

# Overview of Opto-Electrical Terahertz Spectroscopy

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**Abstract** - Terahertz spectrometry offers new opportunities in material research, mostly because THz waves are non-destructive to biological and opaque materials. The technology is still not widely available, but there is a high demand for it. There are three main methods of generating THz waves. The most promising; however, still not a full-fledged method is the opto-electrical method, which is presented in this paper. A demonstration of sample measurements is also presented.

**Keywords** - opto-electrical, photoconductive antennas, spectroscopy, terahertz

## I. INTRODUCTION

Radio frequency (RF) technology is well known and used in telecommunications and radars, which have wide range of use. They are used in weather monitoring, air traffic control, but recent radar development revolutionized other fields, such as geology and civil engineering (for example: ground structure measuring with Ground penetrating radars (GPR) and landslide monitoring with air born Synthetic aperture radars - SAR) and archeology (searching for buried objects with GPR).

Most used RF frequency band is between 2 GHz and 6 GHz. New and not well researched frequency band, called terahertz (THz) band, promises new applications in remote sensing. THz band is located between RF and far infrared spectrum (FIR), from 100 GHz to 10 THz or 3mm to 30  $\mu$ m respectively (1). Since wavelengths of RF spectrum are too long and FIR wavelengths are too short for deeper penetration, THz band offer great opportunity for material analysis, such as paper and cardboard, textile, plastics, gases, etc.

Most materials have spectral “footprints” in THz band. That is well suited for measuring content of certain material in measured media. THz waves cannot penetrate metals and that makes THz spectrometry well suited for many security applications, such as detecting concealed weapons or metal objects at airports, detecting dangerous materials in shipping parcels, etc. Most promising is use of THz spectrometry in biology, chemistry, pharmacy and medicine, since THz waves are considered non-destructive.

Generation of THz waves is challenging. There are three methods: electrical, opto-electrical and optical [1]. Electrical generation of THz waves is limited by frequency limitation of semi conductive materials, presented in [2]. General limit is considered around 300 GHz [2]. There are applications where electrical method is well suited because of its lower price point, but optical method is more suitable because of its wider band of operation. Most common optical method for generating THz waves is by using quantum-cascade-lasers (QCL). The drawback here is that in the lower THz band (up to 5 THz) is hard to achieve, since the QCL must be super cooled for effective generation of THz waves above 1THz (down to

40 K), as stated in [1]. Opto-electrical method is combination of optical components and photoconductive antennas. With the last one we can successfully generate THz waves even bellow 1 THz with relatively high bandwidths (up to few THz). Also, it is only option for generating THz waves from 100 GHz (or even lower) up to few THz, where both electrical and optical methods have major drawbacks or are not plausible.

Opto-electrical method uses well-known optical components in combination with photoconductive antennas or PCAs. This paper is focused on reviewing two main opto-electrical methods for generating THz waves: time domain and frequency domain method. Example on frequency domain spectroscopy platform is presented.

Data processing of THz spectra is divided into two main categories: identification and quantitative analysis. Sample identification can be performed with methods from other spectroscopies like infrared spectroscopy [8]. Quantitative analysis can be divided into modeling, which requires no calibration, and quantization with preliminary calibration. Identification in form of absorption detection and identification based on refractive index are presented.

## II. PHOTOCONDUCTIVE ANTENNAS

Photoconductive antennas are built on photoconductive substrates. Because PCAs should have broadband performance; materials with sub picosecond carrier lifetime should be used. Table 1 presents some of those materials and their characteristics.

TABLE I. SUMMARY OF PHOTOCONDUCTIVE MATERIALS USED FOR PCA [3]

Material	Characteristics	
	Excitation wavelength	Summary
GaAs	800 nm	Poor excitation at 1550 nm, well developed material growth
InGaAs	1550 nm	Decreased dark resistivity
InGa(Al)As	1550 nm	Dar resistivity comparable to LT-GaAs, complex material growth
Other	1550 nm	Materials with limited understanding

Basic PCA is built as shown in Figure 1. On the photoconductive substrate we have metal anode and cathode with gap G between them. PCA should be voltage biased.

