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Time Domain Spectroscopy goniometric setup characterization by the utilization of plastic diffraction grating.

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Abstract—Characterization of the Time Domain Spectroscopy goniometric setup in the THz range is reported. During the construction of the TDS setup many elements need proper adjustment. Additionally, many steering and data processing systems should be optimized. Test phase diffraction grating with a saw blade profile was measured in the setup.
The performance of the TDS system can be optimized on the basis of experimental comparison with theoretical results.

At the end of the 20th century and the beginning of the 21st century researchers focused on the Terahertz radiation (0.1-3.0THz) due to its interesting properties:

- it is not ionizing radiation,
- many materials have unique signatures in the THz range of frequencies,
- it penetrates through the majority of non metallic and non-polar substances.

THz radiation can be used in different domains, like medicine, weaponry, security, telecommunication and many others. The most important applications of this radiation are:

- systems that can see "through walls" or "through clothes",
- detecting explosives and biological hazards,
- spectroscopy systems for cancer diagnostics
- free space telecommunication with a high channel capacity.

A complicated and expensive Time Domain Spectroscopy (TDS) is applied in the THz range because of its broad frequency range (0.1-3.0THz) and high sensitivity. This method requires a dry nitrogen environment for frequencies over 1.5THz.
Typically, TDS is used for material characterization. A sample is measured in the reflection and/or transmission mode. In this configuration a detector and an emitter are on fixed positions [1]. Such systems enable the measurements of a specially prepared sample of the material. By the use of standard sample thickness and proper delay line adjustment it is possible to measure the refractive index, reflection or transmission as a function of frequency.

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Sometimes people use TDS with a fixed emitter and a fixed detector for 2D imaging by moving, scanning or shifting the sample [2].The experiment can be carried out in transmission as well as in reflection.
A typical TDS setup is very sensitive for the beam shape which should exactly fit the detector optics. Terahertz radiation should be exactly focused on the special slit located in the sensor plane. It is worth mentioning that commercially available detectors are prepared to predefined beam geometry (quasi plane, concave, convex spherical with given curvature radii). Any corruption of the expected incoming beam geometry will decrease the sensitivity of the setup.
For additional spatial analysis of the amplitude and phase distribution, goniometric setups are used. The system based on a "rotational goniometric arm" allows to measure angular amplitude and phase distributions. The use of optical fibers improves the system mobility and flexibility. A more complex system – which is under construction in the Femtosecond Laser Laboratory, *Faculty of Physics, Warsaw University of Technology*– is based on a movable *x,y,z* detector. Additionally, the detector can be rotated around two axes. The above construction will enable the measurement on a sphere or on a plane. The system will also enable proper delay line adjustment depending on detector localization.
Moreover, the system will provide easy maintenance of polarization orientation. It can be done by simple sample rotation and does not need any rearrangement of the optical system (rotating emitter and detector).

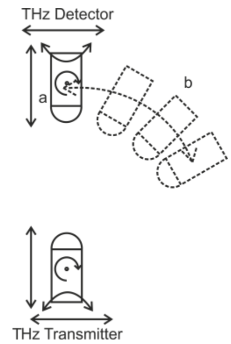

Fig. 1. Scheme of the final goniometric setup: a) detector start position, b) detector in motion.

A TDS goniometric system can be easily characterized by a set of phase diffraction gratings with a saw blade or a rectangular profile. Amplitude and phase angular distributions behind such gratings in the visible range of electromagnetic radiation are well known.

The problem is much more complex for the THz range. Typical parameters of the grating used in the experiment are given below. The grating was manufactured in EX200 plastic by a 3D printing technique. It has the following parameters:

- design wavelength 1.2mm (0.25THz),
- material EX200, n = 1.66, α=3.12cm^{-1}, (0.25THz),
- period 128x39μm = 4.956 mm,
- saw blade grating fringe profile,
- maximum height of the profile 1.81mm.

