The Generation of Terahertz Frequency Radiation by Optical Rectification

K. Radhanpura, S. Hargreaves and R. A. Lewis

Institute for Superconductivity and Electronic Materials,
University of Wollongong, NSW 2522, Australia

Abstract

One of the means of generating terahertz (THz, 10^{12} Hz) frequency radiation is through the bulk second-order nonlinear effect of optical rectification. Optical rectification occurs if high-intensity light is directed onto an electro-optic material such as ZnTe. If the excitation beam contains components of two or more frequencies then difference-frequency mixing, also known as optical rectification, may take place. Depending on the spectrum of the excitation beam, the resulting frequency may be in the THz range. While this phenomenon has been known for some time, and has been studied in various zinc blende crystals, attention does not seem to have been paid to the precise relationship between the *s* and *p* polarised components of the emitted radiation. Moreover, only crystals with (100), (110) or (111) faces appear to have been investigated to date. We extend the previous work by undertaking a careful analysis of the THz radiation emitted by (110) ZnTe as a function of the angle of rotation of the crystal about its surface normal, and by investigating the THz radiation emitted from crystals of other orientations, such as (311).

1. Introduction

Terahertz radiation, sometimes referred to as T-rays, lies between the microwave and visible regions of the electromagnetic spectrum. The frequency range is often taken to span 0.1 to 10 THz, corresponding to the sub-millimeter wavelength range. THz time-domain spectroscopy (TDS) is used to investigate the sample simultaneously in terms of phase as well as amplitude.

THz emission mechanisms may be divided into two types of processes, linear and nonlinear. Linear processes include current surges at semiconductor surfaces induced by photo excitation. The current surge may be produced either by a surface depletion field or by the photo-Dember effect. On the other hand, nonlinear processes include the optical rectification of ultrafast laser pulses. In this case, an electro-optic crystal is used as the rectification medium. Second-order difference-frequency generation or higher-order nonlinear optical process may occur, depending on the optical fluence [1].

Here we study how the emitted THz varies as the crystal is rotated with respect to the fs pump pulse. For (110) ZnTe a signal with three peaks is observed by rotating the sample about surface normal. This can be interpreted as evidence of optical rectification [2, 3]. We also observe a three-peak behaviour for (311) GaAs. In addition, we measure separately the horizontal and vertical polarisation components of the radiation from these emitters. There is good agreement between the calculated results and experimental data.

2. Experimental Setup and Measurement

A mode locked Ti: Sapphire laser with a 12 fs pulse width and a central wavelength of 790 nm is used. The laser gives a near-infrared beam of power level of a few hundred mW. This is divided into a pump beam and a probe beam by a beam splitter. The pump beam passes through a time delay stage and then illuminates the THz emitter crystal. A transmission geometry is employed; that is, the beam is at normal incidence on the emitter crystal and the THz radiation produced is measured in the forward direction. The THz beam is directed by two pairs of gold-coated parabolic mirrors to collimate and focus it. The probe beam is combined with the THz beam by the means of a small mirror, and travels collinearly with THz beam inside a 1-mm thick (110) oriented ZnTe detector crystal. The probe beam polarisation is modulated by the electric field of THz radiation via the electro-optic effect. The probe beam then passes through a quarter wave plate and Wollaston prism before reaching a pair of photodetectors. A lock-in amplifier, with 100 ms time constant and 1 kHz chopping frequency, is used to collect the signal in order to increase the sensitivity of detection at the μW power level [4, 5].

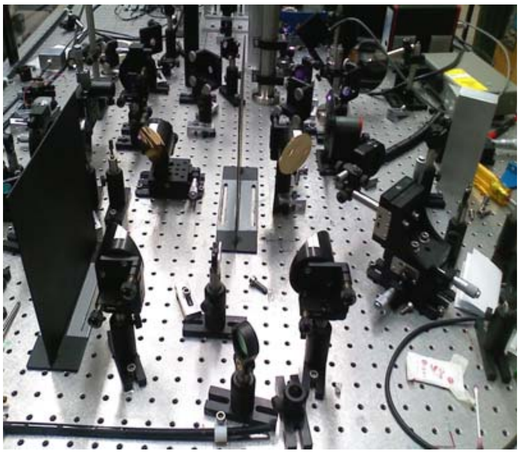

Figure 1. Experimental setup for THz time-domain spectroscopy.

