dressing field frequency as $\omega \neq \omega_0$.

Then performing Fourier transform over the confined two-dimensional space $A = L_x L_y$, we obtain the momen-

tum space(k_x, k_y) representation of Floquet modes

$$\begin{aligned} \phi_{n,m}(k_x, k_y, t) = & \sqrt{L_x} \tilde{\chi}_n(k_y - b \cos(\omega t)) \\ & \times \exp(i\xi - ik_y[d \sin(\omega t) + y_0]), \end{aligned} \quad (9)$$

where

$$\tilde{\chi}_n(k) = \frac{i^n}{\sqrt{2^n n! \sqrt{\pi}}} \left(\frac{1}{\kappa} \right)^{1/2} e^{-\frac{\kappa^2}{2}} \mathcal{H}_n \left(\frac{k}{\kappa} \right) \quad (10)$$

and

$$b \equiv \frac{eE\omega_0^2}{\hbar\omega(\omega_0^2 - \omega^2)} \quad d \equiv \frac{eE}{m_e(\omega_0^2 - \omega^2)}. \quad (11)$$

For details of the formalism the authors refer to Appendix B. Now using Floquet theory, the wave functions derived in Eq. (2) can be written in momentum space as Floquet states

$$\psi_{n,m}(k_x, k_y, t) = \exp \left(-\frac{i}{\hbar} \varepsilon_n t \right) \phi_{n,m}(k_x, k_y, t). \quad (12)$$

IV. INVERSE SCATTERING TIME ANALYSIS

In Ref. [31] Floquet Fermi golden rule has been introduced as a method to analyse transport properties in dressed quantum systems. However, this theory has not been applied for a dressed quantum Hall system and to identify magnetotransport properties in our system we use Floquet Fermi golden rule. With the help of $t - t'$ formalism [31, 33, 55–57] and using Floquet states derived in Eq. (12) we can derive an expression for the inverse scattering time matrix ((l, l') th element) for the N th Landau level, per a given energy ε and momentum k_x value for our considered quantum Hall system as

$$\begin{aligned} & \left(\frac{1}{\tau(\varepsilon, k_x)} \right)_N^{ll'} \\ &= \frac{\varrho^2}{eB} \delta(\varepsilon - \varepsilon_N) \\ & \times \int_{-\infty}^{\infty} dk_1 J_l \left(\frac{b\hbar}{eB} [k_x - k_1] \right) J_{l'} \left(\frac{b\hbar}{eB} [k_x - k_1] \right) \\ & \times \left| \int_{-\infty}^{\infty} dk_2 \chi_N \left(\frac{\hbar}{eB} k_2 \right) \chi_N \left(\frac{\hbar}{eB} [k_1 - k_x - k_2] \right) \right|^2, \end{aligned} \quad (13)$$

where $\varrho \equiv \eta_{imp} L_x [V_{imp}/eB]^{1/2}$, $J_l(\cdot)$ are Bessel functions of the first kind with l th integer order and ε_N is the energy of N th Landau level; see Appendix C. In this study, the perturbation potential is assumed to be formed by an ensemble of randomly distributed impurities, since random impurities in a disordered metal is a better approximation for experimental results. The total scattering potential in 2DEG is then given by the sum over uncorrelated single impurity potentials $v(\mathbf{r})$. Here η_{imp} is the number of impurities in a unit area and $V_{imp} = \langle |V_{k'_x, k_x}|^2 \rangle$ with $V_{k'_x, k_x} = \langle k'_x | v(x) | k_x \rangle$ where $\langle x | k_x \rangle = e^{-ik_x x} / \sqrt{L_x}$.

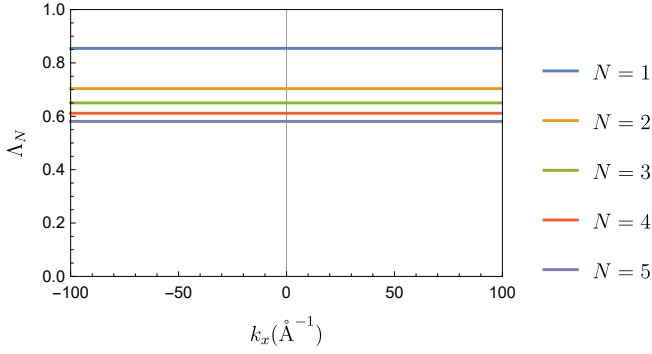


FIG. 2. The dependence of normalized scattering-induced broadening Λ_N for each Landau level ($N = 0, 1, 2, 3, 4$) against x -directional momentum value k_x in a GaAs-based quantum well at a magnetic field $B = 1.2$ T, dressing field with frequency $\omega = 2 \times 10^{12}$ rads^{-1} and intensity $I = 100$ W/cm^2 . In this calculation we have assumed that the natural broadening of 0-th Landau level Γ_0 is 0.24 meV.

Next we are going to analyse the contribution of the inverse scattering time matrix elements to the transport properties in 2DEG. The disorder in the system is not supposed to change the eigenenergies of the bare system [31], hence all off-diagonal elements of the self-energy were neglected and then we can consider only the central diagonal element ($l = l' = 0$) of the inverse scattering time matrix which has the largest contribution to the transport characteristics. Introduce a new parameter with physical meaning of scattering-induced broadening of the Landau level as [30, 46]

$$\Gamma_N^{00}(\varepsilon, k_x) \equiv \hbar \left(\frac{1}{\tau(\varepsilon, k_x)} \right)_N^{00}, \quad (14)$$

and this leads to

$$\begin{aligned} \Gamma_N^{00}(\varepsilon, k_x) &= \frac{g^2}{eB} \delta(\varepsilon - \varepsilon_N) \\ &\times \int_{-\infty}^{\infty} dk'_x J_0^2 \left(\frac{b\hbar}{eB} [k_x - k'_x] \right) \\ &\times \left| \int_{-\infty}^{\infty} dk_2 \chi_N \left(\frac{\hbar}{eB} k_2 \right) \chi_N \left(\frac{\hbar}{eB} [k'_x - k_x - k_2] \right) \right|^2. \end{aligned} \quad (15)$$

In addition, for the case of scattering within a same Landau level, one can present the delta distribution of the energy using the same physical interpretation [30] as follows

$$\delta(\varepsilon - \varepsilon_N) \approx \frac{1}{\pi \Gamma_N^{00}(\varepsilon, k_x)}, \quad (16)$$

and we write the central element of inverse scattering

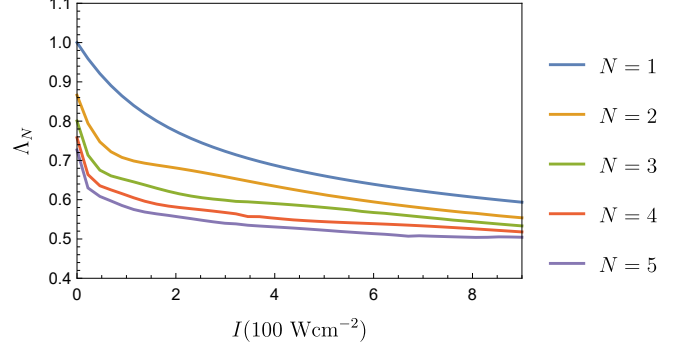


FIG. 3. The dependence of normalized scattering-induced broadening Λ_N for each Landau level ($N = 0, 1, 2, 3, 4$) against dressing field intensity I , in a GaAs-based quantum well at a magnetic field $B = 1.2$ T, dressing field with frequency $\omega = 2 \times 10^{12}$ rads^{-1} . In this calculation we have assumed that the natural broadening of 0-th Landau level Γ_0 is 0.24 meV.

time matrix in more compact form

$$\begin{aligned} \Gamma_N^{00}(\varepsilon, k_x) &= \varrho \left[\int_{-\infty}^{\infty} dk_1 J_0^2(\lambda_1 [k_x - k_1]) \right. \\ &\times \left. \left| \int_{-\infty}^{\infty} dk_2 \tilde{\chi}_N(\lambda_2 k_2) \tilde{\chi}_N(\lambda_2 [k_1 - k_2 - k_x]) \right|^2 \right]^{-\frac{1}{2}}, \end{aligned} \quad (17)$$

where $\lambda_1 \equiv \hbar b / eB$ and $\lambda_2 \equiv \hbar \kappa / eB$. To analyze the contribution of dressing field on the scattering-induced broadening, normalized N -th Landau level scattering-induced broadening can be defined as

$$\Lambda_N(k_x) \equiv \frac{\Gamma_N^{00}(\varepsilon, k_x)}{\Gamma_{N=0}^{00}(\varepsilon, k_x)|_{E=0}}, \quad (18)$$

and this leads to

$$\Lambda_N(k_x) = \left[\frac{\int_{-\infty}^{\infty} dk_1 J_0^2(\lambda_1 [k_x - k_1]) \left| \int_{-\infty}^{\infty} dk_2 \tilde{\chi}_N(\lambda_2 k_2) \tilde{\chi}_N(\lambda_2 [k_1 - k_2 - k_x]) \right|^2}{\int_{-\infty}^{\infty} dk_1 \left| \int_{-\infty}^{\infty} dk_2 \tilde{\chi}_0(\lambda_2 k_2) \tilde{\chi}_0(\lambda_2 [k_1 - k_2 - k_x]) \right|^2} \right]^{1/2}. \quad (19)$$

Normalized energy band broadening against k_x for dif-

ferent Landau levels ($N = 0, 1, 2, 3, 4$) has been calcu-

lated for GaAs-based quantum well and results are given in Fig. (2) and Fig. (3). To make comparison we have selected the experiment parameters to match with analysis done in Ref. [46]. In their study, they have assumed that effective mass of the electron in GaAs-based quantum well system is $m_e = 0.07m$ where m is mass of the electron [31, 46, 58] and the broadening of the natural (without a dressing field) 0-th Landau level Γ_0 is 0.24 meV. Therefore in our calculations, we assumed that the natural least Landau level broadening also has this value: $\Gamma_{N=0}^{00}|_{E=0} = 0.24$ meV. Here we can identify that we can change the each Landau level normalized energy broadening value using applied electromagnetic field. When the applied field's intensity increase the energy broadening gets reduced which make changes in conductivity of 2DEG.