From a simplified theoretical approach we expect only +1 diffractive order with the efficiency almost 100% due to the saw blade fringe profile, the maximal phase retardation is 2π and there is an assumption that the structure is flat. The expected diffraction angle is 14 deg.
One can notice that the period of the grating is c.a. 4λ. The height of the step is c.a. 1.5λ. So the grating is not flat. Additionally, the grating is placed just behind the emitter. THE Emitter has a diameter of 10mm and is illuminated by a spherical convergent wave with a curvature radius of 5cm.
Concluding the above, we should take into account the following facts:

- grating is not flat, so the shadow effect [3] will appear,
- attenuation is significant and should be considered,
- only two periods of the grating are illuminated,
- grating is illuminated by a spherical convergent wave.

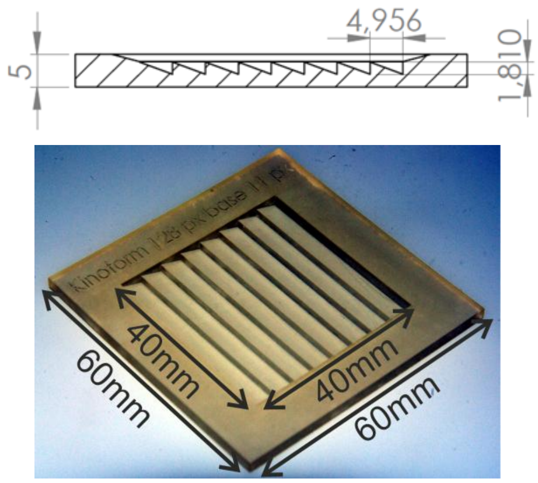

Fig. 2. Design and photo of the grating.

Theoretical considerations of the above setup are very complex. So computer modeling was performed. We used the off axis expansion [4] of the modified convolution approach [5] and off-axis modification of the beam propagation method (BPM) [6].

For modeling purposes it was assumed that the grating is illuminated by a spherical concave wave with an aperture diameter of 10mm and a curvature radius of 50mm. The volume diffraction grating was modeled in the form of 16 slices. Each slice is an amplitude–phase element with a linearly changing fill factor within the propagation step number. The above technique enables to create a proper 3D phase profile and includes the attenuation of the grating.
The propagation in the volume of the grating was modeled with an algorithm based on BPM. Every slice was assumed as a flat element. Proper phase retardation and attenuation for one propagation step was introduced due to the parameters of the EX200 material.Free space propagation for each step was calculated using off-axis expansion of the modified convolution approach. Due to very short propagation distances and sub-wavelength sampling the existence of evanescent waves was considered.
Free space propagation for the distance between grating and detector was used. Figure 3 presents the computer modeling results.

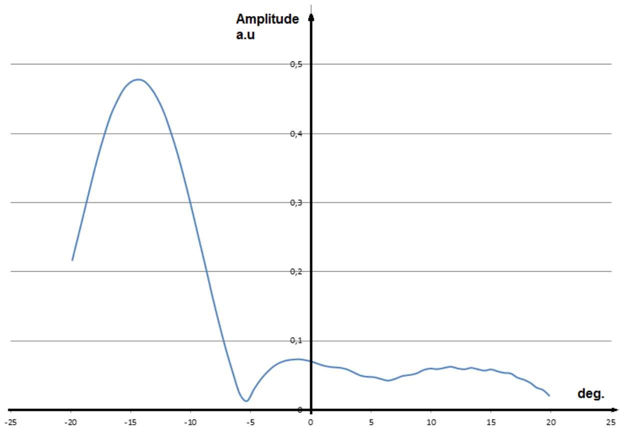

Fig. 3. Modeling results for 0.25 THz.

