

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

Kosala Herath, and Malin Premaratne

*Advanced Computing and Simulation Laboratory(ACL),  
Department of Electrical and Computer Systems Engineering,  
Monash University, Clayton, Victoria 3800, Australia*

(Dated: July 23, 2021)

A generalized mathematical model for the transport properties of quantum systems exposed to a stationary magnetic field and a high intensity 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 impurity 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 conductivity in two-dimensional quantum Hall systems can be manipulated using an external strong light. The outcomes align with the theoretical descriptions for undressed systems 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 nanoscale quantum devices.

## I. INTRODUCTION

Manipulating physical systems as a consequence of light engagements inaugurated 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 specialities 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 their 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 acknowledged the driving field as a perturbation field [27, 28] that is not applicable for systems under high-intensity illuminations [31, 33]. When a high intensity electromagnetic field accounts with a perturbation method, the number of higher-order interaction terms that need to be recognized gets escalate. Then a more accurate and powerful concept needs to be adopted and we need to treat the interacting fermion system and the radiation as 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 Refs. [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 technique to exploit the transport attributes of nanostructures by an intense dressing field.

At the other end, 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 experimental [37–39] and theoretical [40–46] point of view. Akira Endo *et al.* [46] previously presented, the 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 yield 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 nonoscillating 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 charge transport in 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 Refs. [41, 45] and as mentioned in A. Endo *et al.* work [46] those models

yields a semi-elliptical broadening for Landau levels and gives barely fitting representations for the experimental findings.

In the present analysis, we report robust mathematical model for dressed two-dimensional electron gas (2DEG) unveiled to another nonoscillating 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 ( $\sigma^{xx}$ ,  $\sigma^{yy}$ ) components of the conductivity tensor in the periodically driven quantum Hall systems by developing a generalized analytical description to identify transport characteristics of dressed quantum Hall systems using Floquet-Drude conductivity [31]. Finally, we demonstrate that our generalized model is agreed with the state-of-the-art conductivity model [46] already developed for specialized quantum Hall systems that have been considered without the external dressing field. Moreover, optical manipulation can be used as a mechanism to utilize transport behavior in numerous two-dimensional nanostructures which serve as a basis for nanoelectronic devices and we believe that our theoretical analysis and visual depictions of numerical results can be used to understand the basic structure and optimize the performance of nanoscale quantum devices.

The paper is organized as follows. In Sec. II, we introduce our dressed quantum Hall system and the exact wave function solutions for the given configuration. Sec. III, provides the Floquet theory interpretation of these wave functions. We introduce Floquet Fermi golden rule for quantum Hall system in Sec. IV, and we use it in Sec. V to derive analytical expressions for longitudinal components of conductivity. The derived theoretical model is further analyzed numerically using empirical system parameters and compared with previous studies in Sec. VI, followed by concluding remarks in Sec. VII.

## II. SCHRODINGER PROBLEM FOR DRESSED QUANTUM HALL SYSTEM

Our system consist of a 2DEG restrained in the  $(x, y)$  plane of the three-dimensional coordinate space. In our analysis, the 2DEG is subjected to a nonoscillating 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 pick the frequency of the dressing field  $\omega$  such that the optical field behaves as a purely dressing field (unabsorbable). Furthermore, we do our analysis with a linearly polarized light and without limiting the generality we choose  $y$ -polarized electric field  $\mathbf{E} = (0, E \sin(\omega t), 0)^T$  as 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 a 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

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

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 momentum  $p_{x,y}$ . 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  $(n, m)$

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

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 the center of the cyclotron orbit on the  $y$ -axis is given by  $y_0 \equiv -p_x/eB$  with  $p_x = 2\pi\hbar m/L_x$ .  $\chi_n$  are well known solutions for Schrödinger equation of a stationary quantum harmonic oscillator

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

where eigenvalues are given by  $\epsilon_n = \hbar\omega_0(n + 1/2)$  and  $\omega_0 \equiv eB/m_e$  is the cyclotron frequency. Each  $n$  value

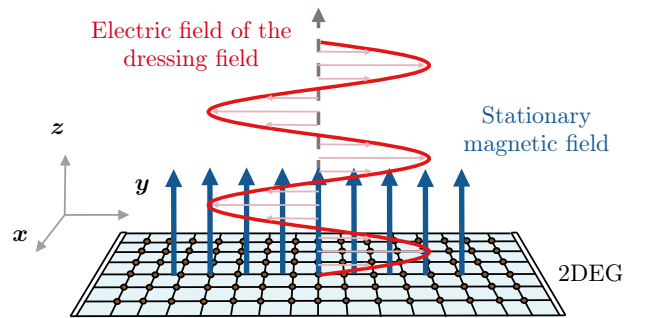


FIG. 1. Our 2DEG system only confined in the  $(x, y)$  plane while both stationary magnetic field  $\mathbf{B}$  and dressing field (with  $y$ -polarized electric field  $\mathbf{E}$ ) are applied perpendicular to the surface of 2DEG.

