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

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1. Introduction

Electromagnetic waves covering the wavelength range from decimetre down to millimetre (in vacuum, frequencies from 300 MHz up to 300 GHz) are called micro- and mm-waves. As these waves can penetrate non-electrically-conductive materials in NDT they are especially suitable for testing of paper, wood, ceramics, concrete, polymeric materials and fibre composites too, mainly when the fibres involved are non-conductive. Insofar humidity plays not an important role the wave can penetrate also clothing to a certain amount which makes the waves in the last years also popular for detecting of concealed weapons or explosives in security applications.
The contribution describes 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. Practical examples are given to profiling of humidity in porous material and to monitor injection moulding of polymers. Special emphasis is laid on the imaging of concealed objects 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 the characterization of the explosive materials ask for a multi-sensor concept, based not alone on the micro and mm wave interaction but also on an infrared spectroscopic application where all of the data are combined by data fusion algorithms in one image for evaluation.

2. Basics and experimental set-up of Fraunhofer IZFP

Figure 1 documents the spectrum of electromagnetic waves which is available. It covers the radio waves used for broadcasting with wave length range of 300m (1MHz) down to 300mm (1GHz) when supposing vacuum as medium for propagation. Then the microwave spectrum follows covering the wave length range from 300mm (1GHz) to 300µm (1000GHz=1THz). The spectral range which became very interesting for research in the last years because sources for excitation became available is then in the wave length interval 300µm (1THz) to 10µm (30THz) followed by the infrared spectrum. In Figure 1 also applications of theses spectra are indicated. As by the physical principles of wave propagation the wave length is the parameter determining spatial resolution to separate two neighboured objects the size of the wavelength controls also the size of an object to be imaged by these types of waves.

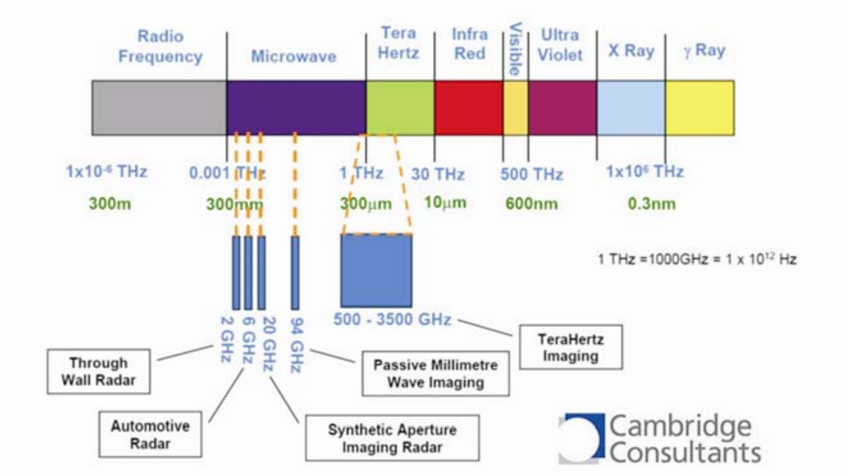


Figure 1. Electromagnetic spectrum

Ground penetrating radar (GPR) is 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 (< 500MHz) or to image ducts of steel tendons in reinforced concrete (< 5GHz) [1]. In military application radar is applied to look through walls in order to see human beings behind, for distance control of cars radar sensors in the frequency range of 6GHz are on the market. Synthetic Aperture Radar (SAR) [2] applied from satellites or air planes works round about 20GHz (15mm wave length). For the detection of hidden weapons passive mm-wave imaging is applied at 94 GHz [3] whereas Terahertz-imaging [4, 5] takes place with waves in the 1-3.5THz range. Higher frequencies are not appropriate because mainly the influence of humidity and high damping. In Table 1 a more detailed separation in micro waves and Terahertz waves is documented.

Table 1. Micro waves and Terahertz waves

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

The experimental set-up used for microwave applications in the Fraunhofer IZFP is documented in Figures 2. and 3.

