Study on characteristics of terahertz radiation in the surface and far field generated by large-aperture photoconductive antennas

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Abstract. The time-domain characteristics of terahertz radiations emitted from a biased large-aperture photoconductive antenna trigged by an ultra-short optical pulse are studied. Succinct explicit expressions in the surface field and in the far field for the emitted THz radiation fields are deduced based on the well-known current-surge model. The expressions indicate that the THz radiations in the surface and far fields are mainly affected by the incident light intensity, the incident light wavelength, the carrier relaxation time, the reflectivity illuminated at the photoconductor, the carrier lifetime, and the incident light pulse width. The characteristics of THz radiation in the surface and far fields are discussed, and the phenomena of changes in the radiation peak values, the radiation pulse width, and the rising edges are explained in details. Especially the changes in surface fields are explained with the increasing of the ratio of luminous flux. The numerical results indicate that the emitted THz radiation intensity can be increased by enhancing the ratio of luminous flux, prolonging the carrier lifetime, or reducing the incident light pulse width. To avoid the shielding effect of the radiation field, an effectively method is presented that the intense of the incident laser pulse could be divided into multiple beams with low energy to trigger the photoconductive antenna, thus the THz radiation power can be further increased significantly.

1. Introduction
Terahertz (THz) waves occupy a large portion of electromagnetic spectrum between the infrared and microwave bands ranging from 0.1 to 10 THz, having wide potential applications in the field of material science, astronomy, and safety guard and so on. Being lack of efficiently generation and detection methods, the terahertz waves are called “THz gap” before the mid-80s, in the 20th century. The terahertz source is an important part in the terahertz technology and it has become the goal pursued by the scientists in terahertz fields in the 21st century [1].

With the rapid development of ultra-short laser pulse technology over the last decades, the terahertz pulse can be obtained by impelling the semiconductor material or non-linear optical crystal through the ultra-short laser pulse. A lot of terahertz radiation generation and detection methods are proposed such as photoconductive antenna, nonlinear optical rectification, Bloch oscillations and semiconductor lasers [1]. The most applied terahertz generation method propagated in free space is the use of femto-second laser pulse to trigger the biased photoconductive antenna [2]. The distance in the two electrodes of the large-aperture photoconductive antenna is greater than the centre wavelength of
electromagnetic radiation. Experimental results show that the use of large-aperture photoconductive antenna can generate relatively strong THz radiation. The mechanism can be depicted by the famous current surge model [3]. The model deems that the THz electromagnetic waves are generated by transient current in photoconductive antenna. Justin T. Darrow [3], A.J. Taylor [4], Sang-Gyu Park [5] and Zhang tongyi [6] discussed the far-field radiation characteristics of the large-aperture THz photoconductive antenna and derived time-domain expression of the THz radiation field. On this basis, the paper further considers the influence of the ratio of luminous flux, carrier lifetime and the incident THz pulses width on the radiation THz pulses in the surface field and in the far field. An effectively method is presented to avoid the shielding effect of the radiation field.

2. Theoretical analysis
Based on the photoconductive incentive mechanism with the large-aperture photoconductive dipole antenna, the conductivity of GaAs is modulated by electron hole pairs generated in GaAs material by the use of ultra-short laser pulse. Suppose that $E_b$ is the DC (direct current) bias electric field between the two electrodes in the chip of photoconductive dipole. When the chip is not illuminated, it lies in high block state. When the chip is illuminated by ultra-short laser pulse, the photo-induced carriers in the chip of GaAs are accelerated and form transient current $J_s$. The accelerated motion of carriers will generate THz radiation pulse. When the incident laser pulse illuminates the chip, the GaAs photoconductive dipole antenna will radiate THz electromagnetic pulse, as shown in Figure 1 [7].

