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Spectral Characteristics of Photoconductive Dipole Antennas Including Photocurrent and Receiving Antenna Effects

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ABSTRACT

Photoconductive dipole antennas are promising candidates for efficiently converting laser light into a broadband terahertz wave. We present a finite integration technique analysis of these antennas in free space by using an analytic transient current excitation in the photoconductive substrate and by including the effects of the receiving antenna. We display that the far-field spectral characteristics coincide well with the measured results. Considering that the model does not require analyzing the full photoconductive antenna structure, design-by-simulation of photoconductive antennas with desired spectral characteristics is seen to be practical in place of design by trial-and-error fabrication. Furthermore, the form of the transient current pulse excitation is determined to be critical in obtaining good agreement between measured and computed results.

Keywords: Terahertz wave, photoconductive antenna, spectral characteristics, terahertz time-domain spectroscopy.

INTRODUCTION

The photoconductive dipole antenna [1], as shown in Figure 1 (a), can radiate a broadband terahertz wave at a relatively high efficiency, which makes it ideal for an emitter or detector in terahertz time-domain spectroscopy. This is due to the fact that the laser light is converted into a terahertz wave at a lower power than generation using nonlinear optical crystals. Continuous terahertz waves can also be generated through a photomixing process using optical beats from two lasers [4, 5] or a single multi-mode laser diode [6, 7]. These antennas are typically fabricated using lithographic techniques or super-fine ink jet (SIJ) printer technology [2, 3]. This process is simple, time efficient, and of relatively low cost. A four-contact electrode structure can control the polarization of the terahertz wave [8]. The electrode structure with a Schottky contact was shown to produce a nonlinear response [9].

To accurately characterize the electrical characteristics of the antenna, such as the far-field spectral characteristics, as a function of the dipole dimensions, an electromagnetic analysis is essential for the antenna design. However, the electromagnetic analysis is extremely challenging because the dimensions of the full model are large compared with the wavelength. Furthermore, it is important to include the effects of the transient current in the photoconductive substrate and the effects of the receiving antenna in order to obtain an effective design. Previous experimental and analytical work has estimated the photoconductive antenna characteristics [10-16], and although estimations of the characteristics including the effects of the receiving antenna have been performed [17], a comparison of the measurement and analysis results has not yet been completed for various dipole lengths. Calculated and measured radiated spectra were first compared in [18], where computed spectra were also presented for several dipole lengths. In [18], a preliminary analysis model

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did not achieve agreement with the measured results, and the authors suggested better agreement could be obtained by including the effect of the receiving antenna. The authors also suggested that measurements agree with corrected analyses calculated using a femtosecond laser pulse width that was too wide.

This paper presents an analysis of a photoconductive dipole antenna that uses an analytic transient current and includes the effects of the receiving antenna by multiplying the magnitudes of the radiated spectra by those of the receiving antenna spectrum [17, 19]. The finite integration technique (FIT) is used to simulate the dipole antenna in free space, and the results are normalized by the effective permittivity. This replaces a time-consuming analysis that includes the dielectric material [10]. For the most accurate design, it is necessary to include the dielectric in the far-field pattern calculation; however this paper focuses on the estimation of the far-field spectral characteristics of an antenna radiating in free space as this gives acceptable agreement with the measurement results. Hence, one can estimate and design a photoconductive antenna with the desired spectral characteristics using a simple model and full-wave electromagnetic analysis.

ANALYSIS

The dipole element of the conventional photoconductive antenna is located at the interface, between air and the photoconductive substrate. Figure 1 (b) shows the analysis model consisting of six absorbing boundary walls to reduce the analysis domain to a practically analyzable one. The co-planar line is in contact with two absorbing boundaries for reflection suppression. The equivalent relative permittivity is $\varepsilon_{\mathrm{eff}} = (\varepsilon_r + 1)/2$, where ε_r is the relative permittivity of the dielectric material.