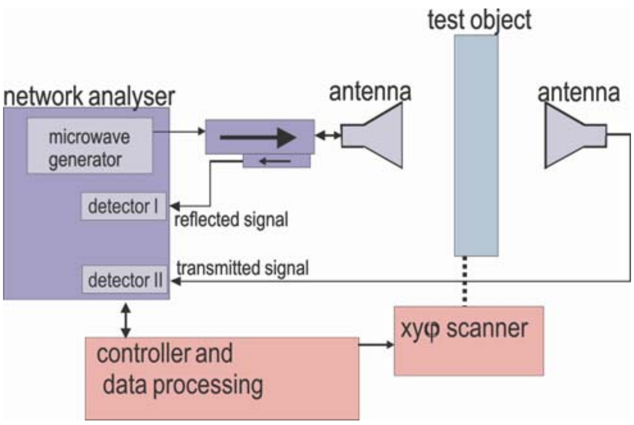


Figure 2. Network analyzer measurements

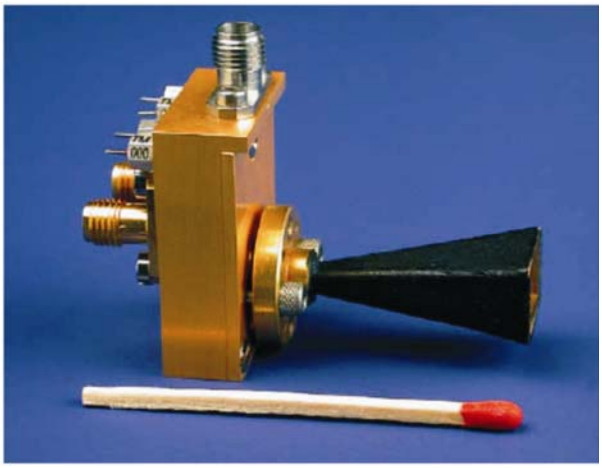


Figure 3. 94 GHz module

The equipment based on the network analyzer (Figure 2) model HP 8510B NWA has been used in the higher frequency range 75-100GHz in order to achieve a high spatial resolution. The instrument works with a synthesizer generator in between 15-20GHz followed by frequency multipliers in the frequency domain. A wide field of horn antenna is available. After narrow-banded reception in

reflection and/or through transmission –so far 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 can be determined.
In the case of the 94GHz module, developed by Fraunhofer IAF (Institute of Applied Solid State Physics) [6], it is a Frequency Modulated Continuous-Wave (FMCW) radar which integrates all microwave-components on a single chip with a size of about 2 mm × 3 mm (MMIC: Monolithic Millimetre-wave Integrated Circuit). This FMCW-radar, whose centre frequency and bandwidth is about 94 GHz (W-band) resp. 5 GHz, is part of an imaging system developed by IZFP to investigate the possibilities of microwave imaging [7]. By mixing the transceived 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-transformation, also here, a pulse-like signal is generated which can be processed in analogue way to real pulses like in conventional radar technique providing the third dimension in the radar image and giving the range information.
Some additional measurements have been performed with a commercial low-cost K-band FMCW-radar from InnoSent with a center frequency of 24.1 GHz and a maximum tuning range of 200 MHz 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 in step-wise manner with constant scan steps or – to save time – in continuous manner. Most of the scans have been carried out with one single antenna for transmission and reception (monostatic mode).

3. Applications

3.1 Materials Characterization and Process Integration by microwave and millimetre NDT

3.1.1 Detection of cavities in the injection moulding process

Thermoplastics like polycarbonates are injection moulded. So far hollow parts are produced (Figure 4) the heated and therefore liquid plastic material is injected in the mould and by pressing inert gas in it the hollow part is formed.

