NON-DESTRUCTIVE TESTING WITH MICRO- AND MM-WAVES - WHERE WE ARE - WHERE WE GO

G. Dobmann, I. Altpeter, C. Sklarczyk and R. Pinchuk

ABSTRACT

Test methods based on microwaves are well suited to characterize mainly electrically non-conducting materials and to detect and image defects in non-destructive and in many cases in contactless way. While in the past the often complicated and expensive microwave equipment prevented the widespread application of microwave methods this situation is now changing due to the increasing availability of low-cost high integrated microwave components. Microwave testing has found an important application in the field of security, e.g. to detect and image dangerous objects hidden under clothes. The principles of this technique can be applied in the domain of joining (e.g. welding of plastics or gluing plastic to plastic) for contactless detection of defects under cover layers.

IIW-Thesaurus keywords: Imaging; Microwaves; Nondestructive testing; Quality assurance.

1 Introduction

Electromagnetic waves covering the wavelength range from decimetre down to millimetre (in vacuum) corresponding to frequencies from 0.3 GHz up to 300 GHz (according to the most often given definition) are called microwaves. Millimetre-waves (mm-waves) as part of the microwaves are situated in the range from 30 GHz to 300 GHz. The fact that these waves can penetrate electrically non-conductive materials can be used in non-destructive testing (NDT) of paper, wood, ceramics, concrete, polymeric materials and fibre composites too, mainly when the fibres involved are non-conductive. As long as humidity does not play an important role the wave can also penetrate clothing to a certain amount which in the last years made the waves also popular for detecting concealed weapons or explosives in security applications.

Since the 1950's there are many activities in the field of microwave NDT but the attractiveness of this method is still limited owing to the sometimes complicated measurement and evaluation methods and in many cases the high price of microwave equipment. This situation is changing now where high integrated low-priced sensors and components, e.g. semiconductor generators, become more and more available. The application spectrum of microwave NDT is increasingly forwarded by the radar and telecommunication technology with its high technological level [1, 2].

This contribution describes non-destructive applications of the microwave method owing to the basic physical interaction of these waves with objects for their detection and characterization based on phenomena like reflection and scattering similar to the propagation of ultrasound in solid state materials. The physical basics are given in [3] in more detail. Practical examples are given of profiling of humidity in porous material and monitoring injection moulding of polymers. In the field of joining and welding, microwave methods have been applied to control the arc welding process, especially to determine the distance and geometry of the weld seam and to detect cracks in welds [4, 5]. Another example is the non-destructive quality control of joining an in-liner into a plastic wastewater pipe with the help of microwaves (see 3.1.2).

Special emphasis is laid in the security domain on the imaging of objects concealed under clothing and the problem to quickly but reliably detect weapons and explosives by scanning persons and using imaging algorithms like SAFT (synthetic aperture focusing technique) and pattern recognition procedures. Especially for characterizing and identifying concealed objects, e.g. explosive materials, imaging them by evaluating the interaction of micro- and mm-waves with the explosive is not sufficient. Here a multi-sensor concept is required, which integrates both microwave imaging and infrared spectroscopic application. All of the data have to be combined by data fusion algorithms in one image for evaluation.

The investigations described in the following chapters have been performed in the wavelength range between about 30 cm and 3 mm in vacuum or air (frequency domain between 1 GHz and 100 GHz) according to the available equipment of IZFP.

Doc. IIW-2172, recommended for publication by Commission V "Quality Control and Quality Assurance of Welded Products."

Table 1 – Microwaves and Terahertz waves

Indication	Metrical indication	Wavelength	Frequency
Microwaves	Decimetre waves (ultra high frequency UHF)	1 m to 10 cm	300 MHz to 3 GHz
	Centimetre waves (super high frequency SHF)	10 cm to 1 cm	3 GHz to 30 GHz
	Millimetre waves (extreme high frequency EHF)	1 cm to 1 mm	30 GHz to 300 GHz
Terahertz waves	Decimillimetre (sub-millimetre) waves	1 mm to 0.1 mm	300 GHz to 3 THz

Table 1 documents one part of the spectrum of electromagnetic waves. The microwave spectrum covers the wavelength range from 1 m (0.3 GHz) to 1 mm (300 GHz = 0.3 THz) and is thus lying above the highest frequency of the radio waves used for broadcasting (maximum frequency 108 MHz corresponding to a wavelength of 2.8 m for vacuum or air as propagation medium). The frequencies for cell phones (0.4-1.9 GHz) are lying within the decimetre waves. Ground penetrating radars (GPR) are applied in investigating soil in geology and archaeology or concrete structures and brick walls in civil engineering of infrastructure. Applications are to detect large stone hindrances when tunnels are drilled (< 500 MHz) or to image ducts of steel tendons in reinforced concrete (< 5 GHz) [6]. In the military domain radars are applied to look through walls in order to see human beings behind. For distance control of cars radar sensors in the frequency range of about 24 to 77 GHz are on the market. The spectral range which became very interesting for research in the last 10-20 years because sources for excitation (e.g. Femtosecond-Laser, quantum cascade laser) became available, is in the wavelength interval 300 μm (1 THz) to 10 μm (30 THz) followed by the infrared spectrum.

Obeying the physical principles of wave propagation the wavelength is the parameter determining spatial resolution to separate two neighboured objects. The best resolution to be attained for standoff applications amounts to about a half wavelength.

In the near-field, however, much higher resolutions can be achieved. Synthetic Aperture Radars (SAR) [7] applied by satellites or air planes work at frequencies from a few GHz to some tens of GHz. For detecting hidden weapons passive mm-wave imaging is applied at about 94 GHz [8] whereas Terahertz-imaging [9, 10] takes place with waves in the 1-3.5 THz range. Higher frequencies are not appropriate because of the strong influence of humidity resulting in high damping of the waves.

2 Basics and experimental set-up of Fraunhofer IZFP

Fraunhofer IZFP has built an experimental set-up used for microwave applications in the area of materials characterization and imaging (Figure 1).

