INVITED PAPER

All-Optoelectronic Terahertz Imaging Systems and Examples of Their Application

THz lasers can be used to image tumors and reveal package contents, inspect rolled steel and other metal surfaces, design antireflection coatings, and detect tooth decay.

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ABSTRACT | We give an overview over several all-optoelectronic measurement systems which we have developed for transmittive and reflective imaging in the terahertz (THz) frequency range. The systems employ either pulsed or continuous-wave THz radiation. In both cases, they work on the basis of single-pixel scanning. Addressing the potential for imaging in the medical and dental field, and the application of THz radiation for industrial surface and interface characterization, we explore dark-field imaging where the imaging contrast originates from diffraction and scattering effects coming from topography or refractive-index variations.

KEYWORDS | Imaging; optoelectronic; terahertz

I. INTRODUCTION

The controlled, direct generation and detection of electromagnetic radiation in the terahertz (THz) frequency regime (300 GHz–10 THz) continue to be challenging tasks. On the generator side, efficient electronic sources remain limited to some hundreds of GHz [1], while promising photonic devices such as the THz quantum cascade laser [2], [3] are still hampered by the need for cryogenic operation conditions. On the detector side, limitations arise from the need for rather high power levels if cryogenic receivers such as bolometers are to be avoided.

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An alternative approach is the optoelectronic generation and detection of THz radiation by nonlinear photomixing of the radiation from pulsed or continuous-wave lasers emitting in the visible or near-infrared spectral range [4]. While the THz power levels tend to be modest, THz optoelectronics combines a superior detectivity with access to an enormous THz bandwidth.

II. PULSED OPTOELECTRONIC SYSTEMS

Photomixing (down-conversion or optical-rectification) techniques were first developed on the basis of laser systems producing ultrashort laser pulses [5] which are then converted to few-cycle electromagnetic pulses covering a wide THz frequency range. If high-repetition-rate femtosecond lasers are employed, down-conversion is achieved either by excitation of photocurrent pulses in semiconductor emitter structures [5]–[7] or by means of nonlinear electrooptically active crystals [8]. With intense laser pulses from Q-switched sources or (more expensive) laser amplifier systems, a variety of other mixing processes (e.g. within laser induce plasmas) are available [9], [10]. Optoelectronic detectors as well are generally based on either photoconductive antennas [6] or electrooptic crystals [7], [11], and they sample the electric field of the incoming THz pulses with a superb sensitivity. With the help of a mechanical delay line or by means of asynchronous optical sampling [12], one maps out the temporal shape of the electric field of the THz pulses, thus allowing for the measurement of the absolute-time-of-flight information which contains all spectroscopic information and permits to determine the complex refractive index of a material brought into the THz beam path via a Fourier analysis.

Next to spectroscopy [13]–[16], the most promising fields of applied THz research pertain to imaging and sensing, which, since their first demonstration [17], [18], have become a rapidly expanding field of research [19]. The potential for interesting applications in package inspection [20], security monitoring [9], [21] and sensing for process control [22] has been demonstrated. In addition, imaging in the biomedical field attracts much interest [23], [24], one reason being the fact that THz radiation is nonionizing and hence cannot—at the employed power levels in the sub-mW regime—induce biochemical modifications in tissue which could be hazardous to living beings as it is the case with X-rays. Although high water content does not allow THz radiation to penetrate deep into tissue, diagnostic applications aiming at the identification of skin and throat cancer, and at the detection of precaries modifications of teeth are being investigated.

The system developments have reached a maturity which allows the adaption of more sophisticated imaging techniques known from the optical region of the spectrum, e.g., near-field [25] and dark-field imaging [22], [26], and microscopic imaging [27]–[29]. The phase sensitivity of THz optoelectronics even permits to go beyond the capabilities of conventional optical techniques to a tomographic analysis of the interior of transparent objects [30].

III. OPTOELECTRONIC SYSTEMS WITH CONTINUOUS-WAVE OPERATION

A major disadvantage of pulsed THz optoelectronics is its dependence on femtosecond lasers which remain to be cost-intensive and mostly bulky. Continuous-wave (cw) laser systems, and here specifically diode lasers, offer an interesting alternative [31]. THz-wave generation by cw photomixing, which was first demonstrated by Brown *et al.* [32], reaches output powers of up to 2 μW at 1 THz based on laser systems operating at 800 nm [33], respectively 10 μW at 1 THz with lasers running at a wavelength of 1.5 μm [34]. Employing narrow-linewidth laser sources permits to reach a high spectral purity desired for local-oscillator applications and for spectroscopy with high spectral resolution.

