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Excitation-wavelength-dependent THz wave modulation via external bias electric field*

Shi-Jia Feng(冯世嘉)[1], Li-Quan Dong(董立泉)[1], Dan-Ni Ma(马丹妮)[1], Tong Wu(吴同)[1], Yong Tan(谭永)[1], Liang-Liang Zhang(张亮亮)[2,†], Cun-Lin Zhang(张存林)[2], and Yue-Jin Zhao(赵跃进)[1,‡]

[1] *Beijing Key Laboratory for Precision Optoelectronic Measurement Instrument and Technology, School of Optics and Photonics, Beijing Institute of Technology, Beijing* 100081, *China*

[2] *Key Laboratory of Terahertz Optoelectronics, Ministry of Education, Beijing Key Laboratory for Terahertz Spectroscopy and Imaging, and Beijing Advanced Innovation Center for Imaging Technology, Department of Physics, Capital Normal University, Beijing* 100048, *China*

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A theoretical model was proposed to describe the effects of external bias electric field on terahertz (THz) generated in air plasma. The model predicted that for a plasma in a bias electric field, the amplification effect of the THz wave intensity increases with the increase of the excitation laser wavelength. We experimentally observed the relationship between the THz enhancement effect and the electric field strength at different wavelengths. Experimental results showed a good agreement with the model predictions. These results enhance our understanding of the physical mechanism by which femtosecond lasers excite air to generate THz and extend the practical applications of THz generation and modulation.

Keywords: THz wave generation, DC bias electric field, ponderomotive force

PACS: 42.65.–k, 87.50.U– **DOI:** 10.1088/1674-1056/ab84d7

1. Introduction

A growing number of researchers are focusing on the development of terahertz (THz) sources.[1–13] Air plasma has always been a major topic in the field of THz sources due to its nondamage threshold.[14–16] Hamster *et al*. found that THz radiation can be observed from plasma generated by ambient air and excited with an ultrafast pulse laser.[17,18] With further research, several approaches have been proposed to modulate air plasma and thereby enhance THz radiation. The most typical ones are the use of a frequency doubling crystal or application of an external electric field. Researchers have discovered that type-I beta barium borate crystals can be used to increase the intensity of THz radiation by at least two orders of magnitude.[19–23] Löffler *et al*. illustrated the generation of THz pulses with the use of a bias electric field through the photoionzation of electrically biased air using amplified laser pulses. The filament generated by the ionization of air with a bias field of 10.6 kV/cm caused the emission of THz pulses, the intensity of which was almost as high as that of THz pulses radiated from a large-area intrinsic field GaAs transmitter.[24] Houard *et al*. observed that the THz energy generated from femtosecond pulse radiation that has undergone filamentation in the air increases by three orders of magnitude in the presence of an electrostatic field; a theoretical model was proposed to explain the experimental results.[25] Sun *et al*. established a theoretical model for describing THz pulses in the air affected by an external electric field on the basis of the nonlinear theory of plasma and four-wave mixing theory. The authors predicted that THz amplitude linearly increases with the value of the external electric field, as previously observed in experiments; it also changes as a cosine function with the rotation angle of the field direction and is proportional to the square of the incident pulse intensity.[26] Wang *et al*. found that the mobile ionization front (or laser) is not necessary to generate THz radiation. The prefabricated plasma applied by the bias electric field can generate THz radiation, and the THz wave radiation can be controlled by changing the parameters of the electric field.[27] Chen *et al*. believed that the THz radiation of a DC-biased filament can be regarded as the sum of an elliptically polarized THz source (generated by a filament without an external electric field) and a linearly polarized THz source (generated by an external electric field acting on the filament). The peak frequency and line width of a linearly polarized THz source are related to the average plasma density of the filament.[28] The analysis by Wang *et al*. shows that THz radiation can be composed of two parts: the first one is generated by a two-color laser-induced filament, and the other one is generated by an external DC electric field.[29] In previous studies, researchers did not investigate the wavelength modulation of pump lasers and basically used the conventional 800-nm laser.