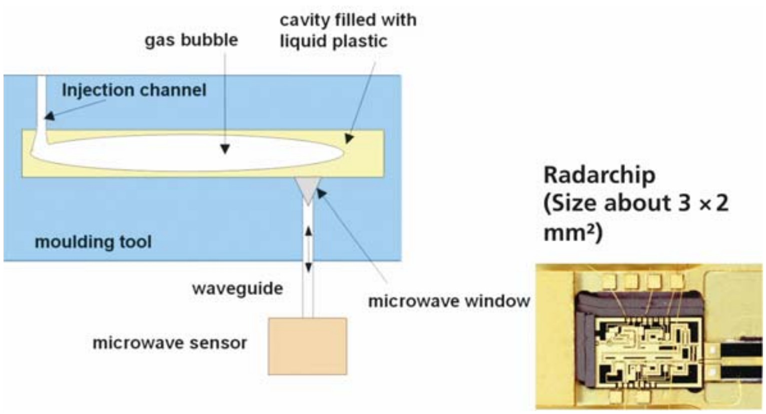


Figure 4. Injection moulding of hollow parts using the 94GHz FMCW module

As a function of the processing time the development of the gas bubble is an essential process parameter to control the wall thickness. Therefore a micro wave window was built in the mould through which continuously in time the process can be monitored. Figure 5 shows how the microwave signal can be used to characterize online the process development.

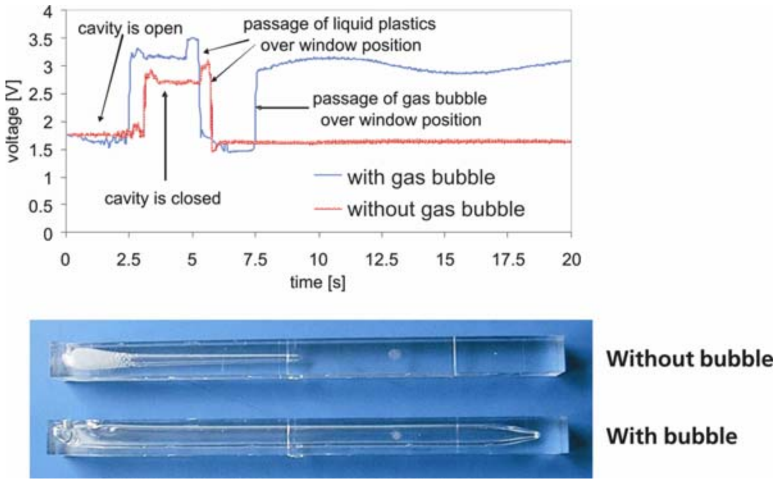
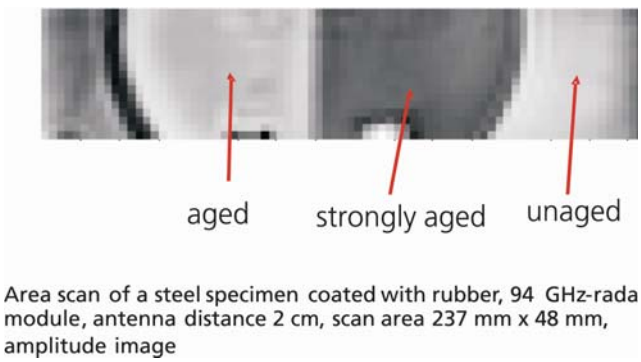


Figure 5. Online monitoring the injection moulding process of polycarbonates, amplitude development with time

3.1.2 Characterization of polymeric coatings on steel substrate

As metallic material, because of the high electrical conductivity, acts like a mirror concerning microwave reflection in the amplitude contrast coating properties like ageing or local thickness changes are imaged. Figure 6 and 7 document such result. Both results were obtained in the near-field of the 94GHz module where an open waveguide (2.4 × 1.3mm^2 aperture) has been used as antenna. In that case wave penetration is low and surface properties are pronounced visualized.



