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Terahertz based non-destructive testing (NDT)

Terahertz-basierte zerstörungsfreie Prüfung (ZfP)

Making the invisible visible

Das Unsichtbare sichtbar machen

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Abstract: Established methods based on X-rays, ultrasound, thermography, eddy current, and optics are very effective in fault detection and structural analysis. However, these methods are limited for some applications, for example, the non-destructive testing of fiber-reinforced plastics, foams, and sandwich or hollow structures. In these cases, terahertz technology offers an innovative method to overcome these limitations. Tremendous advances have been made in this new technology in terms of their industrialization in recent years. This paper presents techniques for use in industrial applications.

Keywords: Terahertz, microwave, sub-millimeter, SAR, MIMO, thickness measurement, coating, composite, honeycomb, foam, security, food, NDT.

Zusammenfassung: Etablierte Methoden, die auf Röntgenstrahlen, Ultraschall, Thermographie, Wirbelstrom und optischen Methoden basieren, sind in der Fehlererkennung und Strukturanalyse sehr effektiv. Insbesondere bei der zerstörungsfreien Prüfung von faserverstärkten Kunststoffen oder Schäumen sowie von Sandwich- und Hohlstrukturen stoßen sie jedoch an ihre Grenzen. Die Terahertz-Technologie bietet hier eine innovative Methode zur Überwindung dieser Schwierigkeiten. In den letzten Jahren wurden große Fortschritte bei der Industrialisierung dieser Technologie erzielt. In diesem Beitrag werden die industriell relevanten Techniken und deren Anwendungen vorgestellt.

Schlagwörter: Terahertz, Mikrowelle, Submillimeter, SAR, MIMO, Dickenmessung, Beschichtung, Verbundmaterial, Wabenstruktur, Schaum, Sicherheitstechnik, Lebensmittel, ZfP.

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1 Introduction

All steps of production require suitable testing methods that objectively determine quality. The requirements on the goods produced continue to increase, while permanent cost pressures require more efficient use of production resources, both materials and time. Considering the digitalization of production, the complete documentation of the various process steps is also necessary.

In some areas today, the suitable measuring and testing techniques to meet the requirements of process and quality controls are still lacking. Established methods based on X-rays, ultrasound, thermography, eddy current, optics, and many others are widely used, but these methods reach their limits, especially, with modern fiber-reinforced plastics or foams as well as sandwich and hollow structures when it comes to fault detection and structural analysis [1]. The electrical eddy current method is not feasible in the case of non-conductive materials and X-ray procedures often also fail, since they are not compatible with one-sided access to a component. Ultrasound usually does not work without direct contact, while thermography and optical methods usually have a very limited penetration depth, which does not provide direct volumetric information.

A newer test method based on terahertz waves allows the generation of very good three-dimensional images of the complete sample in tests performed on non-conductive materials. Such non-contact measurement provides information on all layers, cavities, and adhesive joints, etc. Additionally, the measurement can be based on reflection. Terahertz technology has significant advantages versus other competing methods that rely on x-ray, ultrasonic, microwave, or infrared (IR) systems [1]:

- **versus X-ray:** Terahertz radiation poses no health hazards because of the low photon energy.
- **versus ultrasound:** Terahertz radiation enables non-contact inspection of materials.
- **versus microwave:** Terahertz technology can achieve significantly better spatial resolution because of the

shorter wavelengths. Also, spectroscopic fingerprints are available in the terahertz range, for substance identification.

- **versus IR:** Terahertz radiation penetrates dielectric materials and has relatively low Mie and Rayleigh scattering.

The terahertz frequency range is between 100 GHz and 10 THz. The electromagnetic wavelength is between micro- and millimeter waves and the infrared spectrum. The former includes the frequencies for radios and microwave ovens and mobile phones, while the latter is used by thermal imaging cameras and radiant heaters.

Terahertz waves have the special property of being able to achieve good penetration of electrical insulators such as ceramics, glass, and polymers. However, electrically conductive materials (e. g. metals and carbon fiber reinforced composites) often act as mirrors and cannot be penetrated by terahertz waves. Polar liquids such as water also strongly absorb the terahertz wavelengths, which explains why the penetration depth in humans is so small with most of the radiation being absorbed by the top layers of skin. Similarly, the signal strength and transmitted bandwidth depend on the humidity in the air. As non-ionizing waves, terahertz waves are harmless to humans, eliminating the need for experimental shielding. Applications can now be realized with these special properties of terahertz technology that could not previously be solved using established methods.