Emitter operation is presented in Figure 2. When optical pulse hits the PCA’s surface, it propagates through gap into photoconductive substrate, where it is absorbed and where it

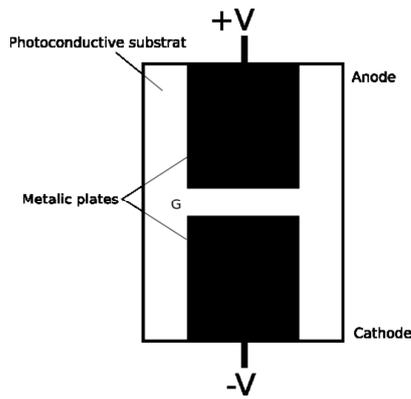


Figure 1. Simple PCA structure

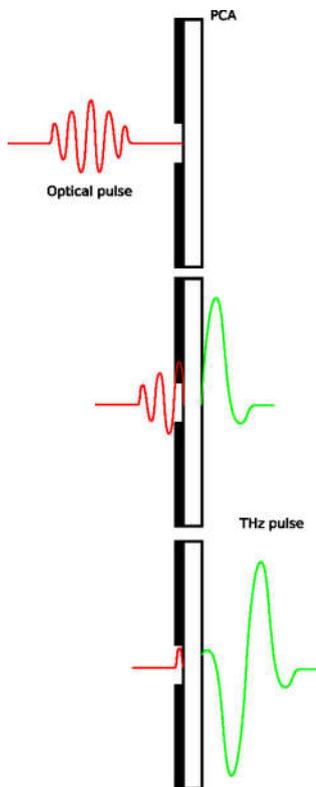


Figure 2. Principle of PCA's operation

creates photocarriers. Bias field accelerates photocarriers, result of which is transient photocurrent. Photocurrent then drives the dipole antenna and emits THz pulse.

For THz wave receiver another PCA can be used. PCA as receiver should not be voltage biased, but we need optical signal from the same source. When THz pulse hits the dipole antenna it overlaps with photocarriers, generated by optical signal. Result is photocurrent, which we can measure.

To get PCA receivers into context, one must get familiar with the structure of pulsed THz spectrometer, which is presented in subsection Time-domain spectrometer, and

continuous-wave (CW) THz spectrometer, which is presented in subsection Frequency-domain spectrometer.

### III. THZ SPECTROMETER BASIC OPERATION

#### A. Time-domain THz spectrometer

Time-domain or pulsed THz spectrometer is built around femtosecond (fs) laser. Basic structure is presented in Figure 3. Emitted IR pulse from fs laser is split in two beams by beam splitter. First beam goes to transmitting PCA, second one goes to adjustable delay stage and then to receiving PCA. As stated in subsection Photoconductive antennas, THz wave and photocarriers overlap in photoconductive substrate. With the delay sweep, we can convolute both signal.

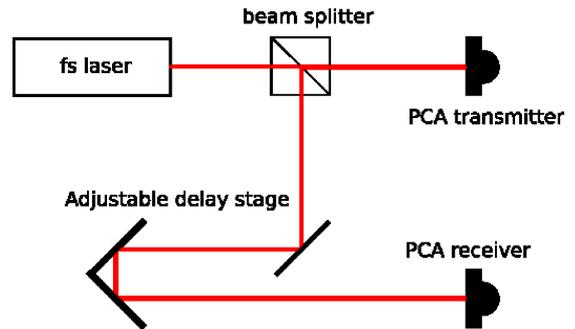


Figure 3. Time-domain THz spectrometer structure

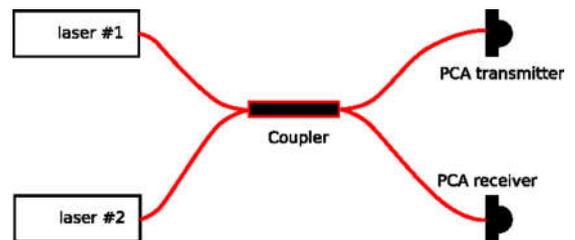


Figure 4. Frequency domain THz spectrometer structure

#### B. Frequency-domain spectrometer

Frequency-domain or CW THz spectrometer if build around optical coupler (most common fiber coupler) and two IR lasers. Basic structure is presented in Figure 4. Both lasers have different wavelength. Optical signals are mixed in coupler and connected to transmitting and receiving antenna. We can perceive mixed optical signal as pulse train. When the pulse train hits PCA, it will generate continuous THz wave. When THz wave hits receiving PCA, Lock-in detection is used for measuring amplitude and phase of the signal.