We derive the transient current by assuming that the magnitude of the terahertz radiation, originating from the carrier-density change, is much larger than that of the terahertz radiation which is proportional to the carrier acceleration [20, 21]. The transient current, proportional to the carrier density N, is used in this analysis, and its time dependence is expressed in terms of N and the laser intensity I as

$$\frac{dN(t)}{dt} = -\frac{N(t)}{\tau_c} + kI\,, \qquad (1)$$

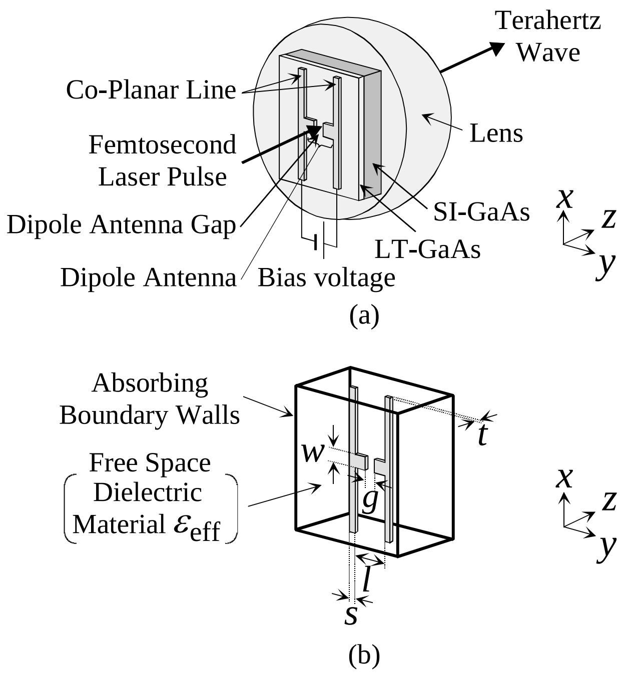

Fig. 1: (a) Photoconductive antenna. (b) Analysis model of photoconductive antenna.

where τ_c is the carrier lifetime and k is the excitation efficiency of the carrier generation rate. The time variation of the laser intensity $I(t)$ is given by

$$I(t) = I_0 \exp\left\{-\frac{(t-t_c)^2}{2\sigma^2}\right\}, \qquad (2)$$

where t_c is the time of the center of the laser pulse and σ^2 is the variance of the Gaussian distribution given in the following form using the full width at half maximum of the laser pulse τ_0: $\sigma = \tau_0 / \left(2\sqrt{2\log_e 2}\right)$. The boundary between the Fresnel region and the far-field region is $2l^2/\lambda$, where l is the antenna length, and the distance between the receiving and transmitting antenna is in the far-field region for this terahertz time-domain spectroscopy measurement [22].

RESULTS AND DISCUSSION

Figure 2 (a) shows the femtosecond laser pulse and transient current of the excited carriers. The full width at half maximum of the laser pulse is 120 fs, and the carrier lifetime for the low-temperature grown GaAs substrate is 500 fs. Figure 2 (b) shows the spectral characteristics of the transient current. The relative permittivity of the dielectric material is 12.25. The far-field spectrum computed using the FIT in CST Microwave Studio is shown in Figure 3 (a). The solid and dashed lines show the spectrum characteristics with and without the effects of the receiving antenna, respectively. The far-field spectra on a logarithmic scale are shown in Figure 3 (b). The solid lines show the analysis results of the spectrum characteristics with the effect of the receiving antenna. The magnitudes of the radiated spectra are normalized so that the maximum magnitude of the simulated data for the 200 μm dipole length including the receiving antenna effect is the same as that of the corresponding measured data [18]. The width and gap of the dipole antenna are 10 μm and 5 μm, respectively, and the width of the co-planar line is 10 μm. The receiving dipole antenna has the same width and gap dimensions and has a dipole length of 70 μm.

