Vol 13 No 10, October 2004
1009-1963/2004/13(10)/1742-05

Chinese Physics

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Study of the surface and far fields of terahertz radiation generated by large-aperture photoconductive antennas*

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(Received 5 March 2004; revised manuscript received 30 March 2004)

We have studied analytically the temporal characteristics of terahertz radiation emitted from a biased large-aperture photoconductive antenna triggered by an ultrashort optical pulse. We have included the effects of the finite lifetime and transient mobility dynamics of photogenerated carriers in the analysis. Succinct explicit expressions are obtained for the emitted radiation in the surface field and in the far field. The dependence of the waveforms of the radiated field on the fluence and duration of triggering optical pulse, carrier relaxation time and carrier lifetime are discussed in detail using the obtained expressions.

Keywords: terahertz radiation, photoconductive antenna, current surge, ultrafast optical techniques
PACC: 4280W, 7240, 4110H

1. Introduction

In the last decade, terahertz (THz) technology has attracted much attention of scientists and technicians.[1,2] A large number of techniques for generation and detection of THz radiation have been proposed and/or demonstrated, such as transient photoconductivity,[3,4] optical rectification in crystals with large second order nonlinearity,[5,6] difference frequency generation in non-linear media,[7,8] various quantum oscillations like Bloch oscillations,[9] heavy-hole light-hole beats[10] or oscillations in double-quantum-well structures,[11] negative-effective-mass oscillation,[12,13] 2-dimensional hot-electrons,[14] impurity in a perfect lattice,[15] superconducting thin films,[16] etc. Perhaps the most intriguing application for commercializing THz technology at this time is in the area of THz time-domain spectroscopy or T-ray imaging.[17−24] This technology is based on the generation, detection, and free propagation of sub-picosecond THz electrical pulses. One of the most widely used methods of generating a free propagating THz pulse is through illuminating biased photoconductive antennas with femtosecond laser pulses. It has been shown that intense THz pulses can be generated by large-aperture photoconductive antennas.[25−27] The mechanism of the THz radiation generation from a biased large-aperture photoconductor is generally understood by the well-known current surge model.[28] In this model, a THz electromagnetic field is radiated by a transient current generated at the surface of a photoconductor. The characteristics of the radiation field at the surface and at the far field have been discussed by Hattori *et al.*[27,29] In their analyses, the carrier lifetime is assumed to be infinite, the carrier mobility is considered to be a constant, and the temporal profiles of the generated pulses are simulated by numerical methods. However, Rodriguez *et al*[30] have shown that the transient mobility does influence the characteristics of radiated THz pulses, though they also assumed the carrier lifetime is infinite. However, for the currently widely-used materials, such as low temperature grown GaAs, the carrier lifetime is not so long as to be considered as infinite compared with the radiated THz pulse, thus the carrier lifetime would affect the waveform of the THz radiation. Therefore,

*Project supported by the Major Projects of the National Natural Science Foundation of China (Grant No 10390162), the Special Funds for Major State Basic Research Project (Grant Nos 2001CCA02800G and G20000683), and the Shanghai Municipal Commission of Science and Technology (Grant Nos 03JC14082 and 011661075).

a more detailed analysis including the transient mobility and finite carrier lifetime is needed to describe the characteristics of the radiated THz field more accurately.

In this paper, we include transient mobility and finite carrier lifetime into the current surge model, and get succinct explicit analytic expressions for the radiation field at the surface and in the far field. From the presented expressions, the dependence of the fields on carrier lifetime, transient mobility, and the duration and fluence of the exciting optical pulse is explicit. The dependence has been studied both in the saturated region and in the non-saturated region. These formulae could be used to simulate the waveform of emitted THz radiation or to fit the material parameters.

2. Analytic formulations for near-field and far-field

We perform our analysis based on the current surge model.[28] The model assumes that THz electromagnetic field is radiated by a transient current generated at the surface of a photoconductive antenna. The surface current density $J_s(t)$ is determined by Ohm's law

$$J_s(t) = \sigma_s(t)[E_b + E_s(t)], \tag{1}$$

where $\sigma_s(t)$ is the time-dependent surface conductivity, E_b is the static bias field applied to the antenna, and $E_s(t)$ is the generated radiation field at the antenna surface. From the boundary conditions of Maxwell's equations and the finite size of the large-aperture antenna, the generated radiation field at the antenna surface is related to the surface current density by[28]

$$E_s(t) = -\frac{\eta_0}{1+\sqrt{\varepsilon}} J_s(t), \tag{2}$$

where $\eta_0 = 1/(\varepsilon_0 c) = 376.7$; Ω is the impedance of free space (ε_0 is the permittivity of free space and c is the speed of light in vacuum), and ε is the relative dielectric constant of the photoconductor. Using Eqs.(1) and (2), the radiation field at the antenna surface can be expressed through the bias field as

$$E_s(t) = -\frac{\eta_0 \sigma_s(t)}{\eta_0 \sigma_s(t) + (1+\sqrt{\varepsilon})} E_b. \tag{3}$$

