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Continuous wave Terahertz spectrometer with coherent detection

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Abstract. In this paper a continuous wave (cw) spectrometer in the far infrared range covering frequencies between several tens Gigahertz and one Terahertz is presented. The spectrometer employed a coherent detection scheme and therefore measures both the amplitude and phase of THz radiation. First spectroscopic results of Si-wafer and a test Bragg structure are presented.

Key words: terahertz, continuous wave, spectroscopy, coherent detection, Bragg structure.

1. Introduction

Until 1990s the far infrared radiation in the terahertz (THz) range (0.3–10 THz and corresponding wavelengths between 1 mm and 30 μm) were, relatively, poorly explored due to the lack of compact and reliable sources and detectors. Historically, first sources originating from the optical technology were gas lasers. These bulky and power consuming lasers are characterized with very narrow emission lines and high output power [1]. More compact semiconductor lasers operating with intersubband transitions (quantum cascade lasers, QCL) were demonstrated first in 1994 by Capasso *et al.* [2]. Unfortunately, QCL require cryogenic cooling and operate in the upper THz range. Sources originating from microwave technology like back-wave oscillators, gun diodes and multipliers are powerful sources but operate in the sub-THz region and their power quickly drops when operating at higher frequencies [3]. The gap between optical and microwave technology has been closed with an invention of ultrafast Ti:Sapphire lasers, photoconductive switches [4] and low temperature grown Gallium Arsenide:
(LT-GaAs) with sub-ps carrier lifetime. Terahertz time domain spectrometers (TDS) excited with femtosecond lasers are broadband THz sources covering frequency range between about hundred GHz and several THz [5]. Alternatively, mixing beams from two DFB laser diodes in the photomixer allows generation of continues wave (cw) THz radiation [6, 7].

Due to the low photon energy in this wavelength range a detection of THz radiation is very challenging. Detectors for THz, far- and mid-infrared range are in general based on thermal effects. High power sources operating in the upper THz range (wavelengths shorter than 20–30 μm) like FIR gas lasers and QCLs are typically detected by inexpensive thermopile detectors or pyrodetectors. In the longer wavelength range (wavelengths longer than $\sim$1 mm), originating from the microwave technology, fast Schottky diodes are commonly used. Power measurement of THz radiation from pulsed TDS spectrometers require more complicated detectors like Golay-cell or cryogenic cooled bolometers due to low power levels of up to several tens uW. Such detectors are very sensitive, but are not selective and can respond to heat originating from surrounding devices and even residual optical power. Moreover, bolometers, Golay cells and pyrodetectors are not phase sensitive and their bandwidth is limited to about 25 Hz only. A coherent detection scheme in the TDS systems with a second photoconductive switch or nonlinear crystal [8] allows measurements of an amplitude and phase of THz radiation. Unfortunately, power levels from cw photomixing systems are much lower (tens nW to several uW) than form pulsed systems and therefore cw THz systems with a coherent detection are somewhat less explored [9–12]. Most of them were based on highly efficient but very fragile antennas with interdigitated structure in the excitation gap.

In this paper an inexpensive continuous wave THz spectrometer based on two DFB laser diodes and photoconductive antennas with simple excitation gap is presented. THz radiation is generated and coherently detected via photomixing phenomena.

2. Generation and coherent detection of cw THz waves

Generation of continuous wave THz radiation is based on photomixing phenomena. An interference of two optical beams with wavelengths λ_1 and λ_2 on a photoconductive antenna periodically modulates its photoconductance. Under the presence of an external electric field in addition to the DC photocurrent an f_1–f_2 AC component will be flowing through the antenna and thus radiate electromagnetic wave. Power of radiated THz electromagnetic wave depends on:

$$P_{\text{THz}} \propto P_i^2 \cdot V_B^2 \cdot k, \tag{1}$$

a square of incident optical power P_i, a square of applied bias V_B and a factor k which depends on the antenna structure, ra-

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diation efficiency and carrier dynamics in the LT-grown layer. More details about THz generation via photomixing phenomena can be found in [6, 7, 13]. In analogy to the pulsed spectrometers, a coherent detection scheme in cw systems records both phase and amplitude of the incident THz radiation. In order to perform the coherent detection, a second photoconductive antenna has to be illuminated with a part of the two-colour beam that is used for the generation of THz radiation. Optical beating periodically modulates the photoconductance of the detector antenna, similar as in the case of emitter. The THz induced photocurrent flowing in the detector antenna is given by:

$$I_{\mathrm{det}} \propto P_i' \cdot E_{\mathrm{THz}} \cos\left(\frac{\omega_1 - \omega_2}{c}\Delta d\right) \tag{2}$$

where $P_i\prime$ is incident optical power on the detector antenna, E_{THz} strength of the THz wave and Δd is the length difference between the optical paths in the detecting and the generating beam. Scanning with an optical delay line in the emitter or detector path will result in a sine waveform of the measured photocurrent.

