Microwave Scanning Technology for Material Testing

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Abstract. Microwave scanners are introduced as imaging systems for non-destructive multidimensional structure investigations. Some basics of microwave scanning technology are presented. Typical configurations of microwave scanners are described. Some applications are explained to show the high potential of microwave scanning technology.

Introduction

For a broad and increasing variety of quality assurance applications better knowledge of materials inner structure is needed. Science and technology have identified a large number of non–destructive physical principles throughout the last 150 years, that seem to be suited for this. Many of them were transferred to commercially available devices and systems and can be operated as imaging or tomographic methods too.

Microwaves can overcome these disadvantages. Due to radiation character of electromagnetic waves they interact in volumes up to some decimeters depth. They allow flexible configurations of test systems and use very low electromagnetic power. Microwave applicators can be designed for a lot of special applications and penetration depths.

1. Microwave Sensors for NDT

1.1 Microwaves versus other NDT technologies

All state-of-the-art NDT principles have their own fields of application but also have a number of disadvantages especially for testing volume materials. Optical imaging has found broad acceptance, but interacts only in a layer of a few microns at the surface of a material. Ultrasonic testing is a basic technology since decades and allows true volume information and spatial resolutions down to submicron range, but causes a lot of problems with coupling when non–contacting operation is required. X–rays can overcome this easily; their problem is the danger coming from the ionizing radiation leading to high and expensive requirements for safety measures. The same is valid for computer tomography based on radioactive materials. NMR doesn’t show all these problems, but is restricted either to closed magnetic systems like in medicine or, for the case of open systems, to a very limited depth of operation. Radar systems show a real volumetric interaction and therefore have been in use for the detection of inner properties of materials for about 15 years. Their problems are the large wavelengths used in common radar applications, which do not allow the identification of small cracks, and the very time consuming process of processing radar images after the measurement.

Microwave methods have the potential to overcome all these disadvantages. Microwaves show a real volumetric interaction with the dielectric material properties for all non–metallic materials up to some decimeters depth. They can work easily both in reflection and in transmission arrangements. For electromagnetic waves there is no big problem with coupling into a material through air. Microwave material testing systems avoid all dangers due to ionizing radiation due to very low power necessary. Microwave applicators can be designed for a lot of special applications and penetration depths. All these positive features of microwaves lead to the development of microwave scanners for material testing.

1.2 Microwave Basics

Microwave methods for the detection of spatial distribution of material parameters in most cases are based on measurements of the dielectric permittivity of a test object. In the microwave region the permittivity becomes complex and consists of two parts:

$$\underline{\varepsilon}_r = \varepsilon_r' + j\,\varepsilon_r'' = \varepsilon_r' \,(1 + j \tan \delta_\varepsilon) \qquad (1)$$

The real part ε_r' describes the polarizability of the material under test. The imaginary part ε_r'' is standing for dielectric losses according to the phase–shifted movement of polar molecules in an electromagnetic field.

Those dielectric parameters in principle can be measured in all microwave arrangements having stray fields or radiating electromagnetic energy by antennas into the material. In all cases an interaction between dielectric material and electromagnetic field or wave will happen. This interaction can be investigated by microwave applicators in reflection and transmission methods.

Using reflection methods electromagnetic energy is transmitted by a microwave applicator to the material. Both transmitted wave and reflected wave are separated and measured. The reflection coefficient is the ratio of reflected and transmitted wave:

$$\rho = \frac{u_{\text{reflected}}}{u_{\text{transmitted}}}. \qquad (2)$$

Reflection sensors (fig. 1) only need access to one side of the material. They are put onto the material or mounted in a small distance with fixed size. They allow integral measurement of permittivity across the depth of the material but also measurements with some depth resolution.

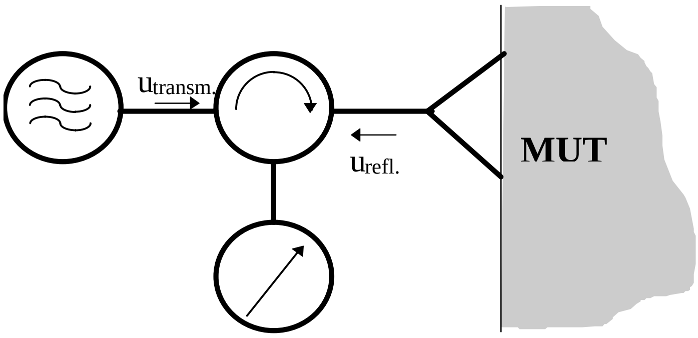


Fig. 1. Microwave reflection measurement

When using transmission methods with transmitter and receiver sitting on opposite sites of the test objects, electromagnetic energy completely penetrates the material. Simple transmission arrangements allow integral measurement of the dielectric properties of the test object.