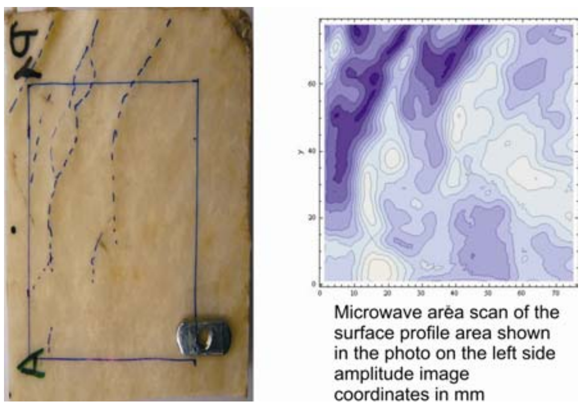


Figure 6. Ageing characterization of rubber

Figure 7. Inliner-inspection in pipes with 94GHz

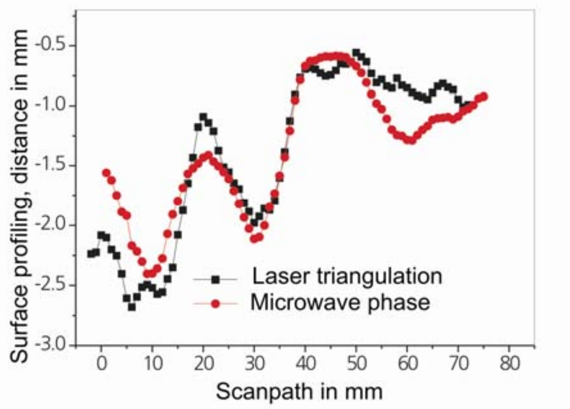


Figure 8. Surface profiling, Laser triangulation compared with microwave phase

Clearly in the amplitude grey scale different ageing states of the rubber coating can be separated (Figure 6). In the case of the liner profile determination (Figure 7) the phase of the microwave signal was compared with a Laser triangulation measurement. The result is shown in Figure 8. The differences between both results are due to the different beam diameter which is in the microwave case large compared with the Laser beam, i.e. the microwave phase profile is a convolution of the real profile and the beam aperture.

3.1.3 Ceramic inspection

Large components of sanitary ceramic 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 component before sintering in order to detect not acceptable voids or dents. Figure 9 documents an example where clearly the irregularity is revealed. The scanning was with 94GHz but the beam was focused by an elliptical mirror.

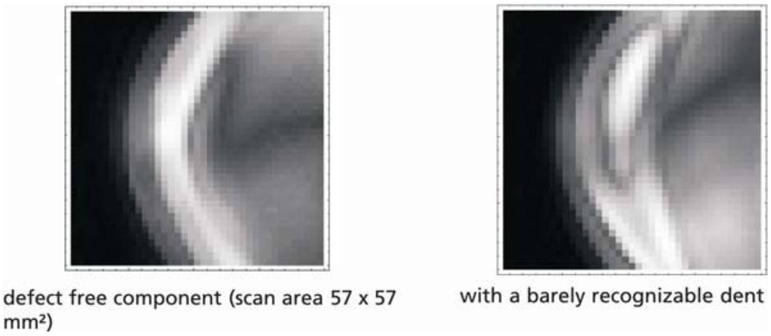


Figure 9. Detection of an unacceptable dent in sanitary ceramic

3.1.4 Glass fibre reinforced epoxy laminate

The car supplying industry works with the objective to replace flat springs made from steel by glass fibre laminates with higher specific strength. However, irregularities produced by lamination have to be detected and the material is hardly to inspect by NDT like UT, because of anisotropy and inhomogeneity. Microwaves have potential to be a reliable and cost-effective alternative to UT and inspection has the advantage to be performed without coupling. Figure 10 compares the optical image with the microwave image.

