Quality Assurance of Chocolate Products with Terahertz Imaging

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Abstract. Quality inspection plays a key role in the food industry. Besides metal detection finding small stones and glass splinters is of great importance. Furthermore, already established devices like conventional metal detectors offer only a low spatial resolution. In contrast to this method a rather novel technique is terahertz time-domain spectroscopy (THz TDS). The experimental set-up to simulate THz TDS consists of a standard free space THz spectrometer with photoconductive emitter and detector antennas driven by a femtosecond laser source. 2D images are obtained by scanning the samples perpendicular to the THz beam. We show 2D THz images that reveal contaminations like a metal screw, a small stone and a glass splitter with a spatial resolution of 1 mm. We go on to propose a measurement technique that allows for faster scanning times compared to the conventional technique. Since THz waves can penetrate different kinds of foods which are opaque in the visible spectrum, THz TDS promises to be a powerful tool in quality monitoring especially for the detection of non-metallic contaminations.

Introduction

Quality inspection gains more and more importance in food industry and in particular in chocolate production. Metal detectors are commonly used to locate metallic contamination, but the spatial resolution is not very high. In the praline industry for example, where there are 50 pieces next to each other in row, high rejection rates are very common. If the metal detector locates any contamination, the whole row of pralines is discarded. And as a precaution the row in front and behind the suspicious row is sorted out, too. It is very likely that only one of the 150 discarded pralines is actually contaminated, while the rest is not. The goal of lowering such high rejection rates could be accomplished with the help of a higher spatial resolution.

There is a large interest from the chocolate industry to detect non-metallic contaminations like stones or glass particles. Stones present in chocolate come from natural products like nuts and glass contaminations can originate from everyday-life objects such as light bulbs. Certain chocolate factories maintain a glass register where all glass materials which are close to the production line are mentioned. This register has to be checked every week for any missing glass equipment. The apparent concern about glass pieces suggests that a detector to find glass contaminations in chocolate bars is highly desirable.

Furthermore, the chocolate industry develops an increasing number of new products especially in the field of truffle production. THz waves in collaboration with other techniques may be used to ascertain that the different parts of the truffle are included in the appropriate proportions. However, currently used THz imaging systems must become much faster to be used in industrial production lines. Therefore a new approach with less scanning time is required, to check a chocolate bar, for example.

1. THz Time-domain Spectroscopy

1.1 Experimental Set-up

Terahertz time-domain spectroscopy (THz TDS) is a rather novel technique in the field of non-destructive and contact less testing. Short electromagnetic pulses with a frequency content between 50 GHz and 2.5 THz are employed to characterize different sample materials. The pulsed nature and broad bandwidth of THz radiation makes it ideal for quality assurance purposes.
To generate the THz radiation we use the optoelectronic approach. Short optical pulses from a femtosecond laser excite photoconductive dipole antennas [1]. On the emitter side a short current pulse is generated, which radiates according to Maxwell´s equations an electromagnetic wave. This wave is called THz pulse. Four off-axis parabolic mirrors are used to guide the THz radiation, which is focussed at first on the sample. After penetrating the sample the radiation is focussed on the detector antenna (cf. Fig. 1). Another portion of the optical pulse that generates the THz pulse is used to gate this detector antenna. The THz waveform is scanned by delaying the two laser pulses in the emitter and detector arm with respect to each other. Every position of the delay line provides a certain time delay that gives one single point of the THz waveform. By moving the delay line the complete THz pulse can be sampled. The frequency content of the pulse is achieved by a fast Fourier transform.

