Linear chirp control of infrared signal in a biased semiconductor thin film

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Abstract. Ultrashort light–matter interactions between a linear chirped pulse and a biased semiconductor thin film GaAs are investigated. Using different chirped pulses, the dependence of infrared spectra on chirp rate is demonstrated for a 5 fs pulse. It is found that the infrared spectra can be controlled by the linear chirp of the pulse. Furthermore, the infrared spectral intensity could be enhanced by two orders of magnitude via appropriately choosing values of the linear chirp rates. Our results suggest a possible scheme to control the infrared signal.

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1. Introduction

It is well known that electrically biased semiconductors excited by a short pulse will yield electromagnetic transients typically found in the far-infrared and mid-infrared range [1]–[3]. Earlier related works on virtual photoconductivity have demonstrated that nonlinearities associated with the virtual transition of electrons and holes can result in very high speed modulation of the intraband current, even for bulk samples [4, 5]. For quantum wells and thin films, this effect is maximized by applying a biased field perpendicular to the in-plane charge carriers.

There are many research results on optical coherent manipulation, for example, Macovei et al [6] discuss the strong-field, steady-state behavior of these systems under the influence of external parameters. In coherent manipulation, chirp control is often a method. It is found that the pulse chirp has very important effects on asymptotically emerging solitons [7], the stability of optical solitons [8], the modification of the group velocity [9], etc. Furthermore, one can utilize the chirp effect to realize coherent manipulation such as optical-harmonic generation [10]; probing proton dynamics in molecules on an attosecond timescale [11]; photoswitching, adaptive femtosecond, quantum control in the liquid phase [12]; transmission performance by using a semiconductor optical amplifier [13]; free carrier injection in GaAs using femtosecond optical pulses [14], and so on.

Recently, ultrashort pulse interaction with a semiconductor was investigated within the regime of resonant optical rectification [15]. They found, using pulse areas of around 1.5–3.5π, that a single shot depends on the carrier-envelope-offset phase. Intrigued by this study, we demonstrate here the chirp effect on the infrared signal in a biased semiconductor thin film. A schematic illustration is given in figure 1. A resonant chirped pulse excites a semiconductor thin film, which leads to oscillation of the carrier density [16]. These density oscillations, when biased with an electric field, manifest in the emission of electromagnetic transients [1, 20]. Here, we consider excitation of the semiconductor thin film with a few-cycle optical pulse of only 5 fs duration.

This paper is organized as follows: in section 2, we present one-dimensional (1D) full-wave Maxwell equations and semiconductor Bloch equations (SBE) for a chirped pulse propagating in a semiconductor thin film. The numerical results are given and discussed in section 3. Finally, some conclusions are given in section 4.

2. Theory model and basic equations

The broadband electron and hole (full band) dispersions [21, 22] in a tight binding approximation are $\epsilon_n = t_0^n - 2t_1^n [\cos(ak_x) + \cos(ak_y) + \cos(ak_z)]$, where $n = e, h$ corresponds to electrons and holes, respectively, and $-\pi/a \leq k_i \leq \pi/a, i = x, y, z$. We take sample parameters close to those for GaAs: $a (= 0.56 \text{nm})$ is the lattice constant, and $t_0^n$ and $t_1^n$ characterize the center of the bands and the width of the bands. The band gap is $E_g (= 1.42 \text{eV})$ and the effective electron and hole masses are $m_e (= 0.069m_0)$, and $m_h (= 0.5m_0)$, where $m_0$ is the free electron mass. The band structure parameters are $t_0^e = \frac{1}{2} E_g + 3(\hbar^2/m_e a^2)$, $t_0^h = \frac{1}{2} E_g + 3(\hbar^2/m_h a^2)$, $t_1^e = \hbar^2/m_e a^2$ and $t_1^h = \hbar^2/m_h a^2$. Since the nonlinear signals are dominated by the huge resonant enhancement at the band edge from the fundamental heavy hole and conduction band transitions, we employ a two-band approximation for the dynamical equations in the present study.

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Figure 1. An ultrashort few-cycle pulse, with initial linear chirp, excites a large density of carries in the semiconductor thin film. Due to the bias, emission dipole-induced electric field propagation in the far field occurs.