The equipment is based on the vector network analyser model HP 8510B and has been used in the higher frequency range 75-100 GHz in order to achieve a high spatial resolution. The instrument generates microwaves in continuous and narrow-banded way using a synthesizer where the frequencies are swept in a stepped way. After reception in reflection and/or through transmission – if the material is transparent for microwaves – a pulse is synthesized by inverse Fourier transform into the time domain so that pulse height (amplitude) and phase resp. time of flight can be determined similarly to a real pulse radar. A wide field of horn antennas is available and can be applied corresponding to the respective testing task.

In the case of the 94 GHz module (Figure 2), developed by Fraunhofer IAF (Institute of Applied Solid State Physics) [11], it is a miniaturized Frequency Modulated Continuous-Wave (FMCW) radar which integrates all microwave-components on a single chip with a size of about 2 mm x 3 mm (MMIC: Monolithic Millimetre-wave Integrated Circuit). The FMCW-radar has a centre frequency and bandwidth of about 94 GHz (W-band) resp. 5 GHz. In order to investigate the possibilities of microwave imaging [12], IZFP has developed an imaging system similar to that shown in Figure 1. However, here the FMCW radar replaces the expensive and cumbersome network analyser. By mixing the transmitted signal with the received signal a low frequency signal (intermediate frequency signal IF) is generated, which can be captured by a conventional digitizer (A/D-) board integrated in a PC. By an inverse Fourier transform, also here, a pulse-

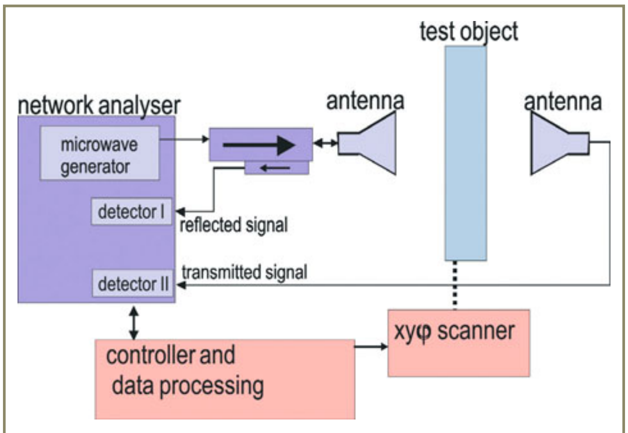


Figure 1 – Network analyser system developed at Fraunhofer IZFP

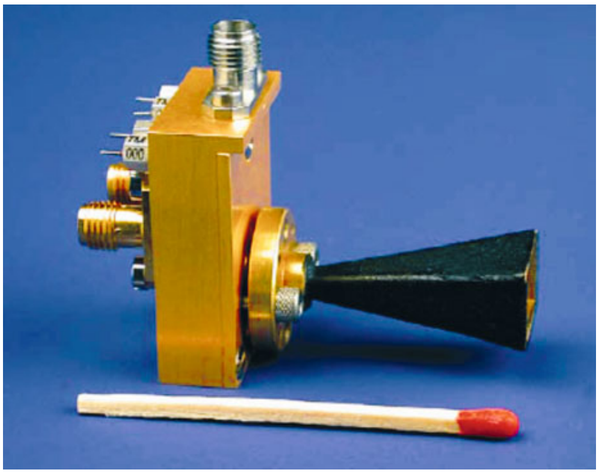


Figure 2 – 94 GHz frequency modulated continuous wave (FMCW) radar developed at Fraunhofer IAF (photo: IAF)

like signal is generated, which can be processed in an analogous way to real pulses like in conventional radar technique providing the third dimension in the radar image, i.e. the range information.

Some additional measurements have been performed with a commercial low-cost K-band FMCW-radar from InnoSent with a centre frequency of 24.1 GHz and a maximum tuning range of 200 MHz (instead of the 94 GHz FMCW radar) over a distance of about 60 cm. The patch-antenna has been integrated in the radar sensor.

Mechanical scanning was performed by two orthogonal linear scanning axes forming a two-dimensional pixel space or by rotation scans forming a cylindrical geometry. Moving of the scanning axes can be done stepwise with constant scan steps or – to save time – continuously. Most of the scans have been carried out with one single antenna for transmission and reception (monostatic mode).

3 Applications of microwaves to NDT

3.1 Materials characterization and process integration by microwave and millimetre NDT

3.1.1 Detection of cavities in gas-assisted injection moulding process

Parts and components made from thermoplastics like polycarbonates are produced by injection moulding processes. In gas-assisted moulding process hollow parts are produced (Figure 3). Here the heated, hence liquid plastic material is injected in the mould and by pressing inert gas in it, the hollow part is formed. The gas helps to preserve the shape of the part and some plastic material is saved.

Depending on the processing time the development of the gas bubble is an essential process parameter to control the wall thickness. Therefore a microwave window was built in the mould through which the process can be monitored continuously in time. Figure 4 shows how the microwave signal can be used to characterize online the process development. If by failure of the injection moulding process no bubble is generated, this can be detected by a missing jump in the voltage curve (red curve).

3.1.2 Characterization of polymeric coatings on steel substrate

A steel plate has been coated with a polymeric layer (some type of rubber). Several sections of this layer have been subjected to different grades of ageing by exposing it to increasing temperature and humidity. Because of the high electrical conductivity the metallic material acts like a mirror concerning microwave reflection. The layer is partly transparent to microwaves and influences the amplitude