defines the occupied energy( $\epsilon_n$ ) 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

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

The exponential phase shifts in Eq. (2) represent the influence done by the stationary magnetic field and dressing field. Therefore, we can accept that magneto-transport characteristics of 2DEG can be renormalized by the nonoscillating magnetic field along with 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 quantum systems exposed to strong radiation using the Floquet-Drude conductivity method introduced recently by M. Wackerl *et al.* [31]. In their analysis they have presented more accurate results than previously existed theoretical descriptions for the conductivity of nanoscale systems in presence of a dressing field. Therefore, we are hoping to apply the Floquet-Drude conductivity method to analyze our 2DEG system which is subjected to both a stationary magnetic field and a dressing field.

First we require to recognize the *quasienergies* and time periodic *Floquet modes* [33] for the previously derived wave functions in Eq. (2). By factorizing the wave function into a linearly time dependent part and a periodic time dependent part, the quasienergies can be present as

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

which is only depended on a 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

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

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 no longer valid [54]. Therefore, in this work we choose the dressing field frequency with the condition  $\omega \neq \omega_0$ .

Then performing Fourier transform over the confined two-dimensional space, we obtain the momentum 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

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

Here we used new parameters

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

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

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

### IV. INVERSE SCATTERING TIME ANALYSIS

In Ref. [31] Floquet Fermi golden rule has been introduced as a method to analyze transport properties in dressed disordered quantum systems. However, this theory has not been applied for a dressed quantum Hall system and to identify magneto-transport 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  $\epsilon$  and momentum  $k_x$  value for our considered quantum Hall system

as

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

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  $\varepsilon_N$  is the energy of  $N$ -th Landau level; see Appendix C. In this derivation, we assumed that the perturbation potential is generated by a group of randomly distributed impurities, since random impurities in a disordered metal is a better approximation for experimental results. Thus, the total scattering potential in 2DEG has been presented as the sum of uncorrelated single impurity potentials  $v(\mathbf{r})$ . Here  $\eta_{imp}$  is the number of impurities in a unit area and  $V_{imp} \equiv \langle |V_{k'_x, k_x}|^2 \rangle_{imp}$  with  $V_{k'_x, k_x} = \langle k'_x | v(x) | k_x \rangle$  where  $\langle x | k_x \rangle = e^{-ik_x x}$ . Here  $\langle \cdot \rangle_{imp}$  represents the average over the impurity disorder.

Next we are going to analyze the contribution of the inverse scattering time matrix elements to the transport properties in 2DEG. Since the disorder in the system can not be alter the eigenenergy values of the undressed system [31], we can neglect the all off-diagonal elements of the self-energy, 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 as scattering-induced broadening of the  $N$ -th Landau level as [30, 46]

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

and this leads to

$$\begin{aligned}
& \Gamma_N^{00}(\varepsilon, k_x) \\
&= \frac{\varrho^2}{eB} \delta(\varepsilon - \varepsilon_N) \\
&\times \int_{-\infty}^{\infty} dk_1 \left[ J_0^2 \left( \frac{b\hbar}{eB} [k_x - k_1] \right) \right. \\
&\times \left. \left| \int_{-\infty}^{\infty} dk_2 \chi_N \left( \frac{\hbar}{eB} k_2 \right) \chi_N \left( \frac{\hbar}{eB} [k_1 - k_x - k_2] \right) \right|^2 \right]. \quad (15)
\end{aligned}$$

In addition, for a scenario of scattering take place inside the same Landau level, we are able to present the delta distribution of the energy using the following interpretation [30]