3. Experimental setup

The experimental setup is shown in Fig. 1. The system consists of two parts: the optical and the THz path. Optical beams from two DFB GaAs/AlGaAs laser diodes are combined by 50:50 beam-splitter cube. The resulting two "two-colour" beams are referred to as the detecting and generating arms, respectively. The emission wavelength of the diodes can be tuned between 857.9 nm and 861.3 nm by changing the temperature of the diode from 1°C to 50°C. Therefore, the maximal difference frequency between the two diodes equals to 1.38 THz. The two-colour beam in the generating arm is guided and focused onto a transmitting LT-GaAs photoconductive antenna. The antenna structure is of dipole shape with a length of 90 μm. Due to relatively low conversion efficiency in photomixing systems, typically highly efficient but fragile antennae with an interdigitated (finger) structure in the excitation gap are used [6–7]. This experimental setup is based on less efficient but very robust antennae with a 5 μm wide excitation gap without any fragile structures. Antennae are illuminated with 40 mW and 17 mW of integrated optical power for emitter and detector antenna, respectively. The transmitting antenna is chopped electrically with a bipolar square waveform with an amplitude of 45 V (90 V peak-to-peak) at 1 kHz. The Terahertz part is depicted with a dashed line in Fig. 1. The THz radiation emitted by the photoconductive dipole antenna is pre-collimated with a High-Resistivity Si-lens of hypersemispherical shape [14, 15]. The beam is guided via four off-axis parabolic mirrors PM1-PM4. Mirrors PM1 and PM3 are used for beam collimation, whereas the PM2 and PM4 for focusing, respectively. The investigated sample is placed in the intermediate focus between the mirrors PM2 and PM3. Finally, the beam is focused on the detector antenna with the same structure as the emitter antenna. The second part of the two-colour beam in the optical part, referred to as a detecting arm, is guided to the optical delay line and than to the receiving antenna. In a case of standard Time Domain spectrometers the optical length of generating detecting arm has to be equal. Here, current flows in the detector antenna regardless the length difference between the generating and detecting arm. The delay line is used to set the phase difference between the optical and the THz signal as described in Eq. (2). THz induced photocurrent in the detector antenna is measured with a lock-in amplifier. Contrary to thermal detectors (bolometer, Golay cell, pyroelectric detector) the coherent detection scheme records both amplitude and phase of the incident THz wave.

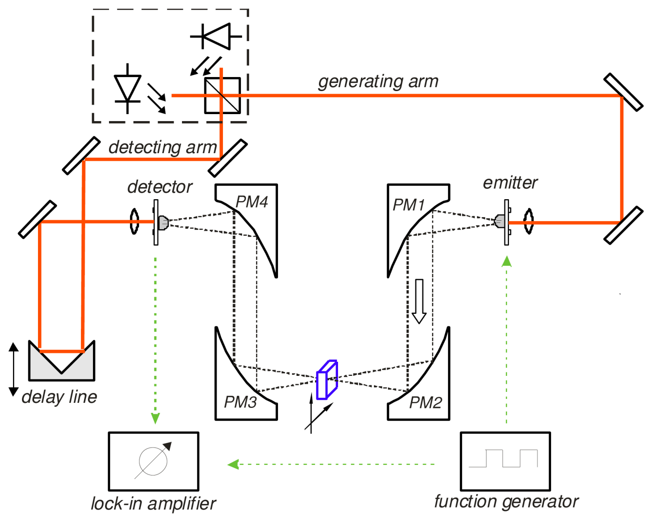

Fig. 1. CW THz spectrometer with coherent detection

4. Experimental results

4.1. Antennae spectrum. As discussed in Sec. 2 a change of optical path length results in a periodic change of the THz induced photocurrent flowing in detector antenna. Figure 2a shows typical measurements for the THz signal of 150 GHz, 300 GHz and 528 GHz. For clarity, the measurements of 150 GHz and 528 GHz have an offset of -25 and $+25$, respectively. The measurement of the 300 GHz signal is accompanied by a sample of the noise measurement. The period of the measured signals decreases with an increase of the THz frequency, as described in Eq. (2). The 150 GHz and 528 GHz signals have smaller amplitude of the electric field because the excitation frequency does not match the resonance of dipole antennae used in the experiment.

Figure 2(b) shows the measured amplitude of the THz signal between 0.1 THz and 1.1 THz radiated and detected by two 90 μm dipole antennas. This measurement was performed with a short integration time and a fast scan of the delay line. The measured spectrum agrees reasonably well with the simulated and measured emission spectrum for the somewhat longer 100 μm dipole, as discussed in [16]. An arrow indicates a water vapor absorption line at 550 GHz.