After the first all-optoelectronic THz measurement system had been implemented in 1998 by Verghese *et al.* [35], we demonstrated cw THz imaging employing a photoconductive receiver [36], [37], while Nahata *et al.* reported imaging with electrooptic detection [38]. Meanwhile also a cw THz system for imaging in reflection mode has been demonstrated [39].

Fig. 1 shows the layout of our imaging system. It is based on a two-color Ti : sapphire laser and LT-GaAs antennas for both generation and detection of the cw THz radiation [40]. Each photomixer is illuminated with 100 mW of dual-wavelength laser radiation. The emitter is biased with a 25-kHz square-wave signal with an amplitude of $\pm$12.5 V.

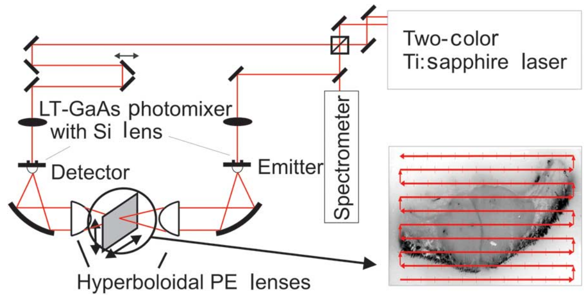

Fig. 1. ***Schematic drawing of an all-optoelectronic cw THz imaging system.***

During THz imaging, the sample is mounted on a computer-controlled x-y translation stage and moved continuously along a meandering path through the focus of the THz beam as indicated in the inset of Fig. 1. During the spatial scan over a horizontal row of the object, the optical delay line is moved with constant velocity without changing its direction. For image formation, both amplitude and phase information at each pixel are exploited (for examples, see [36], [37], and [41]).

In single-scan measurements at 1 THz, with the data acquisition time set to 200 ms per pixel, we achieve a dynamic range (power) of more than three orders of magnitude. The spatial resolution is about one wavelength. With the same antennas, the system is suited to record images in the frequency region between 0.2 and 1.5 THz.

In order to illustrate the imaging capability with cw THz radiation for package inspection, we show exemplarily in Fig. 2 an image taken at 500 GHz from some matches through the closed cardboard matchbox. The image area is 10×15 mm^2 and the image consists of 600 pixel with a spacing of 0.5 mm. The total scan time was about 2 minutes.

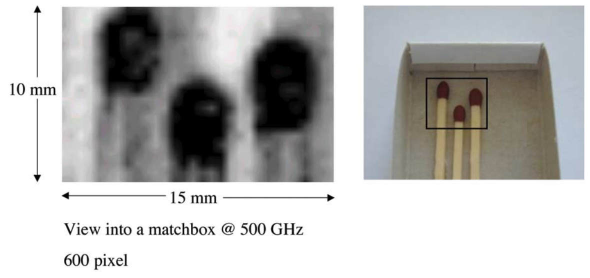

Fig. 2. ***Left: THz—transmission image at 500 GHz of three matches in a closed box. Right: Photograph of the opened box with the matches inside.***

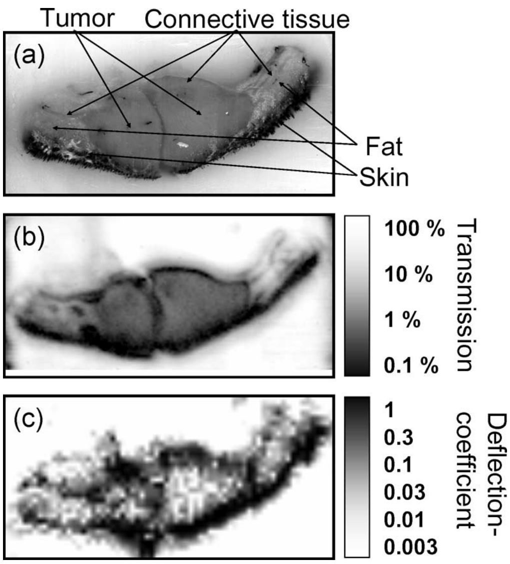

Fig. 3. ***(a) Photograph of an archived tissue sample of a cut through a canine skin tumor. (b) Cw transmission image of the sample at 1 THz. (c) Deflection coefficent at 2 THz obtained with a pulsed dark-field system.***

Fig. 3(b) depicts a transmission image taken from an archived (formaline-fixed, dehydrated and wax-sealed) slice through a canine skin tumor (basal cell tumor). The size of the sample was 32 mm × 24 mm × 3 mm [see photograph in Fig. 3(a)]. Fig. 3(b) displays the transmittivity image of the sample at 1 THz on a logarithmic power scale. The image consists of 11 248 pixels, with a pixel period of 250 μm. The data were recorded during a single meandering scan over a time of 39 min. The various tissue components can be distinguished.

