Time Varying Conductance in THz Photoconductive Antennas

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Abstract: Terahertz (THz) photoconductive antennas are the most common devices for the generation and detection of THz waves. One of the main problems of the current photoconductive antennas as the emitter is that the optical-THz conversion efficiency is very low, thus it is difficult to obtain high power THz radiation. Source conductance of the photoconductive antenna is one of the primary factors which have significant effects on emitted THz power and optical-to- THz conversion efficiency. Thus, in order to assess the performance of the photoconductive antenna, proper evaluation of the photoconductive material conductance is required. In this paper, the time dependant conductivity of the photoconductive material based on a pulsed system is first derived. Then, through this conductivity, the source conductance (=1/resistance) in THz photoconductive antennas is determined which illustrates the influence of different parameters of the laser pulse, photoconductive material, and THz antenna. This new formula can aid in a better theoretical assessment of the total optical-THz conversion efficiency calculation as the source conductance can be more accurately obtained.

Keywords: Terahertz antennas, Photoconductive antennas, Source conductance, Photoconductive material, Pulsed THz system

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1. INTRODUCTION

THz pulsed systems are desired for various applications like art conservation, material spectroscopy and security. However, the low THz output power is one of the major problems which have limited THz systems from wider commercial applications, especially for applications in which high intensities are required. Moreover, the range of laser power (when using Ti:Sapphire) from the excitation source varies from a few tens of milliwatts to a few watts while the radiated THz power as compared to this laser pump power is very low (in the order of a few μW), this means a low power conversion efficiency. How to increase the radiated THz power and conversion efficiency is largely dependent upon the system from the laser to the THz antenna which has many different parameters and variables to be considered. A new formula has recently been derived for the efficiency of the THz photoconductive antenna [1] where three efficiency factors: optical-to-electrical conversion efficiency (η_{OE}), matching efficiency (η_m) and radiation efficiency (η_r), have been taken into account as shown in Eq. (1).

$$\eta_{total} = \eta_{OE}\eta_m\eta_r = \frac{R_s I_{PC}^2}{P_L}\left(1-\left(\frac{Z_a - R_s}{Z_a + R_s}\right)^2\right)\eta_r \tag{1}$$

where R_s is the source resistance, I_{PC} is the photoconductive current, P_L is the laser power, and Z_a is the antenna resistance. It is apparent that the source resistance is a crucial element in obtaining the total optical-THz conversion efficiency. However, how to obtain the source resistance is not an easy task. For example, in the source resistance equation in reference [2] some simplified assumptions have been used: the time varying behaviour of created photo-carriers and the optical absorption coefficient are not considered. Therefore, the aim of this paper is to calculate the exact analytical time variant conductance (= 1/resistance) of the photoconductive material which acts as the source for the THz antenna. This calculation considers the time varying behaviour of created photo-carriers due to laser pulses and photoconductive material property.

2. PHOTOCONDUCTIVE ANTENNAS IN A THZ PULSED SYSTEM

A typical THz photoconductive antenna system (used as the emitter) depicted in Fig. 1 consists of the laser excitation, antenna fabricated on a photoconductive material and a bias voltage.

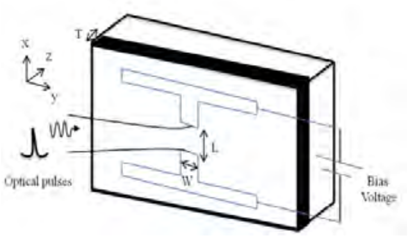

Fig. 1 Geometry of the photoconductive antenna

In this technique, with the illumination of femtosecond laser pulses, electron-hole pairs are created when the laser pulses have higher phonon energy as compared to the bandgap energy of the photoconductive material. The applied bias electric field (E_{bias}) across the antenna then accelerates these photo-excited carriers. Because of the physical separation of the charges (electrons and holes), a macroscopic electron-hole field ($E_{e\text{-}h}$) in reverse direction of the bias field is created. By generation of more electron-hole pairs, $E_{e\text{-}h}$ increases and after a while, the total electric field at the position of carriers (defined as $E_{field}= E_{bias}-E_{e\text{-}h}$) is screened. By the quick change in E_{field}, the transient current is created and finally THz pulses are radiated from the photoconductive antenna.