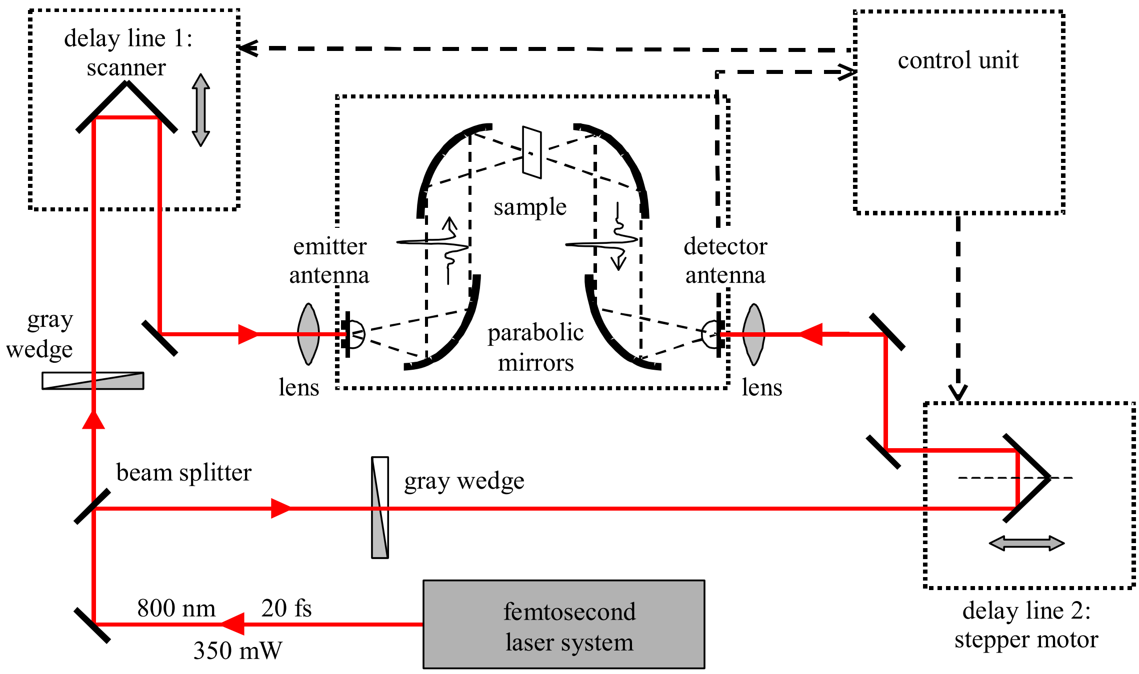


Figure 1. Schematic of the applied THz time-domain spectrometer.

For imaging the sample is mounted on an x and y translation stage and moved perpendicular to the incoming THz beam in a raster pattern. For each spatial position a THz waveform is measured. On this basis Hu *et al.* demonstrated the first THz imaging system [2] in 1995 – exactly 100 years after the first x-ray image. Yet, in contrast to x-rays, THz radiation is not ionising due to its low photon energy and is therefore completely harmless. For imaging applications a fast scanner (delay line 1) is used, whereas for spectroscopic characterization of a material a more accurate measurement utilizes a stepper motor (delay line 2).

Chocolate bars are relatively transparent for THz radiation, since they contain mostly fat with only a very low content of water. Contaminations like small stones, a screw or glass splinters act as scattering objects in terms of the wavelength and change the shape of the measured pulse. Furthermore due to the pulsed nature of the radiation one can draw comparisons to ultrasound. The temporal position of the pulse reveals information about possible contaminations. Compared to conventional metal-detectors and ultrasound techniques, this technique is able to detect non-metallic items without contact.

1.2 Measurement Technique

For every certain time delay one single value of the THz waveform $E(t)$ is measured. By moving the delay line, the whole THz pulse is sampled step by step. With a fast Fourier transform frequency-domain data $F(\omega)$ are obtained (cf. Fig. 2). If a sample is placed in the THz beam (dashed curve) the pulse arrives later in time and its amplitude is reduced compared with a reference pulse through air (solid curve). The time delay between those two pulses is caused by the difference in the refractive index of the sample material compared to that of air. The decrease in amplitude in the time domain can be explained by the spectral damping of the pulse. This absorption can be calculated in the frequency domain by comparing the sample spectrum with the reference spectrum. Without Kramers-Kronig-Relation it is possible to derive the refractive index n and the power absorption coefficient α independently of each other for every frequency value.