IV. TERAHERTZ DARK-FIELD IMAGING

Exploring contrast-formation mechanisms of THz imaging [19], one often finds that scattering and diffraction by: i) spatial refractive-index variations in media and ii) topographic landscapes at surfaces and interfaces, are at least as significant and useful as absorptive features. In order to enhance the sensitivity for scattered and diffracted radiation, we have developed dark-field THz imaging techniques in analogy to the well-established approaches in optical microscopy.

The principle of dark-field imaging 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. This is illustrated in Fig. 4(a) for a reflection setup operated with an amplifier laser system where the THz radiation is generated by a large-area photoconductive emitter [42] and detected with the help of an electrooptic crystal.

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 [26]. Fig. 3(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 [26]) suggests that diffraction is dominant at boundaries while scattering dominates in the region of skin with hairs.

V. INDUSTRIAL SURFACE CHARACTERIZATION

Besides the very popular fields of biomedical and security-related research, one should not neglect more traditional

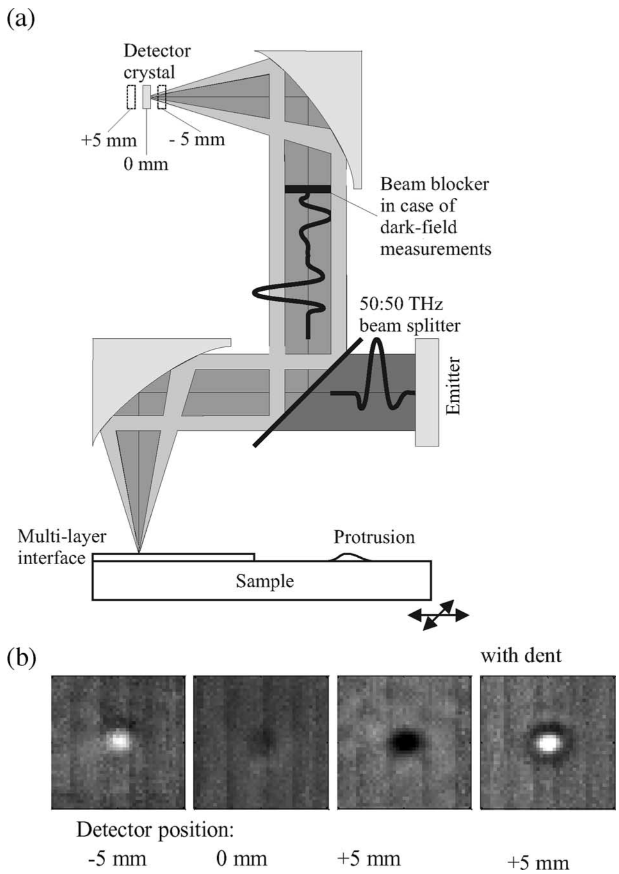

Fig. 4. ***(a) Schematic drawing of the reflection setup for surface and interface characterization. For dark-field measurements, a beam blocker is placed at the indicated position. For out-of-focus detection, the detector crystal is moved out of the normal beam focus. (b) Experimentally observed THz-reflection images at 1 THz 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.***

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 began to examine conceptual aspects of the applicability of THz imaging and sensing for the inspection of the surfaces of rolled steel and other metals. These investigations aim at the online 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 m and sub-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 aluminum present in the iron ore in the course of the reduction of the iron oxides. The online 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, conveyor-belt speed and vibrations, etc.) enforces rather large working distances and fast data acquisition times.

Neglecting the online-operation target for the time being, we were able to show that THz imaging with its large wavelength in the sub-mm range is blind to the natural surface roughness but provides very good sensitivity to the defects to be identified [22]. 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. 4(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. 4(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. 4(b) shows experimental results obtained with this second technique at 1 THz. 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 reversed. It schould be noted, that the shift of the detector position is quite large compared to the depth of focus (250 μm). 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 [22].

