Dual-Mode Terahertz Time-Domain Spectroscopy System

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***Abstract*—Terahertz time-domain spectroscopy (THz-TDS) systems traditionally operate in a single mode, either in reflection or transmission. In cases where the sample has nonunity permeability, measurements in both reflection and transmission geometries are required. The process of shifting and swapping the samples during an experiment increases the measurement uncertainty. This paper therefore presents a system where both reflection and transmission measurements can be performed simultaneously to reduce both experimental error and acquisition time. The measurement results are validated against findings in literature.**

***Index Terms*—Reflection spectroscopy, terahertz, terahertz time-domain spectroscopy (THz-TDS), transmission spectroscopy.**

I. Introduction

Terahertz time-domain spectroscopy (THz-TDS) systems in tabletop environments have seen many improvements in both generated power and detectable bandwidth [1]–[4]. These systems allow for the study of many materials and fabricated samples in either transmission [5]–[7] or reflection modes [8]–[10]. Some samples, particularly metamaterials with a magnetic response, i.e., where the permeability is not equal to unity, require both transmission and reflection measurements to determine the intrinsic electric and magnetic parameters [11]. The proposed system in this paper overcomes this limitation by simultaneously acquiring both reflection and transmission spectra. Additionally, experimental errors due to sample placement and transfers are therefore avoided, leading to reduced experimentation times and lower measurement uncertainty [12].

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Previous systems operating in transmission mode typically make use of off-axis parabolic mirrors to collimate and focus a THz beam. In contrast, a typical reflection mode system consists of elliptical mirrors placed at an inclined angle, to reflect a THz beam onto and from the sample surface for spectroscopic acquisition. Other reflection geometry systems employ a silicon beam-splitter with off-axis parabolic mirrors to obtain similar results via a normal incident beam. Brunner *et al.* [13] has published an innovative system, which is able to acquire both transmission and reflection measurements simultaneously.

The system presented in this paper integrates the off-axis parabolic mirror concept from traditional THz-TDS transmission mode systems, with an additional silicon beam-splitter placed in the back-reflected path for reflection measurements. This work takes a different approach from Brunner *et al.*, as there are no limitations on the emitters or detectors used in the system. Our system does not rely on an electrooptical crystal used as a transceiver, and it only requires a single pass through samples, simplifying calculations for refractive index and absorption. The only drawback to our system is the dumping of 50% of the emitted THz power, which, with currently available emitters, still yields a very usable SNR. In addition, the system setup is simplified as it only requires three components additional to the conventional transmission system, namely, a silicon beam-splitter, an additional off-axis parabolic mirror, and an additional THz detector for the reflected beam.

To verify the system characteristics, two samples are measured. These include a high-impedance (HiZ) float-zone silicon wafer and an n-type (phosphorous doped) silicon wafer. Measurements of the float-zone silicon wafer provide a transmittance and reflectance that can be verified by a Fabry–Pérot analytical model [14], with a previously calculated refractive index. In addition, measurements of the n-type silicon wafer allow for further verification of system performance comparing the Drude model with the measured data.

II. Experimental Setup

The experimental setup of the simultaneous reflection and transmission THz-TDS system has many similarities to that of a transmission mode THz-TDS, where four off-axis parabolic mirrors are used within the THz beam path to focus the beam onto a sample. In addition to this configuration, a float-zone intrinsic silicon wafer of 380-μm thickness is used as a beam-splitter for the back-reflected path and coupled for measurement with an additional off-axis parabolic mirror. A Ti:sapphire Spectra Physics Mai Tai laser with a center wavelength of 800 nm and a pulse length of $\leq$ 100 fs is used as the pump source, while a Gigaoptics Tera-SED large area inter-digitated