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

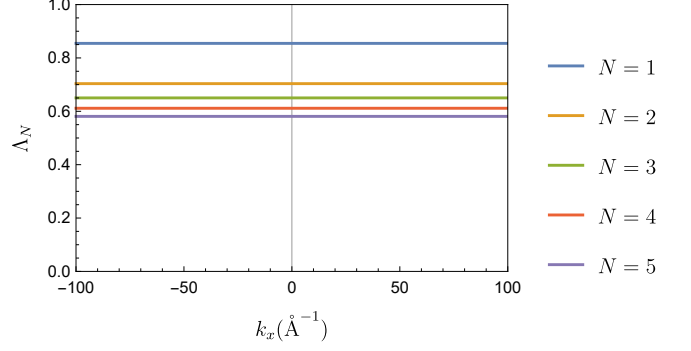


FIG. 2. The dependence of normalized scattering-induced broadening  $\Lambda_N$  for each Landau level ( $N = 0, 1, 2, 3, 4$ ) against  $x$ -directional momentum value  $k_x$  in a GaAs-based quantum well under a nonoscillating magnetic field with  $B = 1.2$  T, dressing field with frequency of  $\omega = 2 \times 10^{12}$  rads $^{-1}$  and intensity  $I = 100$  W/cm $^2$ . In this calculation we have assumed that the natural broadening of 0-th Landau level  $\Gamma_0$  is 0.24 meV.

and we write the central element of inverse scattering time matrix in more compact form

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

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

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

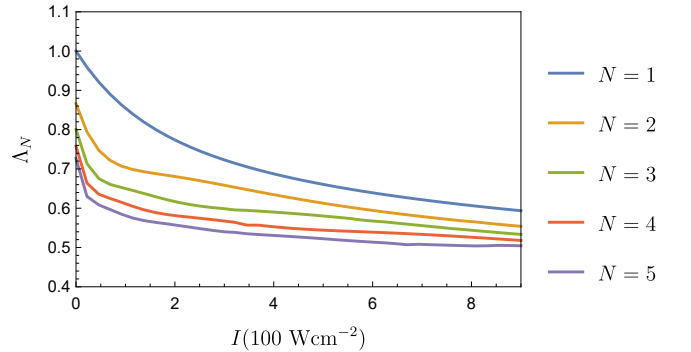


FIG. 3. The dependence of normalized scattering-induced broadening  $\Lambda_N$  for each Landau level ( $N = 0, 1, 2, 3, 4$ ) against dressing field intensity  $I$ , in a GaAs-based quantum well under a nonoscillating magnetic field with  $B = 1.2$  T, dressing field with frequency of  $\omega = 2 \times 10^{12}$  rads $^{-1}$ . In this calculation we have assumed that the natural broadening of 0-th Landau level  $\Gamma_0$  is 0.24 meV.

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 different Landau levels ( $N = 0, 1, 2, 3, 4$ ) has been calculated 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  $m_e \approx 0.07\tilde{m}_e$  where  $\tilde{m}_e$  is mass of the electron [31, 46, 58] and the broadening of the natural(without a dressing field) 0-th Landau level  $\Gamma_0$  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 the each Landau level normalized energy broadening value is independent of the x-directional momentum  $k_x$  value and we are able to change it using applied electromagnetic field. When the applied field's intensity increase the energy broadening gets reduced which make changes in transport properties and in the next section, we are going to derive a analytical expression for the conductivity in dressed quantum Hall systems.

## 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 Refs. [31, 59]. Within this theory, the general x-directional longitudinal DC limit conductivity can be express with

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

where  $j_0^x$  and  $\mathbf{G}^{r,a}(\varepsilon)$  are x-directional electric current operator matrix elements'  $s = 0$  the 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  $s = 0$  Fourier component of the current operator is contributing to the conductivity. In addition,  $A$  is the area of the considering two-dimensional system, partial distribution function is given by  $f$  and  $\Pi$  is a function that can be chosen such that

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

where  $\varepsilon_N$  are quasienergies of all considering Floquet states.

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

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

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

$$\begin{aligned} \sigma^{xx} = & \frac{-1}{4\pi\hbar A} \int_{\Pi-\hbar\omega/2}^{\Pi+\hbar\omega/2} d\varepsilon \left( -\frac{\partial f}{\partial \varepsilon} \right) \frac{1}{V_{k_x}^4} \sum_{k_x} \sum_n \sum_{k_{x1}, k_{x2}, k_{x3}} \sum_{n_1, n_2, n_3} \\ & \times \langle n, k_x | j_0^x | n_1, k_{x1} \rangle \langle n_1, k_{x1} | (\mathbf{G}^r(\varepsilon) - \mathbf{G}^a(\varepsilon)) | n_2, k_{x2} \rangle \langle n_2, k_{x2} | j_0^x | n_3, k_{x3} \rangle \langle n_3, k_{x3} | (\mathbf{G}^r(\varepsilon) - \mathbf{G}^a(\varepsilon)) | n, k_x \rangle. \end{aligned} \quad (23)$$