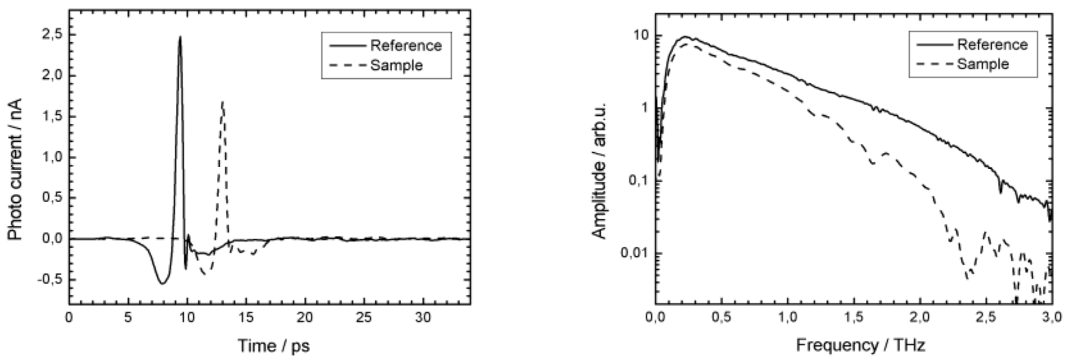


Figure 2. THz waveforms (a) measured with a sample (dashed) and without any sample (solid) placed in the spectrometer. The corresponding frequency amplitude spectra (b) obtained by Fourier transform algorithm (FFT) yield information about the transmission characteristics of the sample.

As mentioned above, the sample is scanned in a two-dimensional raster like pattern to obtain an image. For each spatial position a waveform is measured and the related frequency spectrum is calculated. THz images can contain time-domain data such as the temporal shift of the pulse maximum or frequency-domain data like the integrated intensity in a certain frequency interval [3]. The temporal shift provides information about the difference in the refractive index (assuming no differences in the thickness of the sample), while the integrated intensity in a certain frequency interval reveals the spectral damping. In this way, one THz imaging measurement yields many THz images with different information.

2. Samples

2.1 Chocolate Bars

Standard chocolate bars (whole milk chocolate) were bought at the supermarket and artificially contaminated with different uneatable items such as a small stone (cf. 2.2 Contaminations). The chocolate bars were heated at certain points and the contaminations were layered into these points such that they were not visible from the outside. (cf. Fig. 3). The goal was to come as close as possible to a real-life simulation of a chocolate line production. Packaged chocolate bars in plastic foil were also investigated.

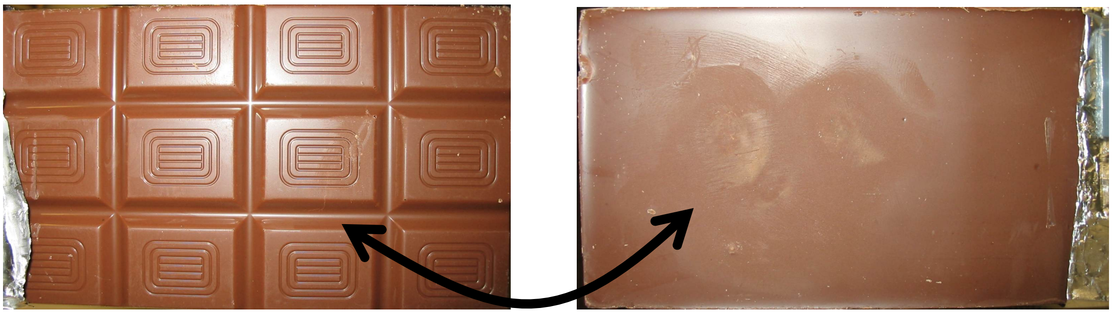


Figure 3. Front and back side of a chocolate bar after artificial contamination with a stone, a M2 metal screw and a glass splinter.