Through the current surge model [3], the surface current $J_s(t)$ can be expressed as

$$J_s(t) = \sigma_s(t)[E_b + E_s(t)]$$

where $\sigma_s(t)$ is the time-dependent surface conductivity of photoconductive materials, $E_b$ is the static bias field, and $E_s(t)$ is the generated radiation electric field on the photoconductor surface. According to boundary conditions of the Maxwell’s equations, the relationship between $J_s(t)$ and $E_s(t)$ is given by [3]
\[ E_s(t) = -\frac{\eta_0}{1 + \sqrt{\varepsilon}} J_s(t) \]  
\[ \text{where } \eta_0 = 120\pi \Omega \text{ is the free-space wave impedance, and } \varepsilon \text{ is the relative permittivity of the photoconductor.} \]

Substituting equation (2) into equation (1), \( E_s(t) \) can be written as

\[ E_s(t) = -\frac{\eta_0 \sigma_s(t)}{\eta_0 \sigma_s(t) + (1 + \sqrt{\varepsilon})} E_b. \]  
Equation (3) is the radiation surface field by the photoconductive antenna.

Substituting equation (3) into equation (2), the relationship between \( J_s(t) \) and \( E_b \) can be expressed as

\[ J_s(t) = \frac{(1 + \sqrt{\varepsilon}) \sigma_s(t)}{\eta_0 \sigma_s(t) + (1 + \sqrt{\varepsilon})} E_b. \]  
In the far field, the THz radiation fields can be denoted as \[ E_{far}(r, t) = -\frac{1}{4 \pi \varepsilon_0 c^2} \frac{A}{(x^2 + y^2 + z^2)^{1/2}} \frac{d}{dt} \left( t - \frac{r}{c} \right) \] 
in which \( A \) is the effective illumination area of photoconductor electrode, \((x, y, z)\) is the coordinate of observation point, and \( r \) is the distance from the radiation centre to the observation point.

Suppose that one detects the THz radiation fields along the photoconductive axis (i.e., \( x = y = 0 \)) and \( t \rightarrow t - (z / c) \), then equation (5) can be reduced as

\[ E_{far}(r, t) \approx -\frac{1}{4 \pi \varepsilon_0 c^2} \frac{A}{z} \frac{d}{dt} J_s(t). \]

Substituting equation (4) into equation (6), \( E_{far}(r, t) \) is further written as

\[ E_{far}(r, t) \approx -E_b \frac{1}{4 \pi \varepsilon_0 c^2} \frac{A}{z} \frac{1}{(1 + \sqrt{\varepsilon})^2} \frac{1}{\eta_0 \sigma_s(t) + (1 + \sqrt{\varepsilon})} \frac{d\sigma_s(t)}{dt}. \]

From reference [3], the conductivity of the semiconductor is given by

\[ \sigma_s(t) = \frac{q(1 - R)}{h \nu} \mu(t - t') I_{opt}(t') \exp \left(-\frac{t - t'}{\tau_e} \right) dt' \] 
in which \( q \) is the electric charge, \( R \) is the photoconductor reflectivity, \( h \nu \) is the photon energy, \( I_{opt} \) is the energy of laser single pulse, \( \tau_e \) is the carrier lifetime, and \( \mu \) is the transient mobility of photo-induced carriers.

When the bias voltage is low, the photo-induced carriers are not transferred from the centre valley to the satellite valley. The transient mobility of photo-induced carriers can be expressed as \[ \mu(t) = \frac{q \tau_s}{m} \left[ 1 - \exp \left(-\frac{t}{\tau_s} \right) \right] \]
in which $m^*$ is the electron effective mass and $\tau_s$ is the relaxation time of photo-induced carriers.

To analyze the influence of the incident light pulse, $I_{opt}$ is supposed to be Gaussian function [4]

$$I_{opt}(t) = \frac{F}{2\sqrt{\pi} \Delta t} \exp\left(-\frac{t^2}{\Delta t^2}\right)$$  \hspace{1cm} (10)

where $F$ is the total luminous flux, and $\sqrt{\ln 2/\Delta t}$ is the full width at half maximum of excitation light pulse. Substituting equation (9) and equation (10) into equation (8), we have:

$$\sigma_s(t) = \frac{q^2 \tau_s (1-R) F}{4h \nu m^*} X(t)$$  \hspace{1cm} (11)

$$\frac{d\sigma_s(t)}{dt} = \frac{q^2 \tau_s (1-R) F}{4h \nu m^*} Y(t)$$  \hspace{1cm} (12)

