Characterization of Surface Structures using THz Radar Techniques with Spatial Beam Filtering and Out-of-Focus Detection

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Abstract. We propose two terahertz reflectometry modalities which are optimized to be sensitive to the curvature of surface features. The first is a dark-field technique which allows to detect protrusions and dents on surfaces with high sensitivity. It cannot distinguish, however, between convex and concave shape. This becomes possible with the second technique, which combines out-of-focus imaging with suitable beam filtering.

A specific application of THz remote sensing may serve as an example to illustrate this point. For an inspection during metal production and processing, one searches for techniques which allow the online, i.e., fast identification of and distinction between protrusions and dents. These typically have a millimeter-scale width and a height (or depth) down to 5 µm. Reliable detection is required to occur under production conditions which include such aspects as a visible surface roughness, vibrations of the objects under test, and a large working distance of more than 10 cm. This report deals with an optimization of THz line or areal scanning for such and related tasks.

The out-of-focus detection allows for the detection of weak changes in the radius of curvature of the surface. The method can therefore detect dents and protrusions with high sensitivity. We will also discuss a modified approach, dark-field detection, which brings an order(s)-of-magnitude signal enhancement at the cost of the loss of discrimination between protrusions and dents.

We reach the conclusion that the combination of these two techniques makes it possible to sensitively detect and discriminate small dents and protrusions, and more generally features of convex and concave shape.

Introduction

Traditionally, most of the THz sensing techniques address the absorption and refraction of THz radiation in the sample [1],[2],[3],[4]. In many cases, additional valuable information can be gathered if the scattering and diffraction properties of a sample are examined. This can be optimized by introducing dark-field techniques in analogy to the well-established approaches in optical microscopy.

The principle of dark-field concepts is to block the radiation which is either ballistically transmitted or specularly reflected in such a way that only scattered or diffracted radiation can reach the detector. It is useful to define a new quantity, the deflection coefficient, as the ratio of the radiation which is deflected from the ballistic (specular) beam path relative to the total transmitted (reflected) power[5]. Fig. 2(c) depicts the deflection coefficient of the canine-tumor sample discussed above at 2 THz. The data show that the tumor region is not a strong deflector quite in contrast to the boundaries between different tissue types and the area of the skin with hairs. Comparison with data taken at 0.6 THz (not shown here, see [5]) suggests that diffraction is dominant at boundaries while scattering dominates in the region of skin with hairs.

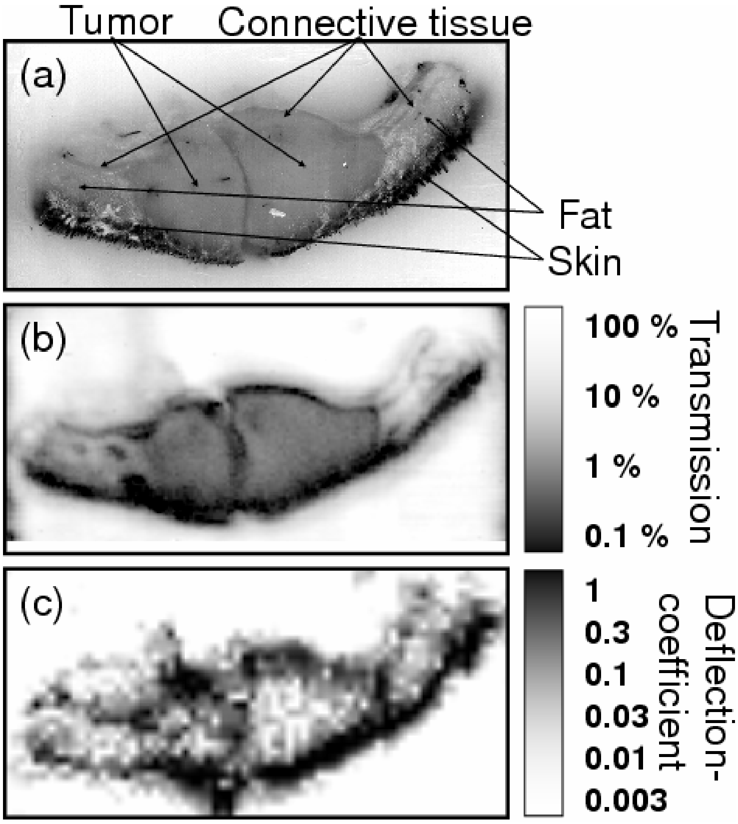

Figure 1. (a) Photograph of an archived tissue sample of a cut through a canine skin tumor. (b) Cw transmission image of the sample at 1 THz.(c) Deflection coefficent at 2 THz obtained with a pulsed dark-field system

Surface Characterization

Besides the very popular fields of biomedical and security-related research, one should not neglect more traditional application areas where THz imaging and sensing may well have its first major impact in the industrial world. In this Chapter, we point out that interesting applications could lie in quality control and process monitoring.