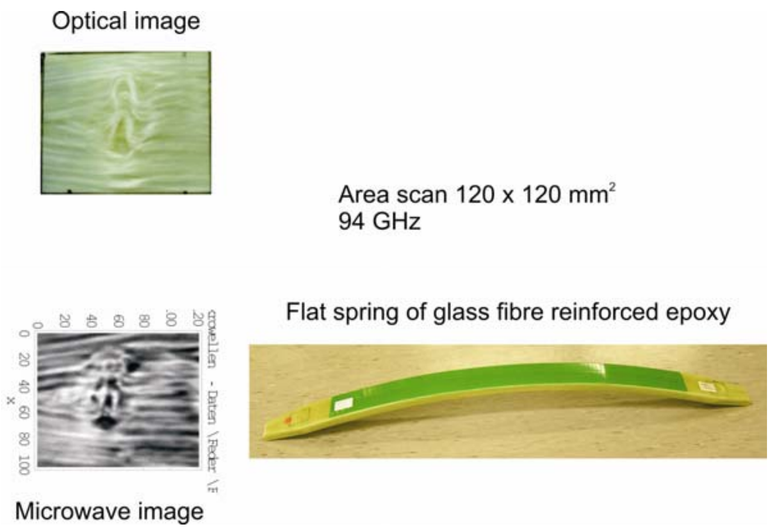


Figure 10. Detection of fibre inhomogeneities in glass fibre reinforced laminates, flat spring

3.2 Security application

In times of growing international terrorism and crime the detection of weapons, explosives, drugs and other forbidden or illegal objects which are worn by humans and are concealed beyond 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 meters and more. X-ray backscattering body scanners generate images with high resolution including all suspicious objects but are also unable to handle bigger distances and are often not accepted to be applied to human beings due to the low but nevertheless existing radiation exposition.
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 range. There exist a few microwave-based systems which are used for the access control of critical areas (e.g. airports) like the active system SafeScout 100 from L3 Communications (developed by Battelle-PNNL-Institute [8]) or the passive system Tadar from Smiths (developed by Farran). These systems are designed as portals and therefore don't work at larger standoff distances. These are covered by several systems (e.g. Brijot Imaging Systems, View Systems-Xytrans, Qinetiq, …[9; 10]) 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 inquiring compact and mobile imaging systems working in real-time over distances of several tens of meters 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 [11]. 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 exposition is smaller than from mobile phone and especially no ionizing radiation is generated. The microwave methods can work in non-contact way even over bigger distances and can be used in very quick manner since the microwaves propagate with the velocity of light.
As documented in the chapter to material characterization, with a single microwave transducer two- or three-dimensional images also 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 is not possible in the microwave domain. In 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 components, a plastic plate or a soap (to simulate explosive agents) concealed under clothes or non-concealed have been scanned with the FMCW-radar (Figure 11). To simulate the influence of the human skin these objects were placed on a wet towel.
A raw evaluation of the signal amplitudes as function of the scanner position only gives some indication of the existence of an external object but doesn't reveal its nature (Fig. 12a). By applying the Synthetic Aperture Techniques which have been developed since the 1950s in the radar (SAR, **S**ynthetic **A**perture **R**adar) [2] and ultrasound (SAFT, **S**ynthetic **A**perture **F**ocusing **T**echnique) domain the lateral resolution can be essentially increased. The lateral or cross resolution R_L for radar with synthetic aperture is given by [12, 13] according to equation (1):