In the current work, we focus on the effects of the wavelength modulation of pump lasers on the THz waves generated by ions in a DC bias electric field. We establish a theoretical

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†Corresponding author. E-mail: zhlliang@126.com

‡Corresponding author. E-mail: yjzhao@bit.edu.cn

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model to describe the physical mechanism of THz generated by plasma in a DC bias electric field. We believe that the observed THz wave generated by the filament in the bias electric field results from the combination of the ponderomotive force and the acceleration of free electrons in the plasma via the external electric field. We predict that a positive correlation exists between the enhancement effect of the external bias electric field on the THz wave and the pump laser wavelength. We verify the accuracy of the theoretical model through experiments.

This paper is arranged as follows. Section 2 describes the theoretical model and predictions made by the model. In Section 3, we show the experimental results for the validation of the theoretical predictions. Finally, Section 4 provides a brief conclusion.

2. Theoretical model and predictions

In their previous research, Houard *et al*. and Chen *et al*. contended that the THz wave generated by the plasma in a DC bias electric field is composed of ponderomotive force-generated and electric field-induced THz.[25,28] Thus, we analyze the physical mechanism through these two parts. First, Hamster *et al*.[17,18] reported that the emitted THz field strength can be given by

$$E_{\text{pon}} \propto \frac{W}{R_0}\left[\frac{\lambda}{\tau}\right]^2, \tag{1}$$

where W is the laser energy, R_0 is the radius of the focused beam, λ is the laser wavelength, and τ is the pulse length.

We define the transmission direction of the pump laser as z and the direction of the applied DC bias electric field as x. We first consider defining a plasma as a homogeneous one to study the mechanism wherein free electrons in the plasma are accelerated by an external electric field to amplify the THz field strength. The bias electric field is defined as $\boldsymbol{E}_{\text{bias}} = \hat{x}E_0$. The velocity of the electrons inside the plasma in the bias electric field can be expressed as follows:[11]

$$\hat{x}V = \hat{x}\left(-\frac{eE_0}{m_{\text{e}}}t + \frac{eP}{m_{\text{e}}c}\right), \tag{2}$$

where P is the vector potential of the plasma response field in the bias electric field and m_{e} is the electron mass.

We assume that the analyzed plasma and applied DC electric field are evenly distributed in space and that the initial electron velocity is zero before the bias field is triggered. Moreover, the motion of all the ions in the plasma is ignored. We can obtain the following expression by combining the wave equations:

$$\frac{\partial^2 P}{\partial t^2} + \omega_{\text{p}}^2 P = 0, \tag{3}$$

where ω_{p} is the frequency of the plasma expressed as $\omega_{\text{p}} = \sqrt{4\pi e^2 n_{\text{e}}/m_{\text{e}}}$ and n_{e} is the plasma density.

The electric field of the plasma response can be given by

$$E_x = E_0\left[\cos\left(\omega_{\text{p}}t\right) - 1\right]. \tag{4}$$

We can treat the effects of electrons being accelerated at different positions y in the plasma channel as the same. When the electron–ion collision period and plasma lifetime are considered, the THz radiation can be expressed as follows:

$$E_{\text{bias}} = E_0\left\{\alpha\cos\left[\omega_{\text{p}}\left(t \pm z/c\right)\right] - 1\right\}\exp\left(t/\tau_{\text{pl}} - t/\tau_{\text{col}}\right), \tag{5}$$

where α is the ω_{p} transfer ratio from the plasma to the vacuum, τ_{col} is the electron–ion collision period, and τ_{pl} is the plasma lifetime. The total THz field strength can be obtained by superimposing the two mechanisms of the ponderomotive and electron acceleration:

$$E_{\text{total}} = E_{\text{pon}} + E_{\text{bias}}. \tag{6}$$

Equation (5) shows that the bias electric field E_{bias} is directly related to the plasma frequency ω_{p}. We can directly affect ω_{p} by changing the wavelength λ. Long wavelength lasers have high ionization thresholds and large focal spot diameters. Hence, an increase in wavelength λ results in a decrease in plasma density n_{e}. This effect indicates that the plasma frequency decreases with increasing wavelength. We obtain the following simple relation from Eq. (5):

$$E_{\text{bias}} \propto \lambda. \tag{7}$$

According to Eq. (1), the THz field intensity generated from air plasma and excited by a monochromatic laser increases as the wavelength increases. By combining Eq. (1) with Eq. (6), we can predict the relationship between the total THz electric field intensity and the pump laser wavelength as