One example is the fast process control for pipe inspection directly after extrusion. The accuracy of measurement for an ultrasound sensor depends on the exact prediction of the temperature profile inside the wall. The sound velocity inside the wall depends directly on the temperature of the material. For sensors based on electromagnetic waves, this effect can be ignored for the most applications. For this reason, in-line inspection systems based on terahertz technology are already in use at various plants.

Another example is in measuring the thickness of steel sheets during and after the rolling process. The conditions in a steel mill are very difficult, such as high dust loads and water in the form of steam and fog. Under these conditions, optical techniques cannot be applied, but precise thickness measurement of the steel sheets is possible using terahertz radiation.

Terahertz imaging is still a niche market because the scanning time for an object is still too long for many NDT applications. Depending on the lateral and depth resolution required and the applied terahertz technique, imaging may take several minutes to a few hours to scan one square meter. Time is the limiting factor in terahertz time domain

spectroscopy as the measurement speed of the system is determined by the mechanical scanning limits of the radar systems. In some special applications, the long measurement time is acceptable because the information obtained by the terahertz technique. In the vast majority of cases, however, run time measurements are required to determine the layer thicknesses or distances at a single spot. Such measurements have to be repeated quickly to enable in-line inspection and control.

In the next section, after a short description of the properties of terahertz waves, different approaches for technical applications are presented. Several terahertz imaging techniques are the focus of Section 3. From the many possible applications, the most important current applications are selected and presented in Section 4. A summary and the list of references conclude this paper.

2 Measurement methods in relation to uses

The so-called “terahertz gap” has closed after many years of research and development. A large number of terahertz products are now commercially available. Terahertz technology has made the leap from the laboratory to practical application and the first industrial applications are being implemented. In fact, two different technologies are available for use in today’s industrial environments.

The systems of choice for multi-layer thickness measurement applications are pulsed optical terahertz systems based on time-domain spectroscopy (TDS). These systems use very short terahertz pulses generated by ultra-short pulse lasers. Both amplitude and phase of the terahertz pulses are measured [2]. These are used to perform very precise transit time analyses (for example, thickness measurement), or spectroscopic investigations (for example, material identification). Using a 600 μm thick silicon wafer, the standard deviation of the time difference between the reflections from front and back surface is less than 5 fs after suitable data processing (for example, zero padding).

A second technology now in use is based on continuously emitting, purely electronic terahertz systems that use waveguides [3] or integrated circuits (ICs) [4]. Generally, these systems use microwave oscillators with increased emission frequencies created by external frequency multipliers to reach the terahertz range. Overall, the hollow-conductor based system is discrete and modular. The IC-based systems are highly integrated and com-

bine as many components as possible on one or a few chips. The development of assemblies currently operating up to approximately 2 THz is possible with high-frequency circuits that use waveguide technology based on semiconductor circuits in InP or GaAs systems [5]. By integrating as many high-frequency circuits as possible on a single chip, the system size is small and has the potential for cost-effective mass production. Currently, most highly integrated IC circuits are based on SiGe technology, which enables the realization of systems up to approximately 300 GHz. ICs up to about 100 GHz are also commercially available. Generally, the current bandwidths realized by ICs are smaller than those of hollow-conductor waveguide systems.

Each of these technologies has its own natural fields of application. A TDS system is the system of choice when thin films (less than 1 mm) or spectroscopic information needs to be measured. Thicker layers or very fast measurements (more than 1,000 measurements per second) require the electronic systems. Costs are also very different in each technology. In most cases, the prices discussed are for the cost of an individual system or a very small quantity. Typically, a TDS system is priced in the range of 100,000 EUR, while the electronic systems are less expensive. If one extrapolates to larger production quantities, the price for a TDS system would be about 30,000 EUR (for more than 100 units per year). An electronic system on the order of 1,000 EUR (for more than 10,000 units per year) is possible due to efficiencies in semiconductor production. The higher the working frequency, the smaller the cost difference between these two approaches.