where

$$X(t) = \left\{ \exp\left(\frac{t}{\tau_c}\right) \exp\left(\frac{\Delta t}{2\tau_c}\right)^2 \left[ 1 + \text{erf}\left(\frac{t}{\Delta t} - \frac{\Delta t}{2\tau_c}\right) \right] - \exp\left[-t\left(\frac{1}{\tau_c} + \frac{1}{\tau_s}\right)\right] \exp\left[\frac{\Delta t}{2}\left(\frac{1}{\tau_c} + \frac{1}{\tau_s}\right)^2\right] \right\} \times \left[ 1 + \text{erf}\left(\frac{t}{\Delta t} - \frac{\Delta t}{2}\left(\frac{1}{\tau_c} + \frac{1}{\tau_s}\right)\right) \right]\}$$  \hspace{1cm} (13)

$$Y(t) = \left\{ \exp\left(\frac{1}{\tau_c} + \frac{1}{\tau_s}\right) \exp\left[-t\left(\frac{1}{\tau_c} + \frac{1}{\tau_s}\right)\right] \exp\left(\frac{\Delta t}{2}\left(\frac{1}{\tau_c} + \frac{1}{\tau_s}\right)^2\right) \left[ 1 + \text{erf}\left(\frac{t}{\Delta t} - \frac{\Delta t}{2}\left(\frac{1}{\tau_c} + \frac{1}{\tau_s}\right)\right) \right] \ight. \\
- \frac{1}{\tau_c} \exp\left(-\frac{t}{\tau_c}\right) \exp\left(\frac{\Delta t}{2\tau_c}\right)^2 \left[ 1 + \text{erf}\left(\frac{t}{\Delta t} - \frac{\Delta t}{2\tau_c}\right) \right] \right\}.$$  \hspace{1cm} (14)

Substituting equations (11) and (12) into equations (3) and (7), the surface field and far field of the terahertz radiation can be written as

$$E_s(t) = -\frac{(F / F_{sat}) X(t)}{1 + (F / F_{sat}) X(t)} E_b$$  \hspace{1cm} (15)

$$E_{far}(t) = \frac{A(1+\sqrt{\varepsilon})}{4\pi \cdot z \cdot 4\pi \cdot 4\pi \cdot z \cdot P} \left(1-F / F_{sat}\right) X(t) E_b$$  \hspace{1cm} (16)

where $4h\nu(1+\sqrt{\varepsilon}) m^* (q^2 \tau_s (1-R) \eta_0)^{-1} = F_{sat}$ denotes the saturated luminous flux, $P = (\varepsilon_0 \eta_0 c^2)^{-1}$. 


3. Analysis and discussion

3.1. The influence of the ratio of luminous flux $F(F_{\text{sat}})^{-1}$ on the THz radiation waveform

Suppose that $A = 1 \text{cm}^2$, $Z = 1 \text{cm}$, $\tau_e = 1 \text{ps}$, $\tau_s = 0.5 \text{ps}$, $\Delta t = 0.1 \text{ps}$ and $F/F_{\text{sat}} = 1.0, 2.0, 3.0, 4.0, 5.0$, we can obtain the THz radiation waveform in the surface and in the far field, as shown in Figures 2(a) and 2(b). The abscissa in Figure 2 and the following figures denotes the delay time, and the ordinate denotes the ratio of the THz radiation field and the incident field.

![Figure 2(a). The surface field waveform of the THz radiation](image)

![Figure 2(b). The far field waveform of the THz radiation](image)

From Figures 2(a) and 2(b), the peak values of the THz radiation in the surface field and in the far field are on rise and the rising edges of radiation pulses become more and more steep with the increasing of $F(F_{\text{sat}})^{-1}$. Meanwhile, the electron hole pairs generated in GaAs become more and more, the carrier concentration becomes higher, and the current change rate versus time becomes larger, which makes the THz radiation intensity in the surface field and in the far field larger and the radiation pulse width smaller in the far fields. Owing to the characteristics of similar steady-state field in the surface field, the transient current on the surface prolongs longer and the radiation pulse width becomes wider and wider. According to the expression of $F/F_{\text{sat}}$, the incident pulse intensity, the incident wavelength, the carrier relaxation time, and the reflectivity in the effective photoconductor illumination area can change the radiation waveform. Therefore, the terahertz radiation field of photoconductive antenna can be improved by increasing $F(F_{\text{sat}})^{-1}$.