### IV. FREQUENCY DOMAIN THZ SPECTROSCOPY

#### A. Overview of THz spectroscopy data processing

Data analysis of THz spectra is based on identification and quantization. Identification technics are based on feature comparison between, but those cannot offer any quantization. One of such technics is analyzing absorption. Many materials have been studied using THz spectroscopy, so absorption lines

are well defined for those. With comparison between measured THz spectra and defined absorption lines, materials in measured media can be determined. Nevertheless, [8] suggest using chemometrics methods, such as principal component analysis and even provides some examples of few examples of using principal component analysis in THz spectroscopy.

Quantization methods are based on modeling and methods based on preliminary calibration. Usually, with help of density functional theory, numerical simulations are performed. There are also methods of analyzing absorption and refractive index in order to get correct measurements. One such example is presented in [6] where dielectric function is derived from transmittance and refractive index of  $\alpha$ -Lactose monohydrate.

Demonstration of transmittance measurement and refractive index analysis are presented in subsections Measuring water vapor absorption and Analyzing refractive index respectively.

### B. CW THz spectroscopy platform

As of latest, time based THz spectroscopy and all electric methods were in use. Newly developed CW-THz spectrometers has shown great results in measuring dielectric function  $\epsilon(\omega)$  of solid-state samples, as shown in [7].

There is readily available CW THz spectroscopy platform from Toptica Photonics, called TeraScan [5], which was used in simple experiments, performed in section Sample's characteristics measurements. Toptica Photonics offer two version of TeraScan, summarized in Table 2.

TABLE II. COMPARISON OF TeraScan 780 AND TeraScan 1550 0 PLATFORMS FROM TOPTICA PHOTOTONICS [8]

TeraScan	
model 780	model 1550
780 nm source	1550 nm source
GaAs photoconductive antennas	InGaAs photoconductive antennas or photomixers
Higher scan range or bandwidth	Higher dynamic range and terahertz power
Highest frequency: 1.8 THz (typ. 2.0 THz)	Highest frequency: 1.2 THz (2.7 THz with extension)

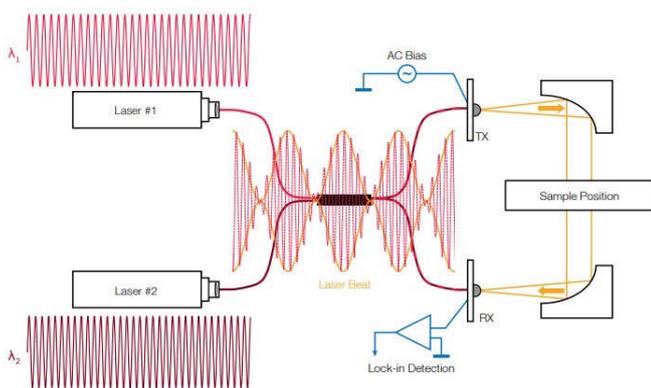


Figure 5. TeraScan configuration [5]

Both system use the same configuration and principle of operation. Configuration is presented in Figure 5. As source, two DFB tunable fiber coupled diodes are used. One is heated,

while the other is cooled in order to get different wave frequencies. Both waves are then mixed in optical coupler. Mixed signal is connected to PCA transmitter and receiver. PCA transmitter is AC biased. On receiving part, Lock-in detection on FPGA is used.

Toptica offers proprietary control unit with software for data acquisition and data analysis. Control unit can also be linked with LabVIEW or python scripts in order of developing custom application.

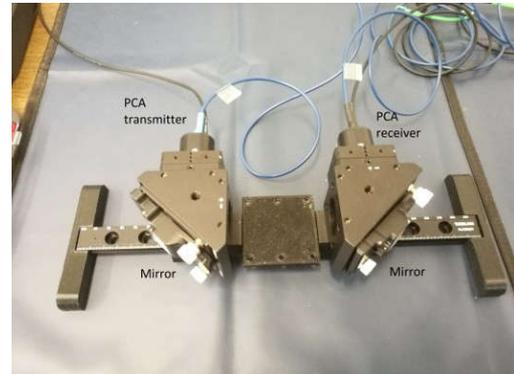


Figure 6. Optical configuration

### C. Measuring water vapour absorption

In order to successfully determine present of water vapors in air, transmittance must be measured. It can be measured with the simple setup, as presented in Figure 6. Both transmitting PCA and receiving PCA are positioned in front of 90° optical mirror and measured sample is placed in between mirrors. In case of measuring water vapors in the air, no other media is placed in between mirrors.