2.1 Terahertz time domain spectroscopy

Since the working frequencies of traditional electronic components do not yet extend far into the terahertz range, a real-time measurement of high terahertz frequencies is not yet possible. The generation and coherent detection of pulsed terahertz radiation (time-domain spectroscopy), is one way of measuring electromagnetic waves in this range. Photoconductive switches are operated by ultra-short laser pulses are the most prominent examples of this principle. Typical commercial fiber lasers (pulse width 100 fs and less) are used to generate and detect frequencies between 100 GHz and 5 THz [2]. All approaches require two synchronized partial beams (from one or more lasers), which are used to operate the transmitters and receivers. Analogous to classical pump-probe experiments, only the relative delay between generation time and detection time

is considered. The relative delay can be introduced by mechanical, electronic, or optical means [2, 6–9]. With terahertz radiation detection systems, the high-frequency signal components in the receiver (charge carrier lifetime below 1 ps) are mixed to lower electronic frequencies. This sampling technique allows the coherent detection of terahertz radiation by electronic components whose bandwidths are in the kHz or MHz range.

The terahertz time-domain spectroscopy allows not only the intensity, but also the direct measurement of the electric field as a function of the delay. This is not the case, when intensity is measured using a power meter or a standard Fourier Transform Infrared (FTIR) spectrometer.

Compared to the reference pulse (measured without the sample being in the transmitted path), the pulse from the sample (measured either as a transmission or reflection) is modified due to the nature of the sample (see Fig. 1). The amplitude is reduced by reflection, absorption, and scattering and the pulse is delayed due to the index of refraction. Additional temporal structures are generated by echoes of multiple reflections inside the sample or due to the spectral information of the sample material. The spectral information is retrieved from the measured terahertz time trace by Fourier transformation [2].

2.2 Terahertz FMCW systems

The operating frequency of terahertz radar technology has greatly increased in the last two decades – driven by the developments in automotive applications as well as broadband data connections [10]. While IC-based systems now operate at 100 to 300 GHz, hollow-waveguide based systems are available up to 2 THz. Both techniques share the frequency chain: starting with a local low frequency oscillator and then using frequency multipliers and mixer concepts to increase this frequency range, which is also referred to as the millimeter and submillimeter wave range.

While pulsed systems are commonly used for wide-range applications such as weather radar, the frequency modulated continuous waves (FMCW) are used for industrial short-range applications such as adaptive cruise control in automobiles. Signal modulation is required to obtain depth-resolved information about the sample. The simplest frequency modulation waveform is a sawtooth. A linear ramp is generated and a part of the transmitted signal is decoupled and mixed with the received signal (see Fig. 2).

A time offset occurs between the sending and receiving signal caused by the transit time of the transmitted signal from the antenna to the reflecting object and back to

Figure 1: Comparison of the reference pulse (black) and the measured pulse after transmission through a PTFE sample (red). The comparison of the waveforms allows statements to be made regarding sample properties such as thickness, porosity, absorption, and moisture etc. A Fourier transformation is used to calculate the spectrum. The absorption lines of water vapor cause oscillations in the measured pulse and are clearly visible in the corresponding spectrum.

Figure 2: Principle of FMCW systems. Left: the ramp generator feeds the transmitter S_t and the mixer. The reflected signal S_r is mixed with the signal from the ramp generator. The mixed signal S_a passes a low pass filter (LP) for further data processing. Right: the ramp generator has to provide a linear frequency sweep characterized by duration T and frequency bandwidth B . The signal requires the transit time τ for the distance from transmitter to reflector and back to the receiver. The time delay between the emitted and received frequency corresponds to an actual frequency difference (ω_a is the angular frequency of the frequency difference).

the receiving antenna. If the received frequencies are compared to the currently transmitted frequency by mixing, a difference frequency results that is directly proportional to the transit time and to the distance between the measuring system and the reflector.

$$S_a \approx A \cdot \cos(\omega \tau t) = A \cdot \cos(\omega_a t) \quad \text{where } \omega = 2\pi B/T$$

B being the modulation bandwidth, T the modulation period, A the amplitude and τ the travel time between emitter, object, and detector.

An important parameter for every radar sensor is range resolution. Range resolution refers to the ability of a radar system to distinguish between two reflection points at different ranges. The range resolution for an FMCW radar depends on the bandwidth used by the system. The theoretical range resolution for a radar system can be calculated using the following equation (3 dB criteria):

culated using the following equation (3 dB criteria):

$$\delta r = \frac{c_0}{2B}$$

δr being the resolution and c_0 being speed of light in a vacuum. Since the bandwidth is limited, the resulting time domain response of signal S_a corresponds in a first approximation to a "sinc(x)" function as shown in Fig. 3 and Fig. 4. Theoretically, with a 3 dB criteria, the range resolution of a radar sensor with 1 GHz bandwidth corresponds to a resolution of 15 cm. For this definition, the scattering centers are assumed to have the same size. If the scatterers have a different size, a very small scattering center may be obscured by the side lobes of the larger scatterer nearby. Typical scatterers are edges or corners. In a realistic measurement configuration, when corners have different dimensions, it is more useful to use the 6 dB criteria for range resolution.