V. FLOQUET-DRUDE CONDUCTIVITY IN QUANTUM HALL SYSTEMS

A general theory for the conductivity in dressed systems with the disorder averaging was introduced by M. Wackerl in Ref. [31, 59]. Within this theory, the general x -directional longitudinal DC limit conductivity can be

express with

$$\sigma^{xx} = \frac{-1}{4\pi\hbar A} \int_{\lambda-\hbar\omega/2}^{\lambda+\hbar\omega/2} d\varepsilon \left[\left(-\frac{\partial f}{\partial \varepsilon} \right) \times \text{tr} [j_0^x(\mathbf{G}^r(\varepsilon) - \mathbf{G}^a(\varepsilon)) j_0^x(\mathbf{G}^r(\varepsilon) - \mathbf{G}^a(\varepsilon))] \right] \quad (20)$$

where j_0^x and $\mathbf{G}^{r,a}(\varepsilon)$ are x -directional electric current operator matrix elements' $s = 0$ th Fourier component (see Appendix D) and white noise disorder averaged Floquet Green function matrix [31, 59] respectively defined against the Floquet modes of the considering system. Here we have assumed that only $s = 0$ th Fourier component of the current operator is contributing to the conductivity. In addition A is the area of the considering two-dimensionl system, partial distribution function is given by f and λ is a function that can be choose such that

$$\lambda - \frac{\hbar\omega}{2} \leq \varepsilon_N < \lambda + \frac{\hbar\omega}{2}, \quad (21)$$

where ε_N are quasienergies of all considering Floquet states.

Then Eq. (20) can be expanded in off resonant regime ($\omega\tau_0 \gg 1$), where τ_0 is the scattering time of the undriven system, using only central entry Fourier components ($l = l' = 0$) of Floquet modes $|\phi_{n,m}\rangle \equiv |n, k_x\rangle$

$$\sigma^{xx} = \frac{-1}{4\pi\hbar A} \int_{\lambda-\hbar\Omega/2}^{\lambda+\hbar\Omega/2} d\varepsilon \left(-\frac{\partial f}{\partial \varepsilon} \right) \frac{1}{V_{k_x}} \sum_{k_x} \sum_n \langle n, k_x | j_0^x(\mathbf{G}^r(\varepsilon) - \mathbf{G}^a(\varepsilon)) j_0^x(\mathbf{G}_0^r(\varepsilon) - \mathbf{G}_0^a(\varepsilon)) | n, k_x \rangle, \quad (22)$$

where V_{k_x} is the volume of considering x -directional momentum space. Then this can evaluate by considering each matrix elements separatly

$$\sigma^{xx} = \frac{-1}{4\pi\hbar A} \int_{\lambda-\hbar\Omega/2}^{\lambda+\hbar\Omega/2} d\varepsilon \left(-\frac{\partial f}{\partial \varepsilon} \right) \frac{1}{V_{k_x}^4} \sum_{k_x} \sum_n \sum_{k_{x1}, k_{x2}, k_{x3}} \sum_{n1, n2, n3} \times \langle n, k_x | j_0^x | n1, k_{x1} \rangle \langle n1, k_{x1} | (\mathbf{G}^r(\varepsilon) - \mathbf{G}^a(\varepsilon)) | n2, k_{x2} \rangle \langle n2, k_{x2} | j_0^x | n3, k_{x3} \rangle \langle n3, k_{x3} | (\mathbf{G}^r(\varepsilon) - \mathbf{G}^a(\varepsilon)) | n, k_x \rangle. \quad (23)$$

Since we can diagonalize the impurity averaged Green's function using unitary trasnformation ($\mathbf{T} \equiv |n, k_x\rangle$) mentioned in Ref. [31, 59, 60] and we evaluate the matrix element of the difference between retarded and advanced Green's functions

$$\langle n1, k_{x1} | \mathbf{T}^\dagger (\mathbf{G}^r(\varepsilon) - \mathbf{G}^a(\varepsilon)) \mathbf{T} | n2, k_{x2} \rangle = \left[\frac{2i\text{Im}(\mathbf{T}^\dagger \mathbf{\Sigma}^r \mathbf{T}) \delta_{n1, n2} \delta_{k_{x1}, k_{x2}}}{\left(\frac{1}{\hbar}\varepsilon - \frac{1}{\hbar}\varepsilon_{n1}\right)^2 + [\text{Im}(\mathbf{T}^\dagger \mathbf{\Sigma}^r \mathbf{T})]^2} \right], \quad (24)$$

and

$$\langle n3, k_{x3} | \mathbf{T}^\dagger (\mathbf{G}^r(\varepsilon) - \mathbf{G}^a(\varepsilon)) \mathbf{T} | n, k_x \rangle = \left[\frac{2i\text{Im}(\mathbf{T}^\dagger \mathbf{\Sigma}^r \mathbf{T}) \delta_{n3, n} \delta_{k_{x3}, k_x}}{\left(\frac{1}{\hbar}\varepsilon - \frac{1}{\hbar}\varepsilon_n\right)^2 + [\text{Im}(\mathbf{T}^\dagger \mathbf{\Sigma}^r \mathbf{T})]^2} \right], \quad (25)$$

using the retared self-energy matrix $\mathbf{\Sigma}^r$ which is the sum over all irreducible diagrams [31, 59]. Applying the matrix elements of electric current operator in Landau levels (see Appendix D) and results form Eq. (24) and Eq. (25) back

into Eq. (23) we obtain

$$\begin{aligned} \sigma^{xx} = & \frac{-1}{4\pi\hbar A} \int_{\lambda-\hbar\Omega/2}^{\lambda+\hbar\Omega/2} d\varepsilon \left(-\frac{\partial f}{\partial \varepsilon} \right) \frac{1}{V_{k_x}} \sum_{k_x} \sum_n \sum_{n_1, n_2} \\ & \times \frac{e^2 B}{m_e} \left(\sqrt{\frac{n+1}{2}} \delta_{n_1, n+1} + \sqrt{\frac{n}{2}} \delta_{n_1, n-1} \right) \left[\frac{2i\text{Im}(\mathbf{T}^\dagger \mathbf{\Sigma}^r \mathbf{T}) \delta_{n_1, n_2}}{\left(\frac{1}{\hbar} \varepsilon - \frac{1}{\hbar} \varepsilon_{n_1} \right)^2 + [\text{Im}(\mathbf{T}^\dagger \mathbf{\Sigma}^r \mathbf{T})]^2} \right] \\ & \times \frac{e^2 B}{m_e} \left(\sqrt{\frac{n_2+1}{2}} \delta_{n, n_2+1} + \sqrt{\frac{n_2}{2}} \delta_{n, n_2-1} \right) \left[\frac{2i\text{Im}(\mathbf{T}^\dagger \mathbf{\Sigma}^r \mathbf{T})}{\left(\frac{1}{\hbar} \varepsilon - \frac{1}{\hbar} \varepsilon_n \right)^2 + [\text{Im}(\mathbf{T}^\dagger \mathbf{\Sigma}^r \mathbf{T})]^2} \right], \end{aligned} \quad (26)$$

and the only non-zero term would be

$$\begin{aligned} \frac{-1}{4\pi\hbar A} \sigma^{xx} = & \frac{e^4 B^2}{m_e^2} \int_{\lambda-\hbar\Omega/2}^{\lambda+\hbar\Omega/2} d\varepsilon \left(-\frac{\partial f}{\partial \varepsilon} \right) \frac{1}{V_{k_x}} \sum_{k_x} \sum_n (n+1) \\ & \times \left[\frac{2i\text{Im}(\mathbf{T}^\dagger \mathbf{\Sigma}^r \mathbf{T})_{\varepsilon_{n+1}}}{\left(\frac{1}{\hbar} \varepsilon - \frac{1}{\hbar} \varepsilon_{n+1} \right)^2 + [\text{Im}(\mathbf{T}^\dagger \mathbf{\Sigma}^r \mathbf{T})_{\varepsilon_{n+1}}]^2} \right] \left[\frac{2i\text{Im}(\mathbf{T}^\dagger \mathbf{\Sigma}^r \mathbf{T})_{\varepsilon_n}}{\left(\frac{1}{\hbar} \varepsilon - \frac{1}{\hbar} \varepsilon_n \right)^2 + [\text{Im}(\mathbf{T}^\dagger \mathbf{\Sigma}^r \mathbf{T})_{\varepsilon_n}]^2} \right]. \end{aligned} \quad (27)$$

