

Terahertz Quasi-Time Domain Spectroscopy using A 808 nm Multimode Diode Laser

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ABSTRACT

We report on a terahertz quasi-time domain spectroscopy (QTDS) system based on a low-cost continuous wave multimode diode laser. Commercially available low-temperature grown gallium arsenide (LT-GaAs) based photoconductive antennas (PCAs) with spiral and dipole configurations were used as emitter and detector, respectively. Terahertz pulses spaced at approximately 55 ps with a bandwidth of 400 GHz were obtained. Parametric measurements of the terahertz peak-to-peak intensity were performed by varying the injection current and temperature while maintaining incident laser power. The highest peak-to-peak intensity was obtained at 170mA injection current and 20° C temperature settings. The change in the THz peak-to-peak intensity is attributed to the mode hopping characteristics of the device which in turn, is dependent on injection current and temperature.

1. Introduction

The standard terahertz (THz) time-domain spectroscopy (TDS) PCA-PCA setup makes use of femtosecond lasers as the primary excitation source. However, femtosecond lasers are usually very expensive which becomes a prohibiting factor even for university-level research laboratories especially in developing countries such as the Philippines. An alternative system for generating THz is being studied as a viable alternative to femtosecond laser-based THz setups for use in sub-THz applications [1]. The alternative quasi-TDS (QTDS) system makes use of photomixing via two single-frequency continuous wave (CW) lasers or a single multimode laser to generate sub-THz radiation [2, 3].

Replacing the ultrafast femtosecond laser with a commercial multimode diode laser yields the same time-domain data which can then be used for optical parameter calculations of materials at low cost [3, 4, 5, 6]. Other successful applications of the QTDS system are the imaging of biological samples [7], and compact outdoor spectroscopy applications [8]. However, the common downside of QTDS system is the low power of the emitted THz due to low conversion efficiency, as well as low bandwidth and signal-to-noise ratio (SNR) compared to conventional systems using femtosecond lasers. There have been studies that aim to improve the shortcomings of the QTDS such as making use of optical feedback to improve the intensity of the generated THz [9] and implementing electrical pulse waves to modulate the multimode laser for the purpose of increasing the THz bandwidth [10].

Terahertz generation via multimode lasers relies on the wave-mixing of laser modes in a photomixer. Photomixing is a superposition of two or more lasers with different optical frequencies [11, 12]. An incident laser beam with multiple frequencies excites free carriers in the semiconductor material of an emitter photoconductive antenna (PCA). Introducing a bias voltage to the emitter PCA accelerates the excited carriers and generates the photocurrent. The photocurrent is then modulated by the resulting optical beats from the mixing of the different mode frequencies [13]. For a PCA antenna used as a photomixer, the high frequency products (such as second harmonics and sum-frequency terms) are ignored due to antenna's slow response [13, 14].

The detected photocurrent will then depend on the difference frequency terms of the laser modes and is given by the equation [15]:

$$I_D(\Delta X) = \sum_{m=1}^{M-m} \frac{M-m}{M^2} A(2\pi m \Delta f) P^2 \cos\left(\frac{\Delta X}{c_0} 2\pi m \Delta f + \phi_m\right) \quad (1)$$

where ΔX is the path difference between the emitter and detector, M is the total number of modes, m is the m th laser mode ($m = 1, 2, 3, \dots, M-1$), $A(2\pi \Delta f)$ is the spectral characteristics of the emitter and detector antenna, and P is the average power of the laser. Eq. 1 assumes the power is evenly distributed between laser modes and the modes are evenly spaced. According to Scheller and Koch, the equidistant frequency spacing of the modes leads to repeating THz pulses where the repetition rate of the pulses is determined by the mode spacing [14].

In this paper, a commercial and low-cost multimode diode laser operating at 808nm wavelength is used in a standard PCA-PCA TDS setup. An 808nm laser diode was chosen because the available PCA emitters and detectors were suited and optimized for 800nm excitation. Parametric measurements on the THz peak-to-peak intensity were performed by varying the injection current and the temperature. Injection current and laser diode temperature can directly affect the lasing characteristics of the device. In particular, the mode hopping characteristics are influenced by these two parameters according to previous work on semiconductor laser stability [16, 17, 18]. Since the THz generation efficiency depends primarily on the probability of wave-mixing from the laser's different lasing modes, it is important to investigate the effect of varying injection currents and temperature.