The surface current can be expressed through the applied electric field from Eqs.(1) and (3) as

$$J_s(t) = -\frac{(1+\sqrt{\varepsilon})\sigma_s(t)}{\eta_0 \sigma_s(t) + (1+\sqrt{\varepsilon})} E_b. \tag{4}$$

The transient current at the antenna surface will radiate electromagnetic waves. From Maxwell's equations, in the Coulomb gauge, the radiation field is given by

$$E_{rad}(r,t) = -\frac{1}{4\pi\varepsilon_0 c^2}\frac{\partial}{\partial t}\int \frac{J_s(r', t-|r-r'|/c)}{|r-r'|} \mathrm{d}s', \tag{5}$$

where J_s is surface current in the emitting antenna evaluated at the retarded time, r is the displacement from the antenna centre, $\mathrm{d}s'$ is the increment of surface area at a displacement r' from the antenna centre, and the integration is taken over the surface of the illuminated region of the antenna. Equation (5) shows that the far field is proportional to the time derivative of the surface current density. At present, we are primarily concerned with the temporal shape of the radiated THz field. As a first order approximation, we substitute the integration by multiplying the area of the radiating surface by the surface current density. Thus the radiation at far field is given by

$$E_{far}(t) = \frac{A}{4\pi\varepsilon_0 c^2 z}\frac{(1+\sqrt{\varepsilon})^2 \dot{\sigma}_s(t-z/c)}{[\eta_0 \sigma_s(t-z/c) + (1+\sqrt{\varepsilon})]^2}, \tag{6}$$

where A is the effective emitting area, z is the distance of observation point away from the centre of the area, and the dot above the $\sigma_s(t)$ implies a differential respective to time.

The surface conductivity induced by an optical beam of intensity $I_{opt}(t)$ is a convolution of $I_{opt}(t)$ with time-dependent mobility μ(t) and the carrier decay

$$\begin{aligned}\sigma_s(t) =& \frac{q(1-R)}{h\nu}\int_{-\infty}^{t} \mu(t-t') I_{opt}(t') \\ & \times \exp\left(-\frac{t-t'}{\tau_c}\right)\mathrm{d}t',\end{aligned} \tag{7}$$

where q is the elementary charge, R is the optical reflectivity of the illuminated surface, $h\nu$ is the photon energy, and τ_c is the lifetime of carrier. From the equation of motion of an electron in an electric field

$$\frac{\mathrm{d}v(t)}{\mathrm{d}t} = \frac{qE}{m^*} - \frac{v(t)}{\tau_s} \tag{8}$$

and the definition of mobility, we obtain the time-dependent mobility

$$\begin{aligned}\mu(t) =& \frac{q\tau_s}{m^*}\left[1 - \exp\left(-\frac{t}{\tau_s}\right)\right] \\ =& \mu_s\left[1 - \exp\left(-\frac{t}{\tau_s}\right)\right],\end{aligned} \tag{9}$$

where m^* is the effective mass of electron, τ_s is the relaxation time, and $\mu_s = q\tau_s/m^*$ is the static mobility.

To analyse the effect of the exciting optical pulse, we assume the pump pulse has a Gauss temporal profile as

$$I_{\rm opt}(t) = \frac{F}{2\sqrt{\pi}\Delta t}\exp\left(-\frac{t^2}{\Delta t^2}\right), \tag{10}$$

where F is the total pump optical fluence, and $\sqrt{\ln 2}\Delta t$ is the full width at half maximum (FWHM) of the optical pulse. By inserting Eqs.(9) and (10) into Eq.(7), we can deduce the time-dependent surface conductivity and its time differential as