Since the inverse scattering time matrix being equal to the diagonalized difference of the retarded and advanced self-energy and on the diagonal the difference of the retarded and advanced Green's function is equal to the imaginary part of the retarded self-energy [31, 59] we can identify the following property

$$\left(\frac{1}{\tau(\varepsilon, k_x)} \right)^{ll} = -2\text{Im}[\mathbf{T}^\dagger \mathbf{\Sigma}^r(\varepsilon, k_x) \mathbf{T}]^{ll}, \quad (28)$$

and using central element ($l = 0$) of the inverse scattering time matrix we can modify the derived conductivity expression

$$\sigma^{xx} = \frac{1}{\pi\hbar A} \frac{e^4 B^2}{m_e^2} \int_{\lambda-\hbar\Omega/2}^{\lambda+\hbar\Omega/2} d\varepsilon \left(-\frac{\partial f}{\partial \varepsilon} \right) \frac{1}{V_{k_x}} \sum_{k_x} \sum_n (n+1) \left[\frac{\Gamma(\varepsilon_{n+1})}{(\varepsilon_F - \varepsilon_{n+1})^2 + \Gamma^2(\varepsilon_{n+1})} \right] \left[\frac{\Gamma(\varepsilon_n)}{(\varepsilon_F - \varepsilon_n)^2 + \Gamma^2(\varepsilon_n)} \right], \quad (29)$$

with $\Gamma(\varepsilon_n, k_x) \equiv (\hbar/2\tau(\varepsilon_n, k_x))^{00}$. We already identified that the inverse scattering time matrix's central element is not k_x dependent we can get the sum over all available momentum space in x direction. However by considering the condition that the center of the force of the oscillator y_0 must physically lie within the considering system $-L_y/2 < y_0 < L_y/2$, we can identify

$$-\frac{m_e \omega_0 L_y}{2\hbar} \leq k_x \leq \frac{m_e \omega_0 L_y}{2\hbar}. \quad (30)$$

Then using Fermi-Dirac distribution as our partial distribution function (f) for this system

$$f(\varepsilon) = \frac{1}{[\exp(\varepsilon - \varepsilon_F)/k_B T] + 1}, \quad (31)$$

where k_B is Boltzmann constant, T is absolute temperature and ε_F is Fermi energy of the system. Considering the above distribution with extremely low temperature conditions we can approximate

$$-\frac{\partial f(\varepsilon)}{\partial \varepsilon} \approx \delta(\varepsilon - \varepsilon_F), \quad (32)$$

and by letting $\lambda = \varepsilon_F$, the expression for conductivity leads to

$$\begin{aligned} \sigma^{xx} = & \frac{e^2}{\hbar} \frac{1}{\pi A} \sum_n \frac{(n+1)}{\gamma_n \gamma_{n+1}} \\ & \times \left[\frac{1}{1 + \left(\frac{X_F - n - 1}{\gamma_{n+1}} \right)^2} \right] \left[\frac{1}{1 + \left(\frac{X_F - n}{\gamma_n} \right)^2} \right], \end{aligned} \quad (33)$$

where $X_F \equiv (\varepsilon_F/\hbar\omega_0 - 1/2)$ and $\gamma_n \equiv \Gamma(\varepsilon_n)/\hbar\omega_0$. Same as above derivation we can derive the transverse conductivity in y -direction by using the current operator derived in Appendix D

$$\begin{aligned} \sigma^{yy} = & \frac{e^2}{\hbar} \frac{1}{\pi A} \frac{1}{e^2 B^2} \sum_n \frac{(n+1)}{\gamma_n \gamma_{n+1}} \\ & \times \left[\frac{1}{1 + \left(\frac{X_F - n - 1}{\gamma_{n+1}} \right)^2} \right] \left[\frac{1}{1 + \left(\frac{X_F - n}{\gamma_n} \right)^2} \right]. \end{aligned} \quad (34)$$

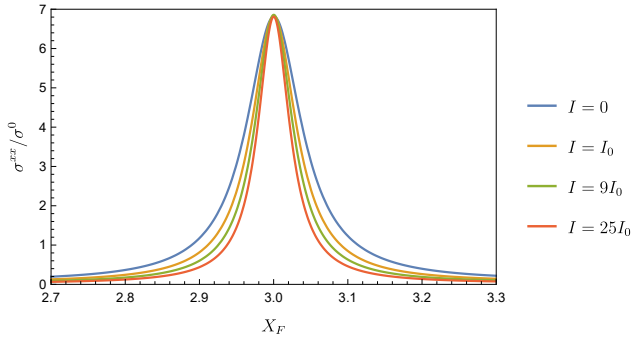


FIG. 4. Normalized transverse conductivity σ_{xx} against Fermi level X_F with different intensities I of the external dressing field in a GaAs-based quantum well at a magnetic field $B = 1.2$ T, dressing field with frequency $\omega = 2 \times 10^{12}$ rads $^{-1}$ and $I_0 = 100$ W/cm 2 . In this calculation we have assumed that the natural broadening of 0-th Landau level Γ_0 is 0.24 meV.

VI. MANIPULATE CONDUCTIVITY IN QUANTUM HALL SYSTEMS

To identify the characteristics of the transverse conductivity of the quantum Hall systems with external dressing field, first we can derive a expression for a normalized transverse conductivity as a function of fermi energy X_F and intensity of the dressing field I . Here we have the normalized x-directional conductivity using the natural conductivity of least Landau level

$$\frac{\sigma_{xx}}{\sigma^0} = \sum_n \frac{(n+1)}{0.0037\Lambda_n\Lambda_{n+1}} \times \left[\frac{1}{1 + \left(\frac{X_F - n - 1}{0.06\Lambda_n} \right)^2} \right] \left[\frac{1}{1 + \left(\frac{X_F - n}{0.06\Lambda_{n+1}} \right)^2} \right], \quad (35)$$

where $\sigma^0 = (e^2/\pi\hbar A)$. We use this expression to illustrate the changes that can be done to the transverse conductivity in 2DEG using external dressing field. As given in Fig. 3 and 4 we can manipulate the transverse conductivity σ_{xx} using external dressing field's intensity and the Fermi level X_F of the considering system. For a given dressing field intensity, the transverse conductivity vary against the Fermi level of the system by creating sharp peaks at each Landau level energy values. Since electrons are restricted to have only Landau level energies, the conductivity gets very low values when the Fermi level is not align with any of the Landau level energy values. In contrast, on Landau levels conductivity can achieve very high values compared to other areas and as illustrates on Fig. 3 the peak value of transverse conductivity on each Landau level gets increase with the Landau level number.

Considering the effect of the external dressing field on transverse conductivity of 2DEG, we can identify that high intensities shrink the conductivity regions near Landau levels. However the peak value of the conductivity at each Landau level has the same value as the undressed

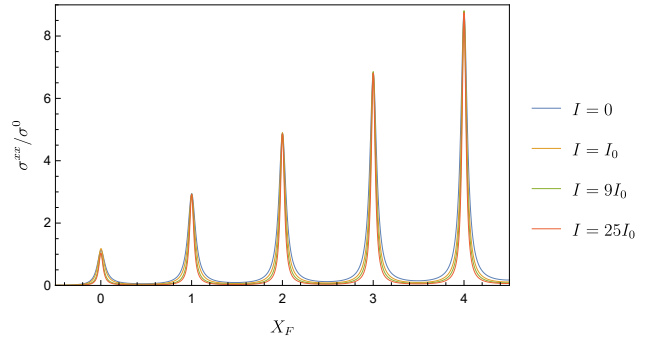


FIG. 5. 3rd Landau level's normalized transverse conductivity σ_{xx} against Fermi level X_F with different intensities I of the external dressing field in a GaAs-based quantum well at a magnetic field $B = 1.2$ T, dressing field with frequency $\omega = 2 \times 10^{12}$ rads $^{-1}$ and $I_0 = 100$ W/cm 2 . In this calculation we have assumed that the natural broadening of 0-th Landau level Γ_0 is 0.24 meV

system. This demonstrate that we are able to tune the width of the regions of conductivity in these quantum Hall systems with the help of a dressing field. These characteristics are align with results demonstrated by K. Dini et al.[30] and as they remarked since the Fermi level of the system can be change with the applied gate voltage of the material this can be used as a 2D switch for opto-electronic applications. Controlling the external dressing field we are able to fine-tune the switching mechanism for optimized performance. Furthermore we can distinguish that the shapes and behavoiur of the conductivity regions illustrated in Fig. 3 and 4 are generally incompatible with the results reported in Ref. [30]. This is due to the selection of the conventional transverse conductivity theory of 2DEG from Ref. [41, 45]. The semi-elliptical conductivity regions illustrated in Ref. [30, 41, 45], have less consistence with the experimentally observed Landau levels representation [46]. In our study on the transport properties of quantum Hall systems, we developed the conductivity expression starting from Floquet-Drude conductivity [31] and our results are much more align with the result represented by A. Endo et al. [46]. The description of conductivities of quantum Hall systems demonstrated in Ref. [46] has excellent agreement between the theory and experiment obtained in a GaAs/AlGaAs 2DES for the low magnetic field range. However they have not consider about the tunability that can be achived with the external strong dressing field. In this analysis we account both magnetic and dressing field effects that can be applied into the transport properties of 2DEG and we have presented a more generalized theory. As a concluding remark, in this study we were able to demonstrate that using Floquet-Drude conductivity method one can derive a more experimental fitting and generalized mathematical model that describes the trasport properties of quantum Hall syatems.