$$E_{\text{total}} \propto \lambda. \tag{8}$$

3. Experiments and discussion

3.1. Experimental setup

Figure 1 presents a schematic diagram of the experimental device. Commercial femtosecond laser amplifiers (Spitfire, Spectra Physics) provide horizontally polarized laser pulses with a pulse duration of 50 fs, a center wavelength of 800 nm, a repetition frequency of 1 kHz, and a maximum pulse energy of 5 mJ. The laser beam is divided into two beams by a beam splitter: the first one is a pump light, and the other one is a probe light. The pump light used to excite the air plasma first passes through an optical parametric amplifier (Topas, Spectra Physics) to generate s-polarized optical pulses at wavelengths tunable from 1200 nm to 1500 nm. The beam then goes through a lens (L1) with a focal length of 150 mm to be focused in the air to form a plasma.

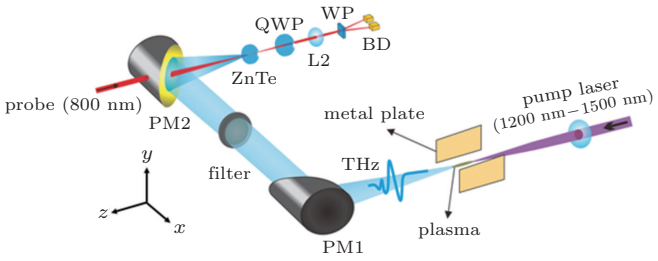


Fig. 1. Experimental setup.

The THz wave that radiates forward from the air plasma is collected and collimated by a parabolic mirror (PM1, the focal length is 100 mm). The collimated THz wave passes through a THz filter (Tydex) and a silicon wafer to eliminate the pump laser. The THz wave is then focused on the ZnTe crystal by an off-axis parabolic mirror (PM2, focal length 100 mm).

We use a standard electro–optic sampling method to detect the THz field. The probe light passes through a small hole in the second parabolic mirror and is collinearly focused with the THz wave at a 3-mm-thick ZnTe crystal. The light then passes through a quarter wave plate (QWP), a lens (L2, focal length 100 mm), and Wollaston prism (WP) and is then finally detected by a balanced photodiode detector (PD). The relative time delay between the pump and the probe pulses is adjusted at a translation stage to scan the THz time domain waveform. We place our linear bias voltage device at the focal position where the pump light focuses to form the plasma. The device consists of two parallel copper plates with a thickness of 0.5 mm and an area of 10 mm × 10 mm; the distance between the plates is 5 mm. The copper plates are connected to a high-voltage DC power supply. The power supply can provide a high DC voltage of 0 V–5000 V. The applied electric field ranges from 0 V/cm to 10^5 V/cm. The direction of the external electric field is kept horizontal throughout the whole experiment. All experiments are performed in a clean room, the temperature is maintained at 23 °C, and the humidity is kept at 10%.

3.2. Experimental results and discussions

We set the laser wavelength to 1200 nm and keep the laser pulse energy at 0.36 mJ. Figure 2(a) shows the waveforms of the THz time-domain signal under different external bias fields. The peak value of the THz time-domain signal strength changes at equal intervals with the increase of the voltage and bias field strength. Specifically, the amplitude of the THz radiation is linearly proportional to the electric field strength. Equations (4) and (5) show that the relationship between E_{bias} and E_0 is linear, thereby indicating that our model efficiently fits the results shown in Fig. 2(a).

The Fourier transform of the THz time-domain signal is used to obtain the THz frequency-domain waveforms at different electric field intensities (Fig. 2(b)). The figure shows that when the intensity of the applied external bias field gradually increases, the spectral waveform curve remains basically the same. However, the center frequency decreases from 0.84 THz to 0.60 THz. A bias electric field intensity of 1000 V/cm greatly reduces the THz center frequency relative to a THz signal produced by a monochromatic laser field that is unaffected by an external electric field. The center frequency continues to decrease with the continued increase of the strength of the bias electric field, and no remarkable change occurs after the field intensity of 2000 V/cm. We analyze the main reasons for this phenomenon.

Equations (4) and (5) demonstrate that the frequency of the generated THz signal by a biased DC electric field is equal to the plasma frequency ω_{p}. When no bias electric field is applied, the frequency of the THz signal is determined by part E_{pon} generated by a monochrome source. The strength of the THz field generated by the bias electric field E_{bias} rises with the continued increase of the bias electric field strength. Thus, the spectral characteristics of the total THz signal are dominated by E_{bias}, and those of E_{pon} are overwhelmed when the bias electric field strength is larger than 2000 V/cm (Fig. 2(b)).