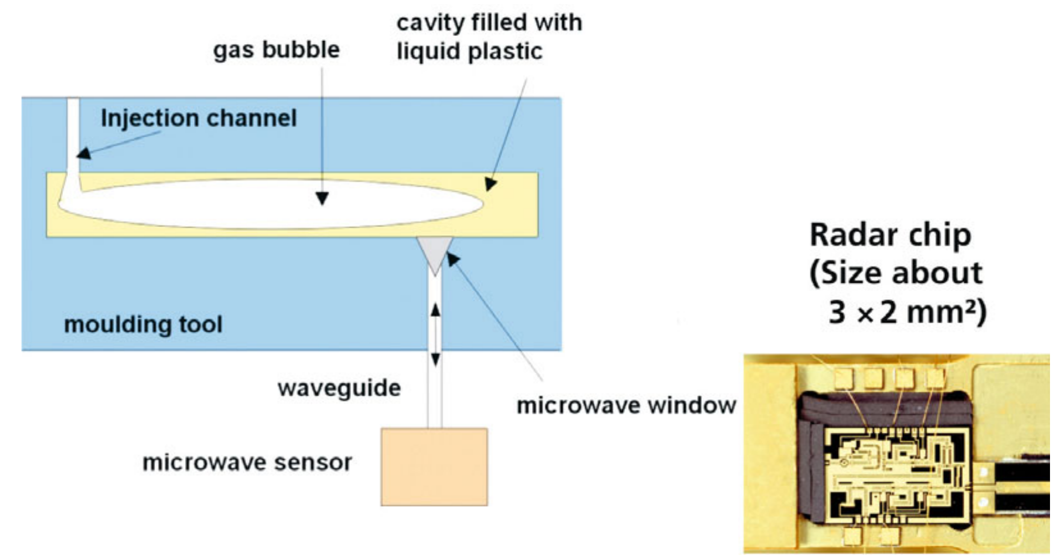


Figure 3 – Monitoring of injection moulding process of hollow parts using the 94 GHz FMCW module

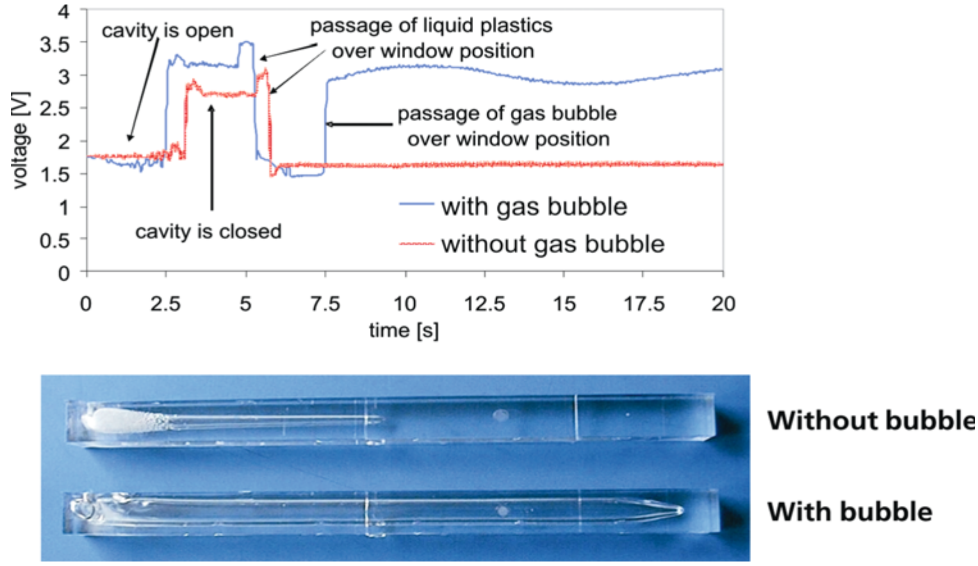
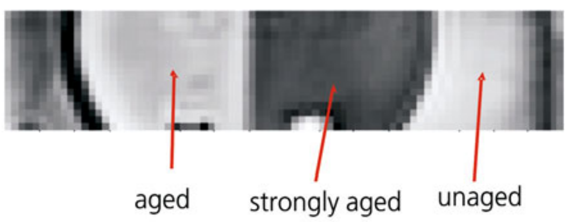


Figure 4 – Online monitoring of injection moulding process of polycarbonates, amplitude development with time

and phase of the transmitted microwaves depending on the dielectric layer properties which on their part depend on the ageing condition and thickness change of the layer. The received microwave amplitude is the outcome of the interference of the microwaves reflected at the interface air-rubber and at the interface rubber-steel. Figures 5 and 6 document such results. Both results were obtained in the near-field of the 94 GHz module where an open waveguide (2.4 × 1.3 mm^2 aperture) has been used as an antenna. In that case wave penetration into the layer is low and surface properties are pronouncedly visualized.

As can be seen in Figure 5 the combination of thickness change and change in the material properties reveals no difference in the amplitudes of the unaged and the moderately aged section (white: high amplitude, black: low amplitude). However, there is a big difference for the strongly aged section compared to the other sections.

Repair of wastewater pipes made from plastics is performed by in-liners which are joined to the pipe in that area which contains the flaw or other defect. To assess the quality of the repair in a non-destructive and contactless way, microwave methods can be used. By scanning the inner surface of the in-liner with the 94 GHz-FMCW-module in a distance of some few cm and by evaluating the phase of the received microwave signal, it was possible to determine the surface profile and to scale it in absolute units. This is shown in Figure 6 where an optical distance sensor (laser triangulation) has been used for comparison. The dotted lines in the optical photo (left Figure) representing the heights can be found in the microwave image (dark spots in right Figure), too. One cutting line is shown in Figure 7 where the microwave and the optical results can be compared in absolute units. The



Area scan of a steel specimen coated with rubber, 94 GHz-radar-module, antenna distance 2 cm, scan area 237 mm x 48 mm, amplitude image