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

$$\langle n_1, k_{x1} | \mathbf{T}^\dagger (\mathbf{G}^r(\varepsilon) - \mathbf{G}^a(\varepsilon)) \mathbf{T} | n_2, k_{x2} \rangle = \left[ \frac{2i\text{Im}(\mathbf{T}^\dagger \Sigma^r \mathbf{T}) \delta_{n_1, n_2} \delta_{k_{x1}, k_{x2}}}{\left( \frac{1}{\hbar} \varepsilon - \frac{1}{\hbar} \varepsilon_{n_1} \right)^2 + [\text{Im}(\mathbf{T}^\dagger \Sigma^r \mathbf{T})]^2} \right], \quad (24)$$



and

$$\langle n_3, k_{x3} | \mathbf{T}^\dagger (\mathbf{G}^r(\varepsilon) - \mathbf{G}^a(\varepsilon)) \mathbf{T} | n, k_x \rangle = \left[ \frac{2i \text{Im}(\mathbf{T}^\dagger \mathbf{\Sigma}^r \mathbf{T}) \delta_{n_3, n} \delta_{k_{x3}, k_x}}{(\frac{1}{\hbar} \varepsilon - \frac{1}{\hbar} \varepsilon_n)^2 + [\text{Im}(\mathbf{T}^\dagger \mathbf{\Sigma}^r \mathbf{T})]^2} \right], \quad (25)$$

using the retarded self-energy matrix  $\mathbf{\Sigma}^r$  which is the sum of all irreducible diagrams [31, 59]. Using the matrix elements of electric current operator in Landau levels (see Appendix D) and results from Eq. (24) and Eq. (25) back into Eq. (23) we obtain

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

and the only non-zero term would be

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

Since the inverse scattering time matrix being equal to the diagonalized contrast of the retarded and advanced self-energy and on the diagonal the contrast of the retarded and advanced Green's function can be represented with the imaginary component 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

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

with  $\tilde{\Gamma}(\varepsilon_n, k_x) \equiv (\hbar/2\tau(\varepsilon_n, k_x))^{00}$ . 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 we use the 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  $\varepsilon_F$  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  $\Pi = \varepsilon_F$ , the expression for conductivity

leads to

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

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

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

## VI. MANIPULATE CONDUCTIVITY IN QUANTUM HALL SYSTEMS

To identify the characteristics of the longitudinal conductivity of the quantum Hall systems with external dressing field, first we can derive an expression for a normalized longitudinal 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 the 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 longitudinal conductivity in 2DEG using an external dressing field. As given in Fig. 4 and 5 we can manipulate the longitudinal conductivity  $\sigma_{xx}$  using an external dressing field's intensity and the Fermi level  $X_F$  of the considering system. For a given dressing field intensity, the longitudinal 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 aligned with any of the Landau level energy values. In contrast, on each Landau level, the conductivity can achieve very high values compared to other areas and as illustrates in Fig. 4 the peak value of longitudinal conductivity on each Landau level gets increase with the Landau level number.

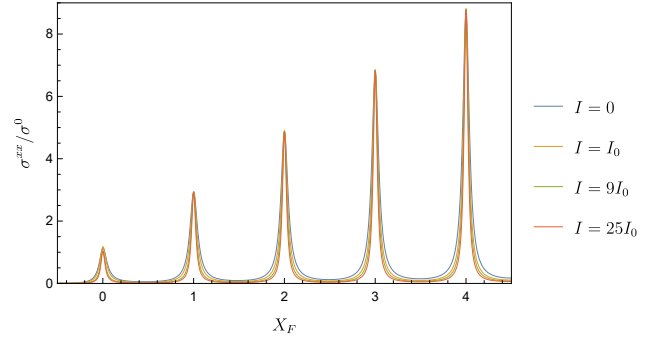


FIG. 4. Normalized longitudinal conductivity  $\sigma_{xx}$  against Fermi level  $X_F$  with different intensities  $I$  of the external dressing field in a GaAs-based quantum well under a nonoscillating magnetic field with  $B = 1.2$  T, dressing field with frequency of  $\omega = 2 \times 10^{12}$   $\text{rads}^{-1}$  and  $I_0 = 100$   $\text{W/cm}^2$ . In this calculation we have assumed that the natural broadening of 0-th Landau level  $\Gamma_0$  is 0.24 meV.