2. Methods

The experimental setup is a standard pump-probe terahertz time-domain spectroscopy (TDS) setup as seen in Fig. 1. The excitation laser is a Thorlabs L808P200 semiconductor laser diode with 808nm central wavelength. The threshold current of the laser diode is 100 mA with a maximum operating temperature of 50° C. The laser diode is designed for multimode operation with a mode spacing of 7.45 GHz according to manufacturer specifications. The emitter and detector photoconductive antennas (PCAs) used in the experiment were commercial BATOP spiral and butterfly LT-GaAs PCAs, respectively. The incident power at the emitter PCA was limited to 20 mW and 18 mW for the detector PCA. The incident laser power for both emitter and detector were kept constant for all measurements using non-linear density filters. A 20 Vpp voltage bias at 20 kHz frequency was used for the emitter PCA.

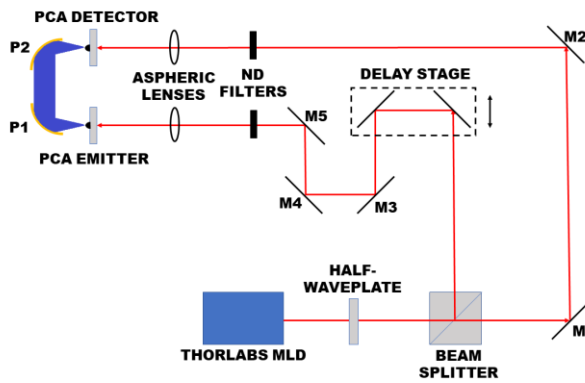


Fig 1. The experimental setup using Thorlabs L808P200 multimode diode laser with spiral PCA emitter and butterfly PCA detector

Parametric TDS measurements were performed by varying the injection current and the temperature of the laser system. Modification of the temperature and injection current were done via their respective controllers. The injection current controller was limited to 200mA. The laser temperatures used were 15° C, 20° C, 30° C, and 40° C while the injection current was varied from 150mA to 190mA in 10mA increments for each temperature setting. The values of temperature and injection current were selected based on the operational limitations of the current controller and the laser diode.

3. Results and Discussion

The signal obtained from the multimode laser diode QTDS system is shown in Fig. 2a using 150 mA injection current and 15°C temperature settings. Two THz pulses were obtained within a 100 ps time window. The spacing between modes is approximately 7.45 GHz according to the specifications of the manufacturer. This corresponds to a THz pulse repetition of around 134 ps. However, the experimentally obtained QTDS pulses were separated by approximately 55 ps. The FFT of the signal was obtained and shown in Fig. 2b.

The first THz pulse was optimized further in preparation for parametric measurements and is shown in Fig. 3a using a 55-ps window. Using the 55-ps window to include only the first THz pulse leads to a smoother FFT spectra shown in Fig. 3b when compared to the spectra in Fig. 2b. The signal-to-noise ratio of the system is around 40dB with a bandwidth of 400 GHz. The THz intensities as well as the signal-to-noise ratio and bandwidth obtained from the proposed QTDS system are still inferior to conventional TDS systems that utilize ultrafast femtosecond laser sources. The frequency resolution for both systems is limited by their scanning distance which is derived from temporal delay mechanism used. The overall SNR also limits the frequency resolution. Comparing Fig. 2b and 3b shows that a smaller scanning window is needed to maintain a relatively smooth spectrum which comes at the price of lower frequency resolution. Conventional TDS setups can afford longer scanning distances due to their overall higher SNR. However, the proposed QTDS system was still able to obtain an SNR of 40dB, and a bandwidth of 400GHz at 20GHz frequency resolution in a 55ps window. The bandwidth and SNR of the proposed QTDS system is comparable to a TDS system using monolithically integrated electrically pumped mode-locked semiconductor laser operating at 1550nm wavelength [19].