Figure 5 – Ageing characterization of rubber

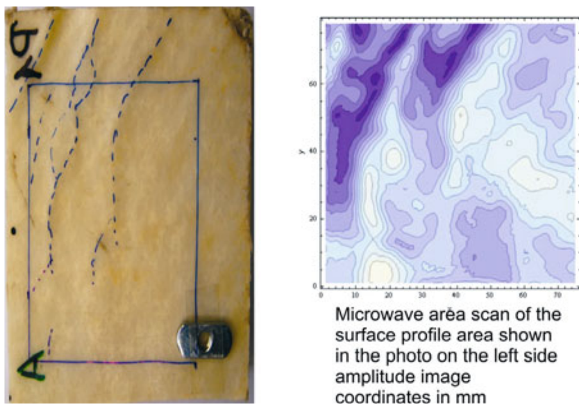


Figure 6 – In-liner-inspection in pipes with 94 GHz

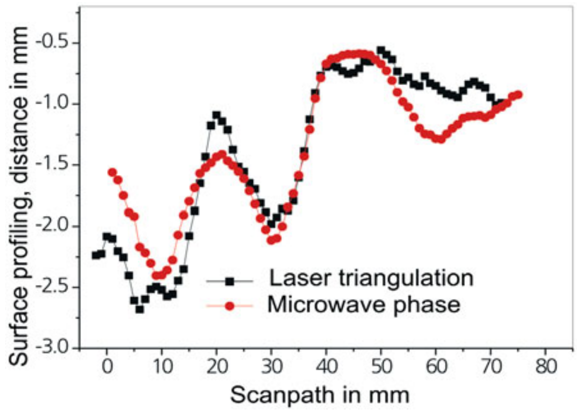


Figure 7 – Surface profiling, laser triangulation compared with microwave phase

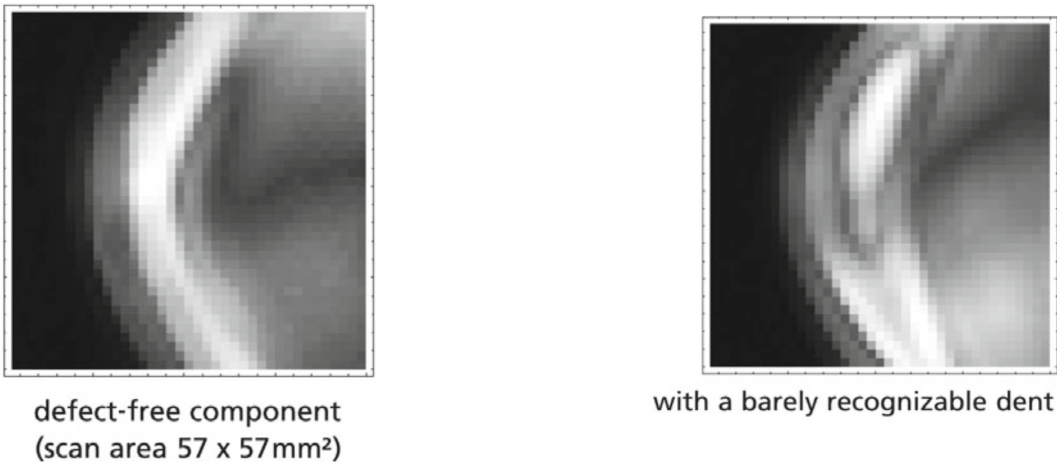


Figure 8 – Detection of an unacceptable dent in a ceramic plate (right Figure)

differences between both results are due to the different beam diameter which in the microwave case is large compared with the laser beam, i.e. the microwave phase profile is a convolution of the real profile and the beam aperture. It is thinkable to develop a pipe scraper or pig based on microwaves for inspecting the in-liner from the interior of the pipe where at this point not only the inner surface but the whole wall of the pipe is scanned.

3.1.3 Ceramic inspection

Ceramic parts and components, e.g. plates, are produced by slip-casting followed by drying and sintering. In order to avoid the expensive energy consumption obviously it is of advantage to inspect the components before sintering in order to detect unacceptable voids or dents. Figure 8 documents an example where the irregularity is clearly revealed. The scanning was performed with 94 GHz but the beam was focused by an elliptical mirror.

3.1.4 Glass-fibre reinforced epoxy laminate

The car supplying industry works with the objective to replace leaf springs made from steel by glass-fibre laminates with a higher specific strength. However, irregularities produced by lamination have to be detected and it is difficult to inspect the material by NDT like ultrasonic testing (UT), because of anisotropy and inhomogeneity. Microwaves have the potential to be a reliable and cost-effective alternative to UT and inspection has the advantage to be performed without coupling. Figure 9 compares the optical image with the microwave image showing similar defect structures. In practice the defects can occur in deeper layers where the optical inspection is no more possible or the area to be inspected is covered by protective optically non-transparent layers. In this case the microwave inspection is still feasible due to its bigger penetration depth.

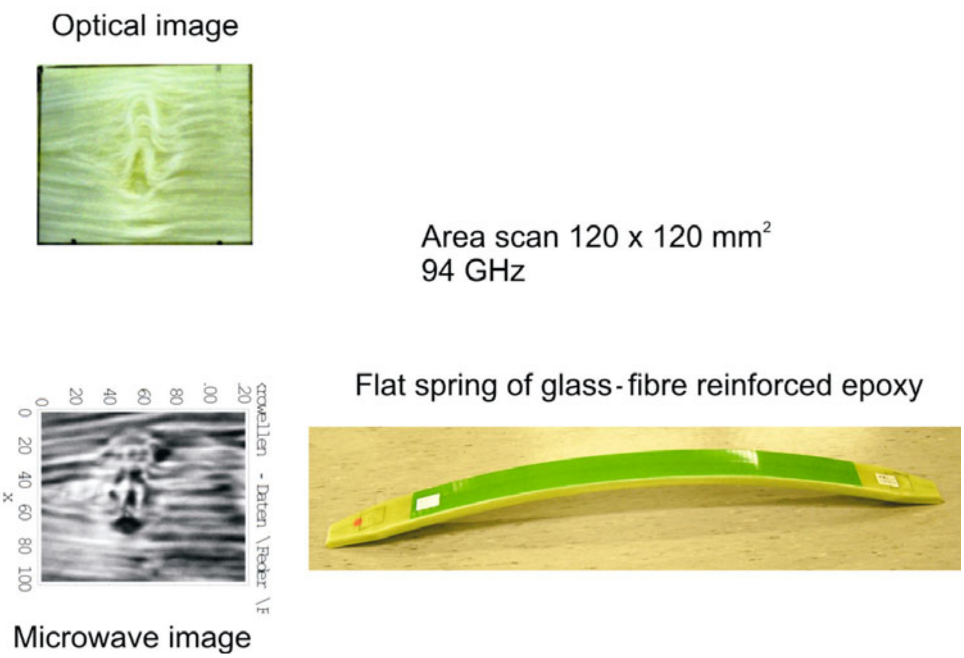


Figure 9 – Detection of fibre inhomogeneities in a leaf spring made from glass-fibre reinforced laminates