Laying a fictive grid over the surface of the test object and measuring in the grid points leads to at least two–dimensional images of the spatial distribution of permittivity and other physical properties derived from it (fig. 2). The measurement with reflection type applicator of fixed penetration depth gives the dielectric properties in one layer of the material.

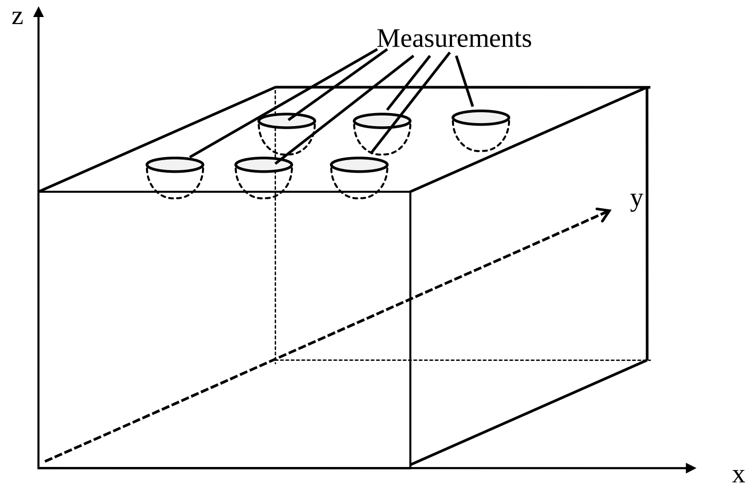


Fig. 2. Lateral distribution of measuring volumina in one layer – Reflective Measurement

A big advantage of microwave technology is that it can use a broad variety of electromagnetic principles. This way a large number of microwave applicator types can be designed. For the commonly used ISM frequencies 2.45 GHz and 5.8 GHz the table below gives typical orders of field geometries, ranges and spatial resolutions.

Table 1. Microwave applicator types and orders of their interaction geometry

Applicator type	Spat. Resolution	Field range	Measuring vol.
strayfield linear (lines)	mm	mm	some mm^3
strayfield linear (resonators)	mm	cm	up to some cm^3
strayfield round, symmetrical	cm	cm	up to 100 cm^3
radiation field, planar, not directed	cm	dm	up to 10 l
radiation field, planar, directed	cm	dm to m	up to 200 l

This shows that microwaves can generate interactions in various geometries even with applicators small in comparison to the test object dimensions.

Not only the spatial distribution of permittivity can be measured, but also a broad spectrum of material and object properties derived from them, like

- material moisture and leakages
- material density
- material inhomogenities (cracks)
- geometry of layers and layered media
- presence and geometry of construction elements
- arrangements and filling levels in closed non–metallic packages properties of tissue
- leakages in packages.

1.3 Multidimensional material parameter distributions

For getting information concerning the dielectric parameter distribution in the z–axis microwave applicators with different penetration depths can be used (see table 1). Such probes already exist in the EM VISION microwave scanner system. EM VISION contains probes with field ranges between centimeters and decimeters. For many applications such a gradation is sufficient for getting informations regarding inner structures.

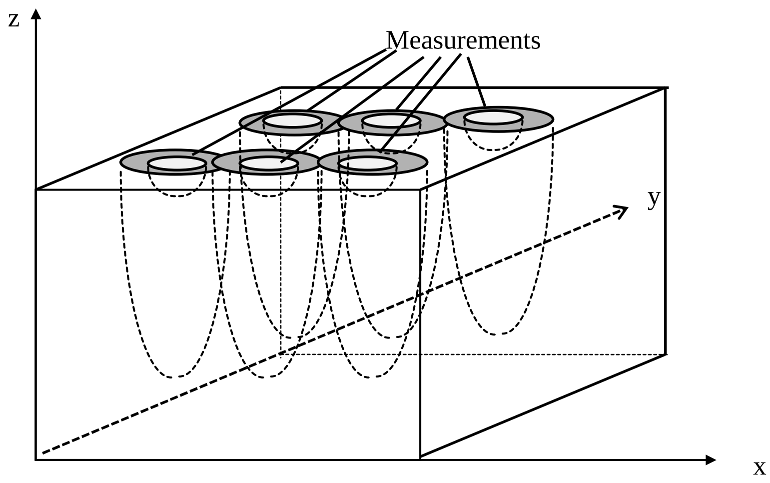


Fig. 3. Distribution of measuring volumina with two different microwave applicators