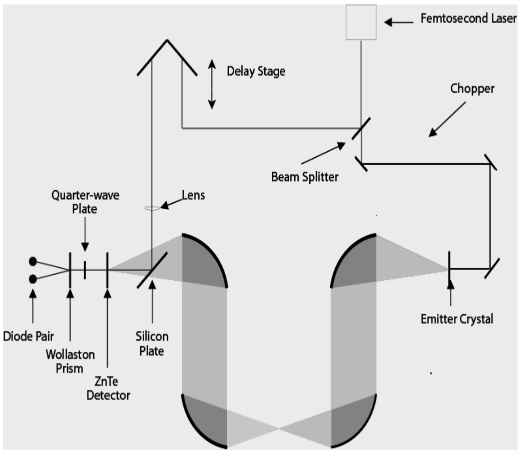

Figure 2. Corresponding block diagram of THz TDS system.

The THZ radiation may be due to photocarrier acceleration in the static field region or to nonlinear optical rectification, as discussed in the Introduction. In this experiment, the THz emitters are used in normal incidence in order to eliminate the photocarrier effect. Both the surface and photo-Dember fields and perpendicular to the surface, and so dipoles produce by such fields will not radiate in the forward direction. Any radiation detected in this experimental geometry can be assumed to arise purely from optical rectification [2].

By using a variable time delay line, the electric field of the THz pulse in the time domain is obtained. A Fourier transform of the time-domain data gives the frequency spectrum of the THz radiation. In order to obtain the azimuthal angle dependence of the THz radiation, the emitter is rotated by 360º about its surface normal in 10º intervals. The two polarisation components of the emitted radiation are separated using a wire-grid polariser. The pump radiation is horizontally (*p*) polarised in all cases. Light polarised parallel and perpendicular to this is termed *p* and *s* polarised, respectively.

Figure 1 shows the experimental setup for these measurements and Figure 2 is the block diagram of the system. The THz emitters used are a ZnTe crystal with (110) crystallographic orientation and GaAs crystal with (311) crystallographic orientation.

3. Results and Discussion

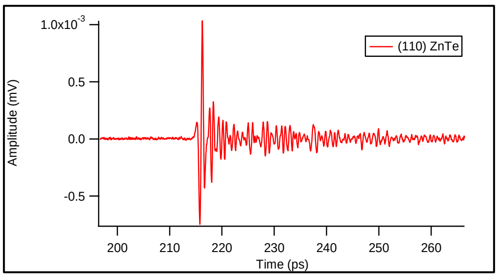

Figure 3. THz time domain signal for (110) ZnTe.

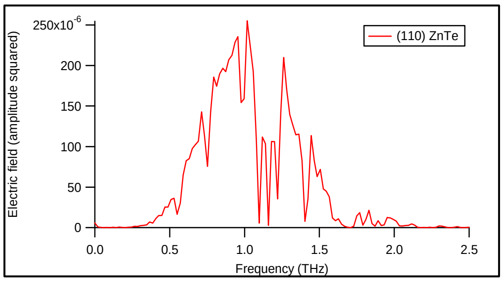

Figure 4. Corresponding Fourier transform for (110) ZnTe.

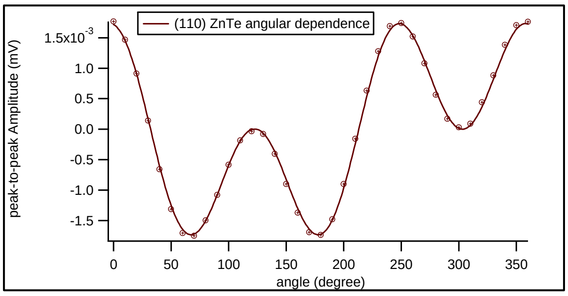

Figure 5. (110) ZnTe azimuthal angle dependence.