2.2 Contaminations

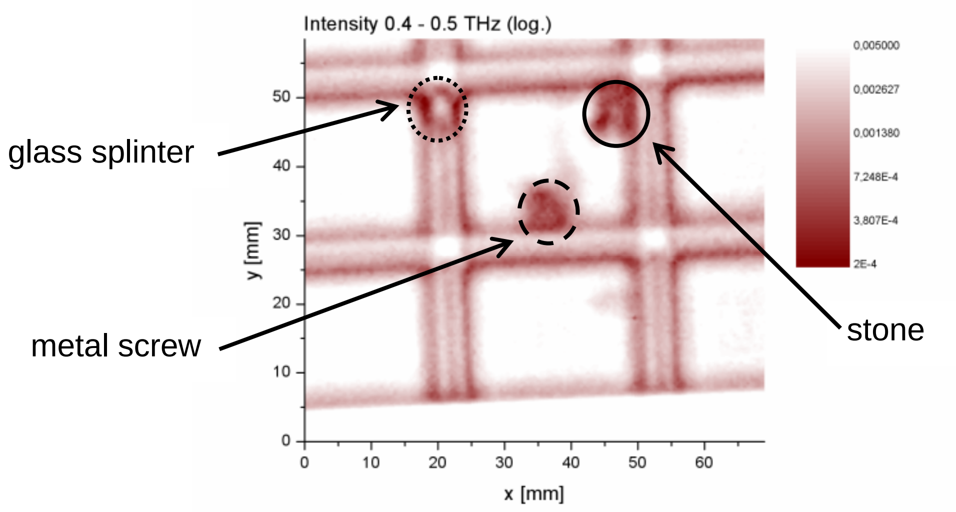
Metal screws, glass splinters and small stones were used for artificial contamination purposes (cf. 2.1 Chocolate bars). Examples of these contaminators are given in figure 4.

Figure 4. Photograph of different kind of contaminations like a small stone, a glass splinter and a M2 metal screw. The M2 screw may help for size reference.

3. Results and Discussion

3.1 THz Imaging of Contaminated Chocolate Bars

Metal, stone, or glass contaminations can be detected in chocolate bars with a spatial resolution of less than 1 mm (cf. Fig. 5). Both pictures below show diagrams for the transmitted intensity between 0.4 and 0.5 THz on a logarithmic scale. The size of both pieces is roughly 5 cm by 6 cm. The transmitted intensity for glass and stone contaminations is lower due to higher absorption and scattering losses. Metal, on the other hand, reflects all THz radiation and decreases therefore the transmitted intensity. Even if the chocolate is measured in its own original plastic package the contamination is clearly visible. Plastic foil is nearly transparent to THz radiation. Aluminium foil on the other hand reflects all THz radiation and hence chocolate bars wrapped in aluminium foil cannot be investigated with THz radiation.