VII. CONCLUSIONS

In this analysis, we reported a generalized mathematical model for transport properties in a 2DEG under a stationary magnetic field and a dressing field. With the uniform magnetic field charged particles can only settle in discrete energy values and this leads to the Landau quantization. We modelled the behaviour of electrons in Landau levels under the dressing field utilizing Floquet-Drude conductivity method by accounting impurities in the material as Gaussian random scattering potential. Finally we derived expressions for x-directional and y-directional longitudinal components of electric conductivity tensor for the considering system.

Our derived analytical expressions revealed that the electric conductivity of the dressed quantum Hall system can be controlled by the applied dressing field's intensity. Using detailed numerical calculations with empirical system parameters, we further analysed the manipulation of conductivity components using the dressing field. We found that the graphical illustrations we gained are capable of produce the same behaviour as the experiment conductivity found in quantum Hall systems without a dressing field. Furthermore we identified that by regulating the intensity of radiation, the conductivity regions near Landau levels can be squeezed. Despite this behaviour has been identified previous works, their results are not coincide with the more accurate description of conductivity components in undressed quantum Hall systems. However our generalized analysis of conductivity in dressed quantum Hall system provides well-suited description for these special quantum Hall systems.

In summary, the primary purpose of this paper were to expand the current descriptions on transport properties in dressed quantum Hall systems and our detailed theoretical analysis shows that we were able to demonstrate that recently introduced Floquet-Drude conductivity model can be adopted to extend the models that are used to describe the transport characteristics in quantum Hall systems. Due to owing the ability of controlling the conductivity regions, high intensity external illumination can be used as a trigger for two-dimensional quantum switching devices which are employed as the building blocks of next generation nano-electronic devices. Finally, we identified that our findings of this paper can be used towards understanding nanoscale quantum devices, enhancing their performance and inventing novel appliance.

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Appendix A: Wave function solutions of dressed Landau levels

The deriving process of solutions for Schrödinger equation with Hamiltonian of an electron in 2DEG (Eq. 1) quite similar to that followed in Refs. [30, 50]. We start with expanding the Hamiltonian for two-dimensional case

$$\hat{H}_e(t) = \frac{1}{2m_e} \left[(\hat{p}_x + eBy)^2 + \left(\hat{p}_y - \frac{eE}{\omega} \cos(\omega t) \right)^2 \right], \quad (\text{A1})$$

and since $[\hat{H}_e(t), \hat{p}_x] = 0$ both operators share same (simultaneous) eigen functions $\frac{1}{\sqrt{L_x}} \exp\left(\frac{ip_x x}{\hbar}\right)$ with $p_x = 2\pi\hbar m/L_x$, $m \in \mathbb{Z}$. Therefore we re-arrange the Hamiltonian using definition of canonical momentum in y-direction to derive

$$\hat{H}_e(t) = \frac{1}{2m_e} \left[(p_x + eBy)^2 + \left(-i\hbar \frac{\partial}{\partial y} - \frac{eE}{\omega} \cos(\omega t) \right)^2 \right]. \quad (\text{A2})$$

We now define the *center of the cyclotron orbit* along y axis $y_0 \equiv -p_x/eB$ and the *cyclotron frequency* $\omega_0 \equiv eB/m_e$. This leads to a new arrangement of the Hamiltonian

$$\hat{H}_e(t) = \frac{m_e \omega_0^2}{2} \tilde{y}^2 + \frac{1}{2m_e} \left[-\hbar^2 \frac{\partial^2}{\partial \tilde{y}^2} + \frac{2i\hbar eE}{\omega} \cos(\omega t) \frac{\partial}{\partial \tilde{y}} + \frac{e^2 E^2}{\omega^2} \cos^2(\omega t) \right], \quad (\text{A3})$$

where we used a variable substitution $\tilde{y} = (y - y_0)$. Now we are assuming that the solutions for the time-dependent Schrödinger equation

$$i\hbar \frac{d\psi}{dt} = \hat{H}_e(t)\psi, \quad (\text{A4})$$

can present by the following form

$$\psi_m(x, \tilde{y}, t) = \frac{1}{\sqrt{L_x}} \exp\left(\frac{ip_x x}{\hbar} + \frac{ieE\tilde{y}}{\hbar\omega} \cos(\omega t)\right) \vartheta(\tilde{y}, t), \quad (\text{A5})$$

where $\vartheta(\tilde{y}, t)$ is a function that need to be find to satisfy the following property

$$\left[\frac{m_e \omega_0^2}{2} \tilde{y}^2 - eE\tilde{y} \sin(\omega t) - \frac{\hbar^2}{2m_e} \frac{\partial^2}{\partial \tilde{y}^2} - i\hbar \frac{d}{dt} \right] \vartheta(\tilde{y}, t) = 0. \quad (\text{A6})$$

If we turn off the strong dressing field ($E = 0$), this equation leads to simple harmonic oscillator Hamiltonian

$$i\hbar \frac{d\vartheta(\tilde{y}, t)}{dt} = \left[\frac{\hat{p}_{\tilde{y}}^2}{2m_e} + \frac{1}{2} m_e \omega_0^2 \tilde{y}^2 \right] \vartheta(\tilde{y}, t). \quad (\text{A7})$$

It is important to notice that we can identify the $S(t) \equiv eE \sin(\omega t)$ part as a external force act on the harmonic

oscillator and we can solve this as a forced harmonic oscillator in \tilde{y} axis.

$$i\hbar \frac{d\vartheta(\tilde{y}, t)}{dt} = \left[-\frac{\hbar^2}{2m_e} \frac{\partial^2}{\partial \tilde{y}^2} + \frac{1}{2} m_e \omega_0^2 \tilde{y}^2 - \tilde{y} S(t) \right] \vartheta(\tilde{y}, t). \quad (\text{A8})$$

This system can be exactly solvable and we can solve the equation using the methods explained by Husimi [50] as follows. We introduce a time dependent shifted coordinate $y' = \tilde{y} - \zeta(t)$ and perform following unitary transformation

$$\vartheta(y', t) = \exp\left(\frac{im_e \dot{\zeta} y'}{\hbar}\right) \varphi(y', t), \quad (\text{A9})$$

and this yields

$$\begin{aligned} i\hbar \frac{\partial \varphi(y', t)}{\partial t} = & \left[-\frac{\hbar^2}{2m_e} \frac{\partial^2}{\partial y'^2} + \frac{1}{2} m_e \omega_0^2 y'^2 \right. \\ & + \left[m_e \ddot{\zeta} + m_e \omega_0^2 \zeta - S(t) \right] y' \\ & \left. + \left[-\frac{1}{2} m_e \dot{\zeta}^2 + \frac{1}{2} m_e \omega_0^2 \zeta^2 - \zeta S(t) \right] \right] \varphi(y', t). \end{aligned} \quad (\text{A10})$$

Then we can restrict our $\zeta(t)$ function such that

$$m_e \ddot{\zeta} + m_e \omega_0^2 \zeta = S(t), \quad (\text{A11})$$

and that leads to

$$\begin{aligned} i\hbar \frac{\partial \varphi(y', t)}{\partial t} = & \left[-\frac{\hbar^2}{2m_e} \frac{\partial^2}{\partial y'^2} + \frac{1}{2} m_e \omega_0^2 y'^2 \right. \\ & \left. - L(\zeta, \dot{\zeta}, t) \right] \varphi(y', t), \end{aligned} \quad (\text{A12})$$

where

$$L(\zeta, \dot{\zeta}, t) \equiv \frac{1}{2} m_e \dot{\zeta}^2 - \frac{1}{2} m_e \omega_0^2 \zeta^2 + \zeta S(t), \quad (\text{A13})$$

is the lagrangian of a classical driven oscillator. To proceed further, another unitary transform can be introduced as follows

$$\varphi(y', t) = \exp\left(\frac{i}{\hbar} \int_0^t dt' L(\zeta, \dot{\zeta}, t')\right) \chi(y', t), \quad (\text{A14})$$

and substituting Eq. (A14) back in Eq. (A12) yields

$$i\hbar \frac{\partial}{\partial t} \chi(y', t) = \left[-\frac{\hbar^2}{2m_e} \frac{\partial^2}{\partial y'^2} + \frac{1}{2} m_e \omega_0^2 y'^2 \right] \chi(y', t). \quad (\text{A15})$$