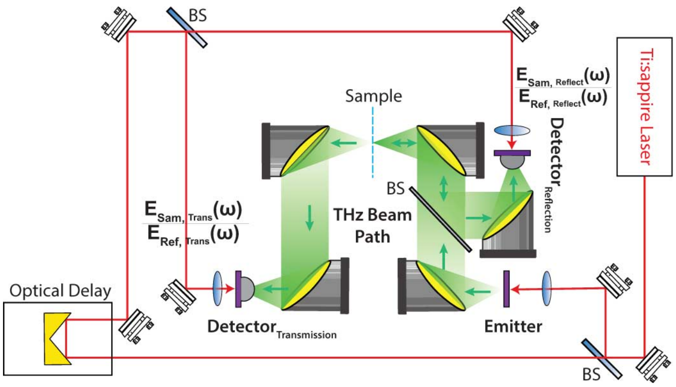


Fig. 1. Diagram of the simultaneous reflection and transmission THz-TDS system. The path of the 800-nm laser beam is depicted in red, while the THz beam path is shown in green, with all beams horizontally polarized. The sample is placed in the focus of the parabolic mirrors and, for a reference measurement in reflection geometry, a mirror is used.

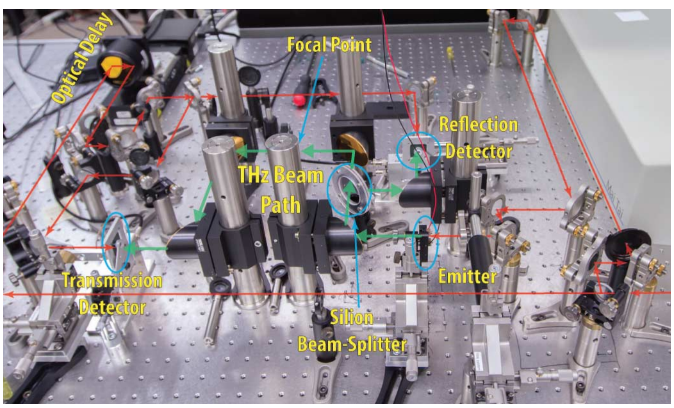


Fig. 2. Photograph of the physical setup. The emitter and detectors for the transmitted and reflected THz beams are circled in blue, along with the silicon beam-splitter. The laser and THz beam paths are shown in red and green, respectively.

array emitter is used as the THz emitter biased with a ±10-V square-wave with a chopping frequency of 10 kHz. As can be seen in Fig. 1, the emitter does not have a silicon lens present, as the array structure collimates the emitted THz beam. The detectors used for the measuring of the transmitted and reflected THz beams are Menlo Systems TERA8–1 H-dipole-based photoconductive antennas, coupled with Tydex 10-mm—diameter hyper-hemispherical lenses to collect the THz beam onto the antenna. Two Stanford Instruments SR-830 lock-in amplifiers are used to recover the induced current for the detectors and allow for simultaneous data acquisition. A diagram of the system setup can be seen in Fig. 1, while a photograph of the physically realized system can be seen in Fig. 2.

All experiments are performed at ambient temperature in dry atmospheric conditions. Two reference measurements are initially required for comparison with sample data acquired from transmission and reflection geometries. To minimize errors due to the shift in reference or sample position in a reflection geometry, a fixed CCD camera is placed over the focal point of the terahertz beam. This allows both the sample and mirror surfaces to be placed in the same longitudinal position, within a micrometer of accuracy. This enables the refractive index and absorption calculated in reflection mode to be accurately compared with

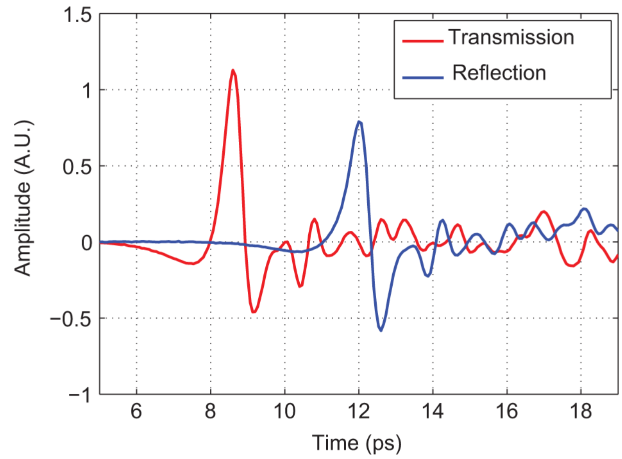


Fig. 3. Time-domain representation of the measured air reference pulses. The red line shows the transmitted pulse, while the blue line shows the reflected pulse. The fluctuations after the main pulse are due to the water vapor present in the laboratory atmosphere. The pulses are offset for viewing ease.