To reduce the side lobe level (SLL) a weighting function such as a Hamming window can be used. The side lobes can be lowered further to resolve smaller targets by weighting the amplitudes of the measured frequencies with an appropriate function. Unfortunately, weighting functions decrease the range resolution. A distinction has to be made between distance resolution and distance measurement accuracy. Distance can be measured much more accurately if there is only one scattering center in the distance cell, (for example, through zero padding, phase information, or more sophisticated methods).

High accuracy and reproducibility depend strongly on the linearity of the frequency ramp and a low phase noise system design. Considering these aspects, systems that measure the thickness of steel sheets during the rolling process or the wall thickness of plastic pipes in extrud-

Figure 3: The depth resolution of a FMCW system depends on the bandwidth B of the frequency sweep. If two spaced reflectors are closer than the distance $\delta_{range, 6dB}$ they are no longer separable.

ers can achieve a measuring accuracy in the two- to three-digit μm range under actual operating conditions. Radar sensors at 30 GHz with 4 GHz bandwidth are used for the width measurements.

3 Imaging techniques

In many cases, a single point measurement is not sufficient for the application and the so-called one- or two-dimensional imaging is required. Several approaches for terahertz imaging have been developed and the most promising ones are discussed here. Depending on the system design, imaging can be performed in transmission, reflection, or scatter configuration.

An important aspect is the spatial resolution of the recorded images. A distinction must be between two dimensions: the resolution perpendicular to the beam direction (lateral) and the resolution in beam direction (depth resolution). The latter is method-dependent: using TDS, beam direction resolution is determined by the duration of the terahertz pulse and its detection (a few micrometers). Using FCMW, resolution is determined by the bandwidth

of the frequency sweep (at least, about 1 mm within a sample and tens of micrometers for distance measurement). According to conventional optics, the lateral (perpendicular) resolution depends on the wavelength and the optics. The larger the wavelength and the longer the focus of the imaging optics, the poorer the lateral resolution. In particular, the dependency on wavelength is important because the terahertz spectrum covers a wide range – from 30 μm (10 THz in air) to 3 mm (100 GHz in air), which means a factor of 100 in wavelength. Using standard optics with focal length on the order of 50–100 mm, the achievable lateral resolution ranges from tenths of a millimeter to several millimeters.

Focusing optics are usually used for the close-range imaging of objects, whereby the device under test (DUT) is located in the focal plane. If the DUT and/or the optics are moving, the DUT can be imaged two-dimensionally. Usually, a meandering scan of the object is performed using an XY scanner (see Fig. 5, left). However, this mechanical movement is relatively slow due to continuous acceleration and deceleration.

For faster imaging of the DUT, it is advisable to have the antenna scan a helical path (see Fig. 5, right). In this approach, the sensor can move with a constant and comparably higher speed, because the time-consuming acceleration and deceleration is avoided. A disadvantage in this approach is the creation of ghost images during image reconstruction or even unscanned areas. The inhomogeneous density of measurement points through the different fields of view in the non-rectangular grid produces circular effects. Another drawback accompanies the use of an antenna with linear polarization. Because of the circular movement and antenna orientation, the transmitted and received polarization changes between the center and the sides of the conveyor. A thin linear object like a wire can be

Figure 4: For a scenario with two point reflectors at 5 cm distance, the figure on the left shows the frequency response of the received signal with 25 GHz bandwidth and on the right side after a FFT the corresponding response in the frequency domain.

Figure 5: Different imaging approaches. The sensor is moved either in meandering or helical pattern. Both approaches can be applied when the DUT is in motion, for example, with the DUT placed on a conveyor belt. If the DUT does not move, it is easier to use the meandering pattern for scanning.

Figure 6: SAMMI® (Stand Alone Millimeter Wave Image) [10]. Left: Scheme of SAMMI system; The DUT moves on the conveyor belt while the transmitter and receiver synchronously rotate. In this way, a transmission image of the DUT is recorded using helical scanning. Middle and right: Images of a package with chocolate pralines.

visible in one part of the conveyor and invisible in another area. Figure 6 shows an example of a helical scanning system called SAMMI® (Stand Alone Millimeter Wave Image, SAMMI). This system is transmission-based and operates at a single frequency around 78 GHz [11]. A high number of individual measurements in phase and amplitude can be performed very precisely using only a single frequency. Specifically 30,000 measurements can be made per second. The speed is limited by the maximum rotation speed of the rotary couplings.

