Strong-Coupling Model for Pulsed Light Propagation and Quantum Kinetics of Electron-Hole Plasmas in Quantum Wire Arrays

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Abstract: A quantum-kinetic model is proposed for ultrafast carrier-scattering dynamics in quantum wires coupled to resonant scattering of ultrashort light pulses. The model includes effects from transverse, longitudinal, and applied DC fields on the wires.

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1. Introduction

A self-consistent quantum-kinetic model is proposed for studying the strong coupling between ultrafast carrier-scattering dynamics of photo-excited electron-hole plasmas in quantum wires and the resonant scattering of an ultrashort light pulse incident on a quantum wire array. The individual electron and hole distributions in momentum space are further driven by an applied DC electric field along the wires, including a resistive force for momentum relaxation due to intrinsic phonon and Coulomb scattering of photo-excited carriers. The combination of an applied DC field with a localized longitudinal electromagnetic field is able to effectively modify an induced transverse polarization field as a quantum back-action of electrons on the propagating light pulse. This strong-coupling model allows us to study the correlation between the localized electronic response of quantum wires and the spatial-temporal features and phases of the scattered light pulses. Additionally, this strong-coupling theory can also reveal a unique correlation between the DC current from the driven electron-hole plasma and the localized longitudinal electromagnetic field due to induced long-lasting plasma oscillations in quantum wires.

2. Theory

2.1. Pulse Propagation

A 2D near-IR laser pulse electric field $\mathbf{E}(x,y,t)$ is initially polarized primarily in the x-direction, the magnetic field is purely in the z-direction $\mathbf{H}(x,y,t)$, and is propagating in the y-direction along the quantum wire as shown in Fig. 1. The propagation is simulated by solving the Maxwell equations for the electric and magnetic fields in a non-magnetic medium. For this, a Psuedo-Spectral Time Domain method is used that casts the Maxwell equations in the Fourier transformed wave-vector ($\mathbf{q}$) space. [1]

2.2. Laser-Semiconductor Plasma Interaction

For photo-excited spin-degenerated electrons and holes in the jth quantum wire, the quantum-kinetic semiconductor Bloch equations are given by [2–4]

$$\frac{dn^{\mathrm{e}}_{j,k}(t)}{dt} = \frac{2}{\hbar}\sum_{k'} \mathrm{Im}\left\{\mathbf{p}_{j,k,k'}(t)\cdot\mathbf{Q}_{j,k',k}(t)\right\} + \left.\frac{\partial n^{\mathrm{e}}_{j,k}(t)}{\partial t}\right|_{\mathrm{rel}}, \tag{1}$$

$$\frac{dn^{\mathrm{h}}_{j,k'}(t)}{dt} = \frac{2}{\hbar}\sum_{k} \mathrm{Im}\left\{\mathbf{p}_{j,k,k'}(t)\cdot\mathbf{Q}_{j,k',k}(t)\right\} + \left.\frac{\partial n^{\mathrm{h}}_{j,k'}(t)}{\partial t}\right|_{\mathrm{rel}}, \tag{2}$$

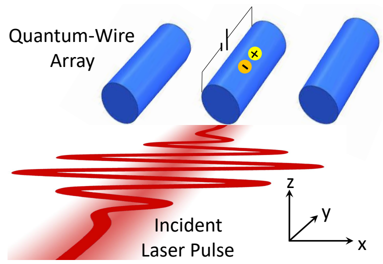

Fig. 1. Illustration of a light pulse propagating within a dielectric layer along the quantum-wire array.

$$
i\hbar\,\frac{d\mathbf{p}_{j,k,k'}(t)}{dt} = \Big[\varepsilon_k^{\rm e}+\varepsilon_{k'}^{\rm h}+\varepsilon_{\rm G}+\Delta\varepsilon_{j,k}^{\rm e}+\Delta\varepsilon_{j,k'}^{\rm h}-i\hbar\Delta_{j,k,k'}^{\rm eh}(t)\Big]\,\mathbf{p}_{j,k,k'}(t)-\Big[1-n_k^{\rm e}(t)-n_{k'}^{\rm h}(t)\Big]\,\mathbf{Q}_{j,k,k'}(t) \qquad (3)
$$
$$
+\,i\hbar\sum_{q\neq 0}\Lambda_{j,k,q}^{\rm e}(t)\,\mathbf{p}_{j,k+q,k'}(t)+i\hbar\sum_{q'\neq 0}\Lambda_{j,k',q'}^{\rm h}(t)\,\mathbf{p}_{j,k,k'+q'}(t)\ ,
$$