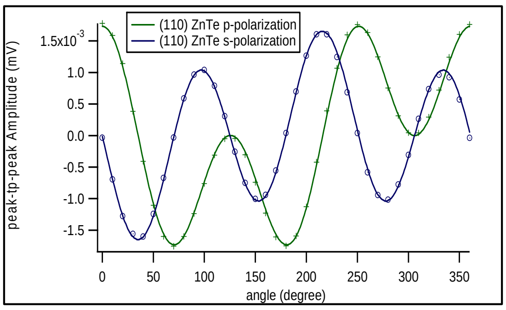

Figure 6. (110) ZnTe *p*-polarisation and *s*-polarisation data.

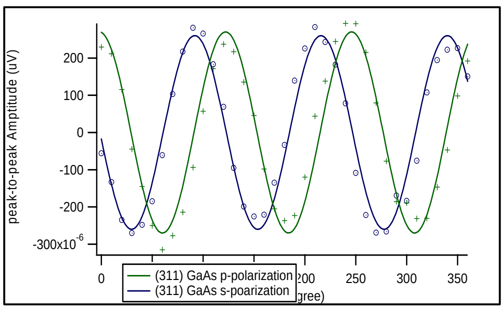

Figure 7. (311) GaAs *p*-polarisation and *s*-polarisation data.

The generation of THz radiation by optical rectification has its physical origin in the changing polarisation field within the emitter crystal; more precisely, the THz electric field varies as the second time derivative of polarisation. The polarisation in turn depends on the optical coefficients of the crystal and the orientation of the electric field of the excitation radiation relative to the crystal axes. For a (110) emitter crystal, the equations for two types of polarisation corresponding to light polarised parallel to detector axis and light polarised perpendicular to detector axis are [2]:

$$P_{\parallel}\ (p\text{-polarisation}) = \tfrac{3}{4}\, \varepsilon_0\, d_{14}\, E^2 (\cos 3\theta - \cos \theta)$$

$$P_{\perp}\ (s\text{-polarisation}) = \tfrac{1}{4}\, \varepsilon_0\, d_{14}\, E^2 (3 \cos 3\theta + \cos \theta)$$

where d_{14} is the nonlinear optical coefficient,
E is the electric field of the optical beam and
ε_0 is the free space permittivity.

These equations lead to a three-peak dependence in both vertical and horizontal polarisations.

Figures 3 and 4 shows a time-domain scan and its corresponding Fourier transform for a (110) ZnTe emitter crystal. Figure 5 shows the azimuthal angle dependence for this emitter while Figures 6 and 7 show the angular dependence for *p* and *s*-polarisation for (110) ZnTe and (311) GaAs, respectively. From these graph we observe a three-peak dependence with different behaviour in the *s* and *p*- polarisations for (110) ZnTe. The solid line shows theoretical data obtained from above equations for the (110) crystal and a sine curve for the (311) crystal while the markers represents experimental values, namely, the measured peak-to-peak value of the time domain signal for each 10º interval position of the THz emitter.

4. Conclusion

The generation of THz radiation from (110) ZnTe and (311) GaAs crystal in these experiments is largely through the electro-optic effect, as demonstrated by the azimuthal angle dependence of the horizontal and vertical polarisation components. The experimental and theoretical results reveal that second order optical rectification is the main nonlinear process which produces THz radiation in these samples.

Acknowledgments

This work was supported by the University of Wollongong and by the Australian Research Council.

References

[1] Gu P, Tani M, Kono S, Sakai K and Zhang X-C 2002 *Journal of Applied Physics* **91** 5533

[2] Rice A, Jin Y, Ma X F, Zhang X-C, Bliss D, Larkin J and Alexander M 1994 *Applied Physics Letters* **64** 1324

[3] Jin Y H and Zhang X-C 1995 *Journal of Nonlinear Optical Physics and Materials* **4** 459

[4] Zhang Z, Zhang Y, Zhao G and Zhang C 2007 *Optics* **118** 325

[5] Davies A G, Burnett A D, Fan W, Linfield E H and Cunningham J C 2008 *Materials Today* **11** 3