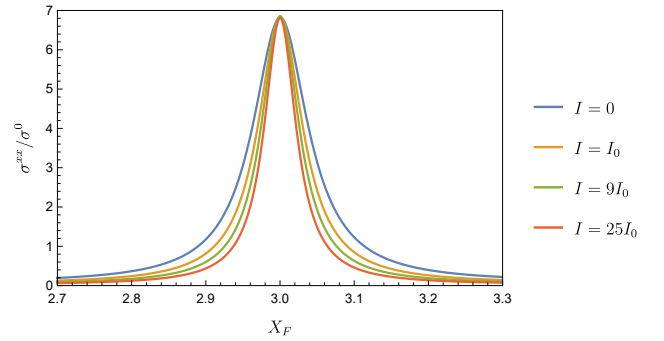


FIG. 5. 3rd Landau level's normalized longitudinal conductivity  $\sigma_{xx}$  against Fermi level  $X_F$  with different intensities  $I$  of the external dressing field in a GaAs-based quantum well under a nonoscillating magnetic field with  $B = 1.2$  T, dressing field with frequency of  $\omega = 2 \times 10^{12}$   $\text{rads}^{-1}$  and  $I_0 = 100$   $\text{W/cm}^2$ . In this calculation we have assumed that the natural broadening of 0-th Landau level  $\Gamma_0$  is 0.24 meV.

Considering the effect of the external dressing field on the longitudinal 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 system. This demonstrates 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 aligned with results demonstrated by K. Dini *et al.* [30] and as they remarked since the Fermi level of the system can be changed with the applied gate voltage of the material this can be used as a 2D switch for nanoscale optoelectronics 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 behavior of the conductivity regions illustrated in

Fig. 4 and 5 are generally incompatible with the results reported in Ref. [30]. This is due to the selection of the conventional longitudinal conductivity theory of 2DEG from Refs. [41, 45]. The semi-elliptical conductivity regions illustrated in Refs. [30, 41, 45], have less consistency 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 aligned with the result mentioned in Ref. [46]. The description of conductivity of quantum Hall systems demonstrated in Ref. [46] has an excellent agreement between the theory and experiment obtained in a GaAs/AlGaAs 2DES for the low magnetic field range. However, they have not considered the tunability that can be achieved with the external strong dressing field. In this analysis, we account for both magnetic and dressing field effects that can be applied to 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 transport properties of quantum Hall systems.

## VII. CONCLUSIONS

In this analysis, we reported a generalized mathematical model for transport properties in a 2DEG under a nonoscillating magnetic field and a high intensity light. With the uniform magnetic field, the charged particles can only settle in discrete energy values and this leads to the Landau quantization. We modeled the behavior of electrons in Landau levels under the dressing field utilizing the 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 considered system.

Our derived analytical expressions disclosed that the transport characteristics 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 analyzed the manipulation of conductivity components using the dressing field. We found that the graphical illustrations we gained are capable of produce the same behavior as the experiment conductivity found in quantum Hall systems without a dressing field. Furthermore, we identified that by regulating the intensity of the radiation, the conductivity regions near the Landau levels can be squeezed. Despite, this behavior has been identified in previous works, their results are not coinciding 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-

sued description for these special quantum Hall systems.

In summary, the primary purpose of this study was to broaden the modern descriptions on transport properties in dressed quantum Hall systems and our detailed theoretical analysis shows that we were able to demonstrate that the 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 to control 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 nanoelectronic devices. Finally, we identified that our findings of this paper can be used towards understanding nanoscale quantum devices, enhancing their performance, and inventing novel appliances.

## ACKNOWLEDGMENTS

K.H wish to acknowledge the members of A $\chi$ L at Monash University for their encouragement and support and specially T. Perera and R.T.Wijesekara for insightful discussions. The work of K.H is supported by the Monash University Institute of Graduate Research.

## Appendix A: Wave function solutions of dressed Landau levels

The deriving process of solutions for time dependent Schrödinger equation with the Hamiltonian of our system (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) eigenfunctions  $\frac{1}{\sqrt{L_x}} \exp\left(\frac{ip_x x}{\hbar}\right)$  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* on the  $y$ -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 Hamil-



tonian

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

where we used a variable substitution  $\tilde{y} = (y - y_0)$ . Now we assume that the wave function solutions for the time-dependent Schrödinger equation of considering quantum system

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

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 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

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

It is important to notice that we can identify the  $S(t) \equiv eE \sin(\omega t)$  part as an 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

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

where

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

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]

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

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

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

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

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

Since set  $\{\chi_n(x)\}$  functions forms a complete set, any general solution  $\vartheta(\tilde{y}, t)$  can be presented with the help of solutions derived 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 time dependent Schrödinger equation Eq. (A4) as follows

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

## 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

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

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

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

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  $2\omega$  frequency. Now using these parameters we can factorize the wave function Eq. (2) as linearly time dependent part and periodic time dependent part as follows

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

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

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

### 2. Momentum space representation

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

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

where

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

Next using the Fourier transform 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

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

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

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

Substituting  $k'_y = k_y - \gamma(t)$  and  $y' = y - \mu(t)$  and assuming that size of the 2DEG sample in  $y$ -direction is considerably 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 for dressed quantum Hall systems

