THz Imaging and Spectroscopy for Nondestructive Testing
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Abstract

Pulsed broadband THz radiation is, in principle, well suited for applications in nondestructive testing. Imaging capabilities together with spectroscopic information make this technique very attractive for a variety of applications. In order to make the technique useful for industrial applications THz technology has to be adjusted to industrial needs. We report on experimental results of THz imaging and spectroscopy for nondestructive testing in industrial applications using a completely fiber laser based THz system which was operated both in transmission and reflection geometry. Typical examples for the determination of thickness, concentrations, impurities and surface quality are discussed.

1. Introduction

THz radiation offers unique features which can be applied for non-destructive testing of samples. Non-contact THz spectroscopy and imaging can provide additional information on the sample under investigation. Critical features like content, concentration, thickness or shape are detectable [1,2]. Most items consisting of dielectrics like paper, wood, plastics, ceramics or clothes are transparent for THz waves. So THz imaging can detect properties even for items within packages. For non-transparent samples a setup working in reflection is required. In the case of metals the object acts as an ideal reflector so that features within the beam path like layers or coatings can be measured. Additionally, at all interfaces of materials with a different refractive index a part of the THz intensity is reflected back revealing inner structures of a sample. There are in particular: non-contact measurements of e.g. hot materials (ceramics in liquid stadium) or touch-sensitive surfaces (wet painting [3]), measurement of water-free fluids and powders [4] and in general measurements of opaque and non-conductive materials. THz techniques also allow to resolve complex multilayer structures made out of different materials.

2. Results

To show the detection possibilities for the measurement of thin films a sample consisting of a set of different layers of Scotch tape was attached to a Teflon holder. The propagation velocity of THz waves in a medium depends on the refractive index of the material. Therefore a pulse which propagates through a THz-transparent medium is retarded. A sample with a thickness D and a refractive index n_{THz} delays the THz pulse in single-pass by $\Delta T = D \cdot (n_{\mathrm{THz}} - 1)/c_0$ (c_0: speed of light in vacuum). Measuring the run-time difference ΔT to a certain reference the thickness of the sample can be determined by

$$D = \frac{c_0 \cdot \Delta T}{n_{\mathrm{THz}} - 1} \; . \qquad (1)$$

In the left part of figure 1 transmission measurements of different numbers of adhesive tape layers are shown. The pulse detected without any layer is set as reference. Since each single film has a fixed thickness of about 50 µm, the time shift of consecutive pulses is nearly constant. Only small deviations are detectable due to different production conditions. With the refractive index of the adhesive tape $n_{\mathrm{THz}} = 1.5$ the layers' thicknesses D can be calculated. Even without using special data evaluation software it is possible to resolve thicknesses down to 10 µm. Since the absorption is rising with the number of adhesive layers the amplitude reduces. The surface losses due to Fresnel reflections are constant for all numbers of layers.

To measure materials on substrates which are not transparent for THz waves the reflection mode is used. Here the THz beam is incident under an angle α to normal incidence. Hence the beam is reflected and refracted. In contrast to the transmission measurements both the transmitted and the reflected parts are detected. The time shift ΔT between the reflected part and the transmitted part, which after reflection on the layer's backside propagates twice through the material, contains the thickness information of the medium. Since this technique is self-referencing there is no need to do a second reference measurement. However, the knowledge of the refractive index n_{THz} of the medium and the angle of incidence α is required to calculate the thickness which is given by

$$D = \frac{c_0 \cdot \Delta T}{2 \cdot n_{\mathrm{THz}} \cdot \cos[\arcsin(\sin(\alpha)/n_{\mathrm{THz}})]} \quad . \tag{2}$$

In the right part of figure 1 reflection measurements of different numbers of adhesive tape layers on a metallic substrate are shown. For more than one layer the pulses can be easily separated and the thicknesses can be calculated by equation (2). The results are in good agreement with the transmission measurements presented before and the mechanically measured values.

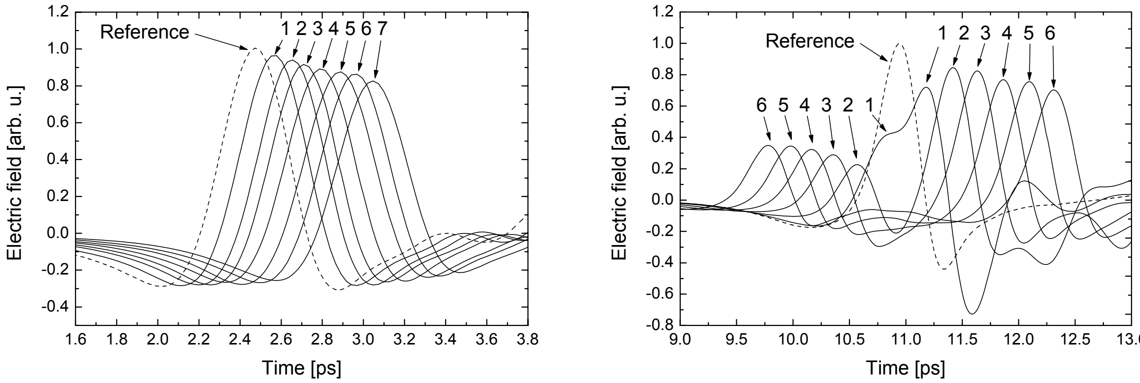

Fig. 1: The numbers of adhesive tapes are given in the figures. The dashed lines are the references without any layer. *Left*: Measurement in transmission mode. *Right*: Measurement in reflection mode with an angle of incidence of $\alpha = 45°$.