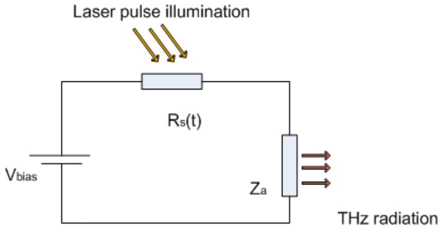

Fig. 2 The equivalent circuit of the photoconductive antenna as the emitter

Due to the special excitation of the THz photoconductive antenna, as compared to conventional microwave antenna, no transmission line connects photoconductive antennas to the excitation source (laser). It is noteworthy that in photoconductive antennas, connected transmission lines are used for applying the DC bias voltage. In continuous wave THz systems, transmission lines are designed in a way to minimise the leakage down the bias line in particular working frequency of the system [3]; but this concept for pulsed system due to its ultra wideband nature is not applicable. Therefore, since the photoconductive material acts as the current source for the antenna, its impedance is denoted as the source impedance for the antenna. Thus, as shown in the equivalent circuit of the THz photoconductive antenna in Fig. 2, for calculating matching efficiency between the antenna (with impedance of Z_a) and the photoconductive material and also optical-electrical conversion efficiency according (1), evaluation of the $R_s(t)$ is required. In the following section a new analytical formula for the conductance of the photoconductive material is derived by considering the laser pulses and photoconductive material.

3. THEORY AND DISCUSSION

The THz photoconductive antenna, shown in Fig. 1, with an electrode gap of L and width of W is employed for analysis. Also, the thickness of the active layer of the substrate (where electron-hole pairs are created) is $T_{LT\text{-}GaAs}$.

The electric field distribution of Gaussian laser pulses at any distance along the axis of propagation (here z) can be written as [4]:

$$E(r,z) = (\frac{w_0}{w})\exp(-\frac{r^2}{w_0^2} - jkz - \frac{j\pi r^2}{D\lambda} + j\varphi_0) \tag{2}$$

where r is the perpendicular distant from z axis, w_0 is the beam waist radius at z = 0, w is the beam radius, D is radius of curvature and φ_0 is the Gaussian beam phase shift. Here, it is assumed that at z = 0, beam waist of laser pulses is on the gap of antenna. Also, to include the time dependency of the laser beam [5], Eq. (2) is modified as:

$$E(r,z) = \exp(-\frac{r^2}{w_0^2})\exp(-\frac{t^2}{\tau_l^2}) \tag{3}$$

where τ_l is the laser pulse duration.

The transmitted optical pulse intensity to the semiconductor is in proportion of the square of the incident electric field. By considering the optical reflection coefficient in air-photoconductive material interface, $R= (n_{air}-n_{sub})^2/(n_{air}+n_{sub})^2$, the optical pulse intensity can be written as:

$$I(r,t) = I_l(1-R)\exp(-\frac{2r^2}{w_0^2})\exp(-\frac{2t^2}{\tau_l^2}) \tag{4}$$

where I_l is the peak laser intensity. When the laser pulses illuminate the photoconductive material, free photo-carriers are created. The time dependant behaviour of the generated carrier density is given by [6]:

$$\frac{dN(t)}{dt}=-\frac{N(t)}{\tau_c}+\frac{\alpha}{h\upsilon}I(r,t) \tag{5}$$

where τ_c is the carrier lifetime, h is the Planck's constant (6.626×10^{-34}), v is the laser frequency and α is the optical absorption coefficient. By replacing (4) in (5) and considering the appropriate initial value condition which matches with the photo-carrier generation; the solution of equation (5) becomes:

$$N(t)=I_l\exp(-\frac{2r^2}{w_0^2})(1-R)\frac{\alpha}{h\upsilon}\frac{\sqrt{2\pi}}{4}\tau_l\exp(-\frac{\tau_l^2}{8\tau_c^2})\exp(-\frac{t}{\tau_c})(erf(\frac{\sqrt{2}t}{\tau_l}-\frac{\sqrt{2}\tau_l}{4\tau_c})+1) \tag{6}$$

Where $erf(x)=\int_0^x e^{-t^2}dt$.