Recently, we started the examination of the conceptual applicability of THz imaging and sensing for the inspection of the surfaces of rolled steel and other metals. These investigations aim at the on-line monitoring task of identifying small surface defects such as protrusions, scratches and voids with vertical dimensions from a few to hundreds of µm and lateral dimensions in the mm-range. In the case of steel, the protrusions and voids may originate from air bubbles caught in the iron melt, the scratches from hard sapphire particles formed by the oxidation of aluminium present in the iron ore in the course of the reduction of the iron oxides. The on-line identification of such surface faults by conventional optical means turns out to be difficult because the surface of the rolled steel is so rough that it scatters visible light strongly. The industrial environment (heat, conveyorbelt speed and vibrations, etc.) requires rather large working distances and fast data acquisition times.

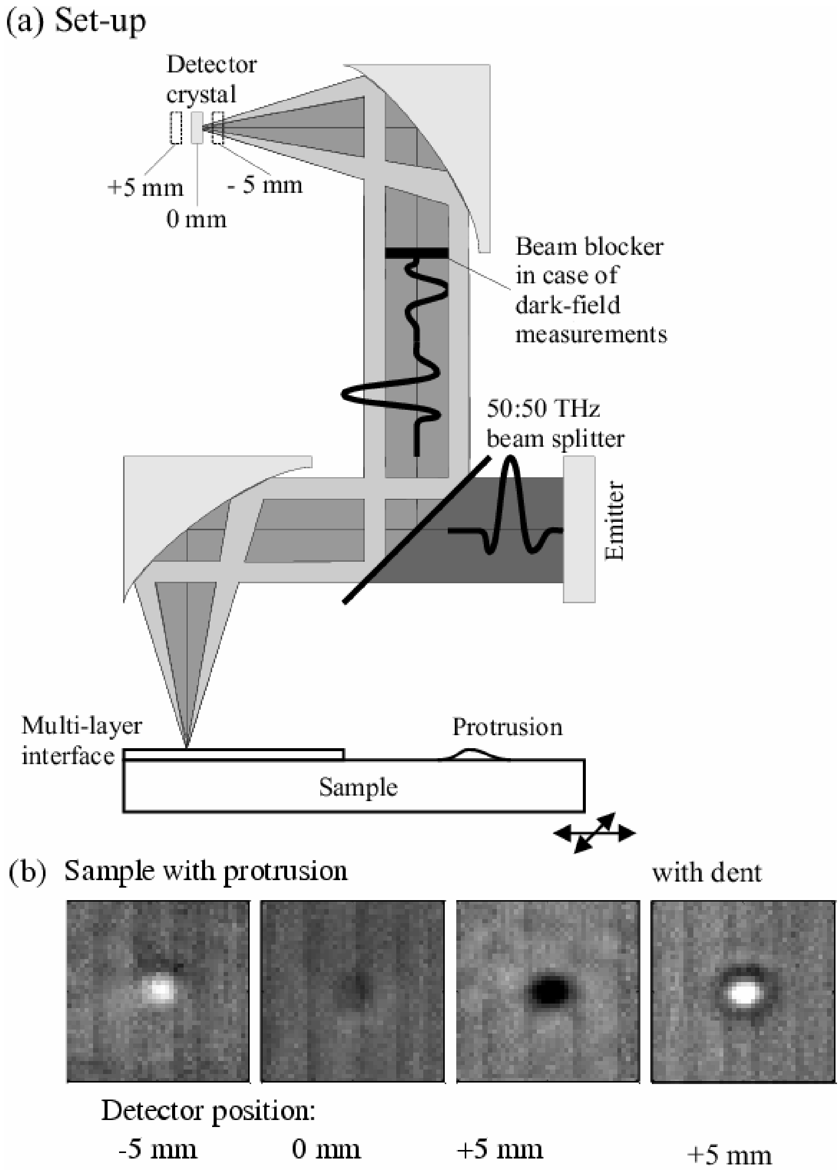

Figure 2. a) Schematic drawing of the reflection set--up for surface and interface characterization. For dark-field measurements, a beam blocker is placed at the indicated position. For out-of-focus detection, the detector crystal is moved out of the normal beam focus. (b) Experimentally observed THz-reflection images achieved with different detector positions for a sample containing a protrusion (convex surface in center) or a dent (concave surface in center). White coloring indicates a strong signal, black a weak signal.