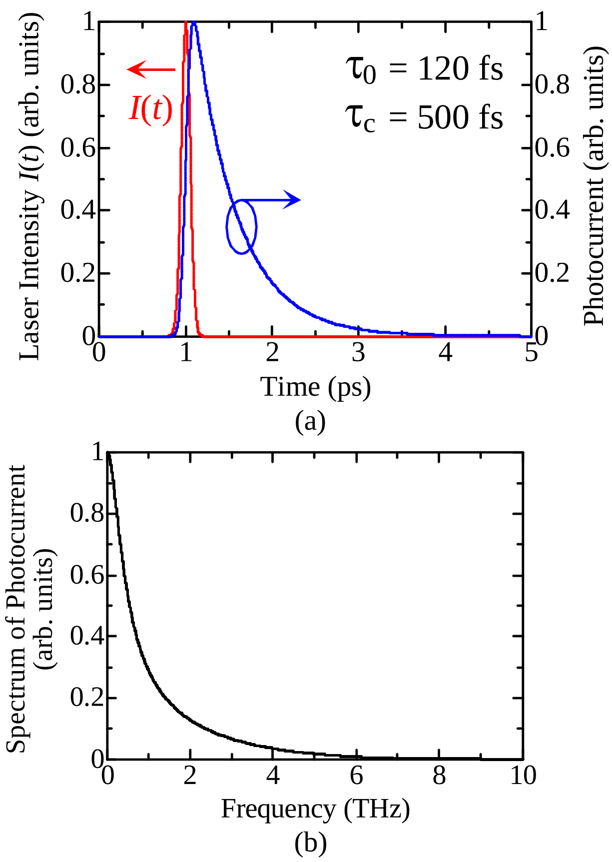

Fig. 2: (a) Femtosecond laser pulse and transient current of the excited carriers. (b) Spectral characteristics of the transient current.

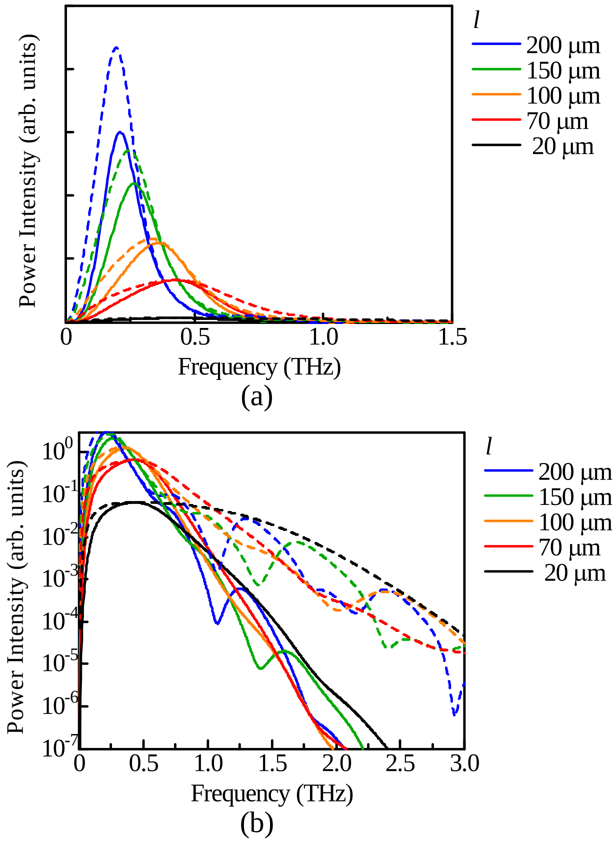

Fig. 3: (a) Simulated spectral characteristics. (b) Simulated spectral characteristics on a logarithmic scale. Solid and dashed lines show the spectral characteristics with and without the effects of the receiving antenna, respectively.

The spectrum characteristics for the 200 μm dipole length including the receiving antenna effect is a reference for the normalization, so the local maximum values without the effects are stronger than those with the effects. Spectra of the receiving antenna have a narrower bandwidth than those without the effects of the receiving antenna. The discrepancies between the computed and measured results at high frequencies should decrease further by taking the transmission function of the optical system into account. Hence, we can conclude that this simple analysis model is a feasible method for antenna design. We note here that this means that a trial-and-error fabrication design method is not required. Furthermore, we have confirmed that the femtosecond laser pulse width should be chosen carefully.

CONCLUSION

In summary, the photoconductive dipole antenna has been analyzed using a good approximation of the photocurrent and including the effects of the receiving antenna. Previous discrepancies between the simulated and measured data were shown to be due to an approximate expression for the photocurrent in the photoconductive substrate. This paper has presented an analysis that uses a more appropriate estimation of the input photocurrent, and the analysis and measurement results exhibit much better agreement as a result. Hence, direct analysis of photoconductive antennas to obtain specific spectral characteristics was shown to be practical.

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