$$\begin{aligned}\sigma_{\rm s}(t) =& \frac{q^2\tau_{\rm s}}{m^*}\frac{(1-R)F}{4h\nu}\left\{\exp\left(-\frac{t}{\tau_{\rm c}}\right)\exp\left(\frac{\Delta t}{2\tau_{\rm c}}\right)^2\right.\\ &\times\left[1+{\rm erf}\left(\frac{t}{\Delta t}-\frac{\Delta t}{2\tau_{\rm c}}\right)\right]\\ &-\exp\left(-t\left(\frac{1}{\tau_{\rm c}}+\frac{1}{\tau_{\rm s}}\right)\right)\exp\left(\frac{\Delta t}{2}\left(\frac{1}{\tau_{\rm c}}+\frac{1}{\tau_{\rm s}}\right)\right)^2\\ &\left.\times\left[1+{\rm erf}\left(\frac{t}{\Delta t}-\frac{\Delta t}{2}\left(\frac{1}{\tau_{\rm c}}+\frac{1}{\tau_{\rm s}}\right)\right)\right]\right\},\end{aligned} \tag{11}$$

and

$$\begin{aligned}\dot\sigma_{\rm s}(t) =& \frac{q^2\tau_{\rm s}}{m^*}\frac{(1-R)F}{4h\nu}\left\{\left(\frac{1}{\tau_{\rm c}}+\frac{1}{\tau_{\rm s}}\right)\right.\\ &\times\exp\left(-t\left(\frac{1}{\tau_{\rm c}}+\frac{1}{\tau_{\rm s}}\right)\right)\\ &\times\exp\left(\frac{\Delta t}{2}\left(\frac{1}{\tau_{\rm c}}+\frac{1}{\tau_{\rm s}}\right)\right)^2\\ &\times\left[1+{\rm erf}\left(\frac{t}{\Delta t}-\frac{\Delta t}{2}\left(\frac{1}{\tau_{\rm c}}+\frac{1}{\tau_{\rm s}}\right)\right)\right]\\ &-\frac{1}{\tau_{\rm c}}\exp\left(-\frac{t}{\tau_{\rm c}}\right)\exp\left(\frac{\Delta t}{2\tau_{\rm c}}\right)^2\\ &\left.\times\left[1+{\rm erf}\left(\frac{t}{\Delta t}-\frac{\Delta t}{2\tau_{\rm c}}\right)\right]\right\}.\end{aligned} \tag{12}$$

Substituting Eq.(11) into Eq.(3), and Eq.(12) into Eq.(6), we obtain the explicit expressions for the surface field and the far field. The second term in the brace brackets in Eq.(11) and the first term in the brace brackets in Eq.(12) contain the effect of transient carrier mobility on the waveforms of the surface and radiated fields. The error function is the result of the convolution of optical intensity and the exponential decay. It reflects the two competing processes of carrier accumulation by photo-generation and carrier decay by recombination.

By defining a saturation fluence $F_{\rm sat}$:

$$F_{\rm sat} = \frac{4h\nu(1+\sqrt{\varepsilon})}{q\mu_{\rm s}\eta_0(1-R)}, \tag{13}$$

and denoting the parts in brace brackets in Eq.(11) and Eq.(12) as $\Sigma_1(t)$ and $\Sigma_2(t)$, respectively, we can express the radiation field at the surface and in the far field in more compact forms, from which the saturation property of the surface field at large $F/F_{\rm sat}$ is more obvious,

$$E_{\rm s}(t) = -\frac{\dfrac{F}{F_{\rm sat}}\Sigma_1(t)}{1+\dfrac{F}{F_{\rm sat}}\Sigma_1(t)}E_{\rm b}, \tag{14}$$

and

$$E_{\rm far}(t) = \frac{A(1+\sqrt{\varepsilon})}{4\pi c}\frac{\dfrac{F}{F_{\rm sat}}\Sigma_2(t-z/c)}{z\left[1+\dfrac{F}{F_{\rm sat}}\Sigma_1(t-z/c)\right]^2}E_{\rm b}. \tag{15}$$

3. Characteristics of surface-field and far-field

Using the expressions obtained in the previous section, we discuss the waveforms of radiation fields. In Fig.1 we show the temporal shapes of the surface field calculated by Eq.(14). The normalized fluence $F/F_{\rm sat}$ varies from 1 to 10 at step 1. The following typical values for GaAs are used: $\tau_{\rm c}$ = 1ps, $\tau_{\rm s}$ = 0.5ps, Δt = 0.1ps. The figure shows that the risetimes of the surface fields are about 500 fs. It indicates that the risetime of the surface field is determined by the carrier relaxation time. This is because it takes a little time for the transient mobility to reach its quasi-equilibrium value. With the saturation property shown in Eq.(14), the spacing between the amplitudes of the surface fields is being reduced as $F/F_{\rm sat}$ increases.