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

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

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

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

where *Floquet Hamiltonian* defined as

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

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

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

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 turned on at the reference time  $t = t_0$ , then the  $t-t'$ -Schrödinger equation becomes

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

and this introduce a new wave function solution  $\Psi_{n,m}$  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

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

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

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

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

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

This drive us to the  $t-t'$ -Schrödinger equation representation in the interaction picture

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

with the recursive solution [48, 49]

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

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

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

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

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

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

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

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

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

Now consider a scattering phenomenon from a  $t$ - $t'$ -Floquet state  $|\psi_\beta(t, t')\rangle$  into a distinct  $t$ - $t'$ -Floquet state  $|\Psi_\alpha(t, t')\rangle$  that occupied with a constant quansienrgy  $\varepsilon$  (Fig. 6):

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

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)

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

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

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

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

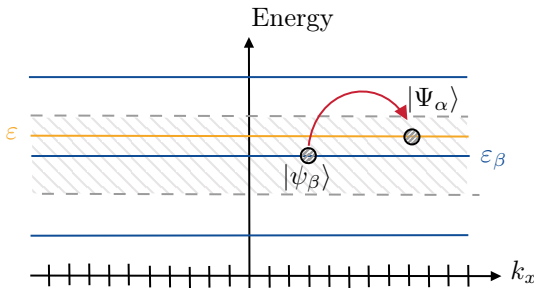


FIG. 6. Scattering from  $|\psi_\beta(t, t')\rangle$  to constant energy state  $|\Psi_\alpha(t, t')\rangle$  due to scattering potential created by impurities.

Since we are presenting the the perturbation potential  $V(\mathbf{r})$  by using a group of randomly distributed impurities, we take into account  $N_{imp}$  number of identical single impurity potentials distributed at randomly but in fixed positions  $\mathbf{r}_i$ . Then scattering potential  $V(\mathbf{r})$  can be identified as the sum of 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 assumes 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 wavelength of radiation or scattering electrons is much greater 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  $\Upsilon_{imp}$  is strength of the delta potential and a random potential  $V(\mathbf{r})$  with this property is called white noise [64]. Then we can approximately model 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

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

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

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

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 scatters  $N_{imp}$  is microscopically 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  $\eta_{imp}$  is number of impurities in a unit area. It is important to notice that  $\langle x | k_x \rangle = e^{-ik_x x}$ .

Now using Eq. (9) and Eq. (C25b) on Eq. (C19), we obtain (with changing variable  $t' \rightarrow t$ )

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

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

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

To avoid the energy exchange from the dressing field and electrons in Landau levels, the applied radiation must be a purely dressing field. Therefore, in this study we assume that the dressing field only can renormalize the the probability of electron scattering inside a same Landau energy 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

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

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

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

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

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

and then the Fourier series component can be identified as

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

Now define *transition probability matrix* as

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

and this becomes

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

Then describing the square of the delta distribution using following interpretation [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 executing the time derivation operation on each matrix element we receive the *transition amplitude matrix* elements:

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

An impurity average of white noise potential allows to identify  $\langle |V_{k'_x, k_x}|^2 \rangle_{imp} = V_{imp}$ . Furthermore, the inverse scattering time matrix can be identified as the sum of all available momentum over the impurity averaged transition probability matrix element [31, 59]

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

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

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

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 as follows

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

#### 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

in 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

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

and the particle current operator for our system [48, 49] can be identified as

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

where  $\tilde{m}$  is mass of the considering particle.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