There are two main reasons why pure image scanning processes are unsuitable if the device under test is large, complex and thick. First, the optics used for depth-dependent spatial resolution have only a limited depth of field. Outside this range, the image blurs. Second, the pointwise scanning is very time consuming and therefore, not appropriate for most applications.

One way to obtain clear images without depth-dependent spatial resolution is to use synthetic aperture radar (SAR). In simple terms, the DUT is scanned by one or more sensors without imaging optics, but with wide lobes. Amplitudes and phases are determined for each measurement location. The image is then reconstructed from the individual measurements, for example, by means

of the “back-projection” method, which produces a three-dimensional image of the DUT (see Fig. 7).

The SAR method solves the problem of the depth-dependent resolution, but scanning is still necessary. Ideally, a SAR camera with many pixels would eliminate the need for scanning, but high price and technical complexity prohibit the use of such cameras at this time. Research projects are underway to overcome these technical challenges.

An intermediate approach based on linear SAR cameras is available. Imaging requires either the linear camera or the DUT to be in motion. The latter is often the case present in the production environment. A linear SAR camera consisting of many SAR sensor elements can obtain sufficient spatial resolution, but this kind of camera is very expensive. To reduce the number of sensors, another technique is applied: MIMO (multiple input – multiple output). It reduces number of transmitters and receivers and positions these elements in a fixed configuration. Typically, a time-sequenced multiplexing approach is used in which all receivers are active and the transmitters are switched on sequentially. In this way, signals from all receivers are recorded for each activated transmitter. Since the geometric arrangement of the transmitters and

Figure 7: SAR laboratory system. Left: photo of the scanner, the sensor travel is drawn in red. Middle: photo of a dry wall construction. Right: Reconstructed SAR image. Internal structures are clearly visible as is the boundary layer between the two sheetrock panels that form the front and the back (red).

Figure 8: Photo of first experimental MIMO systems. Left: System based on hollow waveguide elements at 100 GHz with 12 transmit and 12 receive channels. Right: System based on IC elements at 120 GHz with 24 transmit and 24 receive channels mounted on a circular aperture.

receivers is known, it is possible to determine the propagation times and the position of the reflectors. A complete image can be reconstructed after completing the activation of all transmitters. The spatial resolution obtained by MIMO systems depends on the number of elements used as well as on the geometric design. The most prominent example of such a MIMO system is the R&S@QPS body scanner from Rohde & Schwarz, which is now installed at numerous international airports [12].

The first experimental MIMO system for NDT application is realized at 100 GHz and 120 GHz center frequency (see Fig. 8) [13, 14]. A large number of high-frequency components are commercially available for this frequency range. Multichannel chip designs that use the Silicon-Germanium (SiGe) manufacturing process, which is well established for components used in the automotive industry, can be used. The phase stability between the individual transmitters and receivers is the major challenge with distributed channels. Ideally, the transmit frequency is centrally generated and then distributed to the individual transmission antennas. Two possibilities exist to transmit the centrally generated signal to the antennas: waveguide or cable. Cables have high losses at the targeted frequency

of 120 GHz, while waveguides exhibit lower transmission losses. Waveguides, however, cannot be integrated on the chip due to the required construction volume and higher weight. An alternate method is to centrally generate one basic frequency and distribute an intermediate frequency (IF) level. The transmitted frequency signal is then processed separately in each transmission path via frequency multipliers or phase-locked loops (PLLs). The disadvantage of this approach is that after distribution of the IF frequencies through the parallel channels, the coherency decreases. Clearly, a compromise is needed: the IF signal should be low enough to be distributed without large losses, while on the other hand, the highest possible IF level must be selected to achieve the high coherence necessary between the individual channels. In this case, a compromise of 30 GHz was chosen because the complete IF distribution can be implemented on a single board [14].

Many industrial applications require image reconstruction and evaluation in real-time. To achieve real-time operational results, computationally efficient digital beamforming (DBF) algorithms are essential. Different approaches have been tested for parallel processing and implemented on a graphics processing unit (GPU) using

Figure 9: Terahertz coating thickness measurement is suitable for many different applications. The method has great advantages, especially, in the analysis of complex multilayer systems, e. g. for lightweight materials, ceramics, paints and coatings. The measurement can be carried out by hand or by robot. The principle of thickness measurement is a time of flight analysis (right). Here, the sample is a two-layer PU coating with 100 μm and 150 μm nominal layer thickness, respectively.

the MIMO system shown in the left photograph of Fig. 8 [13]. Examples of efficient algorithms that benefit considerably from the parallelization of image reconstruction are the back projection (BP) method and the fast-factorized back projection (FFBP), since they both perform the same computations for each voxel. An even more efficient alternative is the range migration algorithm (RMA), which uses the fast Fourier transformation (FFT). However, the economic MIMO concept hinders the application of this approach, because the Nyquist sampling criterion is violated.