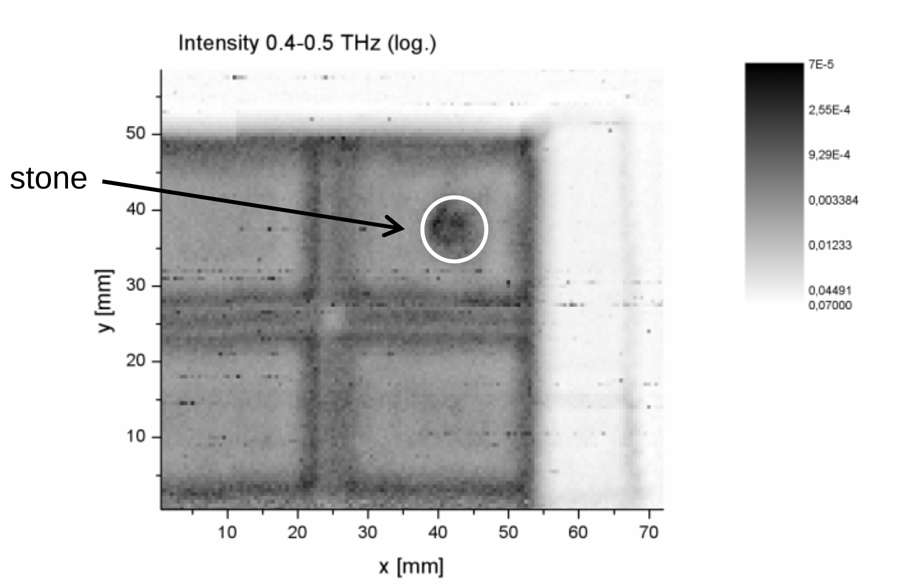


Figure 5. THz images of two artificially contaminated chocolate bars: a stone (solid circle), a M2 metal screw (dashed circle) and a glass splinter (dotted circle). Below: Another chocolate bar contaminated with a stone in its original plastic package.

3.2 THz TDS of a Glass Splinter inside a Chocolate Bar

A waterfall plot of THz waveforms measured by moving the chocolate bar with a glass splinter in steps of 0.5 mm across the THz beam is given in Fig. 6. The waveforms in the front show that the signal is undisturbed and passed only through bulk chocolate. Step by step the main peak decreases and a second smaller peak appears, which increases step by step in the middle of the waterfall plot. One half of the THz beam propagates through the glass contamination and the other half propagates through the uncontaminated part of the chocolate. The transmitted intensity is lower compared to the pulse through the uncontaminated part of the chocolate. In between the middle and the backside of the waterfall plot, the second peak decreases while the main peak again increases. In the end the THz beam passes completely through bulk chocolate again. Finally, the pulse shape is the same as in the beginning of the waterfall plot. The second peak is later in time compared to the main peak due to the higher refractive index of the glass material compared to the chocolate (cf. 1.2 Measurement technique). The difference in the refractive index causes the time delay. The higher the difference the larger the time delay.

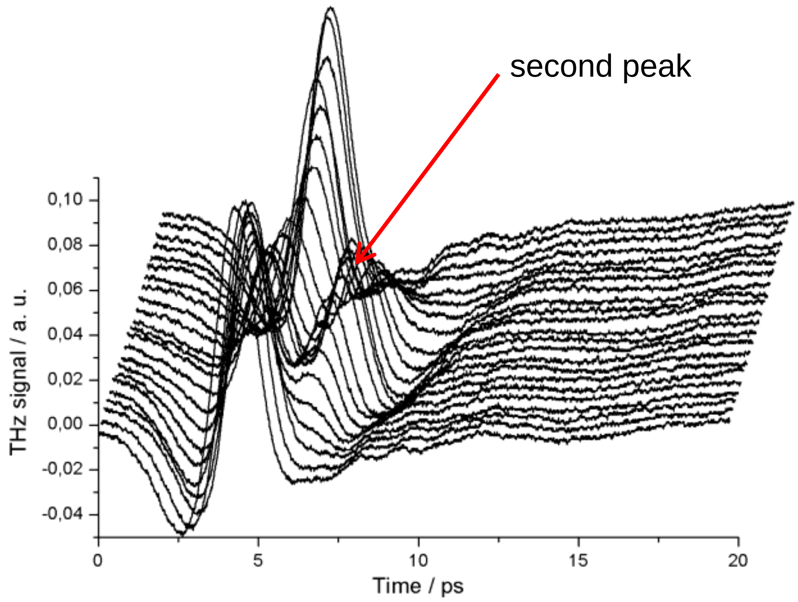


Figure 6. Waterfall plot of THz waveforms measured moving the chocolate bar with a glass splinter step by step across the THz beam.