operator as

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

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

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

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 as

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

- 
- [1] G. Grynberg, A. Aspect, and C. Fabre, *Introduction to Quantum Optics: From the Semi-classical Approach to Quantized Light* (Cambridge University Press, 2010).
- [2] Y. Liu, N. O. Weiss, X. Duan, H. C. Cheng, Y. Huang, and X. Duan, *Nat. Rev. Mater.* **1**, 16042 (2016).
- [3] R. T. Wijesekara, S. D. Gunapala, M. I. Stockman, and M. Premaratne, *Phys. Rev. B* **101**, 245402 (2020).
- [4] L. Tao, Z. Chen, Z. Li, J. Wang, X. Xu, and J.-B. Xu, *InfoMat* **3**, 36 (2020).
- [5] D. Rodrigo, O. Lima, D. Janner, D. Etezadi, F. J. G. De Abajo, V. Pruneri, and H. Altug, *Science* **349**, 165 (2015).
- [6] S. Pirandola, B. R. Bardhan, T. Gehring, C. Weedbrook, and S. Lloyd, *Nat. Photonics* **12**, 724 (2018).
- [7] H. Hapuarachchi, S. Mallawaarachchi, H. T. Hattori, W. Zhu, and M. Premaratne, *J. Phys. Condens. Matter.* **30**, 054006 (2018).
- [8] M. Yuan, M. Liu, and E. H. Sargent, *Nature Energy* **1**, 16016 (2016).
- [9] B. Sun, O. Ouellette, F. P. G. de Arquer, O. Voznyy, Y. Kim, M. Wei, A. H. Proppe, M. I. Saidaminov, J. Xu, M. Liu, *et al.*, *Nat. Commun.* **9**, 4003 (2018).
- [10] J. Huh, G. G. Guerreschi, B. Peropadre, J. R. McClean, and A. Aspuru-Guzik, *Nat. Photonics* **9**, 615 (2015).
- [11] S. Slussarenko and G. J. Pryde, *Appl. Phys. Rev.* **6**, 041303 (2019).
- [12] U. L. Andersen, *Nature* **591**, 40 (2021).
- [13] A. Marais, B. Adams, A. K. Ringsmuth, M. Ferretti, J. M. Gruber, R. Hendrikx, M. Schuld, S. L. Smith, I. Sinayskiy, T. P. Krüger, *et al.*, *J. R. Soc. Interface* **15**, 20180640 (2018).
- [14] F. Bian, L. Sun, L. Cai, Y. Wang, and Y. Zhao, *Proc. Natl. Acad. Sci.* **117**, 22736 (2020).
- [15] N. Rivera and I. Kaminer, *Nat. Rev. Phys.* **2**, 538 (2020).
- [16] V. M. Shalaev, *Nat. Photonics* **1**, 41 (2007).
- [17] K. J. Si, D. Sikdar, Y. Chen, F. Eftekhari, Z. Xu, Y. Tang, W. Xiong, P. Guo, S. Zhang, Y. Lu, *et al.*, *ACS Nano* **8**, 11086 (2014).
- [18] H. Hapuarachchi, S. D. Gunapala, and M. Premaratne, *J. Phys. Condens. Matter.* **31**, 325301 (2019).
- [19] T. Perera, S. D. Gunapala, M. I. Stockman, and M. Premaratne, *J. Phys. Chem. C* **124**, 27694 (2020).
- [20] Y. Zhang, R. E. Russo, and S. S. Mao, *Appl. Phys. Lett.* **87**, 043106 (2005).
- [21] W. W. Chow and F. Jahnke, *Prog. Quantum. Electron.* **37**, 109 (2013).
- [22] M. Tsang, *Phys. Rev. A* **81**, 063837 (2010).
- [23] A. Devi, S. D. Gunapala, M. I. Stockman, and M. Premaratne, *Phys. Rev. A* **102**, 013701 (2020).
- [24] T. Kitagawa, T. Oka, A. Brataas, L. Fu, and E. Demler, *Phys. Rev. B* **84**, 235108 (2011).
- [25] Y. Zhou and M. W. Wu, *Phys. Rev. B* **83**, 245436 (2011).
- [26] O. V. Kibis, *Europhys. Lett.* **107**, 57003 (2014).
- [27] A. A. Pervishko, O. V. Kibis, S. Morina, and I. A. Shelykh, *Phys. Rev. B* **92**, 205403 (2015).
- [28] S. Morina, O. V. Kibis, A. A. Pervishko, and I. A. Shelykh, *Phys. Rev. B* **91**, 155312 (2015).
- [29] H. Dehghani, T. Oka, and A. Mitra, *Phys. Rev. B* **91**, 155422 (2015).
- [30] K. Dini, O. V. Kibis, and I. A. Shelykh, *Phys. Rev. B* **93**, 235411 (2016).
- [31] M. Wackerl, P. Wenk, and J. Schliemann, *Phys. Rev. B* **101**, 184204 (2020).
- [32] M. Premaratne and G. P. Agrawal, *Theoretical Foundations of Nanoscale Quantum Devices* (Cambridge University Press, 2021).
- [33] M. Grifoni and P. Hänggi, *Phys. Rep.* **304**, 229 (1998).
- [34] C. Cohen-Tannoudji, J. Dupont-Roc, and G. Grynberg, *Atom—Photon Interactions* (John Wiley & Sons, Ltd, 1998).
- [35] M. Scully and M. Zubairy, *Introduction to Quantum Optics* (Cambridge University Press, 2001).