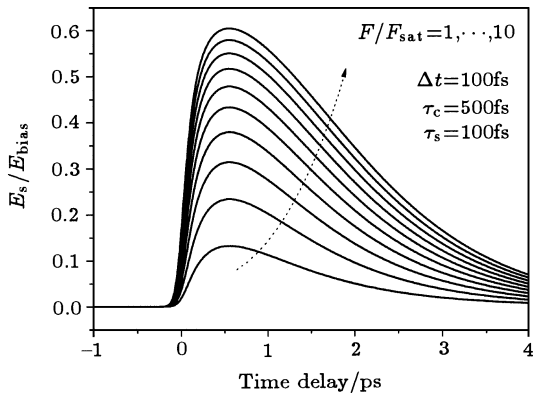


Fig.1. Temporal profiles of surface field at different optical fluence. The curves from bottom to top correspond to varying normalized optical fluence $F/F_{\rm sat}$ from 1 to 10 at step 1. The following standard values: $\tau_{\rm c}$=1 ps, $\tau_{\rm s}$=0.5ps, Δt=0.1ps are used.

In Fig.2 we show the temporal shapes of the radiation far field calculated by Eq.(15) with the main pulses shown inset. The parameters used are the same as in Fig.1, and the distance z is equal to 1 cm. As the fluence increases, the peak of the radiation field increases and tend to saturation; the peak arrives earlier in time, the risetime of the main pulse decreases, and the pulse width decreases also.

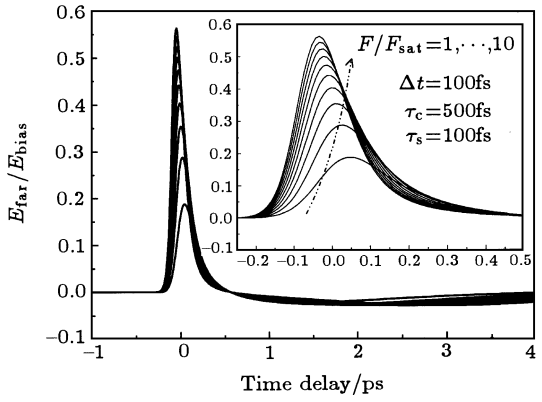


Fig.2. Temporal profiles of radiated field at different optical fluence. The curves from bottom to top correspond to varying normalized optical fluence F/F_{sat} from 1 to 10 at step 1 respectively. The following typical parameter values: τ_c=1ps, τ_s=0.5ps, Δt=0.1ps, z=1cm, A=1cm^2 are used. The inset shows the main pulse.

To see the amplitude saturation and pulse width decrease of the radiation far field more clearly, we display the peak values and pulse width values vs F/F_{sat} in Fig.3. The amplitudes (normalized to bias field) increase from 0.17 to 0.55 and the pulse widths decrease from 240fs to 157fs as F/F_{sat} varies from 1 to 10. The saturation tendency is evident.

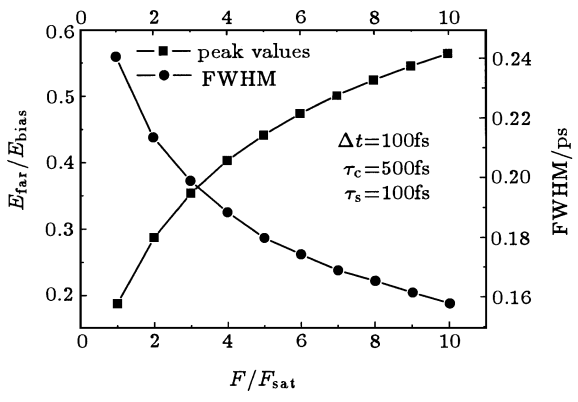


Fig.3. Optical fluence dependence of the peak values and pulse width of the main pulse of the radiated field. The solid square curve shows the shift of the peak values and the solid circle curve shows the narrowing of the pulse width (FWHM).

In Fig.4(a) and Fig.4(b), we show the influence of the relaxation time and the carrier lifetime on the amplitudes of the radiated far field at different optical fluence, respectively. It is not surprising that a long relaxation time results in a small amplitude value. This is due to the carriers reaching their static mobility more slowly, thus the average velocity or the conductivity is low. Longer lifetime of the carriers results in a slightly larger amplitude of the radiation field. This is due to accumulation of more carriers and a larger current generated at the surface. But the influence of carrier lifetime is less pronounced than the influence of relaxation time.