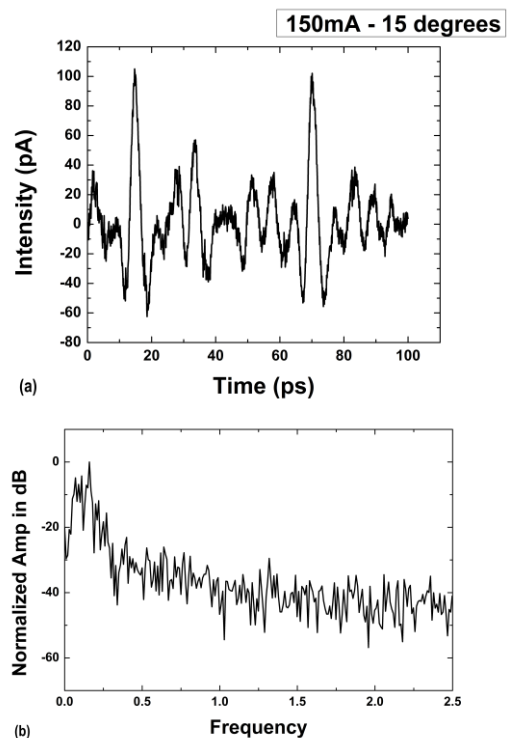
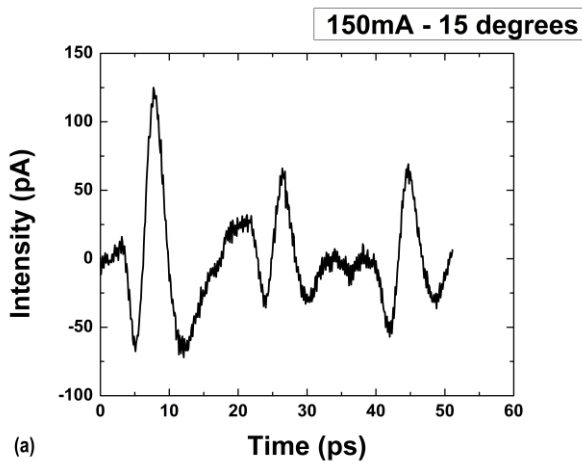
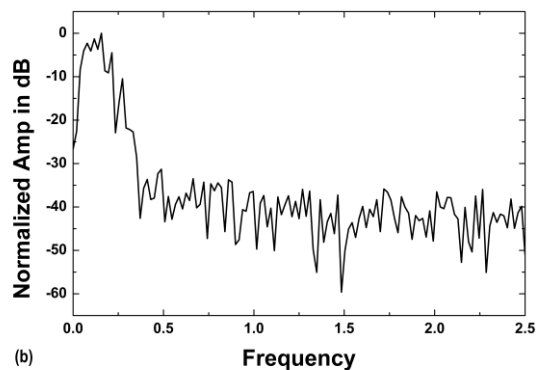


Fig 2. TDS scan (a) at 150mA and 15° C temperature showing two THz peaks and the FFT spectrum (b).



(a)



(b)

As discussed in the Methods section, parametric **Fig 3.** A 55-picosecond time window TDS scan (a) at 150 mA and 15°C and the corresponding FFT spectrum (b).

measurements of injection current and temperature were performed. For each temperature value, the THz signal was measured from 150mA to 190mA in increments of 10mA. The results of the parametric measurements are shown in Fig. 4 in terms of the THz peak-to-peak intensity. Peak-to-peak intensity was calculated as the sum of the positive peak at 8ps and the absolute value of the negative peak at 12ps. An injection current of 170 mA and temperature of 20°C was observed to have the highest peak-to-peak THz intensity. It is shown in Fig. 4 that the THz peak-to-peak intensity changes with respect to the injection current and temperature despite maintaining the average incident laser power at a constant value (20mW for emitter and 18mw for detector) for all measurements. This observation lends proof that the efficiency of THz generation is dependent on the mode hopping characteristics of the laser diode. Fig. 4 shows that the rate of change in the peak-to-peak THz intensity at higher temperatures is slower compared to lower temperatures in response to increasing injection current. This could imply that at higher temperatures, the mode hopping characteristics of the device is less affected by changes in injection current.

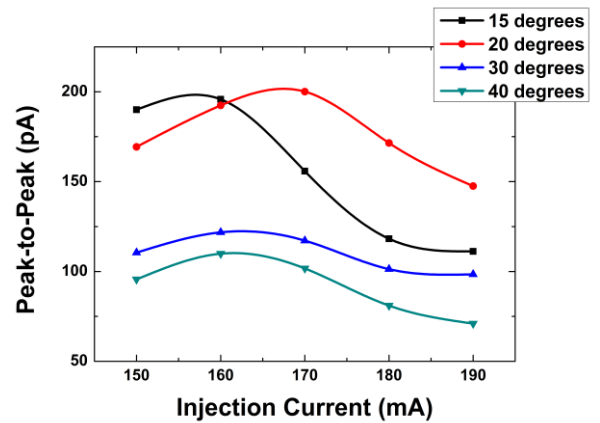


Fig 4. THz Peak-to-peak measurements of the QTDS system at varying injection currents and temperatures.

4. Conclusion

This work is successful as a proof of concept demonstration of a working QTDS system using a low-cost multimode diode laser. The system exhibits a bandwidth of 400 GHz with a signal-to-noise ratio of 40dB. Parametric measurement of the THz peak-to-peak intensity was performed showing that the THz peak-to-peak intensity varies with the injection current and temperature even under constant incident laser power. An optimal setting for injection current and temperature was obtained based on the highest peak-to-peak intensity. This paper demonstrates the capability of our laboratory to engage in modest THz photonics without the burdens of procuring an ultrafast laser source which costs hundreds of times more than a multi-mode CW laser diode.

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