- [36] S. Girvin and R. Prange, *The quantum Hall effect* (Springer-Verlag, New York, 1990).
- [37] A. Allerman, W. Xu, N. Hauser, and C. Jagadish, *J. Appl. Phys.* **77**, 2052 (1995).
- [38] B. Tieke, R. Fletcher, U. Zeitler, A. Geim, M. Henini, and J. Maan, *Phys. Rev. Lett.* **78**, 4621 (1997).
- [39] W. Pan, J. Xia, H. Stormer, D. Tsui, C. Vicente, E. Adams, N. Sullivan, L. Pfeiffer, K. Baldwin, and K. West, *Phys. Rev. Lett.* **95**, 066808 (2005).
- [40] T. Ando, Y. Matsumoto, Y. Uemura, M. Kobayashi, and K. F. Komatsubara, *J. Phys. Soc. Jpn.* **32**, 859 (1972).
- [41] T. Ando and Y. Uemura, *J. Phys. Soc. Jpn.* **36**, 959 (1974).
- [42] T. Ando, *J. Phys. Soc. Jpn.* **36**, 1521 (1974).
- [43] T. Ando, *J. Phys. Soc. Jpn.* **37**, 622 (1974).
- [44] T. Ando and Y. Uemura, *J. Phys. Soc. Jpn.* **37**, 1233 (1974).
- [45] T. Ando, A. B. Fowler, and F. Stern, *Rev. Mod. Phys.* **54**, 437 (1982).
- [46] A. Endo, N. Hatano, H. Nakamura, and R. Shirasaki, *J. Phys.: Condens. Matter* **21**, 345803 (2009).
- [47] L. Landau, *Z. Physik* **64**, 629 (1930).
- [48] G. D. Mahan, *Many-particle physics* (Springer Science & Business Media, New York, 2000).
- [49] H. Bruus and K. Flensberg, *Many-body quantum theory in condensed matter physics: an introduction* (Oxford University Press, New York, 2004).
- [50] K. Husimi, *Prog. Theor. Phys.* **9**, 381 (1953).
- [51] T. Dittrich, P. Hänggi, G. L. Ingold, B. Kramer, G. Schön, and W. Zwerger, *Quantum Transport and Dissipation* (Wiley-VCH, Weinheim, 1998).
- [52] G. Floquet, *Scientific annals of the École Normale Supérieure* **12**, 47 (1883).
- [53] M. Holthaus, *J. Phys. B: At., Mol. Opt. Phys.* **49**, 013001 (2015).
- [54] V. Popov and A. Perelomov, *J. Exp. Theor. Phys.* **30**, 910 (1970).
- [55] H. Sambe, *Phys. Rev. A* **7**, 2203 (1975).
- [56] U. Peskin, R. Kosloff, and N. Moiseyev, *J. Chem. Phys.* **100**, 8849 (1994).
- [57] S. C. Althorpe, D. J. Kouri, D. K. Hoffman, and N. Moiseyev, *Chem. Phys.* **217**, 289 (1997).
- [58] R. Winkler, *Spin-orbit Coupling Effects in Two-Dimensional Electron and Hole Systems* (Springer, Berlin, 2003).
- [59] M. Wackerl, *Transport in Periodically Driven Systems*, Ph.D. thesis, University of Regensburg (2020).
- [60] N. Tsuji, T. Oka, and H. Aoki, *Phys. Rev. B* **78**, 235124 (2008).
- [61] D. J. Griffiths and D. F. Schroeter, *Introduction to Quantum Mechanics* (Cambridge University Press, 2018).
- [62] R. Shankar, *Principles of Quantum Mechanics* (Springer, New York, 1994).
- [63] E. Celeghini, M. Gadella, and M. A. del Olmo, *Symmetry* **13**, 853 (2021).
- [64] E. Akkermans and G. Montambaux, *Mesoscopic Physics of Electrons and Photons* (Cambridge University Press, 2010).
- [65] G. Arfken, *Mathematical Methods for Physicists* (Academic Press, Inc., San Diego, 1985).
- [66] R. Bracewell, *The Fourier Transform and Its Applications* (McGraw-Hill, New York, 1978).
- [67] A. Cuyt, V. Petersen, B. Verdonk, H. Waadeland, and W. Jones, *Handbook of Continued Fractions for Special Functions* (Springer, Dordrecht, 2008).
- [68] M. Abramowitz and I. A. Stegun, *Handbook of Mathematical Functions with Formulas, Graphs, and Mathematical Tables* (Dover, New York, 1964).
- [69] V. Vedenyapin, A. Sinitsyn, and E. Dulov, *Kinetic Boltzmann, Vlasov and Related Equations* (Elsevier, Amsterdam, 2011).
- [70] G. Szegő, *Orthogonal Polynomials* (American Mathematical Society, New York, 1959).