This is the well known Schrödinger equation of the quantum harmonic oscillator. This allows us to identify with the well-known eigenfunctions [61, 62]

$$\chi_n(y) \equiv \frac{\sqrt{\kappa}}{\sqrt{2^n n!}} e^{-\kappa^2 y^2 / 2} \mathcal{H}_n(\kappa y) \quad \text{with} \quad \kappa = \sqrt{\frac{m_e \omega_0}{\hbar}}, \quad (\text{A16})$$

which are proportional to the Hermite polynomials \mathcal{H}_n , with eigenvalues

$$\varepsilon_n = \hbar \omega_0 \left(n + \frac{1}{2} \right), \quad n \in \mathbb{Z}_0^+. \quad (\text{A17})$$

Therefore we can identify the solutions of Eq. (A8) as

$$\begin{aligned} \vartheta_n(\tilde{y}, t) = \chi_n(\tilde{y} - \zeta(t)) \exp & \left(\frac{i}{\hbar} \left[-\varepsilon_n t + m_e \dot{\zeta}(t) (\tilde{y} - \zeta(t)) \right. \right. \\ & \left. \left. + \int_0^t dt' L(\zeta, \dot{\zeta}, t') \right] \right). \end{aligned} \quad (\text{A18})$$

The set $\{\chi_n(x)\}$ functions forms a complete set and thus any general solution $\vartheta(\tilde{y}, t)$ can be expanded in terms of the solutions given in Eq. (A18).

Finally we consider our scenario where we assumed that $S(t) = eE \sin(\omega t)$ and we can derive the solution for Eq. (A11)

$$\zeta(t) = \frac{eE}{m_e(\omega_0^2 - \omega^2)} \sin(\omega t). \quad (\text{A19})$$

Substituting solutions in Eq. (A18) back in Eq. (A5), we can obtain the set of wave functions with two different quantum number (n, m) that satisfy the Schrödinger equation Eq. (A4)

$$\begin{aligned} \psi_{n,m}(x, y, t) = & \frac{1}{\sqrt{L_x}} \chi_n[y - y_0 - \zeta(t)] \exp \left(\frac{i}{\hbar} \left[-\varepsilon_n t \right. \right. \\ & + p_x x + \frac{eE(y - y_0)}{\omega} \cos(\omega t) + m_e \dot{\zeta}(t) [y - y_0 - \zeta(t)] \\ & \left. \left. + \int_0^t dt' L(\zeta, \dot{\zeta}, t') \right] \right). \end{aligned} \quad (\text{A20})$$

Appendix B: Floquet modes and quasienergies

1. Position space representation

First define the time integral of Lagrangian of the classical oscillator given in Eq. (5), over a $T = 2\pi/\omega$ period as

$$\Delta_\varepsilon \equiv \frac{1}{T} \int_0^T dt' L(\zeta, \dot{\zeta}, t'), \quad (\text{B1})$$

and after performing the integral using Eq. (4), we can obtain more simplified result:

$$\Delta_\varepsilon = \frac{(eE)^2}{4m_e(\omega_0^2 - \omega^2)}. \quad (\text{B2})$$

Next define another parameter

$$\xi \equiv \int_0^t dt' L(\zeta, \dot{\zeta}, t') - \Delta_\varepsilon t, \quad (\text{B3})$$

and after simplifying, this leads to

$$\xi = \frac{(eE)^2(3\omega^2 - \omega_0^2)}{8m_e\omega(\omega_0^2 - \omega^2)^2} \sin(2\omega t), \quad (\text{B4})$$

which is a periodic function in time with 2ω frequency. Now using these parameters we can factorize the wavefunction Eq. (2) as linearly time dependent part and periodic time dependent part as follows

$$\begin{aligned} \psi_\alpha(x, y, t) = & \exp\left(\frac{i}{\hbar}[-\varepsilon_n t + \Delta_\varepsilon t]\right) \frac{1}{\sqrt{L_x}} \chi_n(y - y_0 - \zeta(t)) \\ & \times \exp\left(\frac{i}{\hbar}\left[p_x x + \frac{eEy}{\omega} \cos(\omega t) \right. \right. \\ & \left. \left. + m_e \dot{\zeta}(t)[y - \zeta(t)] + \int_0^t dt' L(\zeta, \dot{\zeta}, t') - \Delta_\varepsilon t\right]\right), \end{aligned} \quad (\text{B5})$$

and this leads to separate linear time dependent phase component as the quasienergies

$$\varepsilon_n = \hbar\omega_0\left(n + \frac{1}{2}\right) - \Delta_\varepsilon, \quad (\text{B6})$$

while rest of the components as time-periodic Floquet modes

$$\begin{aligned} \phi_{n,m}(x, y, t) \equiv & \frac{1}{\sqrt{L_x}} \chi_n[y - y_0 - \zeta(t)] \exp\left(\frac{i}{\hbar}\left[p_x x \right. \right. \\ & \left. \left. + \frac{eE(y - y_0)}{\omega} \cos(\omega t) \right. \right. \\ & \left. \left. + m_e \dot{\zeta}(t)[y - y_0 - \zeta(t)] + \xi\right]\right). \end{aligned} \quad (\text{B7})$$

2. Momentum space representation

To write the Floquet modes in momentum space, we perform continuous Fourier transform over the considered confined space $A = L_x L_y$ for Eq. (7):

$$\begin{aligned} \phi_{n,m}(k_x, k_y, t) &= \exp\left(\frac{-i\gamma(t)}{\hbar} y_0\right) \exp\left(\frac{-i}{\hbar} \left[m_e \dot{\zeta}(t) \zeta(t) - \xi\right]\right) \\ &\times \int_{-L_y/2}^{L_y/2} dy \exp(-i[k_y - \gamma(t)]y) \chi_n[y - \mu(t)] \\ &\times \frac{1}{\sqrt{L_x}} \int_{-L_x/2}^{L_x/2} dx \exp(-ik_x x) \exp\left(\frac{ip_x}{\hbar} x\right), \end{aligned} \quad (\text{B8})$$

where

$$\mu(t) \equiv \frac{eE \sin(\omega t)}{m_e(\omega_0^2 - \omega^2)} + y_0, \quad \gamma(t) \equiv \frac{eE\omega_0^2 \cos(\omega t)}{\hbar\omega(\omega_0^2 - \omega^2)}. \quad (\text{B9})$$

Next using the identity [49]

$$\int_{L_x} dx \exp\left(-ik_x x + \frac{ip_x}{\hbar} x\right) = L_x \delta_{k_x, \frac{p_x}{\hbar}}, \quad (\text{B10})$$

we can derive

$$\begin{aligned} \phi_{n,m}(k_x, k_y, t) &= \Phi_{n,m}(k_y, t) \delta_{k_x, \frac{p_x}{\hbar}} \\ &\times \exp\left(\frac{-i\gamma(t)}{\hbar} y_0\right) \exp\left(\frac{-i}{\hbar} \left[m_e \dot{\zeta}(t) \zeta(t) - \xi\right]\right). \end{aligned} \quad (\text{B11})$$

Here we defined $\Phi_{n,m}(k_y, t)$ as

$$\begin{aligned} \Phi_{n,m}(k_y, t) \equiv & \sqrt{L_x} \int_{-L_y/2}^{L_y/2} dy \chi_n[y - \mu(t)] \\ & \times \exp(-i[k_y - \gamma(t)]y). \end{aligned} \quad (\text{B12})$$

Substituting $k'_y = k_y - \gamma(t)$ and $y' = y - \mu(t)$ and assuming that size of the 2DEG sample in y -direction is large ($L_y \rightarrow \infty$), we can obtain

$$\Phi_{n,m}(k'_y, t) = \sqrt{L_x} e^{-ik'_y \mu} \int_{-\infty}^{\infty} dy' \chi_n(y') \exp(-ik'_y y'). \quad (\text{B13})$$

We can identify that the integral represents the Fourier transform of $\{\chi_n\}$ functions and using the symmetric conditions [63] for the Fourier transform of Gauss-Hermite functions $\theta_n(x)$:

$$\mathcal{FT}[\theta_n(\kappa x), x, k] = \frac{i^n}{|\kappa|} \theta_n(k/\kappa), \quad (\text{B14})$$

Eq. (B13) can be simplified as

$$\Phi_{n,m}(k'_y, t) = \sqrt{L_x} e^{-ik'_y \mu} \tilde{\chi}_n(k'_y), \quad (\text{B15})$$

with

$$\tilde{\chi}_n(k) = \frac{i^n}{\sqrt{2^n n! \sqrt{\pi}}} \left(\frac{1}{\kappa}\right)^{1/2} e^{-\frac{k^2}{2\kappa^2}} \mathcal{H}_n\left(\frac{k}{\kappa}\right). \quad (\text{B16})$$

Substitute Eq. (B15) back in Eq. (B11) and this leads to

$$\begin{aligned} \phi_{n,m}(k_x, k_y, t) &= \sqrt{L_x} \tilde{\chi}_n(k_y - b \cos(\omega t)) \\ &\times \exp\left(i\xi - ik_y \left[d \sin(\omega t) + \frac{\hbar k_x}{eB}\right]\right), \end{aligned} \quad (\text{B17})$$

where

$$b \equiv \frac{eE\omega_0^2}{\hbar\omega(\omega_0^2 - \omega^2)} \quad d \equiv \frac{eE}{m_e(\omega_0^2 - \omega^2)}, \quad (\text{B18})$$

and it is necessary to notice that k_x is quantized with $k_x = 2\pi m/L_x$, $m \in \mathbb{Z}$.