where $\mathbf{p}_{j,k,k'}(t)=\sum_{\sigma=x,y}p_{j,k,k'}^{\sigma}(t)\,\hat{\mathbf{e}}_{\mathbf{d}}^{\sigma}$ is the microscopic polarization, $\mathbf{Q}_{j,k,k'}(t)=\sum_{\sigma=x,y}Q_{j,k,k'}^{\sigma}(t)\,\hat{\mathbf{e}}_{\mathbf{d}}^{\sigma}$ is the renormalized Rabi frequency, $n_{j,k}^{\rm e}(t)$ and $n_{j,k'}^{\rm h}(t)$ are the electron (e) and hole (h) occupation numbers at momenta $\hbar k$, and $\hbar k'$, respectively. In Eq. (3) $\varepsilon_{\rm G}$ is the wire bandgap, $\varepsilon_{j,k}^{\rm e}$ and $\varepsilon_{j,k'}^{\rm h}$ are the kinetic energies of electrons and holes, $\Delta\varepsilon_{j,k}^{\rm e}$ and $\Delta\varepsilon_{j,k'}^{\rm h}$ are the Coulomb renormalization [5] of the kinetic energies of electrons and holes, $\Delta_{j,k,k'}^{\rm eh}(t)=\Delta_{j,k}^{\rm e}(t)+\Delta_{j,k'}^{\rm h}(t)$ is the diagonal dephasing rate [6] (quasi-particle lifetime), while $\Lambda_{j,k,q}^{\rm e}(t)$ and $\Lambda_{j,k',q'}^{\rm h}(t)$ are the off-diagonal dephasing rates [6] (pair-scattering) for electrons and holes. The Boltzmann relaxation terms in Eqs. (1) and (2) contain carrier-carrier Coulomb scattering, carrier-phonon scattering, and a drift term resulting from an applied DC field. From these solutions we calculate the 1D wire polarization [7] for use in the Maxwell Equations:

$$
\tilde{\mathbf{P}}_{\rm qw}(\mathbf{q},t)=\sum_{\sigma=x,y}\tilde{P}_{\rm qw}^{\sigma}(\mathbf{q},t)\,\hat{\mathbf{e}}_{\mathbf{d}}^{\sigma}=\sum_j {\rm e}^{-iq_x x_j^{\perp}-q_x^2/4\alpha^2}\sum_{\sigma=x,y}\tilde{P}_j^{\sigma}(q_y,t)\,\hat{\mathbf{e}}_{\mathbf{d}}^{\sigma}\ , \qquad (4a)
$$
$$
\tilde{P}_j^{\sigma}(q_y,t)=\frac{d_{\rm cv}\alpha}{2\delta_0\mathscr{L}}\sum_k p_{j,k+q_y,k}^{\sigma}(t)+\text{H.C.}\ , \qquad (4b)
$$

where $\mathbf{p}_{j,k+q_y,k}(t)$ is determined by Eq. (3), $x_j^{\perp}$ is the transverse position of the jth quantum wire, δ_0 is the thickness of each quantum wire, $d_{\rm cv}$ is the 2D isotropic dipole moment between the valence and conduction band, and H.C. stands for the Hermitian conjugate term. The 1D free-charge density distribution in the wire is given for the Maxwell equations by $\tilde{\rho}_j^{\rm 1D}(q_y,t)=\tilde{\rho}_j^{\rm h}(q_y,t)+\tilde{\rho}_j^{\rm e}(q_y,t)$, where $\tilde{\rho}_j^{\rm h}(q_y,t)$ and $\tilde{\rho}_j^{\rm e}(q_y,t)$ are the charge-density distributions of holes and electrons in the jth quantum wire, which we calculate within the random-phase approximation [8].

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