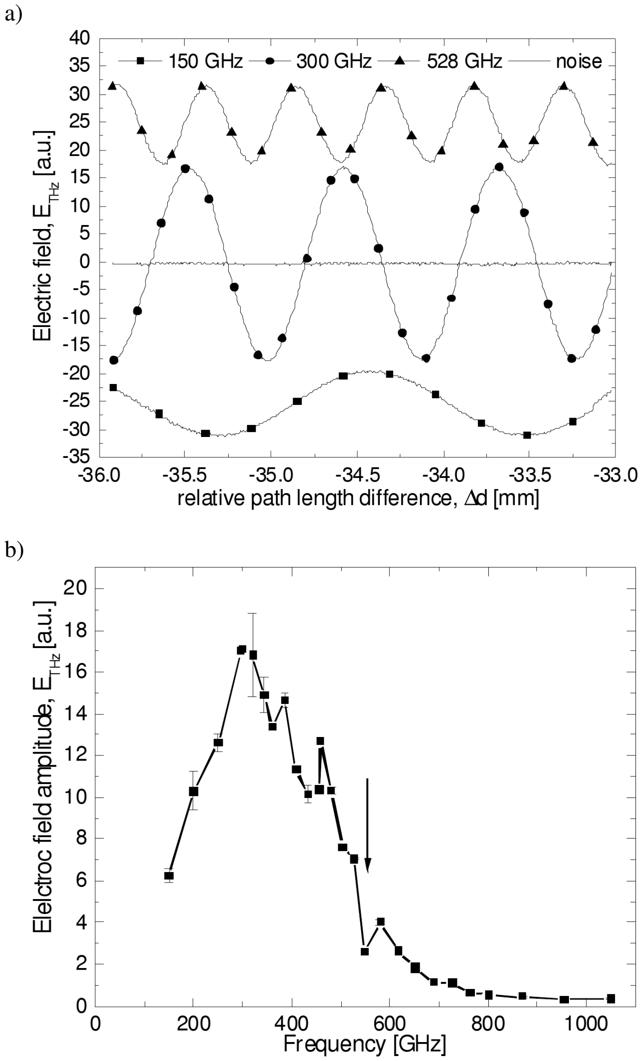

Fig. 2. The measured cw THz signals for several frequencies (a) and spectrum of 90 μm dipole antenna (b)

4.2. Transmission measurements. Figure 3a shows a power transmission spectrum of the Bragg mirror designed for THz frequency range. The mirror consists of four high resistivity Silicon layers with a thickness of 63 μm which are sandwiched between five Polypropylene (PP) foils with a thickness of 150 μm. Refractive indexes in the THz range equal to 3.418 [5] and 1.530 for Si and PP, respectively. The layers are stapled in a metal holder as shown in Fig. 3b.

The transmission characteristic of multilayer structure was calculated using transfer matrix method [17]. This dielectric mirror is designed to exhibit a broad reflection-band between 240 GHz and 370 GHz. More details about the tested Bragg structure and measurements performed using time-domain spectrometer can be found in [18]. The transmission measurement was performed with a frequency step of about 3 GHz. In order to archive a comparable resolution with a standard TDS spectrometer, the measurement would require $\tau = 330$ ps long time window ($\Delta f = 1/\tau$), which is much longer than typically used time windows with a length of approx. 50 ps. The experimentally measured and simulated transmission spectra agree reasonably well with each other. In particular, the sharp spectral fringes around 200, 420 and 480 GHz are easily resolved.