Fig. 5 highlights the sensitivity reached by THz imaging with dark-field filtering for typical surface defects encountered in steel production. The sample was a steel plate with a roughness typical for rolled steel. A single protrusion of 30-μm height and 4-mm diameter was located in the plate's center. The image in the lower part of Fig. 5 was recorded with a video camera and shows speckles resulting from the surface roughness, but no convincing evidence for the presence of the surface defect. The image in the upper part of Fig. 5 is a THz dark-field image obtained at a frequency of 1.95 THz with the first of the two techniques outlined above. Signatures of the surface roughness are suppressed, but the single surface defect is very evident and can be detected with a contrast of 100 : 1.

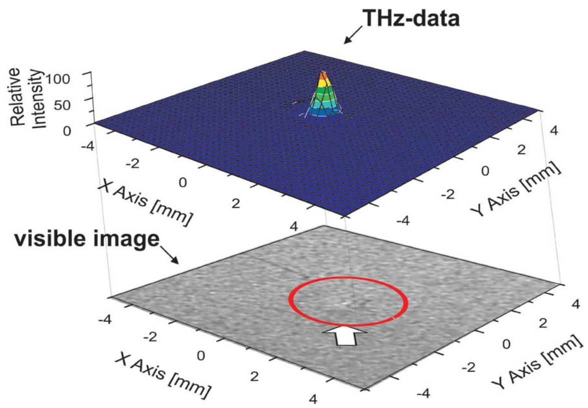

Fig. 5. ***Comparison of the THz dark-field data with an visible image of an steel sample with a protrution of 30-μm height an 4-mm diameter.***

This example shows, that THz radiation may 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 amplifier pulsed THz-imaging system, a transfer of the concept to nonamplified fs-pulsed or a cw optoelectronic THz system should be straightforward, becuase the system does not rely on the increased THz pulse energies of the amplifier system. The signal-to-noise ratio of typical raster-scan THz imaging systems is more than sufficient to produce THz dark-field images, although the main part of the THz beam is blocked. The measurement time for THz dark-field imaging is therefore not increased compared to normal raster scan THz imaging.

VI. TERAHERTZ ANTIREFLECTION 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 antireflection concepts from optics, we developed an antireflection coating which can be applied to many materials because the refractive index can be adjusted to suit the substrate to be coated.

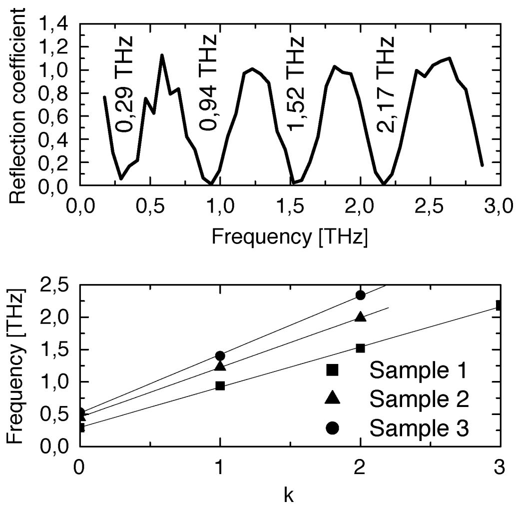

Fig. 6. ***Top: Measured reflectivity of an antireflection-coated silicon wafer. Bottom: Frequency of the observed reflection minima versus order number*** k ***for three samples. The lines indicate linear fits.***

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.

Fig. 6 shows experimental results for a semi-insulating Si wafer with a single-layer antireflection coating. The data were taken with the help of the THz measurements setup of Fig. 4. The measured spectrum of the reflection coefficient (see top of Fig. 6) exhibits the modulation typical for single-layer coatings. Signal components at 625 GHz and multiples hereof are fully reflected while signals at 625 GHz $\times (k + (1/2))$, with k being an integer, exhibit vanishingly weak reflection.

The lower panel of Fig. 6 displays the frequencies of the reflection minima as a function of the order number k for three samples of varying coating thickness. The data illustrate that antireflection coatings can be produced for target frequencies over a large frequency range.

VII. POTENTIAL FOR THE DETECTION OF TOOTH DECAY WITH THz RADIATION

A fascinating opportunity for the application of THz radiation in the medical field seemed to arise several years ago when Teraview Ltd., a company dedicated to the exploitation of THz radiation, and other research groups began to investigate transmission imaging through dry human teeth [43], [44]. It was found that buried lesions could be identified with large contrast, and that demineralization, which occurs prior to the development of caries, could be detected.