From the basic conduction theory and by considering that the mobility of electrons, μ_e, is much higher than the mobility of holes, the conductivity of a photoconductive material with electron charges, e, is $\sigma(t)=eN(t)\mu_e$. Thus, the time varying conductance of the photoconductive material based on principle basics, equivalent conductivity (considering the optical nonuniform absorption in the semiconductor along z axis) and assuming that beam radius of the Gaussian beam at the gap of antenna uniformly covers the whole gap of the shown antenna in Fig. 1 is derived as:

$$G_s(t)=\frac{W(1-e^{\alpha T_{LT-GaAs}})}{L}e\mu_e I_l\exp(-2)(1-R)\frac{\sqrt{2\pi}}{4h\upsilon}\tau_l\exp(-\frac{\tau_l^2}{8\tau_c^2})\exp(-\frac{t}{\tau_c})(erf(\frac{\sqrt{2}t}{\tau_l}-\frac{\sqrt{2}\tau_l}{4\tau_c})+1) \tag{7}$$

Since the time variant resistance of photoconductive material is the inverse of equation (7) ($R_s(t) = 1/G_s(t)$), it can be used to calculate the time (frequency) variant impedance matching efficiency of the THz photoconductive antenna.

Moreover, the average conductance of the photoconductive material (includes both the laser is on and off in a period) can be presented as the time average of the instantaneous conductance, $G_s(t)$, based on the laser pulse period($1/f_{rep}$). Assuming that the duration of laser pulses is much shorter than the carrier lifetime of photoconductive material (τ_l << τ_c); then the average conductance of photoconductive source can be approximated as:

$$G_{av}\approx f_{rep}\frac{W(1-e^{\alpha T_{LT-GaAs}})}{L}e\mu_e I_l\exp(-2)(1-R)\frac{2\sqrt{2\pi}}{4h\upsilon}\tau_l\tau_c\exp(1-\frac{1}{f_{rep}\tau_c}) \tag{8}$$

To illustrate more clearly the time dependant source resistance of the THz photoconductive antenna, typical values of a THz pulsed system are chosen (as an example) as: μ_e= 1000 $cm^2V^{-1}s^{-1}$, R = 0.318 (for LT-GaAs), α = 10000 cm^{-1} , v = 375 *THz* (at λ = 800 *nm*), f_{rep} =80 *MHz*, τ_l = 100 *fs*, laser average power = 500 *mW*, τ_c= 0.5 *ps*, L = 10 μm, W = 10 μm and $T_{LT-GaAs}$ = 1 μm. With these values the related time variant conductance of the photoconductive source in THz photoconductive antenna is depicted in Fig. 3. Here the resistance which corresponds to the maximum conductivity of the photoconductive material (under peak laser power illumination) is

~ 3.2 *Ω* and through inverse of Eq. (8) the average resistance is ~ 64.3 *kΩ*. The peak resistance of few (ten) ohms in pulsed system during laser illumination has been reported in [7].

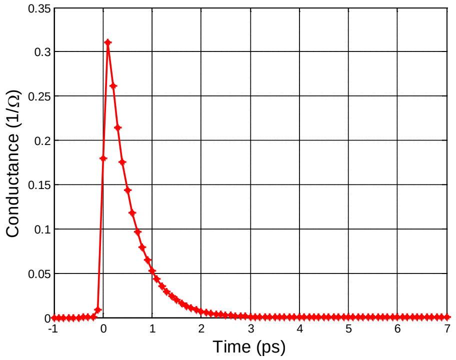

Fig. 3 The time dependant conductance of a photoconductive material

Moreover, as it is obvious from Eq. (7), the source conductance of the photoconductive antenna varies by the changing of both optical source and photoconductive material properties. Here the effect of some of these parameters on the time variant source conductance concerning photoconductive antennas is investigated. As depicted in Fig. 4; by increasing the average pump power the conductance (resistance) of the source in photoconductive antennas increases (decreases) because here the gap size of the antenna is kept fixed and a higher optical power results in a higher photo-carrier generation and greater conductance. This is one of the contrasts between the photoconductive antenna and the RF/microwave antenna where in latter, the source impedance is constant and it does not differ by changing the input power.

