Inspection of glass-fiber reinforced composites with a continuous wave THz imaging system

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***Abstract*— We investigate different glass-fiber reinforced composites using a two diode laser cw THz spectrometer with a coherent detection scheme. On the basis of the obtained images we are able to identify different features of the samples which can be useful for quality inspection.**

I. Introduction and Background

During the past years THz spectroscopy has attracted increasing attention in the field of non-destructive testing. Mostly THz time-domain spectroscopy (TDS) is employed. This technique is very powerful providing a wealth of information, e.g. on internal interfaces of investigated samples [1,2]. However, it is also expensive for the use of femtosecond laser systems. A cost effective alternative is given by photomixer based cw spectroscopy systems employing simple diode lasers [3-5]. Yet, as these spectrometers work at a single frequency (if no time-consuming frequency sweep is carried out) less information on the investigated sample is obtained than with a THz TDS system. Furthermore the interpretation of data is complicated due to interference effects within the sample.

Here we investigate different composite materials made from glass-fiber or natural-fiber reinforced polymers consisting of an epoxy based resin. With our experiments we aim to evaluate whether different features of the samples like thickness variations, changes in material composition and refractive index can be indentified.

II. Experimental Setup

Our continuous wave spectrometer is based on two commercially available laser diodes emitting around 860 nm. As photomixing material we use standard low-temperature grown GaAs with a carrier life-time of 200 fs [6]. Both, emitter and detector antenna are H-type dipole structures with a dipole length of 90 µm. The antennas have a simple excitation gap with a width of 5 µm and without any interdigitated electrodes. The spectrometer covers frequencies up to 1 THz, with a peak SNR exceeding 40dB for as low lock-in integration time as 30ms. The measurements are performed at a fixed position of the optical delay line where the sinusoidal THz wave has its maximum with air as reference. Then the sample is scanned through the focus in a raster like pattern.

III. Results

As an example Fig. 1 shows a photograph of a glass-fiber reinforced composite sample which is illuminated from the back to improve the visibility of the different internal layers. In the corresponding THz image areas which differ in structure are clearly visible. From top to the bottom these areas are: i) 5 layers of glass-fiber in a linen woven style, ii) 1-2 layers of glass-fiber (appears as magenta strip), iii) resin only, with agglomerates of air bubbles (the brightest area) and iv) air (red area in the lower left). The section with the 5 layers is also superimposed by light thickness variations of the sample whereas the pure resin area is totally flat but somewhat thinner than the rest of the sample. The brighter fields in the lower part lie between the air bubble agglomerates which are smeared out due to a relatively low spatial resolution.

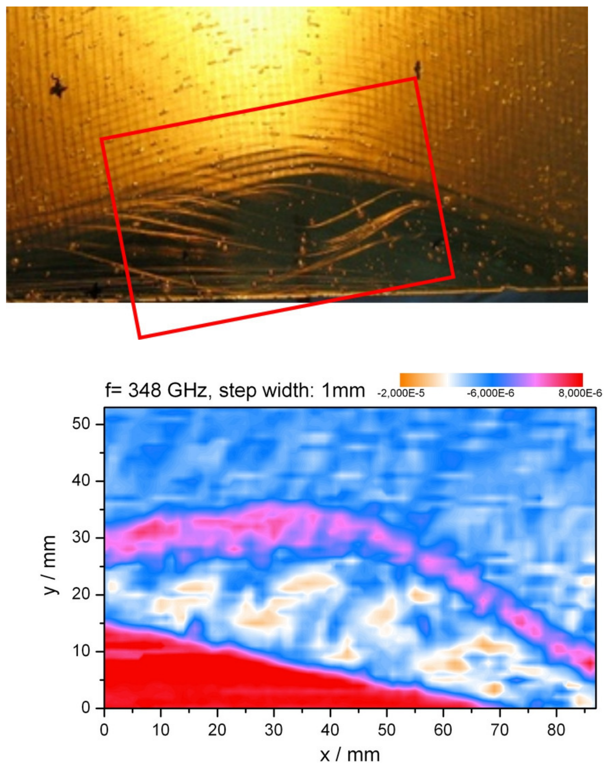

Fig. 1: (Top) Photograph of the sample with marked scanning area taken at back light. (Bottom) THz Image obtained at 348 GHz on a glass-fiber reinforced composite which includes areas of different structure (see text).