For describing the ultrafast light–matter interactions, we adopt the finite-difference, time-domain method to solve the 1D Maxwell equations without any approximation of the slowly varying envelope approximations. The Maxwell equations take the forms:

\[
\frac{\partial}{\partial t} H_y = -\frac{1}{\mu_0} \frac{\partial}{\partial z} E_x, \tag{1}
\]

\[
\frac{\partial}{\partial t} D_x = \frac{\partial}{\partial z} H_y. \tag{2}
\]

Here, \( D_x = \epsilon_0 \epsilon_r E_x + P_{nl} \) is the electric flux density. \( E_x \) is the electric field, \( H_y \) the magnetic field, \( \epsilon_r \) the relative electric permittivity, and \( P_{nl} \) the macroscopic nonlinear polarization along the \( x \)-axis.

On the driving face (\( z = 0 \)), the incident chirped pulse we apply is \( E(z = 0, t) = E_0 \text{sech} \left[-(t - t_0)/\tau_0\right] \cos(\omega t + \chi t^2/2) \), where \( E_0 \) is the amplitude of the pulse, \( t_0 \) the pulse offset, \( \tau_p \left( = 2 \text{arcosh} (\sqrt{2})\tau_0 \right) \) the full width at half maximum of the pulse envelope (5 fs), \( \omega \left( = 1.24 \text{eV} \right) \) the center frequency of the pulse (corresponding to a wavelength of around 1000 nm, which can be realized with a Ti:sapphire laser), and \( \chi \) is the linear chirp rate.

The nonlinear polarization can be obtained using SBE by accounting for two bands and the full region of wave vector space \[23\]

\[
\dot{\rho}_{k}^{\text{ch}}(t) = -i(\epsilon_+ + \epsilon_-)/\hbar \rho_k^{\text{ch}} - i(\rho_k^{\text{ee}} + \rho_k^{\text{hh}} - 1)\Omega_k - \gamma \dot{\rho}_k^{\text{ch}}, \tag{3}
\]

\[
\dot{\rho}_k^{\text{ee}/\text{hh}}(t) = -2\text{Im}[\Omega_k(\rho_k^{\text{eh}})^*]. \tag{4}
\]

Here, \( \Omega_k \left( = d_k E/\hbar \right) \) is the Rabi frequency, with the \( \vec{k} \)-dependent dipole moment \( d_k = d_0 E_g/(\epsilon_+ + \epsilon_-) \) and the optical dipole moment \( d_0 = 0.4e \text{ nm} \). Considering intraband scattering within a relaxation time approximation, we adopt \( \gamma = 40 \text{ fs}^{-1} \) in this paper although it has been verified to be negligible for 5 fs excitation \[15\]. We use the fourth-order Runge–Kutta

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Figure 2. The emitted field spectra 1 cm away from GaAs thin film when the amplitude of the incident pulse is $3 \times 10^9$ V m$^{-1}$. The chirp rate ranges from $-0.025$ to $0.025$ (legend in the figure).

method to solve the SBE. The macroscopic polarization that feeds back to the Maxwell equations are obtained from $P_{nl}(t) = 2V^{-1} \sum_{\vec{k}} d_{k}[\rho_{k}^{eh}(\vec{k}, t) + \text{H.c.}] + P_{\text{surf}}^{(2)}(t)$, where H.c. denotes the Hermitian conjugate. $P_{\text{surf}}^{(2)}(t)$ is phenomenologically taken into account because of important propagational effects and a background or surface second-harmonic-generation contribution to the polarization. We use an average nonlinear susceptibility $\chi^{(2)} = 150$ pm V$^{-1}$ [24] which is independent of the frequency.

The emitted dipole-induced field initiated by the biased field is $E_d = -\mu_0 \bar{P}_d/4\pi r$, though the actual spatial dependence will depend on the geometry. In our numerical analysis, all the material parameters we adopt are based on [15]. We take $r = 1$ cm which results in electromagnetic transients with peak field strength of about 10 kV cm$^{-1}$, comparable to another study [25]. Here, $P_d$ is the dipole field: $P_d = dN_{2D}(t)A$, with $d$ being the bias-induced dipole moment, $A$ being the area of the optical pulse on the sample, which are taken to be 0.8e nm and $\pi(5 \mu m)^2$, respectively. $N_{2D}$ is the 2D sheet density within the thin film which is taken to be 20 nm in thickness with a relative electric permittivity $\epsilon_r = 10.9$, mounted on a sapphire substrate with $\epsilon_r = 3.1$ [26].
3. Results and discussion