A modified RMA was developed at ITWM to provide good results in combination with suitable sparse arrays. Since the back-projection methods benefit most from the parallelization of the image reconstruction, the choice of algorithm in terms of data processing speed depends on the number of voxels per scene that need to be reconstructed within a certain time. While MIMO systems based on discrete waveguide components enable a very flexible sensor arrangement, IC-based systems offer a more compact and cost-effective solution.

4 Current applications

Industrially relevant and promising terahertz applications have emerged in recent years. The “roll out” of terahertz applications begins with measurement technology. These include non-destructive testing of layer thickness and plastic components, spectroscopy in the areas of process control and security monitoring, as well as near-field measurements of conductivity distributions on semiconductor components. This paper does not include the most

promising application in the pharmaceutical and medical branches, which is based on spectroscopic features and is used for substance identification. However, it does not belong to the traditional NDT and these branches are very cautious about introducing new technologies.

In addition to the applications mentioned above, selected applications and the technologies they use are discussed in the next section.

4.1 Measuring thickness applications

Currently the most important applications for pulsed optical terahertz systems is non-contact coating thickness measurement for complex multi-layer coatings [15], such as those found in the automotive industry (see Fig. 9). In addition to the visual appearance, coatings have a very important protective function for the underlying components, not only in the automotive sector. Each individual layer represents a functional layer whose thickness is decisive for the effectiveness. The thickness of all layers within a multi-layer system should be measured individually and non-destructively. Even systems consisting of four paint layers with similar material parameters in each layer can be reliably measured using terahertz layer thickness analysis, with measurement errors that are far below the wavelength and can be well below 1 μm depending on the system. As optical techniques, these methods measure the optical thickness that corresponds to the product of geometric thickness and index of refraction. For the calculation the geometric thickness the index of refraction has to be known, either from literature or from a suitable calibration. The temperature dependency of the index of

Figure 10: Wall thickness measurement on a foamed PVC pipe. Left: Close-up view of a four-channel terahertz system to measure inline the wall thickness of multilayer pipes. Right: Distribution of the measured wall thicknesses of the individual layers along the pipe circumference. Values of radial direction in mm.

refraction can be neglected in the most cases at room or slightly elevated temperature. Due to the non-contact use and the short measuring times (significantly less than one second), such systems can be used directly in the line for 100 percent inspection.

Wind turbine paints, especially in offshore operations, shield the composite materials underneath from the harsh climatic influences. Reliable inspection of the paintwork prior to final assembly and commissioning is essential to ensure long time operation. Ceramic coatings on turbine blades protect the underlying metals from excessive heating and can also be reliably and non-destructively inspected using terahertz layer-thickness measurement. This is of great relevance to both power plants and aircraft turbines. The correct layer thickness can be determined without the usual destructive micrograph generation and an immediate decision can be made whether to recoat if the thickness is too low, or to remove and recoat if the thickness is too high. Even in complicated geometries, a compact terahertz sensor can be used to measure the thickness of the layer and the terahertz technique can thus ensure 100 percent control.

The wall thickness of extruded plastic pipes determines the product's mechanical properties and its manufacturing cost. For example, if we can achieve a material saving of just 1 percent assuming an average mass throughput of approx. 1 ton per hour; 8,000 production hours per year; and a material value of 1,500 € per ton, the cost saving would be 120,000 €/year. Such material savings are easily achieved by optimizing the wall thickness through precise measurement and adjustments. For many