that calculated from transmission-mode measurements and conforms with the acceptable range of error in literature [15], [16]. An optical-grade gold mirror is employed in the reference measurements in a reflection geometry and reflects more than 98% of the THz beam in the reference measurement. It is assumed that the losses are negligible and within experimental error of measurements.

III. Results and Verification

Reference measurements of the system in both reflection and transmission mode show the system performed within expectation, where the silicon beam-splitter reflects off approximately 50% of the generated power. The reference waveform in reflection mode, $E_{\mathrm{ref,rx}}(\omega)$ is acquired by placing a mirror surface at the point of focus of the parabolic mirrors, while the transmission reference, $E_{\mathrm{ref,tx}}(\omega)$ is obtained without obstructing the THz beam path, apart from the silicon beam-splitter, as outlined in Fig. 1. To determine the loss of the system, a transmission reference is recorded and subtracted from a measurement in transmission mode without the silicon beam-splitter. This conforms to expectations that approximately 50% of the generated power is dumped by the silicon beam-splitter. The reference spectra shows that bandwidths of approximately 3 THz are achievable in both geometries. Figs. 3 and 4 show the time-domain waveforms and spectra of both the reflection and transmission reference measurements.

The waveforms of samples in both reflection and transmission can also be obtained in the same fashion, with the reflected waveform obtained by the reflected pulse $E_{\mathrm{sam,rx}}(\omega)$ from the sample surface and the transmitted waveform from the transmission through the sample $E_{\mathrm{sam,tx}}(\omega)$. Thus, the relative reflection and transmission spectra of the sample with respect to the reference can be determined by the following equations:

$$R(\omega) = \frac{E_{\mathrm{sam,rx}}(\omega)}{E_{\mathrm{ref,rx}}(\omega)} \tag{1a}$$

$$T(\omega) = \frac{E_{\mathrm{sam,tx}}(\omega)}{E_{\mathrm{ref,tx}}(\omega)}\quad . \tag{1b}$$

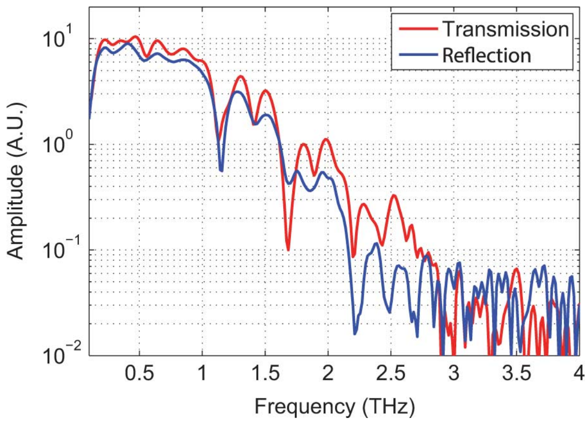


Fig. 4. Frequency spectra of the transmitted and reflected air reference pulses of in red and blue respectively. The maximum bandwidth achievable from this system in both reflection and transmission modes is approximately 3 THz. Water absorption can be clearly seen at approximately 1.1, 1.6, and 2.2 THz.