Additional to the image the refractive indexes are measured at a position with all glass-fiber layers included and another one with no fibers at all. At both positions and without the sample with air as reference a few cycles of the sinusoidal curve are measured to calculate the refractive index with the following equation:

$$n = \frac{\Delta\varphi + m\dfrac{c}{f_{THz}}}{d} + n_0$$

As parameters the phase difference $\Delta\varphi$ of the measurement curves in meters, m as a natural number, the thickness d of the sample at the respective sample position, the THz frequency f_{THz} and the refractive index n_0 of the reference medium are used. The refractive index at a position with all layers of glass-fiber is n_{GRP}=2.11 and with pure resin n_{resin}=2.18, respectively.

The next investigated sample is a natural-fiber composite with a linen woven textile combined with a glass-fiber capping layer on both sides. A photograph of the back illuminated sample is shown at the top in Fig. 2.

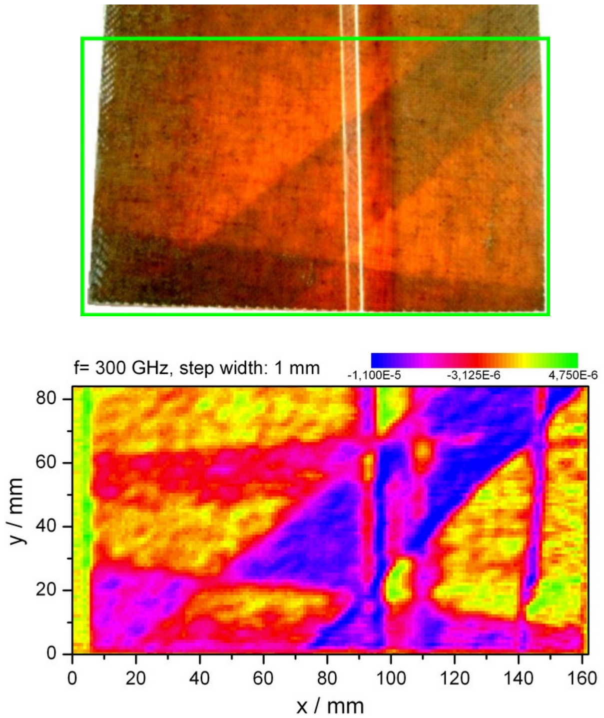

Fig. 2: (Top) Photograph of the back illuminated natural-fiber/glass-fiber composite sample. The overlapping natural-fiber layers emerge very clearly as darker areas. (Bottom) Corresponding cw THz image of the amplitudes obtained at 300 GHz. An explanation of the different features is given in the text.

Due to the light transmitted through the sample the overlapping layers of the natural-fibers are visible in evidence as darker areas. Another feature of the sample is its flute ranging from 90 mm to 110 mm of the x-axis. The overall sample thickness varies slightly around 2.2 mm, however, the areas with the overlapping layers are considerably thicker depending on how many layers are stacked. One additional layer increased the thickness by 0.4 mm, so the thickness at the junction of the two overlapping layers seen in the upper part with the third layer at the lower part of the sample is around 3 mm and hence, at this position three layers are stacked.

Both above mentioned features, the thickness changing and the flute can be clearly identified in the THz image, respectively. The latter feature causes an amplitude change at both edges due to a longer propagation and due to diffraction.

At the junction, where the three layers are overlapped the signal amplitude in the THz image is nearly the same as in the single layer area. This could be due to the thickness changing of 0.8 mm which corresponds to a phase change of nearly one or more half periods of the THz wave inside the material. All other areas with two overlapping layers show nearly the same thickness. For this interpretation the probably slightly higher absorption due to the additional layers is neglected.

On the right part of the THz image a thin vertical strip is recognizable which appears in blue/magenta and results from a small and thicker area of resin accumulation on the backing layer. It is allusively visible in the photograph.

The horizontal strip at the y-axis ranging from 50 mm to 60 mm in the image results from two ore more overlapping capping glass-fiber layers. This area is invisible in the photograph. Distributed over the entire image a cloudy structure is discernable which arose from a rough-textured rear surface due to the production process. The front side is totally flat.

IV. Summary

We investigated two different composite materials from glass-fiber and natural-fiber reinforced polymers using a cw THz spectrometer. In the first sample we observe structures which arise from a different number of glass-fiber layers. The second composite sample with natural and glass-fiber reinforced polymer exhibits areas where different material layers overlap. Also relative thickness variation can be observed.

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