Appendix C: Floquet Fermi golden rule in quantum Hall systems

The derivation of the Floquet Fermi golden rule for our quantum Hall system with the help of $t-t'$ formalism is given here in detail. The $t-t'$ -Floquet states [31, 33]

$$|\psi_{n,m}(t, t')\rangle = \exp\left(-\frac{i}{\hbar} \varepsilon_n t\right) |\phi_{n,m}(t')\rangle. \quad (\text{C1})$$

derived by separating the aperiodic and periodic components of Eq. (12), fulfill the t - t' -Schrödinger equation [31, 33]

$$i\hbar \frac{\partial}{\partial t} |\psi_{n,m}(t, t')\rangle = H_F(t') |\psi_{n,m}(t, t')\rangle, \quad (C2)$$

where *Floquet Hamiltonian* defined as

$$H_F(t') \equiv H_e(t') - i\hbar \frac{\partial}{\partial t'}. \quad (C3)$$

Next we can identify the time evolution operator corresponding to the t - t' -Schrödinger equation

$$U_F(t, t_0; t') = \exp\left(-\frac{i}{\hbar} H_F(t') [t - t_0]\right), \quad (C4)$$

and the advantage of t - t' formalism lies on this time evolution operator which avoids any time ordering operators [31].

For our scenario, consider a time-independent total perturbation $V(\mathbf{r})$ which has been switched on at the reference time $t = t_0$, then the t - t' -Schrödinger equation becomes

$$i\hbar \frac{\partial}{\partial t} |\Psi_{n,m}(t, t')\rangle = [H_F(t') + V(\mathbf{r})] |\Psi_{n,m}(t, t')\rangle, \quad (C5)$$

by introducing new wave function $\Psi_{n,m}$ for the system with the given total perturbation. If $t \leq t_0$, both solutions of the Schrödinger equations (Eq. (C2) and Eq. (C5)) coincide

$$|\psi_{n,m}(t, t')\rangle = |\Psi_{n,m}(t, t')\rangle \quad \text{when } t \leq t_0. \quad (C6)$$

Now move into the interaction picture representation [48, 49] of the t - t' -Floquet state

$$|\Psi_{n,m}(t, t')\rangle_I = U_0^\dagger(t, t_0; t') |\Psi_{n,m}(t, t')\rangle, \quad (C7)$$

and due to time independency, the perturbation in the interaction picture has the same form as Schrödinger picture

$$V_I(\mathbf{r}) = U_0^\dagger(t, t_0; t') V(\mathbf{r}) U_0(t, t_0; t') = V(\mathbf{r}). \quad (C8)$$

This leads to the t - t' -Schrödinger equation in the interaction picture

$$i\hbar \frac{\partial}{\partial t} |\Psi_{n,m}(t, t')\rangle_I = V_I(\mathbf{r}) |\Psi_{n,m}(t, t')\rangle_I, \quad (C9)$$

with the recursive solution [48, 49]

$$\begin{aligned} |\Psi_{n,m}(t, t')\rangle_I &= |\Psi_{n,m}(t_0, t')\rangle_I \\ &+ \frac{1}{i\hbar} \int_{t_0}^t dt_1 V_I(\mathbf{r}) |\Psi_{n,m}(t_1, t')\rangle_I. \end{aligned} \quad (C10)$$

Iterating the solution only upto the first order (Born approximation) we obtain

$$\begin{aligned} |\Psi_{n,m}(t, t')\rangle_I &\approx |\psi_{n,m}(t_0, t')\rangle \\ &+ \frac{1}{i\hbar} \int_{t_0}^t dt_1 V_I(\mathbf{r}) |\psi_{n,m}(t_0, t')\rangle. \end{aligned} \quad (C11)$$

In addition, since our Floquet states create a basis we can represent any solution using these Floquet states

$$|\Psi_\alpha(t, t')\rangle = \sum_{\beta} a_{\alpha,\beta}(t, t') |\psi_\beta(t, t')\rangle. \quad (C12)$$

where we used a single notation to represent two quantum numbers; $\alpha \equiv (n_\alpha, m_\alpha)$ and $\beta \equiv (n_\beta, m_\beta)$. Then we can identify the *scattering amplitude* as $a_{\alpha,\beta}(t, t') = \langle \psi_\beta(t, t') | \Psi_\alpha(t, t') \rangle$ and this can evaluate with

$$\begin{aligned} a_{\alpha,\beta}(t, t') &= \langle \psi_\beta(t, t') | \Psi_\alpha(t, t') \rangle \\ &+ \frac{1}{i\hbar} \int_{t_0}^t dt_1 \langle \psi_\beta(t_1, t') | V(\mathbf{r}) | \Psi_\alpha(t_1, t') \rangle. \end{aligned} \quad (C13)$$

Since the t - t' -Floquet states are orthonormal and assuming $t_0 = 0$ and $\alpha \neq \beta$ this leads to

$$a_{\alpha,\beta}(t, t') = -\frac{i}{\hbar} \int_0^t dt_1 \langle \psi_\beta(t_1, t') | V(\mathbf{r}) | \Psi_\alpha(t_1, t') \rangle. \quad (C14)$$

Now consider a scattering event from a t - t' -Floquet state $|\psi_\beta(t, t')\rangle$ into another t - t' -Floquet state $|\Psi_\alpha(t, t')\rangle$ with constant quasienergy ε :

$$\begin{aligned} |\psi_\beta(t, t')\rangle &= \exp\left(-\frac{i}{\hbar} \varepsilon_\beta t\right) |\phi_\beta(t')\rangle \\ &\longrightarrow |\Psi_\alpha(t, t')\rangle = \exp\left(-\frac{i}{\hbar} \varepsilon t\right) |\Phi_\alpha(t')\rangle. \end{aligned} \quad (C15)$$

It is important to remember that a state of this considering system can be represented by two independent quantum numbers: n represents the Landau level and m represents the quantized momentum in x -direction. The scattering amplitude for this scattering scenario can be calculated using the equation derived in Eq. (C14)

$$a_{\alpha,\beta}(t, t') = -\frac{i}{\hbar} \int_0^t dt_1 e^{\frac{i}{\hbar}(\varepsilon_\beta - \varepsilon)t_1} \langle \phi_\beta(t') | V(\mathbf{r}) | \phi_\alpha(t') \rangle, \quad (C16)$$

and assuming for a long time $t \rightarrow \infty$, we can turn this integral into a delta distribution

$$a_{\alpha,\beta}(t') = -2\pi i \delta(\varepsilon_\beta - \varepsilon) Q, \quad (C17)$$

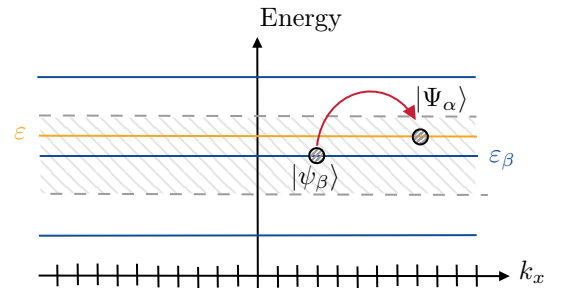


FIG. 6. Scattering from $|\psi_\beta(t, t')\rangle$ to constant energy state $|\Psi_\alpha(t, t')\rangle$ due to scattering potential created by impurities.

where $Q \equiv \langle \phi_\beta(t') | V(\mathbf{r}) | \phi_\alpha(t') \rangle$ and using completeness properties we can re-write this as

$$Q = \sum_{\mathbf{k}} \sum_{\mathbf{k}'} \langle \phi_\beta(t') | \mathbf{k}' \rangle \langle \mathbf{k}' | V(\mathbf{r}) | \mathbf{k} \rangle \langle \mathbf{k} | \phi_\alpha(t') \rangle, \quad (\text{C18})$$

and separating x and y directional momentums we can derive (we already assumed that $L_y \rightarrow \infty$)

$$Q = \sum_{k_x} \sum_{k'_x} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} dk_y dk'_y V_{\mathbf{k}', \mathbf{k}} \phi_\beta^\dagger(\mathbf{k}', t') \phi_\alpha(\mathbf{k}, t'). \quad (\text{C19})$$

with $V_{\mathbf{k}', \mathbf{k}} \equiv \langle \mathbf{k}' | V(\mathbf{r}) | \mathbf{k} \rangle$.