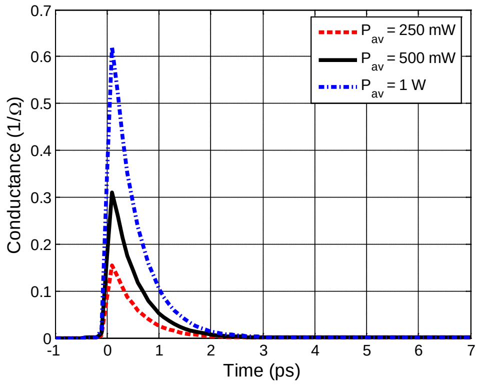

Fig. 4 Variation of the time dependant conductance of a photoconductive material by increasing the average optical power when τ_c= 0.5 *ps*, and α = 10000 cm^{-1}

Furthermore, the influence of carrier lifetime of photoconductive material on the source conductance is studied. Fig. 5 illustrates that the shorter the carrier lifetime, the sharper the conductance roll off. Higher carrier lifetime (which it is affected by the fabrication process of the LT-GaAs) leads to long-lived photo-carriers, prevents creation of new electron-hole pairs and their contribution to generation of photocurrent and therefore due to screening effect, the performance of the antenna decreases. This observation also matches with the behavior of the created photocurrent in antenna in relation to carrier lifetime. Here, the laser pulse duration is kept constant; thus, the rise time behavior of the conductance in these three cases is identical and their peak conductance are very close.

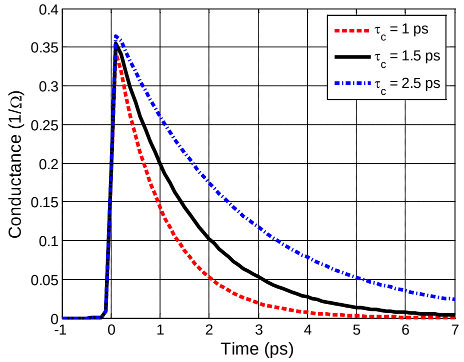

Fig. 5 Change of the time dependant conductance of a photoconductive material by increasing the carrier lifetime of photoconductive material when P_{av}= 500 *mW* and α = 10000 *cm*$^{-1}$

The final investigated parameter is the impact of optical absorption coefficient, *α*. This coefficient in photoconductive materials is strongly dependant on the laser optical wavelength and for common cases where the laser wavelength is around 800 nm and substrate material is GaAs; it is between 1000 *cm*$^{-1}$ to 10000 *cm*$^{-1}$[8]. A higher *α* means that most of the laser power is absorbed in the active layer of the substrate and there is greater contribution to the generation of photo-carriers and ultimately photocurrent. This agrees well with the source conductance behavior shown in Fig. 6 where greater *α* results higher conductance (lower resistance).

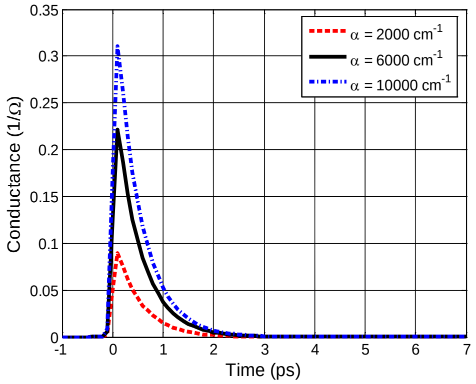

Fig. 6 Increase of the time dependant conductance of a photoconductive material by increasing the optical absorption coefficient when P_{av}= 500 *mW*, and τ_c= 0.5 *ps*,

4. CONCLUSIONS

A new formula for the time variant source conductance (1/resistance) of the photoconductive terahertz antenna based on a THz pulsed system has been derived. In addition, the effect of some parameters related to the optical source and the photoconductive material with respect to source conductance has been investigated. In previously derived equation for the source resistance [2] some simplified assumptions were used. Here, by having considered the time dependant behavior of the generated photo-carrier and absorption of optical pulses in active layer of the substrate, the newly derived equation can more accurately present the effective parameters (such as carrier lifetime, laser pulse duration, antenna geometry) concerning the source conductance of the photoconductive antenna. This equation can be used as part of the circuit model for pulsed THz antennas and also for calculating the impedance mismatch between the photoconductive source material and the antenna. The new equation can therefore provide a more accurate efficiency assessment of a THz photoconductive antenna.

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