The measurement was performed in the TDS setup. The source of light pulses is the femtosecond laser which is emitting the 100 fs pulses having the wavelength λ=800nm. The pulse is divided on the beam splitter. In the right arm of the system we placed the delay line and mounted a retro-reflector on it. After the reflection from it the beam is directed to the collimator and coupled into the fiber which illuminates the detector. The optical path difference being the consequence of the spatial shift between the detector and the emitter must be compensated by the delay line. In the left arm of the system the optical chopper is synchronized with the lock-

in amplifier. After passing through the chopper the incident beam is illuminating the collimator coupling it into a fiber leading the light to the emitter. The emitter is biased with the 24V. The signal coming from the detector is amplified and then is connected to the lock-in. The results are sent to the controlling computer. Thanks to the use of fibers both the detector and the emitter can be arbitrarily placed in relation to the sample.
A photoconductive parallel line antenna was used as a transmitter and a photoconductive butterfly as a receiver antenna. The scheme of the TDS setup is shown in Fig. 4.

The detector was moved from -24.8º to +18.8 º into a step of 2.5º. On each step the detector was stopped and the TDS pulse was recorded. The experimental data for 0.25 THz are shown in Fig. 5.

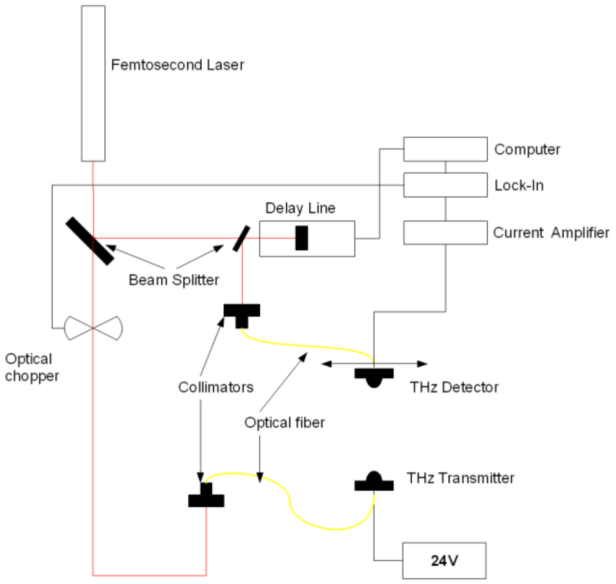

Fig. 4. Scheme of the experimental setup.

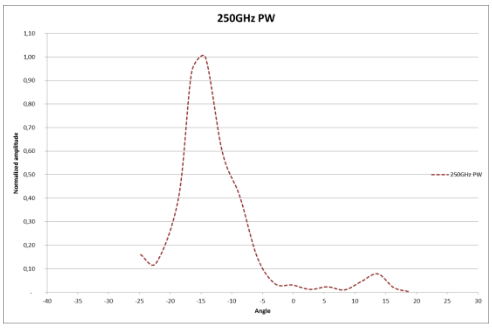

Fig. 5. Experimental results for 0.25THz.

It is worth highlighting that TDS enables to analyze simultaneously the amplitude and phase distributions for a broad frequency range (0.1–1.5THz in air).

For other frequencies the analyzed grating gives a different spatial distribution. It can be also used for calibration of the TDS setup. Interference peaks will be detected for different angles. Moreover, phase retardation varies with a wavelength. We should remember that the dependence of the refractive index of the EX200 material on frequency is very weak for the whole THz range.

For example, for 0.5THz (λ=0.6mm) the grating shows a modulation depth of 4π instead of 2π and the period c.a. 8λ. The grating works as a second order kinoform and provides generally unchanged angular and frequency signal amplitude distribution. However, EX200 attenuation increases rapidly above 0.5THz.

For example, for 0.125THz (λ=2.4mm) the grating shows a modulation depth of 1π instead 2π and the period c.a. 2λ. This increases diffraction angles for "+1" and "-1" orders of diffraction and additionally, "0" order peak will appear.

The diffraction grating for terahertz radiation has already been presented in the literature but this grating has "-1" and "1" diffraction order, our solution has only "-1" order and operates at a specific frequency.

We plan to use additional prisms or diffraction gratings to reduce pulse dispersion in the optical fibers.

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