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

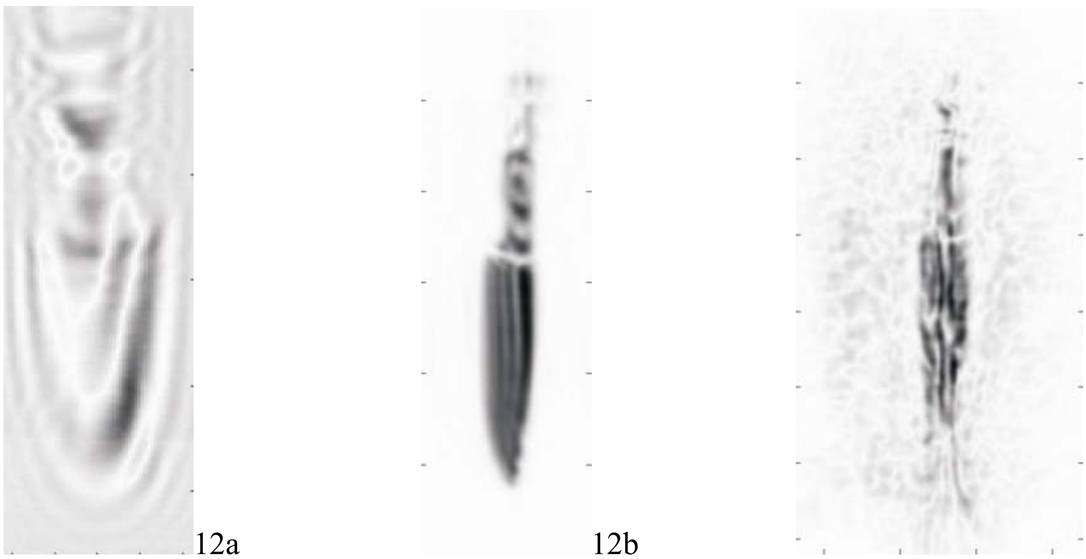
Here $\lambda_{\min}$ is the wave length of lowest frequency in the pulse and d_a is the real aperture of the antenna.

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

$$(2) \qquad R_A = \frac{c}{2B}$$, c is the velocity of light and B 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-Transformation technique the evaluation time can be shortened by two or three orders in magnitude providing the same results (Figure 12b). The ceramic knife from Fig. 12a 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, knops, pleats) belonging to it. In Fig. 12c a zipper made of plastics acts as a scattering centre and disturbs the reconstructed image. But nevertheless the knife can be recognized.

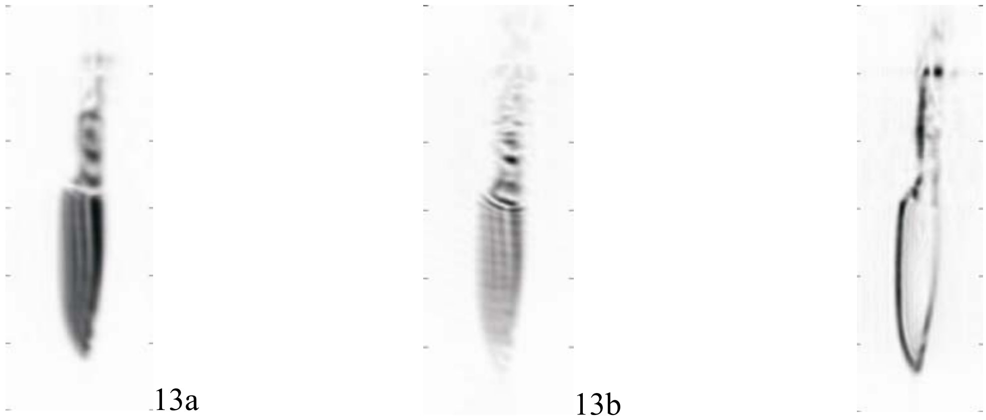
Figure 11. Mechanical two-axes-scan of objects concealed under a jacket with FMCW-radar



12a 12b 12c

Figure 12. 94 GHz-scan of a ceramic knife, antenna-object-distance 40 cm
12a: Knife non-concealed, raw amplitude data, displayed area 92 × 263 mm²
12b: Knife, non-concealed, 3D-FT-SAFT, displayed area 100 × 300 mm²
12c: Knife concealed under waistcoat with zipper, 3D-FT-SAFT, displayed area 180 × 360 mm²