Since the perturbation potential $V(\mathbf{r})$ is assumed to be formed by an ensemble of randomly distributed impurities, consider N_{imp} identical impurities positioned at randomly distributed but fixed positions \mathbf{r}_i . Then scattering potential $V(\mathbf{r})$ is given by the sum over uncorrelated single impurity potentials $v(\mathbf{r})$

$$V(\mathbf{r}) \equiv \sum_{i=1}^{N_{imp}} v(\mathbf{r} - \mathbf{r}_i). \quad (\text{C20})$$

Next we model the perturbation $V(\mathbf{r})$ as a Gaussian random potential where one can choose the zero of energy such that the potential is zero on average. This model is characterized by [64]

$$\langle v(\mathbf{r}) \rangle_{imp} = 0, \quad (\text{C21a})$$

$$\langle v(\mathbf{r}) v(\mathbf{r}') \rangle_{imp} = \Upsilon(\mathbf{r} - \mathbf{r}'), \quad (\text{C21b})$$

where $\langle \cdot \rangle_{imp}$ denoted the average over realizations of the impurity disorder and $\Upsilon(\mathbf{r} - \mathbf{r}')$ is any decaying function depends only on $\mathbf{r} - \mathbf{r}'$. In addition, this model assume that $v(\mathbf{r} - \mathbf{r}')$ only depends on the position difference $|\mathbf{r} - \mathbf{r}'|$ and it decays with a characteristic length r_c . Since this study considers the case where the waveleagth of radiation or scattering electrons is much faster than r_c , it is a good approximation to make two-point correlation function to be

$$\langle v(\mathbf{r}) v(\mathbf{r}') \rangle_{imp} = \Upsilon_{imp}^2 \delta(\mathbf{r} - \mathbf{r}'), \quad (\text{C22})$$

where Υ_{imp} is strength of the delta potential and a random potential $V(\mathbf{r})$ with this property is called white noise [64]. Then we can model approximately the total scattering potential as

$$V(\mathbf{r}) = \sum_{i=1}^{N_{imp}} \Upsilon_{imp} \delta(\mathbf{r} - \mathbf{r}_i). \quad (\text{C23})$$

Then we can calculate $V_{\mathbf{k}', \mathbf{k}}$ using this assumption as

follows

$$V_{\mathbf{k}', \mathbf{k}} = \left\langle \mathbf{k}' \left| \sum_{i=1}^{N_{imp}} \Upsilon_{imp} \delta(\mathbf{r} - \mathbf{r}_i) \right| \mathbf{k} \right\rangle \quad (\text{C24a})$$

$$= \sum_{i=1}^{N_{imp}} \int_{-\infty}^{\infty} dy \left[\frac{1}{\sqrt{L_x L_y}} e^{ik'_y y} \delta(y - y_i) \right. \\ \left. \times \frac{1}{\sqrt{L_x L_y}} e^{-ik_y y} \langle k'_x | \Upsilon_{imp} \delta(x - x_i) | k_x \rangle \right] \quad (\text{C24b})$$

$$= \sum_{i=1}^{N_{imp}} \frac{1}{L_x L_y} e^{i(k'_y - k_y)y} \langle k'_x | \Upsilon_{imp} \delta(x - x_i) | k_x \rangle. \quad (\text{C24c})$$

Since $v(\mathbf{r})$ in momentum space is a constant value, each impurity produce same impurity potential for every x -directional momentum pairs and assuming the total number of scatterers N_{imp} is macroscopically large, we can derive

$$V_{\mathbf{k}', \mathbf{k}} = V_{k'_x, k_x} \frac{N_{imp}}{L_y L_x} \int_{-\infty}^{\infty} dy_i e^{i(k'_y - k_y)y_i} \quad (\text{C25a})$$

$$= \eta_{imp} V_{k'_x, k_x} \delta(k'_y - k_y), \quad (\text{C25b})$$

where

$$V_{k'_x, k_x} \equiv \langle k'_x | \Upsilon_{imp} \delta(x - x_i) | k_x \rangle. \quad (\text{C26})$$

is a constant value for every i impurity and η_{imp} is number of impurities in a unit area. It is important to notice that $|k_x\rangle = e^{-ik_x x}$.

Now using Eq. (9) and Eq. (C25) on Eq. (C19), we obtain (with changing variable $t' \rightarrow t'$)

$$Q = \sum_{k_x} \sum_{k'_x} \eta_{imp} V_{k'_x, k_x} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} dk_y dk'_y \delta(k'_y - k_y) \\ \times \sqrt{L_x} \exp(ik'_y [d \sin(\omega t) + y'_0]) \tilde{\chi}_{n_\beta}(k'_y - b \cos(\omega t)) \\ \times \sqrt{L_x} \exp(-ik_y [d \sin(\omega t) + y_0]) \tilde{\chi}_{n_\alpha}(k_y - b \cos(\omega t)), \quad (\text{C27})$$

and this can simplify as

$$Q = \sum_{k_x} \sum_{k'_x} \eta_{imp} L_x V_{k'_x, k_x} I, \quad (\text{C28})$$

with

$$I \equiv \int_{-\infty}^{\infty} dk_y \tilde{\chi}_{n_\beta}(k_y - b \cos(\omega t)) \tilde{\chi}_{n_\alpha}(k_y - b \cos(\omega t)) \\ \times \exp(-ik_y [y_0 - y'_0]). \quad (\text{C29})$$

To avoid the energy exchange from external strong field and electrons, the applied radiation should be a purely dressing field. Therefore, the only effect of the dressing field on 2DEG is the renormalization of the probability of elastic electron scattering within the same Landau level

($n_\alpha = n_\beta = N$). This transform the Eq. (C29) to

$$I = \int_{-\infty}^{\infty} dk_y \tilde{\chi}_N^2(k_y - b \cos(\omega t)) \exp(-ik_y[y_0 - y'_0]). \quad (\text{C30})$$

Using Fourier transform of Gauss-Hermite functions [63] and convolution theorem [65, 66] we can derive

$$I = 2\pi \exp(b[y'_0 - y_0] \cos(\omega t)) \times \int_{-\infty}^{\infty} dy \chi_N(y) \chi_N(y_0 - y'_0 - y). \quad (\text{C31})$$

Therefore finally the scattering amplitude derived in Eq. (C17) can be evaluated for given $k_x = 2\pi m_\alpha/L_x$ and $k'_x = 2\pi m_\beta/L_x$ as

$$a_{\alpha\beta}(k_x, k'_x, t) = -2\pi i \eta_{imp} L_x V_{k'_x, k_x} \delta(\varepsilon_N - \varepsilon) \times \exp(b[y'_0 - y_0] \cos(\omega t)) \times \int_{-\infty}^{\infty} dy \chi_N(y) \chi_N(y_0 - y'_0 - y), \quad (\text{C32})$$

Since this scattering amplitude is time-periodic we can write this as a Fourier series expansion

$$a_{\alpha\beta}(k_x, k'_x, t) = \sum_{l=-\infty}^{\infty} a_{\alpha\beta}^l(k_x, k'_x) e^{-il\omega t}. \quad (\text{C33})$$

In addition, using Jacobi-Anger expansion [67, 68]

$$e^{iz \cos(\theta)} = \sum_{l=-\infty}^{\infty} i^l J_l(z) e^{-il\theta}, \quad (\text{C34})$$

where $J_l(z)$ are Bessel functions of the first kind with l -th integer order and we can re-write the Eq. (C32) as follows

$$a_{\alpha\beta}(k_x, k'_x, t) = \sum_{l=-\infty}^{\infty} -2\pi i^{l+1} \eta_{imp} L_x V_{k'_x, k_x} \delta(\varepsilon_N - \varepsilon) \times J_l(b[y'_0 - y_0]) \times \int_{-\infty}^{\infty} dy \chi_N(y) \chi_N(y_0 - y'_0 - y) e^{-il\omega t}, \quad (\text{C35})$$

and then the Fourier series component can be identified as

$$a_{\alpha\beta}^l(k_x, k'_x) = -2\pi i^{l+1} \eta_{imp} L_x V_{k'_x, k_x} \times \delta(\varepsilon_N - \varepsilon) J_l(b[y'_0 - y_0]) \times \int_{-\infty}^{\infty} dy \chi_{n_\beta}(y) \chi_{n_\beta}(y_0 - y'_0 - y). \quad (\text{C36})$$