3.2 Security application

Security applications are an important field in the world of microwave-NDT since they represent the front of development of this technique with respect to both hardware (e.g. miniaturization) and software (evaluation algorithms). On their part these applications stimulate the other fields. In times of growing international terrorism and crime the detection of weapons, explosives, drugs and other forbidden or illegal objects worn by humans and concealed under their clothes becomes more and more important. Metal detectors are suited to detect metallic weapons but are unable to detect non-metallic objects. Moreover, they are unable to detect these objects over distances of several metres and more. X-ray backscattering body scanners generate images with high resolution including all suspicious objects but are also unable to handle larger distances and are often not accepted to be applied to human beings due to the low but nevertheless existing radiation exposure.

So the only known method to detect objects concealed under clothes which is innocuous to humans is based on high-frequency electromagnetic waves in the centimetre-, millimetre- and sub-millimetre ranges. There exist a few microwave-based systems which are used for the access control of critical areas (e.g. airports) like the active system ProVision from L3 Communications (developed by Battelle-PNNL-Institute [13]) or the passive system Tadar from Smiths (developed by Farran). These systems are designed as portals and therefore do not work at larger standoff distances. These are covered by several systems (e.g. Brijot Imaging Systems, View Systems, ThruVision, Qinetiq, … [14, 15]) but the images suffer from a loss of object resolution.

Apart from access control at airports, seaports, railway stations, governmental buildings etc. police authorities are investigating compact and mobile imaging systems working in real-time over distances of several tens of metres to prevent criminal acts from terrorists, criminals or armed demonstrators.

Microwaves are reflected in different manner by the human skin and by external objects worn by man [16]. Clothes are partly transparent to microwaves where the degree of transparency depends on the type of clothes and the microwave frequency. Microwaves are safe to humans and innocuous to objects since the radiation exposure is less than that from mobile phones and especially no ionizing radiation is generated. Microwave methods can work in a non-contact way even over larger distances and can be used in a very quick manner since the microwaves propagate at the velocity of light.

As documented in section 3.1, with a single microwave transducer also two- or three-dimensional images of human beings can be produced by mechanical scanning. Since this procedure takes some time it can be shortened by using arrays of antennas or transducers. Thereby the mechanical system components become simpler. However the electronic components become more expensive. Here it should be emphasised that the object recognition is performed by its two- and three-dimensional shape and contour and its changed contrast and pattern compared to its surroundings.

A material identification due to spectroscopic features, mainly by material-specific absorption lines or bands, is not possible in the microwave domain. In the THz-domain it is principally feasible beyond about 0.7 THz. However, at that frequency the absorption of THz-waves by humidity in the air and by the attenuation and scattering in the clothes will severely impede spectroscopic methods.

3.2.1 Experimental investigations by Fraunhofer IZFP

Several objects like a metallic revolver, a ceramic knife without any metallic component, a plastic plate or a soap (to simulate explosive agents) concealed under clothes or non-concealed have been scanned with the FMCW-radar (Figure 10). To simulate the influence of the human skin these objects were placed on a wet towel.

A raw evaluation of the signal amplitudes as a function of the scanner position only gives some indication of the existence of an external object but does not reveal its nature [Figure 11 a)]. By applying the Synthetic Aperture Techniques which have been developed since the 1950's in the radar (SAR, **S**ynthetic **A**perture **R**adar) [7] and ultrasound (SAFT, **S**ynthetic **A**perture **F**ocusing **T**echnique) domains the lateral resolution can be essentially increased. The lateral or cross resolution R_L for radar with synthetic aperture is given by [17, 18] according to Equation (1):

$$R_L = \max\left(\frac{\lambda_{min}}{2}, \frac{d_a}{2}\right) \quad (1)$$

where

λ_{min} is the lowest frequency wavelength in the pulse and

d_a is the real antenna aperture .

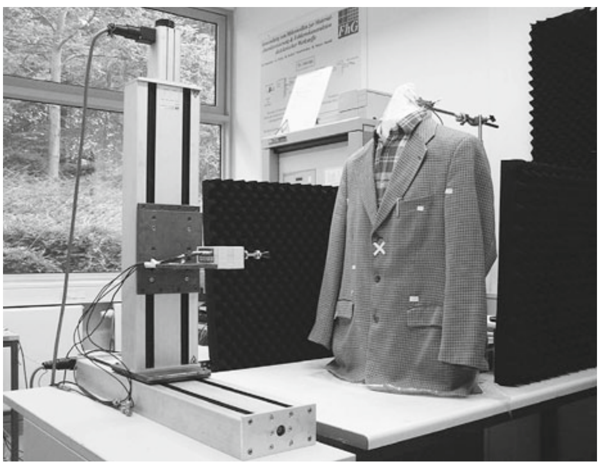


Figure 10 – Mechanical two-axis-scan of objects concealed under a jacket with FMCW-radar

Axial resolution R_A, however, is not enhanced by the synthetic aperture technique and is determined only by the frequency bandwidth:

$$R_A = \frac{c}{2B} \quad (2),$$

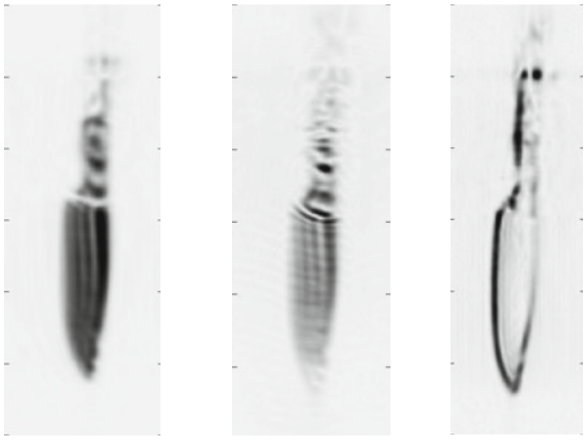
where

c is the velocity of light and

B is the pulse bandwidth.