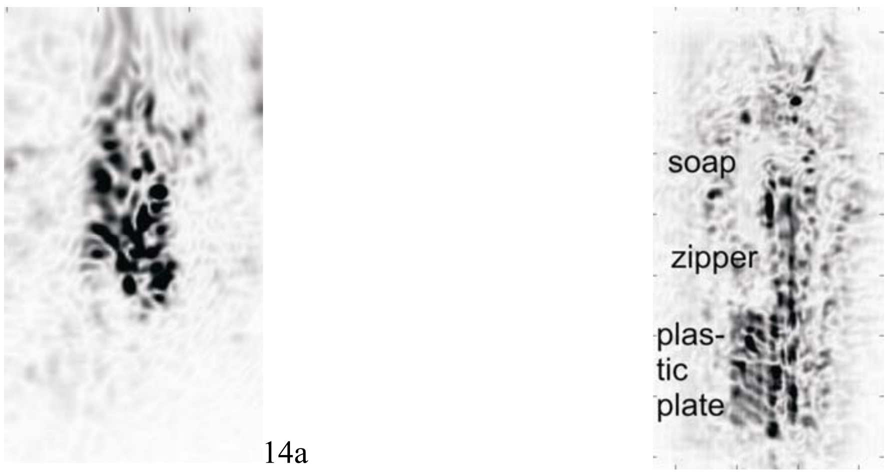
If the knife is rotated by its longitudinal axis the bright indication from the blade gradually disappears but the blade edge is still identifiable since it acts as scattering centre (Fig. 13). It is important that the object is illuminated from different aspects in order to produce an image which shows the object as complete as possible and to avoid glory effects which would impede object recognition.



13a 13b 13c

Figure 13: Reconstruction of ceramic knife with 3D-FT-SAFT
13a: normal incidence, displayed area 100 × 300 mm²
13b: analogue to Fig. 13a, but incidence angle 10°
13c: analogue to Fig. 13a, but incidence angle 15°

Organic objects give the lowest contrast in comparison to the surrounding since their reflectivity is the lowest. Even though the clothes and the zipper produce attenuation and disturbances which are relatively stronger than in case of metallic or ceramic objects, the images from 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 (Figure14).



14a 14b

Figure 14: Detection of organic objects (simulation of explosive agents) reconstructed with 3D-FT-SAFT
14a: Oval soap (ε_r = 2.8, length 9.5 cm) in breast pocket of a flanell shirt (reconstructed area: 14.3×25.1 cm²)
15b: Soap and rectangular plastics plate, concealed behind waistcoat (reconstructed area 19×38 cm²); the zipper acts as disturbing scattering object

Application of synthetic aperture is possible with the commercial 24.1 GHz-sensor, too. In Figure 15 the object (revolver at 60 cm distance) can be recognized, however, the angular resp. lateral resolution is worse than the 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.

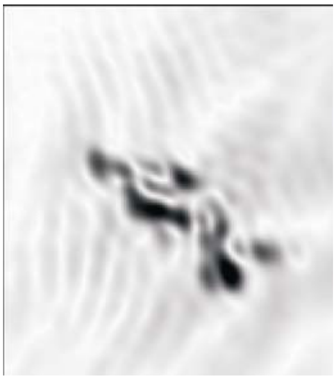
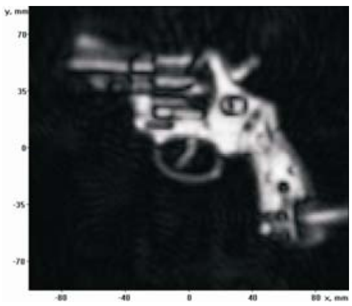


Figure 15. Reconstruction of a non-concealed revolver at a distance of 60 cm with a low-cost radar sensor (centre frequency 24.1 GHz)