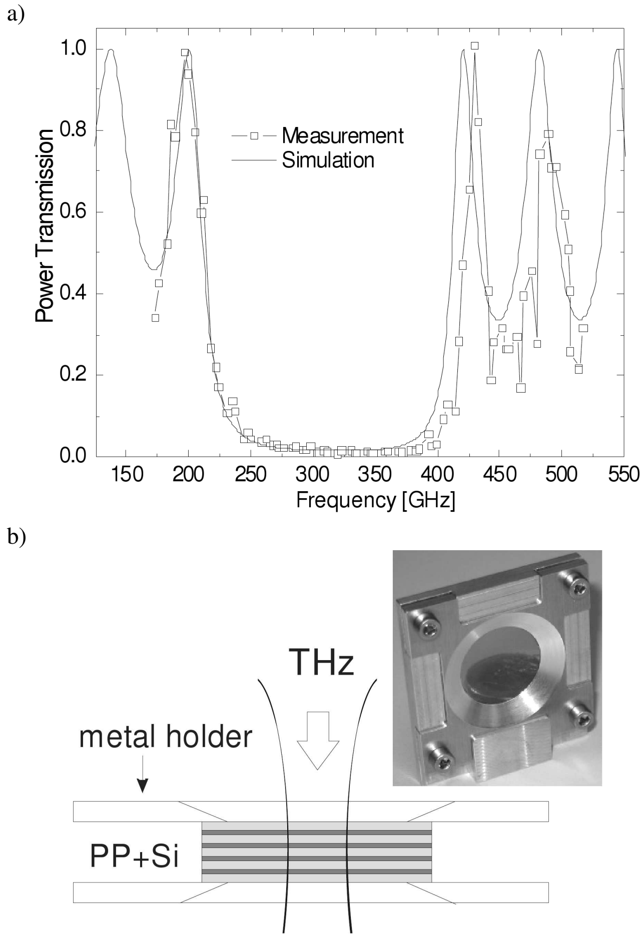

Fig. 3. THz transmission of Polypropylene/Si Bragg reflector (a), schematics and a photo (b)

4.3. Refractive index measurements. As discussed in the previous paragraphs the THz spectrometer with a coherent detection is capable of measuring both an amplitude and a phase information of the incident THz radiation. With a sample under test in the THz beam path, the phase of THz signal will be shifted with respect to the reference measurement, as shown in Fig. 4a. This phase shift is proportional to the frequency of THz wave, sample thickness and refractive index of the sample under investigation. Because the measured signal is periodic the phase information has to be unwrapped over entire frequency range. The refractive index of the sample can be calculated from the following relation:

$$n(\omega) = n_0 + \frac{c_0}{\omega_{THz} d} \Delta\varphi, \tag{3}$$

where n_0 is refractive index of air, c_0 is speed of light, ω_{THz} is angular frequency of THz radiation and $\Delta\varphi$ is the phase difference between the sine-waves of the reference and the sample, respectively. Figure 4a shows a measurement of 540 μm thick Silicon sample at 280 GHz. In this case the optical thickness of the sample exceeds wavelength of THz radiation and therefore an offset of $+2\pi$ has to be added to the phase difference between the recorded reference and sample signals.

a)

b)

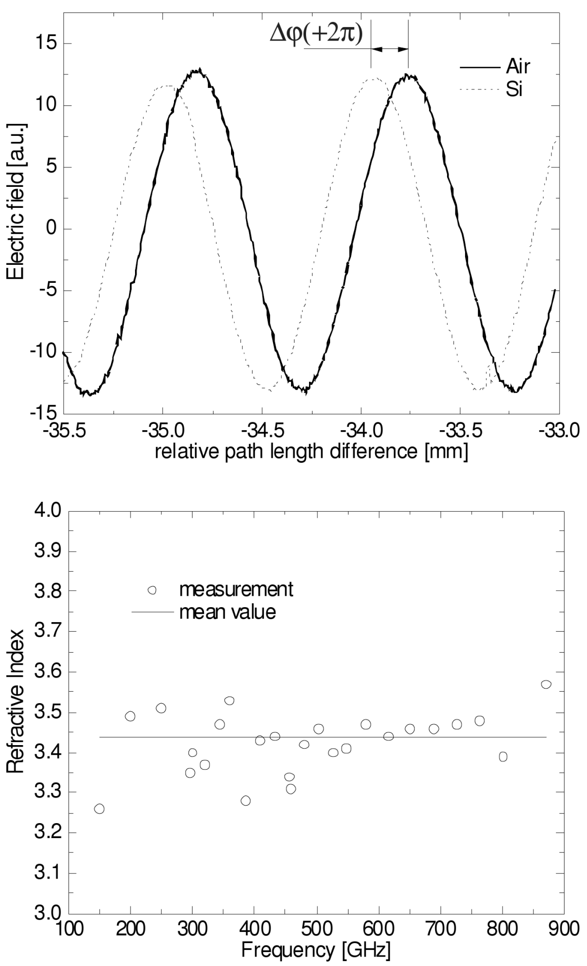

Fig. 4. THz spectroscopy of thin Si waver

Figure 4b shows the measured refractive index over a broad frequency range. Although the curve has a rippled shape, its mean value of 3.424 matches well the value of 3.418 [5] measured by the well developed THz time domain spectrometer. In the similar manner, the presented spectrometer could be used to measure the thickness profile for a known value of refractive index [19].

5. Conclusions

In this paper an inexpensive THz spectrometer based on two DFB laser diodes and two LT-GaAs photomixers is presented. The spectrometer is based on a coherent detection scheme and therefore does not require any expensive and elaborated thermal detectors like liquid helium cooled bolometer. Coherent detection scheme is sensitive for both the phase and amplitude of incident THz wave and therefore enables measurements of absorption coefficient and refractive index in THz range. First spectroscopic measurements of Bragg structure and high resistivity silicon wafer were presented.

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