The conventional Synthetic Aperture technique in the time domain is very time-consuming even on modern PC's. But with the three-dimensional Fourier-Transform (FT) technique the evaluation time can be shortened by two or three orders in magnitude while providing the same results [Figure 11 b)]. The ceramic knife from Figure 11 a) can now be recognized very clearly, especially its blade. If the knife is concealed behind some clothes the reconstruction result degrades in dependence on the type of clothes and some components (zipper, buttons, pleats) belonging to it. In Figure 11 c) a zipper made of plastics acts as a scattering centre and disturbs the reconstructed image. But nevertheless the knife can be recognized.

If the knife is rotated about its longitudinal axis the bright indication from the blade gradually disappears [Figures 12 a) and b)] but for incidence angles > 10° the blade edge gains in importance as scattering centre [Figure 12 c)] and the contour of the knife can now be identified in a better way than in Figure 12 b). It is important that the object be illuminated from different angles in order to produce an image showing the object as complete as possible and to avoid glory effects which would impede object recognition.



a) Normal incidence, displayed area 100 × 300 mm²

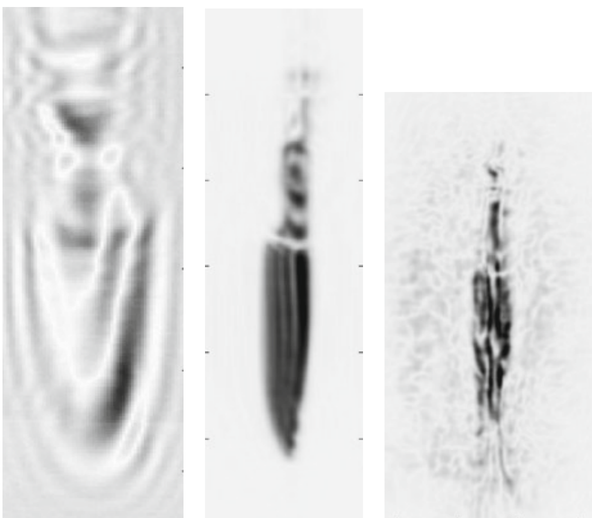
b) Analogue to Figure 12 a), but incidence angle 10°

c) Analogue to Figure 12 a), but incidence angle 15°

Figure 12 – Reconstruction of ceramic knife with 3D-FT-SAFT

Organic objects give the lowest contrast in comparison with the surrounding since their reflectivity is the lowest. Even though the clothes and the zipper produce some apparent attenuation and disturbances, the images of the soap and the plastic plate clearly show that there are objects whose nature should be investigated in more detail in case of real application (Figure 13).

Application of synthetic aperture is possible with the commercial 24.1 GHz-sensor, too. In Figure 14 the object (revolver at 60 cm distance) can be recognized, however, the angular resolution resp. lateral resolution (perpendicular to the main direction of the radar ray) is worse than the

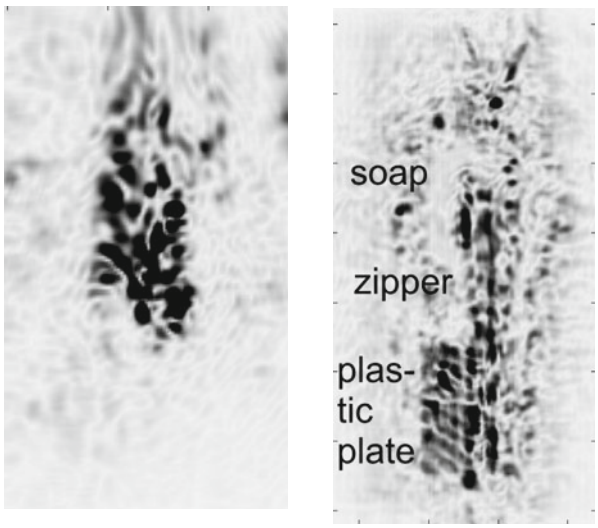


a) Knife, non-concealed, raw amplitude data, displayed area 92 × 263 mm²

b) Knife, non-concealed, 3D-FT-SAFT, displayed area 100 × 300 mm²

c) Knife, concealed under waistcoat with zipper, 3D-FT-SAFT, displayed area 180 × 360 mm²

Figure 11 – 94 GHz-scan of a ceramic knife, antenna-object-distance 40 cm



The zipper acts as a disturbing scattering object.

a) Oval soap ($\varepsilon_r = 2.8$, length 9.5 cm) in breast pocket of a flannel shirt (reconstructed area: 14.3 × 25.1 cm²)

b) Soap and rectangular plastics plate, concealed behind waistcoat (reconstructed area 19 × 38 cm²);

Figure 13 – Detection of organic objects (simulation of explosive agents) reconstructed with 3D-FT-SAFT

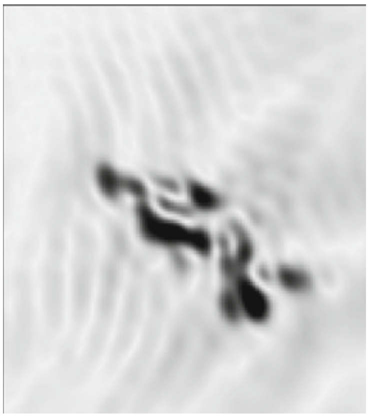


Figure 14 – Reconstruction of a non-concealed revolver at a distance of 60 cm with a low-cost radar sensor (centre frequency 24.1 GHz)

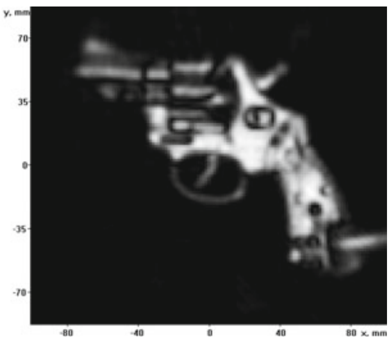
image gained with the 94 GHz-radar sensor. According to Equation (1) the main limitation of lateral resolution is the size of the antenna whose aperture is about 5 cm. The aperture of the 94 GHz-antenna is much less (about 1 cm), resulting in a much better resolution. By optimizing the antenna geometry a better resolution could be achieved at 24 GHz, too. However, a better resolution than about half the wavelength (ca. 6 mm at 24 GHz) cannot be achieved.