These equations can then be used to calculate the complex refractive index $\tilde{n}(\omega) = n(\omega) - i\kappa(\omega)$, at normal incidence, as well as the absorption coefficient $\alpha(\omega) = 4\pi\kappa(\omega)/c$ [15], by the following equations:

$$R(\omega) = \frac{1-\tilde{n}(\omega)}{1+\tilde{n}(\omega)} + \frac{\frac{4\tilde{n}(\omega)[\tilde{n}(\omega)-1]}{(\tilde{n}(\omega)+1)^3}\cdot\exp[-i2\tilde{n}(\omega)\frac{\omega}{c}d]}{1-(\frac{\tilde{n}(\omega)-1}{\tilde{n}(\omega)+1})^2\cdot\exp[-i2\tilde{n}(\omega)\frac{\omega}{c}d]} \quad (2a)$$

$$T(\omega) = \frac{4\tilde{n}(\omega)}{[\tilde{n}(\omega)+1]^2}\cdot\frac{\exp\left\{-i[\tilde{n}(\omega)-1]\frac{\omega}{c}d\right\}}{1-(\frac{\tilde{n}(\omega)-1}{\tilde{n}(\omega)+1})^2\cdot\exp[-i2\tilde{n}(\omega)\frac{\omega}{c}d]} \quad (2b)$$

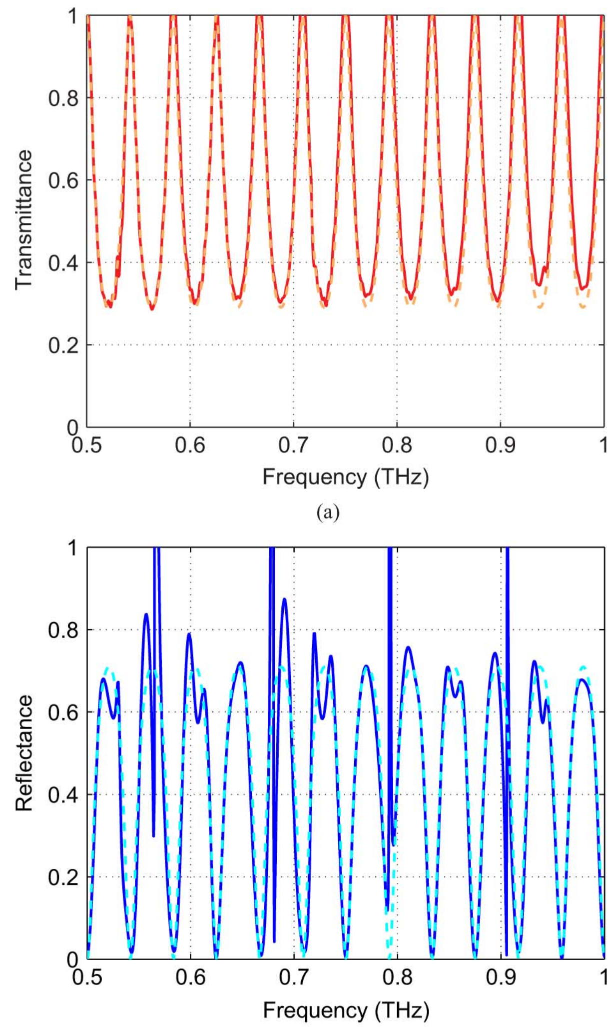
where c is the speed of light, and d is the thickness of the sample.

A. Characterization of Float-Zone Silicon

For verification that the spectroscopic data obtained from both detectors are accurate, a float-zone silicon wafer is measured, as it provides a known transmittance and reflectance from a precalculated refractive index of $n_{\text{silicon}} \approx 3.418$. From this refractive index, the transmission and reflection spectra can be calculated from standard Fabry–Pérot equations and their corresponding Fresnel coefficients [(2a) and (2b)] [14], [15]. As can be seen in Fig. 5(a) and (b), the theoretical model is in good agreement with the measured data. The calculated thickness of the wafer is found to be 1052 μm by varying the thickness until the modeled curves overlapped the measured data. This value differs slightly from the manufacturer-quoted thickness of 1 mm. The good agreement between the theoretical model and the measured data shows that the system is operating as expected. Also of note, the obtained transmission and reflection magnitudes in some instances is higher than unity due to long-term laser drift in measurements [12], which cannot be removed by averaging.