Neglecting the on-line-operation target for the time being, we were able to show that THz imaging with its large wavelength in the sub-mm range is insensitive to the natural surface roughness but provides very good sensitivity to the defects to be identified [6]. We explored two THz-reflectometry modalities both optimized to be sensitive to the curvature of surface features. The first is a dark-field technique (with a beam blocker, as indicated in Fig. 2(a)) which exhibits superior contrast but cannot distinguish between convex and concave shapes. The latter is achieved (at the price of a somewhat reduced contrast) with a second technique which employs out-of-focus imaging. In this second approach (without a beam blocker), we take advantage of the fact that the focal length of the THz beam at the detector becomes longer (shorter) when the THz beam reflects off a concave (convex) surface. Shifting the detector forward and backward (see Fig. 2(a)) thus allows us to maximize the detected signal for the respective case and to distinguish positive and negative surface curvatures of the sample. Fig. 2(b) shows experimental results. At the detector position marked as +5 mm, the signal is enhanced for dents (concave surface in the center) and reduced for protrusions (convex shape in the center). At the opposite detector position (-5 mm), the situation is vice versa. The signal enhancements can be understood quantitatively if beam-filtering effects in the detector crystal inherent to the principles of electrooptic mixing are taken into account.

This example shows, that THz radiation might be very useful for surface characterization if the surface features to be detected have lateral dimensions in the order of or larger than the THz wavelength. While the experiments were performed with a pulsed THz-imaging system, a transfer of the concept to a cw optoelectronic THz system should be straightforward.

Terahertz Anti-Reflection Coating

Given the fact that refractive indices in the THz frequency range tend to be large, there is a need for techniques to reduce the reflectivity of surfaces. Adopting anti-reflection concepts from optics, we developed an anti-reflection coating which can be applied to many materials because the refractive index can be adjusted to suit the substrate to be coated.

The coating material consists of a mixture of paraffin wax and silicon powder. The refractive index can be tuned by variation of the mass ratio. The material can be processed in the same way as pure wax which allows easy production of thin films.

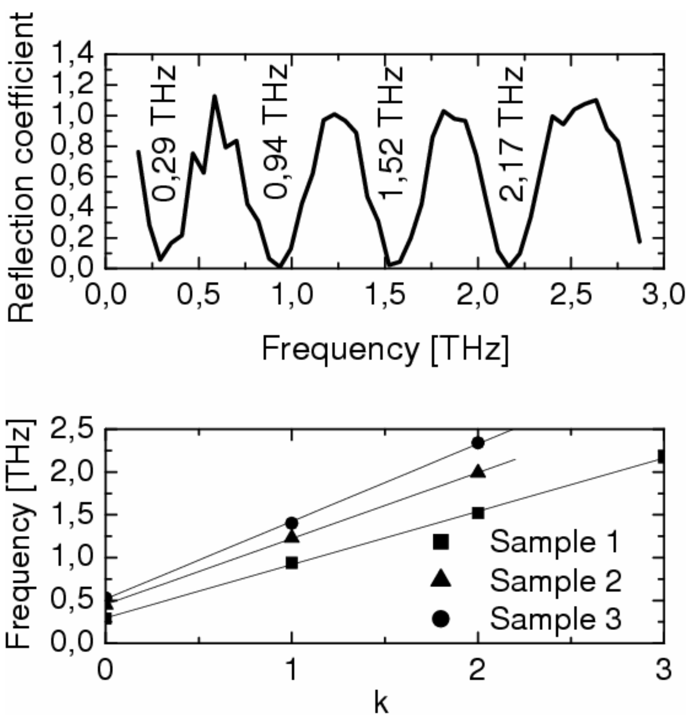

Figure 3. Top: Measured reflectivity of an anti-reflection-coated silicon wafer. Bottom: frequency of the observed reflection minima vs. order number k for three samples.The lines indicate linear fits.

Figure 3 shows experimental results for a semi-insulating Si wafer with a single-layer anti-reflection coating. The data were taken with the help of the THz measurements set-up of Fig. 2. The measured spectrum of the reflection coefficient (see top of Fig. 3) exhibits the modulation typical for single-layer coatings. Signal components at 625 GHz and multiples hereof are fully reflected while signals at 625 GHz x (n + ½) with n being an integer order number, hereof have vanishingly weak reflections.

We produced several samples with varying coating thickness. The lower panel of Fig. 3 displays the frequencies of the reflection minima as a function of the order number n for three samples. The data illustrate that anti-reflection coatings can be produced for target frequencies in a large frequency range.

Conclusion

In summary, we have explored the potential of both pulsed and cw opto-electronic imaging techniques for surface and interface characterization. Although the potential is impressive, practical systems for industrial applications are not likely to be available for some time because the output power of the optoelectronic THz sources is generally too low for real-time image formation. Given the extremely high sensitivity of the optoelectronic receivers, however, real-time multi-pixel detection systems appear feasible if high-power electronic or laser sources of THz radiation are combined with optoelectronic detection methods.

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