3.3 New Approach Towards Faster Quality Control Measurements

It usually takes many minutes to obtain a 200 by 200 pixel image with a typical laboratory system [4]. Yet, industrial processes require a sample rate of several items per second. For example, in the chocolate industry every bar needs to be inspected within 0.1 s, which corresponds to a measurement speed of 1.8 m/s. As we show in the following paragraphs this speed should be feasible. Our approach is not to measure the entire THz waveform. Since all products in an industrial process should be identical much less data is needed to detect any deviations. For example, it could be sufficient to monitor only the maximum or the edge of the THz pulse. Within the tolerances of the fabrication process every item should give the same signal pattern in a 1D scan. If there are any distortions from this pattern one can conclude an imperfect or contaminated product.

As it can be seen below not only contaminations but also thickness variations lead to signal changes. Fig. 7 shows on the left side two pulses, which have travelled through a thin and a thick piece of chocolate of the same chocolate bar (solid and dashed lines). The thickness variations among different pieces within a chocolate bar are typically less than 10% of the absolute thickness. For example, a maximum thickness variation of 0.64 mm creates a pulse delay of 1.7 ps. The maximum of the pulse that passes through the thinner piece lies at the position of the minimum of the pulse that travels through the thicker piece (cf. Fig. 7 a). Consequently, adjusting a fixed time delay (for example 10.3 or 12.0 ps) and measuring a 1D scan (line scan) along a row of chocolate pieces leads to an irregular shaped curve (cf. dashed and dotted lines in Fig. 7 b). Hence, 1D scans obtained with just one fixed time delay cannot be used to inspect spatially inhomogeneous products like chocolate bars. As we will show below, the problem with thickness inhomogeneities can be solved by using more than one time delay.

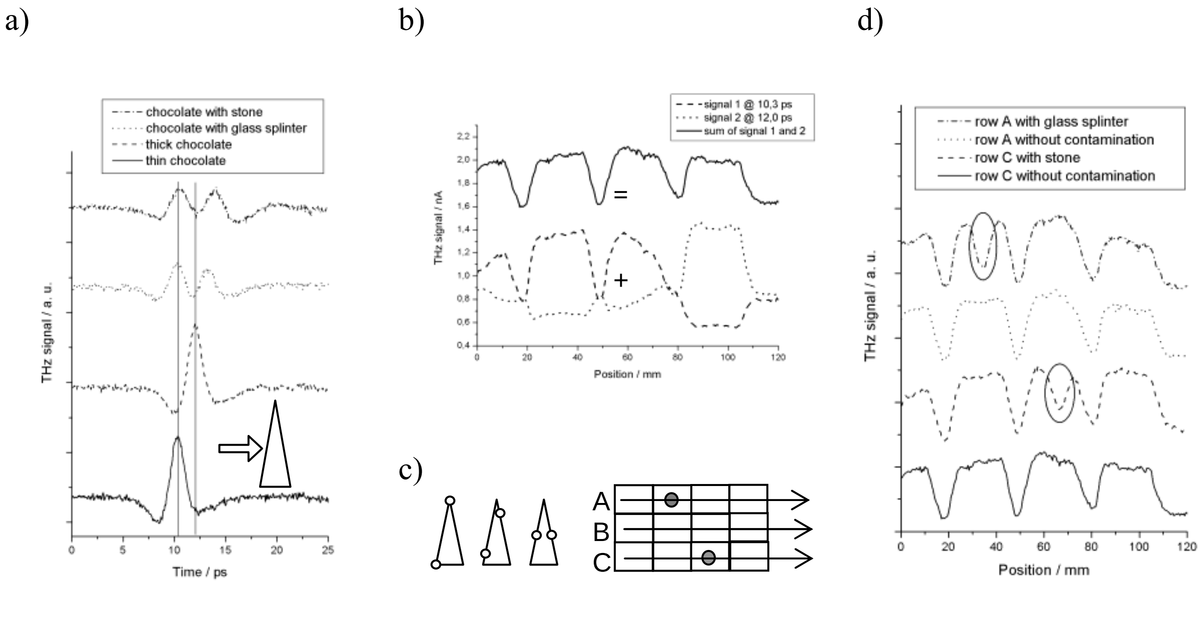


Figure 7. a) THz waveforms through pieces of chocolate with and without contamination, b) adding two line scans, c) approximation of the THz pulse with a triangle, schematic of a chocolate bar with contaminations d) sum of line scans through rows with and without contamination