Now define *transition probability matrix*

$$(A_{\alpha\beta})_{l,l'} \equiv a_{\alpha\beta}^l [a_{\alpha\beta}^{l'}]^*, \quad (\text{C37})$$

and this becomes

$$(A_{\alpha\beta})_{l,l'}(k_x, k'_x) = [2\pi \eta_{imp} L_x |V_{k'_x, k_x}|]^2 \delta^2(\varepsilon_N - \varepsilon) \times J_l(b[y'_0 - y_0]) J_{l'}(b[y'_0 - y_0]) \times \left| \int_{-\infty}^{\infty} dy \chi_{n_\beta}(y) \chi_{n_\beta}(y_0 - y'_0 - y) \right|^2. \quad (\text{C38})$$

Then describing the square of the delta distribution using following procedure [26, 30]

$$\delta^2(\varepsilon) = \delta(\varepsilon) \delta(0) = \frac{\delta(\varepsilon)}{2\pi\hbar} \int_{-t/2}^{t/2} e^{i0 \times t'/\hbar} dt' = \frac{\delta(\varepsilon)t}{2\pi\hbar}, \quad (\text{C39})$$

and performing the time derivation of each matrix element yield the *transition amplitude matrix*:

$$\Gamma_{\alpha\beta}^{ll'}(k_x, k'_x) = \frac{2\pi \eta_{imp}^2 L_x^2}{\hbar} |V_{k'_x, k_x}|^2 \delta(\varepsilon_\beta - \varepsilon) \times J_l(b[y'_0 - y_0]) J_{l'}(b[y'_0 - y_0]) \times \left| \int_{-\infty}^{\infty} dy \chi_N(y) \chi_N(y_0 - y'_0 - y) \right|^2. \quad (\text{C40})$$

An impurity average of white noise potential allows to identify $\langle |V_{k'_x, k_x}|^2 \rangle = V_{imp}$ and the inverse scattering time matrix is the sum over all momentum over the transition probability matrix

$$\left(\frac{1}{\tau(\varepsilon, k_x)} \right)_{\alpha\beta}^{ll'} \equiv \frac{1}{L_x} \sum_{k'_x} \langle \Gamma_{\alpha\beta}^{ll'}(k'_x, k_x) \rangle_{imp}, \quad (\text{C41})$$

and applying the 1-dimensional momentum continuum limit $\sum_{k'_x} \rightarrow L_x/2\pi \int dk'_x$ and this leads to

$$\left(\frac{1}{\tau(\varepsilon, k_x)} \right)_{\alpha\beta}^{ll'} = \frac{2\pi \eta_{imp}^2 L_x^2}{\hbar} \frac{V_{imp}}{2\pi} \delta(\varepsilon_\beta - \varepsilon) = \int_{-\infty}^{\infty} dk'_x J_l\left(\frac{b\hbar}{eB}[k_x - k'_x]\right) J_{l'}\left(\frac{b\hbar}{eB}[k_x - k'_x]\right) \times \left| \int_{-\infty}^{\infty} dy \chi_{n_\beta}(y) \chi_{n_\beta}\left(\frac{\hbar}{eB}[k'_x - k_x] - y\right) \right|^2. \quad (\text{C42})$$

Using substitution $k'_x = k_1$ and $y = \hbar k_2/eB$ finally we can derive our expression for the inverse scattering time matrix for N -th Landau level

$$\left(\frac{1}{\tau(\varepsilon, k_x)} \right)_N^{ll'} = \frac{\eta_{imp}^2 L_x^2 \hbar V_{imp}}{(eB)^2} \delta(\varepsilon - \varepsilon_N) \times \int_{-\infty}^{\infty} dk_1 J_l\left(\frac{b\hbar}{eB}[k_x - k_1]\right) J_{l'}\left(\frac{b\hbar}{eB}[k_x - k_1]\right) \times \left| \int_{-\infty}^{\infty} dk_2 \chi_N\left(\frac{\hbar}{eB}k_2\right) \chi_N\left(\frac{\hbar}{eB}[k_1 - k_x - k_2]\right) \right|^2. \quad (\text{C43})$$

Appendix D: Current operators in dressed Landau levels

In this section we are hoping to derive the current density operator for N -th Landau level. We already found the exact solution for our time dependent Hamiltonian Eq. (1) and we identified them as Floquet states with quasienergies Eq. (12). The Floquet modes derived in Eq. (9) can be represented as states using quantum number for the simplicity of notation as follows

$$|\phi_{n,m}\rangle \equiv |n, k_x\rangle. \quad (D1)$$

Using above complete set of eigenstates of Floquet Hamiltonian Eq. (C3) [31, 33, 53] we can represent the single particle current operator's matrix element as

$$(\mathbf{j})_{nm,n'm'} \equiv \langle n, k_x | \hat{\mathbf{j}} | n', k'_x \rangle, \quad (D2)$$

and particle current operator for our system [48, 49] by

$$\hat{\mathbf{j}} = \frac{1}{m}(\hat{\mathbf{p}} - e[\mathbf{A}_s + \mathbf{A}_d(t)]). \quad (D3)$$

where m is mass of the considering particle.

First consider the transverse conductivity in x -direction and we can identify that x -directional current operator as

$$\hat{j}_x = \frac{1}{m} \left(-i\hbar \frac{\partial}{\partial x} + eBy \right). \quad (D4)$$

Now calculate the matrix elements of x -directional current operator in Floquet mode basis

$$(j_x)_{nm,n'm'} = \langle n, k_x | \frac{1}{m} \left(-i\hbar \frac{\partial}{\partial x} + eBy \right) | n', k'_x \rangle. \quad (D5)$$

Then evaluate these using Floquet modes derived in Eq. (7) and obtain

$$(j_x)_{nm,n'm'} = \frac{1}{m} \delta_{k_x, k'_x} \int dy \left[(\hbar k'_x + eBy) \times \chi_n(y - y_0 - \zeta(t)) \chi_{n'}(y - y_0 - \zeta(t)) \right]. \quad (D6)$$

Then let $y - y_0 - \zeta(t) = \bar{y}$ and we can derive

$$(j_x)_{nm,n'm'} = \frac{1}{m} \delta_{k_x, k'_x} \int d\bar{y} \left[(\hbar k'_x + eB\bar{y} - \hbar k'_x + eB\zeta(t)) \times \chi_n(\bar{y}) \chi_{n'}(\bar{y}) \right]. \quad (D7)$$

Using following integral identities of Floquet modes which are made up with Gauss-Hermite functions [69, 70]

$$\int dy \chi_n(y) \chi_{n'}(y) = \delta_{n',n}, \quad (D8a)$$

$$\int dy y \chi_n(y) \chi_{n'}(y) = \left(\sqrt{\frac{n+1}{2}} \delta_{n',n+1} + \sqrt{\frac{n}{2}} \delta_{n',n-1} \right), \quad (D8b)$$

we simplify the matrix elements of x -directional current operator to

$$(j_x)_{nm,n'm'} = \frac{1}{m} \delta_{k_x, k'_x} eB \times \left[\left(\sqrt{\frac{n+1}{2}} \delta_{n',n+1} + \sqrt{\frac{n}{2}} \delta_{n',n-1} \right) + \zeta(t) \delta_{n',n} \right]. \quad (D9)$$

Due to high complexity of exact solution, in this study we only consider the constant contribution. Therefore we evaluate the $s = 0$ component of the Fourier series with

$$(j_{s=0}^x)_{nm,n'm'} = \frac{eB}{m} \delta_{k_x, k'_x} \times \left(\sqrt{\frac{n+1}{2}} \delta_{n',n+1} + \sqrt{\frac{n}{2}} \delta_{n',n-1} \right). \quad (D10)$$

For electric current operator we can apply the electron's charge and effective mass and this leads to

$$(j_{s=0}^x)^{electron} = \frac{e^2 B}{m_e} \delta_{k_x, k'_x} \times \left(\sqrt{\frac{n+1}{2}} \delta_{n',n+1} + \sqrt{\frac{n}{2}} \delta_{n',n-1} \right). \quad (D11)$$

Next we consider the transverse conductivity in y -direction and we can identify that y -directional current operator as

$$\hat{j}_y = \frac{1}{m} \left(-i\hbar \frac{\partial}{\partial y} - \frac{eE}{\omega} \cos(\omega t) \right). \quad (D12)$$

Then the matrix elements of y -directional current operator in Floquet mode basis are derived as

$$(j_y)_{nm,n'm'} = \langle n, k_x | \frac{1}{m} \left(i\hbar \frac{\partial}{\partial y} + \frac{eE}{\omega} \cos(\omega t) \right) | n', k'_x \rangle. \quad (D13)$$

After following the same steps done for x -directional current operator, we can derive the $s = 0$ component of matrix elements for y -directional electric current operator

$$(j_{s=0}^y)^{electron} = \frac{ie\hbar}{m_e} \delta_{k_x, k'_x} \times \left[\sqrt{\frac{n}{2}} \delta_{n',n-1} - \sqrt{\frac{n+1}{2}} \delta_{n',n+1} \right]. \quad (D14)$$

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