3.2.2 Optimization of the number of scan steps

According to the Nyquist-Shannon-theorem it is necessary to perform scan steps with a length of half the wavelength or less to obtain artefact-free images. Drawing on the example of a revolver scan the effect of the step width can be illustrated. The 94 GHz-scan of a revolver over a distance of circa 20 cm with a step width of 1.5 mm (a little bit less than half the wavelength) gives a clear image with a good lateral resolution [Figure 15 a), note trigger and trigger guard]. If every second scan point is omitted, resulting in a scan step of 3 mm, the resolution is still good [Figure 15 b)]. If an interpolation is performed no difference can be found between the scan with 1.5 mm and 3 mm step widths [Figure 15 c)]. However, if only every fourth scan point is taken corresponding to a step width of 6 mm the reconstruction fails completely [Figure 15 d)]. After interpolation to 1.5 mm step width the revolver is again recognizable, however with some loss in resolution [Figure 15 e)].

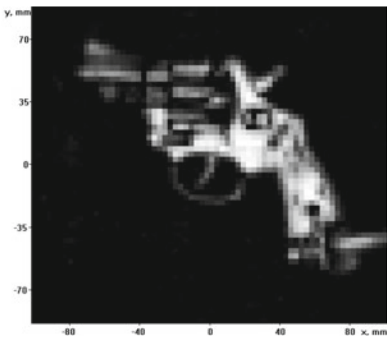
3.2.3 Principle of Sampling Phased Array

These results show that, in case of mechanical scanning of the object, a large number of antenna positions is necessary to get a good image quality in monostatic or quasi-bistatic (transmitter and receiver antenna in close neighbourhood) mode. If no mechanical scanning is performed, a large number of antennas and measuring channels are required. However, in the second case the imaging system will be very complex and expensive. In the first case the scanning process with only one antenna will last for a long time impeding any real-time capability. To overcome the need for a huge number of antennas the principle of Sampling Phased Array (SPA) developed in the field of ultrasound testing can be applied [19]. Here within an

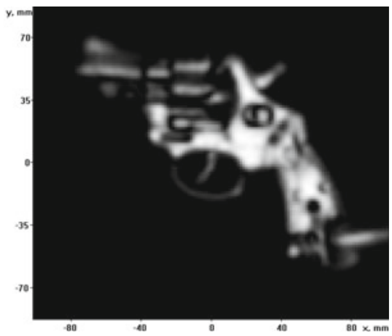


Non-concealed revolver.

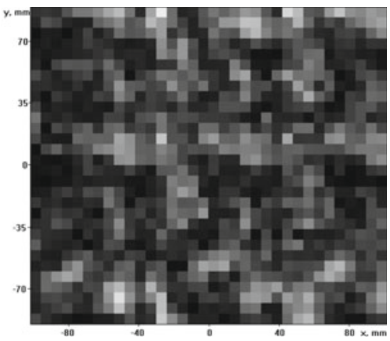
a) Step width 1.5 mm (≈ half wavelength)



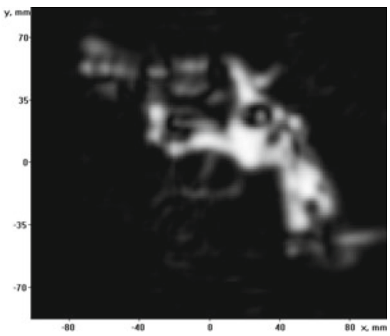
b) Step width 3 mm



c) Step width 3 mm, interpolated to 1.5 mm



d) Step width 6 mm



e) Step width 6 mm, interpolated to 1.5 mm

Figure 15 – Effect of step width on reconstruction quality using synthetic aperture

antenna array the first antenna generates the transmitting impulses while all others receive the waves reflected or scattered at the object. In the next test cycle the next antenna is in transmitting mode and the others are in receiving mode thus filling up a data matrix containing the data from all transmitter-receiver pairs in a very efficient way. Thus, a sparse array can be formed where in the most favourable case only about $(2N)^{1/2}$ antennas are needed, while in the conventional case (with fully-populated array) N antennas are required to generate a high-resolution microwave image. Thus, especially if a high-resolution image is needed the savings in the number of antennas are considerable. Presently this approach is tested experimentally in the mm-wave range at Fraunhofer IZFP.

4 Conclusions and future developments

The experimental results show that microwaves have a high potential both for material characterization and NDT process integration and detecting objects concealed under clothes with microwaves in the mm- and cm-wave regions in a standoff manner. The applications of microwave methods in the non-destructive domain are widespread and concentrate on non-metallic objects. This is true in the field of joining and welding, too. In some cases metallic objects can nevertheless be inspected if surface deviations from nominal values and surface defects are investigated. It is to be expected that the diffusion of microwave testing methods will increase due to the enhanced availability of low-cost high-integrated components (e.g. MMIC's) and computer based evaluation methods partly forwarded by the progresses in the radar and telecommunications technology.