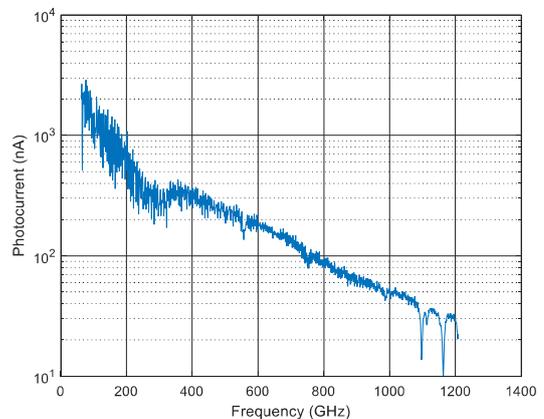


Figure 7. Measured photocurrent versus frequency; water vapor absorption in air, absorption at around 550GHz, 1.1 THz and 1.16 THz

Figure 7 presents experimental results for water vapor absorption measurement from which transmittance can be calculated. Water vapor absorption lines are complied with [7]. TeraScan 1550 with integration time of 3 ms and with 15 overlapping samples was used.

#### D. Measuring refractive index

Experiment was carried out at similar conditions as the water vapor absorption experiment. Configuration and TeraScan 1550's settings were the same. Only difference was that in between both mirrors, media was inserted. Figures 8 present measurement of refraction index of white colored acrylic glass. Refraction index is calculated from phase comparison. Clear acrylic glass has refractive index  $n \sim 1.45$ , while measured refractive index is between  $n \sim 2.15$  and  $n \sim 1.3$ , with center around  $n \sim 1.7$ . This can be explained with difference in additives in both clear acrylic glass and white acrylic glass, used in this experiment.

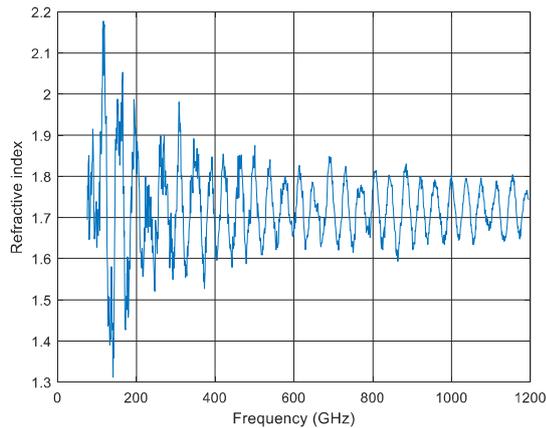


Figure 8. Refractive index versus frequency of white acrylic glass

Refractive index of wood was also measured. From result in Figure 9 we can see that refractive index of wood is rising with frequency. That is because wavelengths closer to visible light cannot penetrate wood as much – wood becomes opaque for higher frequencies.

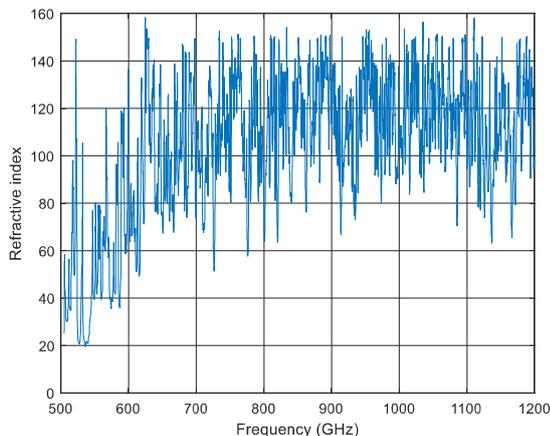


Figure 9: Refractive index versus frequency of wood samples

#### V. CONCLUSION

Overview of opto-electrical methods of generating THz waves was presented. Compared to other methods of generating THz waves, opto-electrical method shows potential in reducing price and complexity of THz spectroscopy, thus widening range of potential applications in material analysis, gas detection, non-destructive testing, quality control and fundamental physics.

Two spectroscopy data analyzing technics for CW THz spectroscopy were presented. Both are basic technics from which material's characteristics can be determined. From calculating transmittance we can determine absorption lines and absorption factor. From calculating difference with phase we can determine refractive index. Both measurements, absorption factor and refractive index, are interconnected.

Demonstrated technics are solid foundation on which we can build further research and development in the field of CW THz spectrometry, or even THz imaging. For basic sample analysis, database of frequency depended absorption factor and refractive index for every material in question, must be constructed. Deep convolutional neural networks could be viable solution for determining content of unknown samples based on constructed database.

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