The hope for dental diagnostic applications of THz imaging diminished drastically, however, when the investigations were extended to teeth in a more natural state which is characterized by a high water content and an ensuing strong absorption of THz radiation. The absorption coefficients and the reactive indices of the main tooth constituents, enamel, and dentin, under conditions approaching those of living teeth were measured by a research group at the University of Leeds [45]. The absorption coefficients, averaged over a wide frequency range around 1 THz, were found to be in the range of 60 to 70 cm^{-1} (see Fig. 7). With the resulting absorption depth of 0.19 mm in enamel and even less in dentin, penetration of a full living tooth with a diameter of 5–10 mm would require a system dynamic range of 20 orders of magnitude. Although extremely high sensitivities can be reached with specialized nonoptoelectronic THz systems employing high-power sources (such as p-Ge lasers or free-electron lasers) and bolometric detection at cryogenic temperatures, for optoelectronic systems, such a sensitivity is currently out of reach. The possibility to perform transmission imaging with 1-THz radiation in a cost-effective manner hence needs to be ruled out.

An examination of living teeth may, however, be possible in reflection geometry employing the interface of enamel and dentin as reflector (see sketch in Fig. 7), and thus enable to monitor the enamel layer where the development of caries starts by demineralization. In this paper, we want to address the question whether such an approach is in principle feasible with the current sensitivity of optoelectronic THz imaging systems.

We estimated the fraction of the THz signal impinging onto a tooth which is reflected from the internal interface between enamel and dentin, and penetrates again out of the tooth. In the calculations, we considered both the measured refractive-index difference of enamel and

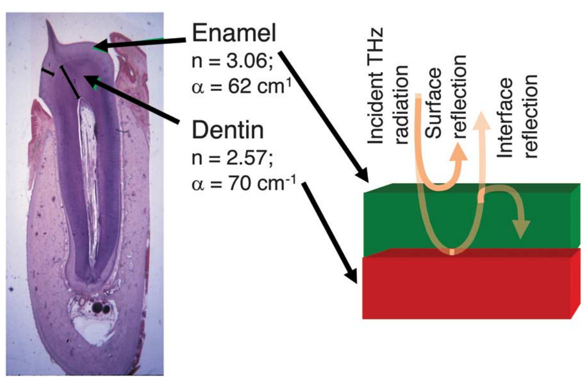

Fig. 7. ***Left: Visual image of the internal structure of a human tooth. Transmission picture taken through a thin slice of a tooth (note that a part of the tooth at the top is broken off). Right: Scheme showing the different components of the reflected signal. Values for the refractive indices and the absorption coefficients are from [45].***

dentin (for the index values, see Fig. 7) and the absorption in the enamel layer which has an average thickness of 0.3–0.4 mm. The result of the calculations is that the electric field returning from the internal interface is somewhat less than 1% of the impinging field. Such a signal can be detected fairly easily with a state-of-the-art THz system [7], [46]. With time-domain THz spectroscopy, the pulse reflected from the internal interface can also be discriminated well from the surface signal by temporal windowing.

It is a different question whether the signature of a lesion can be detected on top of the reflected signal. From the signal-to-noise point of view, it appears feasible that a signature should be detectable if the lesion-induced modulation on the reflected field is on the order of a few percent. With an index-matching coating on the surface of the tooth, the measurement conditions can be further improved. We hence come to the conclusion, that the detection of tooth decay is—from the point of view of the measurement sensitivity—possible with THz radiation if a pulsed THz system is used in reflection mode. Whether THz imaging is useful then, may depend on other issues such as those that regions of special interest are those where teeth touch and which are difficult to access in a reflective measurement geometry.

VIII. CONCLUSIONS

In summary, we have explored both pulsed and cw optoelectronic imaging techniques for surface and interface characterization. Although the potential identified for THz applications is impressive, a major limitation of the present systems (except of expensive amplifier-laser-based systems) is the fact that only single- or few-pixel imaging is possible. This has the consequence that practical imaging systems for real-time 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. Because of the strong interest in security-related THz imaging, one observes a renewed current interest in nonoptoelectronic approaches, employing both electronic sources at the low end of the THz spectrum [47] and laser sources at several THz [48]. Although this has not been a topic of this paper, we point out that real-time multipixel detection systems appear feasible also in a hybrid fashion combining high-power electronic or laser sources of THz radiation with very sensitive optoelectronic detection methods [49]. ■

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