Without additional analysis the separation of the two pulses cannot be evaluated clearly for a single layer. Taking into account that the thin film corresponds to a Fabry-Pérot etalon, the thickness of the film can be calculated out of the superposition of the multiple pulse reflections. To be more precise the setup with the high reflecting substrate corresponds to a Gires-Tournois-interferometer (GTI). We have shown both, experimentally as well as numerically, that in this case no additional group-velocity dispersion is generated. Hence no GTI-effect has to be considered. We are able to measure the thickness of thin films down to less than 16 µm.

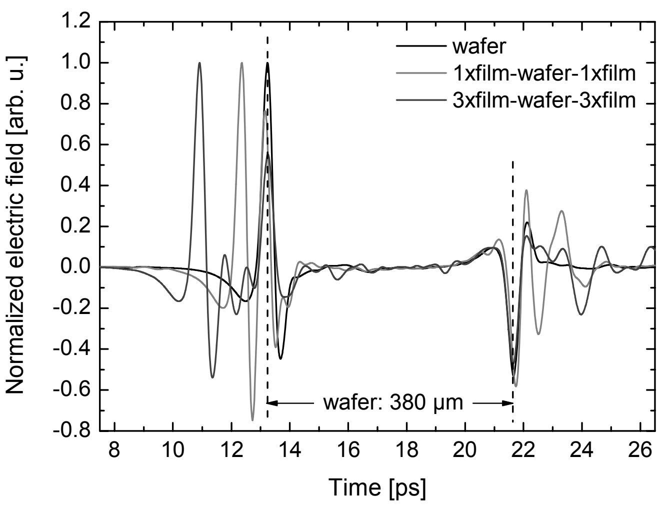

Fig. 2: Reflection measurements of a silicon wafer covered with no, one and three layers of plastic films on both sides.

THz radiation is also able to identify multilayer structures. The only requirements to the layers are transparency in the THz region and differences in the corresponding refractive indices. So at every boundary between two layers a reflection occurs. In the case of a change from an optically thinner to a thicker medium the phase of the reflected pulse changes by 180 °. In figure 2 the reflected THz pulses from a silicon wafer are shown. The wafer is covered with none, one and three thin plastic films on both sides. The thickness of the 380 µm thick wafer was determined with a tolerance of 5 µm. Also the covering films with single thicknesses in the sub-wavelength region of about 85 µm on and behind the opaque wafer were measured.

The focus diameter of the used setups is in the range of twice the wavelength; here it is approx. 1 mm in diameter. Restricting the source to higher frequencies a better spatial resolution is achievable. The data acquisition time for one waveform differs from some tens of milliseconds to minutes for high resolution spectroscopic measurements. Depending on the sample geometry, the data analysis has to be adapted in order to obtain the relevant information. Analysis of intensity (in reflection and/or transmission), absorption at a particular frequency or time delay will permit the determination of different specific parameters of the sample.

The fact that each single scan taken at different parts of the object under investigation contains the full spectroscopic information allows simultaneously spatially resolved spectroscopic measurements Typical examples for this type of measurements including applications in the pharmaceutical industry will be presented in this contribution.

3. References

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INTRODUCTION

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RESULTS

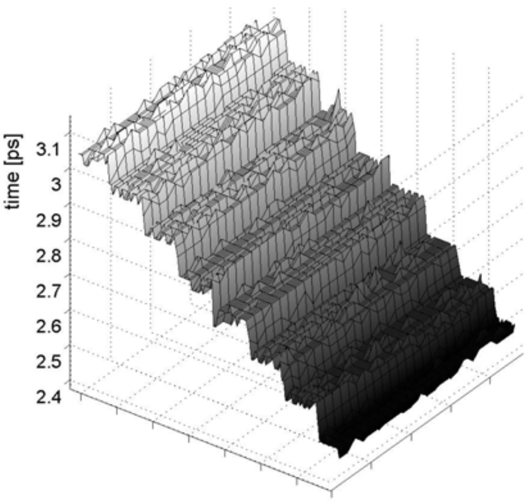

Fig. 1: Imaging of transmission through Scotch tape layers

Fig. 2: Reflection of Scotch tape layers under 45°

To show the detection possibilities a sample consisting of a set of different layers of Scotch tape was attached to a Teflon holder. Due to the high time resolution of the time-domain system each layer can be resolved by measuring the time shift between different reflection signals. Knowing the refractive index of the material the additional time delay can be rescaled into a thickness. Figure 1 indicates the stepwise structure of the sample measured with a raster transmission imaging setup. The height coordinate corresponds to the additional time delay in picoseconds. The same set of layers was attached to a metallic surface. Figure 2 plots the reflected time domain signal for each layer thickness (1 to 6 layers). The reference signal shows the reflection from the plain metallic surface. There are two reflected pulses from the Scotch tape layers: the first reflection is from the interface air-plastic and the second from the metal. The experimentally determined thickness of one layer was 49 μm for transmission, which is in very good agreement with the mechanically measured value of 47 μm.

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REFERENCES

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