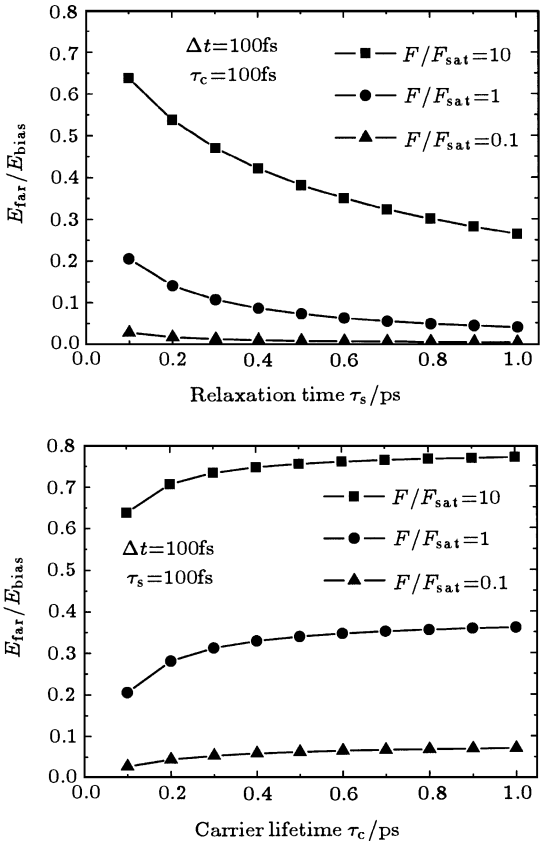


Fig.4. Influence of relaxation time and carrier lifetime on the amplitude of the radiated far field at different optical fluence F/F_{sat}=10, 1, 0.1, respectively: (a) influence of the relaxation time; (b) influence of the carrier lifetime.

The influence of the relaxation time and the carrier lifetime on the pulse width of the radiated far field at different optical fluence are shown in Fig.5(a) and Fig.5(b). The influence of the relaxation time on the pulse width of the radiated far field is much more prominent than the influence of the carrier lifetime. In the strong saturation regime (F/F_{sat} = 10), the influence of the relaxation time is reverse to that in the moderate saturation or in the under-saturation regime

($F/F_{\rm sat} = 1.0$ and $F/F_{\rm sat} = 0.1$). And the influence of the carrier lifetime is not monotonic. There are some fluctuations depending on the optical fluence.

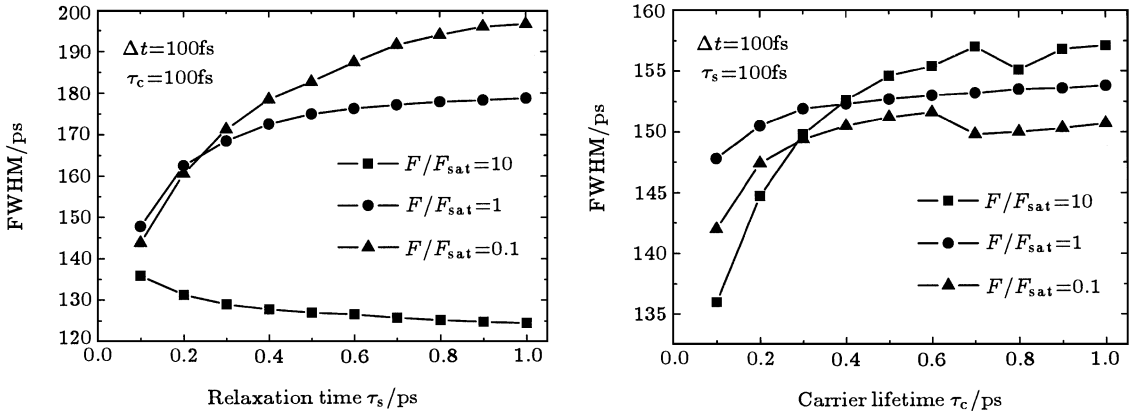


Fig.5. Influence of relaxation time and carrier lifetime on the pulse width of the radiated far field at different optical fluence $F/F_{\rm sat}$=10, 1, 0.1, respectively: (a) influence of the relaxation time; (b) influence of the carrier lifetime.

4. Conclusion

In conclusion, we have presented a model for THz radiation generation by large-aperture photoconductors. We have included the effects of finite carrier lifetime and transient carrier mobility in the model, and obtained succinct expressions for the surface-field and far-field radiation. Using these expressions, the effect of the optical fluence, the carrier relaxation time and the carrier lifetime on the amplitude and the pulse width of the radiated pulse have been discussed in detail.

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