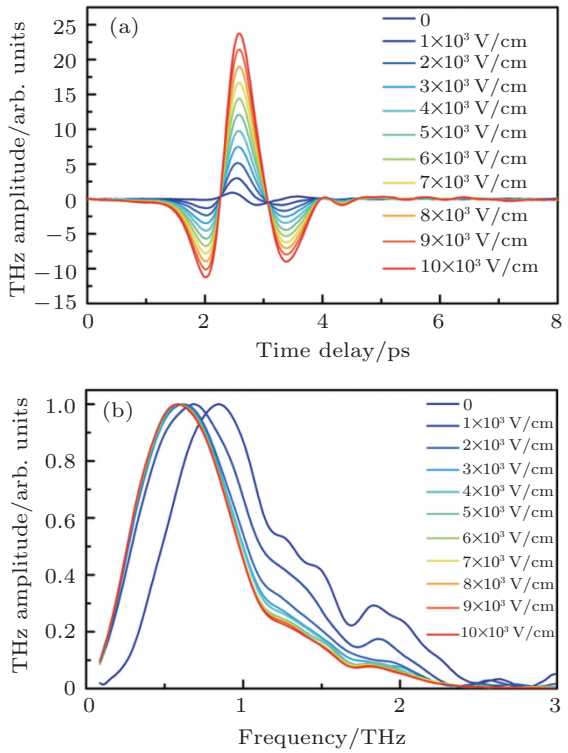


Fig. 2. The THz time-domain (a) and frequency-domain (b) waveforms at different electric field intensities with a laser wavelength of 1200 nm.

We control the lasers of different wavelengths to maintain the same power of 360 mW and then measure the THz intensity produced by each wavelength under different bias electric field intensities (Fig. 3(a)). We discard the data at 1350-nm and 1400-nm wavelengths because our OPA has an abnormal pulse duration when providing these two wavelengths.

Comparing the effects of the bias electric field on the THz waves generated at different wavelengths is inconvenient because the initial THz intensities of the curves in Fig. 3(a) are inconsistent. Therefore, we divide the THz intensity under different electric field intensities by the THz signal intensity without an electric field. We then obtain the relationship between the THz amplification factor and the electric field intensity (Fig. 3(b)). The result demonstrates that the THz enhancement effect intensifies with an increase in wavelength. This result is completely consistent with our analysis in Eq. (7).

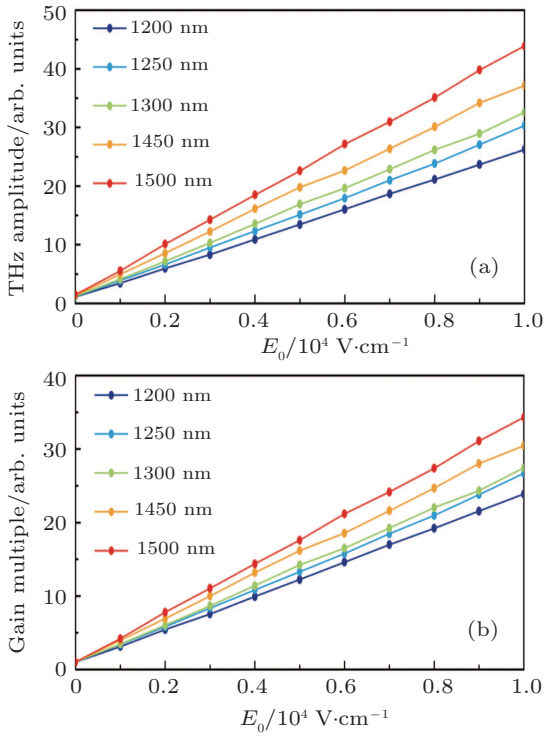


Fig. 3. (a) Relationships between THz and bias electric field intensities produced by laser pulses with different wavelengths, (b) the relationship between THz enhancement effect and electric field intensity.

4. Conclusion

We proposed a theoretical model to describe the characteristics of THz waves generated by air plasma in an external DC bias electric field. The total THz wave is provided by two THz sources: ponderomotive force and DC bias electric field. The enhancement effect of the bias electric field on the intensity of THz waves is positively correlated with the laser wavelength. The experimental results are in good agreement with our theoretical predictions.

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