decades, ultrasonic measurement methods dominated in this application. The transit time of ultrasonic waves introduced into the extrudate is measured and converted into a wall thickness, based on knowledge of the material-specific sound velocity. However, the speed of sound is strongly temperature-dependent. The typical temperature fluctuation in extrusion hinder precise wall thickness measurement and the equipment is relatively expensive. Ultrasonic methods require a coupling medium, for example in the form of water, between the probe and the extrudate. The terahertz technology, in contrast to ultrasonic methods, is characterized by a non-contact measuring method, so that no coupling is required. This significantly reduces the amount of equipment required, which experience has shown to be highly preferred in industry. Furthermore, this measuring method is almost temperature-independent, so for the first time, the wall thickness can be reliably and reproducibly determined, independent of extrusion-related temperature changes. Figure 10 shows a four-channel terahertz system to measure the wall thickness of multilayer pipes during production. Using this kind of inline system, all kind of polymers pipes can be inspected, either as smooth or as corrugated pipe. Due to the different behavior of polymers in the terahertz range, the maximum wall thickness depends on the polymers used: several centimeters for nonpolar polymers for example PE (polyethylene) and PP (polypropylene) due to high transmission – to a few centimeters for polar polymers such as PA (polyamide) and PVC (polyvinylchloride) due to high absorption. Depending on the system design, pipe diameters from 10 mm to 500 mm can be inspected. The ad-

justment to pipe diameter is motorized and automatized. The thinnest layer thickness is on the order of 20 μm . The temperature of the pipe was up to 80 °C during measurement.

4.2 Threat detection in security applications

Security technology was one of the first areas promoted for the application of terahertz technology. Many substances can be unambiguously identified such as drugs, but also explosives. Each substance has characteristic absorption bands in this frequency range, which are used to detect and identify the substance. In principle, this is also possible in the laboratory with Fourier-transformation infrared spectroscopy or Raman analyses, but in the field, terahertz technology stands out from these established techniques. Suspicious substances sent in letters or small parcels are often inaccessible to the established technologies. Since paper and cardboard are transparent to terahertz waves, it is possible to check whether suspicious materials are contained directly in the sealed mail item. The first systems are already on the market [16].

Various advantages of the SAR method, such as depth-independent spatial resolution and greater measuring distance, predestine this technology for security technology, such as modern security scanners at airports. In addition, they can also be used to check suitcases and bags (see Fig. 11).

4.3 Fault detection in composites

Complex composite materials are increasingly used in lightweight construction to balance the requirements for

low weight with high strength and stiffness. Possible composite materials, such as those used in aircraft construction, are usually sandwich constructions consisting of two or more thin glass fiber-reinforced plastic sheets with foam or honeycomb structures between them. Non-destructive testing in lightweight construction poses an unsolvable challenge for established testing methods. This was demonstrated in the DOTNAC project funded by the European Union (full title: Development and Optimization of THz NDT on Aeronautics Composite Multi-layered Structure) when terahertz technology was in direct competition with established methods such as ultrasound, thermography and X-rays. For this purpose, samples with artificial faults were prepared and examined using various techniques. Compared to the other methods in the comparison study, the terahertz technology based system was able to reliably detect, locate, and identify significantly more faults (see Fig. 12). In these investigations, hollow waveguide-based electronic systems are used, since a very good depth resolution is necessary to locate the faults [1].

5 Outlook

The most promising NDT terahertz application is time of flight measurement. Such measurements are useful in measuring distances like the thickness of steel sheets or the thickness of multilayer structures, such as automotive and aeronautic coatings and the wall thickness of pipes. Current research and development is moving in the direction of faster and cheaper systems.

The limiting factor for imaging is the time needed to scan the sample in some way. Terahertz imaging is currently present only in selected niches, where the relatively long measurement time is acceptable, e.g., radome inspection or safety and security control applications. Since only point sensors or cameras with a very small number of pixels are available for imaging, a focus of the current research and development projects worldwide is on the realization of larger terahertz cameras to overcome the limitation of long imaging times.

The terahertz applications mentioned above are all from the field of measurement technology. Terahertz technology has proven its usefulness and reached industrial maturity in recent years. New areas and further possibilities will follow, especially, in the field of information and communication technologies. The trend is that terahertz systems are continuously becoming more powerful and cost-effective. The terahertz measurement technology

Figure 11: SAR reconstruction image of a suitcase at 80 GHz. The mock-up weapon can clearly be seen. The measurement scenario is shown in Fig. 7.

Figure 12: A sandwich reference sample with honeycomb structure. Left: Photo of the sample, right: 3D representation of the detected faults for measurements at 150 GHz. The total sample size is $340 \times 200 \text{ mm}^2$. It consists of three layers: 1 mm glass fiber, 5 mm honeycomb and 1 mm glass fiber. The visible squares are artificial faults made of PTFE and PE foils, air (at the edges only), and have different sizes: 6×6 , 6×12 , 12×12 , and $25 \times 25 \text{ mm}^2$. Since the foils have been placed at a different depth, they appear in slightly different colors.

has great potential to enter into additional market segments with further application-oriented development of the technology. In combination with improved algorithms for data evaluation, terahertz technology receives an additional boost for a wider range of use.