In the field of imaging the best results are obtained with highly reflecting objects made from metal or ceramics. Principally there is no theoretical limit in distance between the antenna and the object. However, to get a good resolution at high standoff distances the aperture or/and the centre frequency have to be increased. A large aperture size may result in an impracticable size of the imaging system while a high frequency of several 100 GHz may result in an excessive attenuation and scattering of the electromagnetic waves. Here a favourable compromise concerning aperture size and centre frequency has to be found. SAR and SAFT algorithms are the reliable tools to refocus the raw data and to enhance the lateral resolution. However, in order to recognize objects with low false alarm rate, pattern recognition based on artificial intelligence procedures should be adopted. In the field of body scanners for security applications many sets of training data have to be acquired on different relevant objects (weapons, explosives, harmless items) under a broad diversity of aspect angles. The patterns of these objects must be extracted from the data and stored in a data bank. By comparing these patterns with those of the unknown object, this object has to be identified and assessed with regard to its dangerousness. Insofar by use of redundancy and diversity the information content can be enhanced. One measure is, for instance, the measurement with different wave polarizations (horizontal, vertical, circular) and to apply SAR and SAFT algorithms which rely also on mode conversion of energy from one into the other polarization direction. A tremendous enhancement of the security application will be obtained if the SAR/SAFT procedure can be performed online. Implementation of the SPA principle will help to achieve this objective. Fraunhofer IZFP is working on these developments. Further enhancement of the detection approaches will be by combining micro- and millimetre wave scanning with other sensor principles, for instance infrared absorption spectroscopy (IRAS), and by data fusion of the information.

The above described principles that have been applied in the field of detection of hidden objects can also be used in detecting and imaging defects like cracks, inclusions, voids or delaminations in joined and welded structures hidden by cover layers. These should at least partly be made of materials with lower electrical conductivity (plastics, glass-fibre reinforced composites, ceramics, …) which ensure a partial transparency to microwaves. If the testing procedure cannot be carried out in near-field but in standoff manner, the lateral resolution can be clearly enhanced by the SAR/SAFT methods. If required, the axial resolution can be enhanced by increasing the bandwidth of used microwaves.

References

[1] Zoughi R. and Kharkovsky S.: Microwave and millimetre wave sensors for crack detection, Fatigue & Fracture of Engineering Materials & Structures, 2008, vol. 31, no. 8, pp. 695-713.

[2] Menzel W.: 50 years of millimeter-waves: A journey of development, Microwave Journal, 2008, vol. 51, no. 8, pp. 28-42.

[3] Ida N.: Microwave NDT, Developments in Electromagnetic theory and applications – vol. 10, Ed. G.F. Roach, Kluwer Academic Publishers, 1992.

[4] Kohler T.: Ein Beitrag zum Einsatz von Mikrowellensensoren im industriellen Umfeld am Beispiel der Schweißtechnik, A contribution for usage of microwave sensors in the industrial environment given on the example of welding technology, Thesis Univ. Chemnitz, Germany, 2003 (in German).

[5] Kerouedan J., Queffelec P., Talbot P. and De Blasi S.: Detection of surface defects in metallic materials using evanescent microwaves, ECNDT 2006, Berlin, Sept. 25-29, 2006, Tu.1.8.5.

[6] Daniels D.: Ground penetrating radar, 2nd edition, The Institution of Electrical Engineers, 2004.

[7] Sandia National Laboratories: What is SAR?, http://www.sandia.gov/radar/whatis.html.

[8] Blankson I.M.: Passive mm-wave Imaging with Super resolution, http://www.ima.umn.edu/talks/workshops/5-4-6.2001/blankson/blankson.pdf.

[9] TeraView: http://www.teraview.com/terahertz/.

[10] Theuer M., Torosyan G., Ellrich F., Jonuscheit J. and Beigang R.: Terahertz imaging in industrial applications, Technisches Messen 75, 2008 (in German).

[11] Tessmann A., Kudszus S., Feltgen T., Riessle M., Sklarczyk C. and Haydl W.H.: Compact single-chip W-Band FMCW radar modules for commercial high-resolution sensor applications, IEEE Transactions on Microwave Theory and Techniques, 2002, vol. 50, no. 12, pp. 2995-3001.

[12] Klausing K. and Holpp W.: Radar mit realer und synthetischer Apertur, Radar with real and synthetic aperture, Oldenbourg, 2000 (in German).

[13] Keller P.E., McMakin D.L., Hall T.E. and Sheen D.M.: Use of a neural network to identify man-made structures in millimeter – wave images for security screening applications, International Joint Conference on Neural Networks, Vancouver, Canada, 2006, pp. 2009-2014.

[14] Appleby R.: Passive millimetre wave imaging and security, European Radar Conference, Amsterdam, Netherlands, 2004, pp. 275–278.

[15] Appleby R. and Wallace H.B.: Standoff detection of weapons and contraband in the 100 GHz to 1 THz Region, IEEE Transactions on Antennas and Propagation, 2007, vol. 55, no. 11, pp. 2044-2056.

[16] Griffiths H.D. and Baker C.J.: Radar imaging for combatting terrorism, imaging for detection and identification, Springer, 2006, pp. 29-48.

[17] Sklarczyk C., Surkov A., Langenberg K.-J. and Mayer K.: 94 GHz radar sensor for process control and imaging, ENCDT 2006, We.2.8.4.

[18] Langenberg K. J., Brandfaß M., Hannemann R., Hofmann Ch., Kaczorowski T., Kostka J., Marklein R., Mayer K. and Pitsch A.: Inverse scattering with acoustic, electromagnetic, and elastic waves as applied in nondestructive testing, In A. Wirgin (ed.), Wavefield Inversion, Springer-Verlag Wien, 1999, pp. 59-118.

[19] Bulavinov A., Dalichow M.H., Kröning M., Kurz J.H., Walte F. and Reddy K.M.: Quantitative ultrasonic testing of pressurized components using Sampling Phased Array, NDE 2006, Seminar on Non-Destructive Testing & International Exhibition, CD-ROM: NDE in Knowledge Society, Hitex Exhibition Center, Hyderabad, India, December 7-9, 2006, Hyderabad: Indian Society for Non-Destructive Testing, 2006, S.TP 130.

About the authors

Dr. Gerd DOBMANN (gerd.dobmann@izfp.fraunhofer.de), Dr.-Ing. Iris ALTPETER (iris.altpeter@izfp.fraunhofer.de), Dr. Christoph SKLARCZYK (christoph.sklarczyk@izfp.fraunhofer.de) and Dr.-Ing. Roman PINCHUK (roman.pinchuk@izfp.fraunhofer.de) are all with FRAUNHOFER IZFP, Saarbrücken (Germany).