In a first attempt we approximate the THz pulse with an isosceles triangle (cf. Fig. 7 a). The two legs of the triangle match the edges of the THz pulse, while the distance between the two minima of one pulse corresponds to the baseline of the triangle. The sum of two adequate line scans with a temporal spacing of half of the baseline gives a signal intensity equal to that at the maximum of the THz pulse (cf. triangles in Fig. 7 c). Hence, adding two line scans with this temporal spacing circumvents the problem arising from minor thickness variations, at least to a first approximation. In general, the time delays among all pulses need to be smaller or equal to half of the baseline of the triangle, which is fulfilled for the investigated chocolate bars. Such a sum of two line scans along one row of the chocolate bar leads to a curve that clearly visualizes a regular structure, shown for example for row B in Fig. 7 b (solid line). The signal is maximum when the THz pulse propagates through a piece of chocolate. If it passes through the groove between two pieces, the pulse arrives earlier and the summarized intensity is smaller. So the single pieces of the chocolate can be identified.

If there are any contaminations inside the chocolate bar, like a stone or a glass splinter on the scale of millimeters, the THz pulses have a different shape (cf. Fig. 7 a, dotted and dashed-dotted line). Basically, two smaller pulses appear close to each other (cf. Fig. 6 in the middle of the waterfall), which are generated by two portions of the main THz pulse. One part of the pulse travels aside the contamination, the second part travels through the contamination and has experienced a time delay due to the higher refractive index of the glass splinter or the small stone. Since the first THz pulse is smaller than the main one, a dip occurs in the sum of two line scans (circled area of the curves in Fig. 7 d) indicating the contamination. If contaminations inside grooves of the chocolate bar should be detected, the time delay for the line scan must be set accordingly. Comparable measurements on chocolate bars show (results are not given here) that scanning speeds of 0.55 m/s are feasible.

4. Conclusions

We have presented THz images and TDS measurements of chocolate bars, which were artificially contaminated with small stones, glass splinters or M2 metal screws. In all three cases the transmitted intensity is lower. Glass and stone decrease the signal due to absorption and scattering losses. Metal reflects all THz radiation. All contaminations can be clearly localized in the THz images.

Furthermore we have explained our new approach towards faster measurements. Only a few key points of the THz waveform are sampled. The amount of data and measurement time is decreased, still all necessary information is collected. With a two point measurement we are able to identify contaminations in plane chocolate bars.

In summary, the power of THz TDS as a non-destructive and contact less testing technique for the detection of non-metallic contaminations in chocolate bars was demonstrated.

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References

[1]P. R. Smith, D. H. Auston, M. C. Nuss, “Subpicosecond photoconduction dipole antennas,” IEEE J. Quantum Electron. QE, vol. 24, pp. 255-260, February 1988.
[2]B. B. Hu, M. C. Nuss, “Imaging with terahertz waves,” Opt. Lett., vol. 16, 1716-1719, August 1995.
[3]M. Herrmann, M. Tani, K. Sakai, “Display Modes in Time-Resolved Terahertz Imaging,” Jpn. J. Appl. Phys. vol. 39, pp. 6254-6258 (2002)
[4] C. Jördens, G. Thorwirth, M. Koch, “An optical design for real-time terahertz imaging,” German Microwave Conference 2006, Karlsruhe, Germany, 2006.