B. Characterization of Doped Semiconductor

In the literature, THz characterization of semiconductors [17]–[21] is well known, and this potentially benefits from our dual-mode system. To show this aspect of the system, a phosphorous-doped n-type silicon wafer of thickness 270 μm



(a)

(b)

Fig. 5. (a) Transmitted and (b) reflected THz power of a 1052-μm-thick float-zone silicon wafer. The dotted lines denote the theoretical Fabry–Pérot model, while the solid lines show the measured data. It should be noted that the data in some instances differ slightly from the theoretical model due to laser drift. The figures have been shortened to frequencies 0.5 to 1 THz for easier reading.

is measured in this system for further verification. The spectra are presented in Fig. 6, where it is possible to see that little to no transmission was measurable and that most of the power is in fact reflected or absorbed in the wafer. The downward trend in reflectance is due to the increase in frequencies approaching the plasma frequency of the highly doped wafer, where the wafer becomes transparent due to the transition from metal to dielectric.

It is possible to characterize this n-doped silicon wafer to achieve the intrinsic values of the carrier concentration and electron mobility. The measured transmission and reflection spectra are fitted with the calculation based on the Drude model, as depicted by the dashed curves in Fig. 6. The plasma frequency and collision frequency of this silicon sample are determined to be $\omega_p/2\pi = 7.87$ THz and $\Gamma/2\pi = 11.21$ THz, respectively. This is equivalent to the doping concentration of 2.0×10^{17} cm^{-3}, the electron mobility of 603 cm^2/V $\cdot$ s,

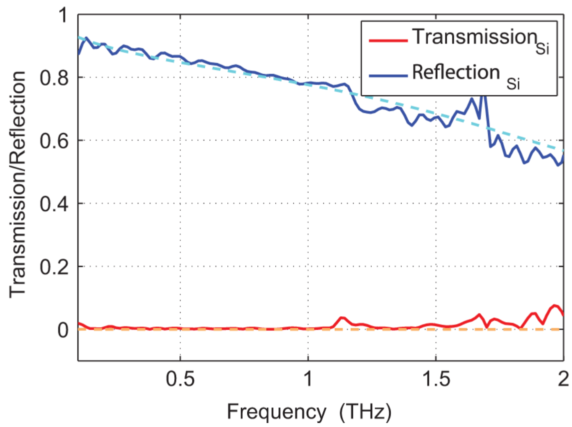


Fig. 6. Reflection and transmission spectra of a highly doped n-type silicon wafer. The transmission of the wafer plotted in red is close to zero, while the blue plot shows that wafer to be mostly reflective, with decreasing reflection until the plasma frequency of 7.87 THz is reached. The dotted lines show the modeled curves of the silicon wafer for transmission and reflection respectively in cyan and orange.

and the dc conductivity of 0.05 $\Omega \cdot$ cm, well within the range specified by the manufacturer.

IV. Conclusion

The presented system performs simultaneously in both reflection and transmission modes, with a usable reference bandwidth of approximately 3 THz. Measurements both float-zone and highly doped n-type silicon wafers allow for the characterization of the system with theoretical models and verify system performance. The simultaneous acquisition of data from samples in both reflection and transmission modes minimizes measurement times and reduces experimental uncertainty. Applications for this system setup are relevant for samples that exhibit both reflectance and transmittance in the THz range, while accurate measurements of losses due to samples can easily be obtained.

Future revisions of the system will incorporate the usage of a higher power emitter such as an electro-optical crystal pumped by an amplified Ti:sapphire laser [24], [25]. Electrooptical sampling can also be used to increase detectable bandwidth and sensitivity. The beam-splitter used could also be changed or modified, by the use of a polarizing beam-splitter and a combination of optics, such that 50% of the power from the incident THz beam generated by the emitter is not wasted as it is currently. An alternative for the silicon beam-splitter is the use of a ratio-adjustable beam-splitter [26], to maximize the detectable power. Finally, imaging and tomography of samples could be performed with the addition of both motorized translation and rotation stages.

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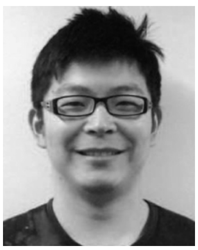

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