3.2. The influence of the carrier lifetime $\tau_e$ on the THz radiation waveform

Suppose that $A = 1 \text{cm}^2$, $Z = 1 \text{cm}$, $F/F_{\text{sat}} = 1.0$, $\tau_s = 0.5 \text{ps}$, $\Delta t = 0.1 \text{ps}$ and $\tau_e = 0.1 \text{ps}, 0.2 \text{ps}, 0.3 \text{ps}, 0.4 \text{ps}, 0.5 \text{ps}$, we can obtain the THz radiation waveforms in the surface field and in the far field, as shown in Figures 3(a) and 3(b).

From Figures 3(a) and 3(b), with the more longer life of the photon-induced carrier, the peak values of THz radiation in the surface field and in the far field are on rise and the rising edges of THz radiation pulses become more and more steep. It is due to fact that with the extension of photon-induced carrier lifetime, more and more photon-induced carriers accumulate in the photoconductor. Thus more current can be obtained under the effect of static bias field and the radiation peak value becomes larger. Hence the transient current on the surface lasts longer and the THz radiation pulse width becomes wider and wider. Therefore, the terahertz radiation field of photoconductive antenna can be improved by selecting photoconductive materials with long lifetime.
3.3. The influence of the full width at half maximum $\sqrt{\ln 2 \Delta t}$ of exciting pulse on the THz radiation waveform

Suppose that $A = 1cm^2$, $Z = 1cm$, $F / F_{sat} = 1.0$, $\tau_s = 0.5ps$ and $\Delta t = 0.1ps, 0.2ps, 0.3ps, 0.4ps, 0.5ps$, we can obtain the THz radiation waveforms in the surface field and in the far field, as shown in Figures 4(a) and 4(b).

From Figures 4(a) and 4(b), with the increasing of the full width at half maximum of drive pulse, the peak values of THz radiation in surface field and far field are decreased continuously, the rising edges of radiation pulses become more slower and the radiation pulse width becomes increasingly wider. It is due to the fact that with the $\Delta t$ lasts longer, the photocurrent change excited in the photoconductor is more slower, the average speed of carriers gets smaller and the conductivity of photoconductive materials gets smaller. Thus the excited THz radiation peak value gets lower and lower, the transient current lasts longer and the excited THz radiation pulse width becomes increasingly wider. Therefore, the terahertz radiation field of photoconductive antenna can be improved by reducing the incident pulse width.

When the incident radiation illuminates on the surface of photoconductor, the number of photo-induced carriers’ increases rapidly in one pulse and the photo-induced carriers are accelerated under the effect of bias electric field. Hence the transient current density increases rapidly, which corresponds to the positive part in the far fields of THz radiation waveform. Then the photo-induced carriers experience an attenuation process rapidly which makes the decrease rate with time of the photo-induced carriers be greater than the increase rate with time of current density caused by the acceleration under the effect of bias field. Thus the current density shows the phenomenon of
attenuation and makes the growth rate is negative, which corresponds to negative part in the far fields of THz radiation waveform. While the surface field does not appear negative values is due to the radiation field on the photoconductive surface has nothing to do with the time rate of change.

4. Conclusions
In this paper, the THz radiation analytical expressions in the surface field and in the far field are obtained through the famous current-surge model by using large-aperture photoconductive antennas. The time-domain waveforms of THz radiation fields are numerical investigated. The results show that the THz radiation in the surface field and in the far field is affected by many factors, such as the incident intensity, the incident wavelength, the carrier relaxation time, the reflectivity illuminated at photoconductor, the carrier lifetime and the incident light pulse width. The THz radiation intensity can be increased by enhancing the ration of luminous flux, prolonging the photo-induced carrier lifetime or reducing the incident light pulse width. However, due to the shielding effect of space charge and the shielding effect of radiation field, the THz radiation field can appear in the saturated phenomenon. In order to improve the THz radiation power, the intense incident laser pulse can be divided into multi-beam pulse with low energy to trigger photoconductive antenna. Thus the shielding effect of the THz radiation field can be avoided effectively to increase the THz radiation power.

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