References

1. E. Cristofani, F. Friederich, S. Wohnsiedler, C. Matheis, J. Jonuscheit, M. Vandewal, and R. Beigang, Non-Destructive Testing Potential Evaluation of a THz Frequency-Modulated Continuous-Wave Imager for Composite Materials Inspection, *Optical Engineering* 53(3) 031211 (2014).
2. M. Theuer, S. S. Harsha, D. Molter, G. Torosyan, and R. Beigang, Terahertz Time-Domain Spectroscopy of Gases, Liquids, and Solids, *ChemPhysChem* 12, 2695–2705 (2011).
3. F. Friederich, W. von Spiegel, M. Bauer, F. Meng, M. D. Thomson, S. Boppel, A. Lisauskas, B. Hils, V. Krozer, A. Keil, T. Löffler, R. Henneberger, A. K. Huhn, G. Spickermann, P. Haring Bolivar, and H. G. Roskos, THz Active Imaging Systems With Real-Time Capabilities, *IEEE Transactions on Terahertz Science and Technology* 1, 182–200 (2011).
4. T. Jaeschke, C. Bredendiek, and N. Pohl, A 240 GHz ultra-wideband FMCW radar system with on-chip antennas for high resolution radar imaging, 2013 IEEE MTT-S International Microwave Symposium Digest (MTT, Seattle, WA), pp. 1–4 (2013).
5. A. Tessmann, A. Leuther, H. Massler, V. Hurm, M. Kuri, M. Zink, M. Riessle, H. P. Stulz, M. Schlechtweg, and O. Ambacher, A 600 GHz low-noise amplifier module, *International Microwave Symposium (IMS)*, Tampa, FL, pp. 1–3 (2014).
6. G. Klatt, M. Nagel, T. Dekorsy, and A. Bartles, Rapid and precise read-out of terahertz sensors by high-speed asynchronous optical sampling, *Electron. Lett.* 45, 310–311 (2009).
7. R. J. B. Dietz, N. Vieweg, T. Puppe, A. Zach, B. Globisch, T. Göbel, P. Leisching, and M. Schell, All fiber-coupled THz-TDS system with kHz measurement rate based on electronically controlled optical sampling, *Optics Lett.* 39, 6482–6485 (2014).
8. R. Wilk, T. Hochrein, M. Koch, M. Mei, and R. Holzwarth, OSCAT: Novel technique for time-resolved experiments without moveable optical delay lines, *J Infrared Milli Terahz Waves* 32, 596–602 (2011).
9. M. Kolano, B. Gräf, S. Weber, D. Molter, and G. von Freymann, Single-laser polarization-controlled optical sampling system for THz-TDS, *Opt. Lett.* 43, 1351–1354 (2018).
10. R. Herschel and S. Pawliczek, 3D Millimeter Wave Screening of Wind Turbine Blade Segments, 2018 15th European Radar Conference (EuRAD), Madrid, pp. 115–117 (2018). doi: 10.23919/EuRAD.2018.8546559.
11. M. Demming et al., Materialanalyse mit SAMMI – Anwendungen und Möglichkeiten, DGZfP-Jahrestagung 2013, Dresden, Poster 28.
12. https://www.rohde-schwarz.com/us/product/qps-productstartpage_63493-332676.html?change_c=true.
13. B. Baccouche, P. Agostini, S. Mohammadzadeh, M. Kahl, C. Weisenstein, J. Jonuscheit, A. Keil, T. Löffler, W. Sauer-Greff, R. Urbansky, P. Haring Bolivar, and F. Friederich, Three-Dimensional Terahertz Imaging With Sparse Multistatic Line Arrays, *IEEE Journal of Selected Topics in Quantum Electronics* 23 (2017).
14. S. Kueppers, S. Wang, H. Cetinkaya, R. Herschel, and N. Pohl, Imaging Characteristics of a Highly Integrated MillimeterWave MIMO Radar, 2018 19th International Radar Symposium (IRS), Bonn, pp. 1–10 (2018). doi: 10.23919/IRS.2018.8448247.
15. J. Jonuscheit, Zerstörungsfreie Analyse – Schichtdicken von Mehrschichtsystemen online messen, *QZ Jahrgang* 59 (2014).
16. <https://www.hubner-photonics.com/products/terahertz-technology/terahertz-spectrometers/t-cognition/>.

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