In figure 2, we show the emitted spectra in the chirp rate range from $-0.025$ to 0.025. The incident electric field from air is taken to be $3 \times 10^9$ V m$^{-1}$, yielding pulse areas of about $3\pi$ within the sample. Obviously, for the energy range from 1.2 to 3.6 eV, spectrum blueshift occurs for positive chirp while redshift occurs for negative chirp, which is consistent with the results of [27, 28]. However, the infrared spectra, whose energy ranges from 0 to about 1 eV, displays complex features. For clarity, the zoom-in infrared spectra are displayed in figure 3, and the peak value of the infrared spectra versus chirp rate is shown in figure 4. One can see from figure 3 that the infrared spectral intensity is enhanced by two orders of magnitude, i.e. from about $1 \times 10^5$ to $6 \times 10^7$ W m$^{-2}$, when the chirp rate changes from $-0.025$ to 0.015. Moreover, one can find, contrary to the spectra for the energy range from 1.2 to 3.6 eV, that a little blueshift of the spectrum emerges for negative chirp, while little or almost no shift occurs for positive chirp. The infrared spectral intensity increases with increasing chirp rate until a threshold value ($\chi \simeq 0.015$) is reached, then decreases with further increase of the chirp rate, as clearly shown in figure 4.
The above phenomenon can be explained as follows. For any inhomogeneously broadened system that yields an electro-optic effect, extremely short pulses with a center frequency $\omega_0$ can create dipole fields at $\omega_0^{dc}$ (usual infrared frequency range). The emission originates from two distinct physical mechanisms: firstly, infrared frequency emission radiates from internal transitions of excitons; secondly, the origin of the infrared frequency emission is transient photocarrier currents, i.e. there is an initial infrared frequency transient, lasting approximately for the duration of the laser pulse, resulting from the polarization created in the biased semiconductor thin film in which the electron and hole wavefunctions are asymmetric because of the bias. The radiation for the second regime has a broad spectrum extending from dc to the inverse width of the optical pulse, and its strength diminishes as the bias is lowered and the flat-band conditions are approached. Such radiation would also be expected from a biased single quantum well or a biased bulk semiconductor, or a typical semiconductor surface with surface space charge field [2], [29]–[31]. In our simulation, the duration of the pulse (5 fs) corresponds to the energy around 0.827 eV, and the infrared spectrum range is from dc to 1 eV in figure 3. They are almost consistent with each other.

The underlying physics behind the chirp signals can be qualitatively understood from simple nonlinear optics arguments. In the course of pulse propagation in the medium, it can bring an intrinsic chirp. It is possible that the infrared spectra showing nonlinear behavior is due to the influence of the intrinsic chirp. In other words, it may be the result of the initial chirp and the intrinsic chirp together. In the electro-optic regime, the emitted spectra are related to the incident pulse and the bias. The chirp can induce the frequency shift and the carrier sheet density change [32]. Hence, the total bias, which equals the sum of the external bias and the bias induced by the carrier sheet density, may vary with the change of the chirp rate. For an initial chirp rate lower than the threshold value, the total bias increases with the increase of the initial chirp rate [33, 34]; correspondingly, the infrared spectra also increase with the increase of the initial chirp rate. However, for an initial chirp rate higher than the threshold...
value, the total bias decreases with the increase of the chirp rate [33, 34]; correspondingly, the infrared spectra also decrease with the increase of the initial chirp rate. As shown in figure 4, the infrared spectra versus chirp rate displays nonlinear properties, which is consistent with above qualitative analysis.

In addition, we also investigate the effect of the pulse amplitude on the spectra and find that the spectral intensity decreases with the decrease of the amplitude, which is consistent with [25]. More importantly, the infrared signal for different amplitudes of the incident pulse shows similar properties, i.e. the spectral intensity increases with increase of the chirp rate until the threshold value ($\chi \simeq 0.015$) is reached, then decreases with increasing chirp rate. Meanwhile, the infrared spectral intensity can be enhanced by two orders of magnitude when the chirp rate changes from $-0.025$ to $0.015$.

4. Conclusions

In conclusion, we have investigated the effect of linear chirp on the emitted spectra in a biased semiconducting thin film. We found that infrared spectral intensity increases with increasing chirp rate until a threshold value ($\chi \simeq 0.015$) is reached and then decreases. The infrared spectral intensity corresponding to the threshold is about two orders of magnitude higher than that of $\chi = -0.025$. These infrared signal features are independent of the amplitude of the incident pulse. Our results may be helpful in technological control of the infrared signal.

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