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 wave length) gives a clear image with a good lateral resolution (Figure 16a, 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 16b). If an interpolation is performed no difference can be found between the scan with 1.5 mm and 3 mm step width (Figure 16c). However, if only every forth scan point is taken corresponding to a step width of 6 mm the reconstruction completely fails (Figure 7d). After interpolation to 1.5 mm step width the revolver is again recognizable, however with some loss in resolution (Figure 7e).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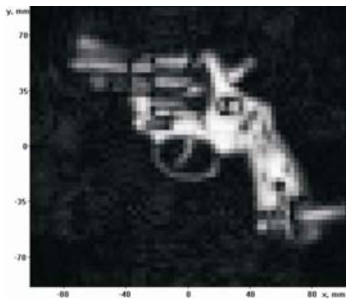
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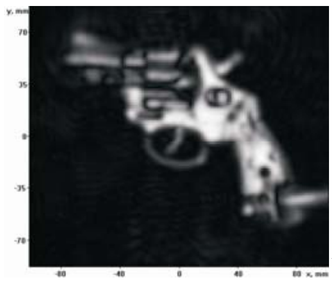
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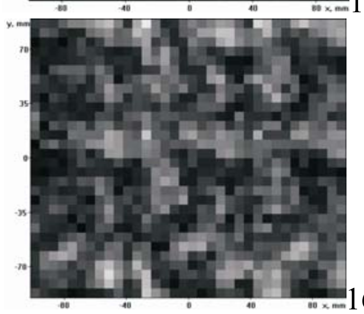
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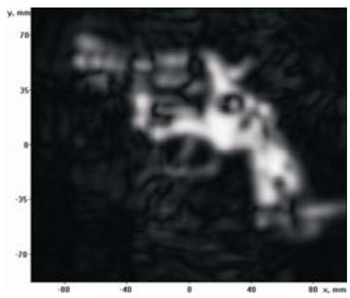
16e

Figure 16: Effect of step width on reconstruction quality using synthetic aperture
16a: Step width 1.5 mm (≈ half wave length); the revolver was non-concealed.
16b: Step width 3 mm
16c: Step width 3 mm, interpolated to 1.5 mm
16d: Step width 6 mm
16e: Step width 6 mm, interpolated to 1.5 mm

3.2.3 Principle of Sampling Phased Array

These results show that, in case of mechanical scanning of the object, a big number of antenna positions is necessary to get a good quality of imaging in monostatic mode. If no mechanical scanning is performed, a big 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 a long time impeding any real-time capability. To overcome the need of a huge number of antennas the principle of **S**ampling **P**hased **A**rray (SPA) developed in the field of ultrasound testing can be applied [14]. Here within an antenna array the first antenna generates the transmitting impulses while all other antennas receive the waves reflected or scattered at the object. In the next test cycle the next antenna is in transmitting mode and the other antennas are in receiving mode thus filling up a data matrix containing the data from all transmit-receive 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 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 antenna number is considerable. Presently this approach is tested experimentally in mm-wave range at Fraunhofer IZFP.

4. Conclusions and future developments

The experimental results show that microwaves have a high potential as well as for material characterization and NDT process integration as well to detect objects concealed under clothes with microwaves in mm- and cm-wave region in standoff manner. The best results are obtained with highly reflecting objects made from metal or ceramics. Principally there is no theoretical limit of distance between the antenna and the object. However, to get good resolution at high standoff distances the aperture or/and the centre frequency has to be increased. A big aperture size may result in an impracticable size of the imaging system while a high frequency of several 100 GHz may result in a too high 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 refocuses the raw data and to enhance the lateral resolution. However, in order to recognize objects with low false alarm rate pattern recognition is asked for also basing on artificial intelligence procedures. So far by use of redundancy and diversity the information content can be enhanced one has to use it. 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 so far the SAR/SAFT procedure can be performed online, Fraunhofer IZFP is working on that developments. Further enhancement of the detection approaches will be by combination of the micro and millimetre wave scanning with other sensor principles, for instance infrared spectroscopy, and by data fusion of the information.

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