For a large part of measuring problems the number of layers to be investigated reduces to the surface layer and a volume layer in the core of the test object. Fig. 3 shows schematically how two different microwave applicators measure in the same grid points. The stray-field applicators only interact with the surface layer. The radiation field applicators interact with the surface layer too but most part of the microwave radiation passes through this layer and therefore it causes only small interaction. Because the permittivity distribution of the surface is known it is possible to conclude to the permittivity distribution in the volume.

As shown in table 1 this principle can be applied to more than two layers. It allows to realize arrangements with minimum depth resolution in steps of some mm for the commonly used ISM frequencies and maximum step sizes in z-direction in the decimeter range.

2. Microwave Scanners

2.1 Laboratory Microwave Scanners

Many applications look for structural investigations of test objects under laboratory conditions with stationary test equipment. For these purposes the laboratory scanner EM VISION LAB was developed. In this scanner the microwave probes can be moved in all three axes.

The laboratory scanner is available in different configurations. The basic configuration was designed for reflective measurements with the necessary microwave probes working parallel. This arrangement actually allows up to 5 measurements per second. A test object with dimensions of 100 cm x 60 cm can be measured within 5 minutes with a lateral resolution of 2,5 cm. For transmission measurements a second y-axis can be added running parallel to the first one.

Fig. 4. Laboratory Scanner EM VISION LAB

2.2 Process Microwave Scanners

In process applications with webs moving at higher speed mechanical drives are to slow and to trouble-prone. For such tasks arranging of the microwave probes in an array is recommended.

The microwave sensors act somewhat like optical sensors or line cameras as pixels. For a lateral resolution of 10 mm on a moving web of 2000 mm width it is necessary to have at least 64 microwave probes of each type. Mounting this array on both sides of the material leads to a complete observation of the whole cross section of the material, if the web is not too thick. A process scanner fulfilling these requirements is shown in fig. 5. Both the upper and the lower scanner module can be varied in height over the moving web.

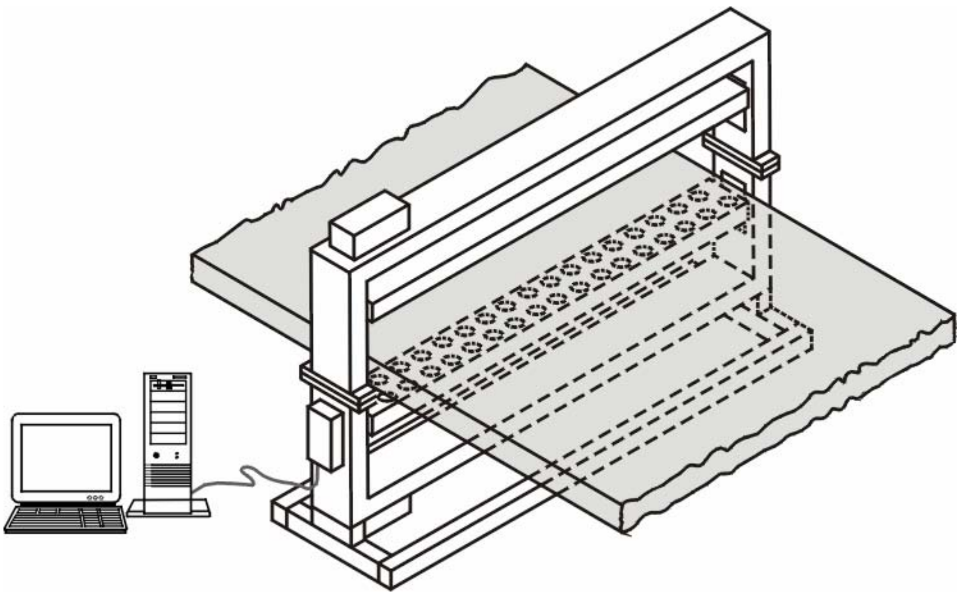


Fig. 5. Microwave Process Scanner EM VISION PROCESS

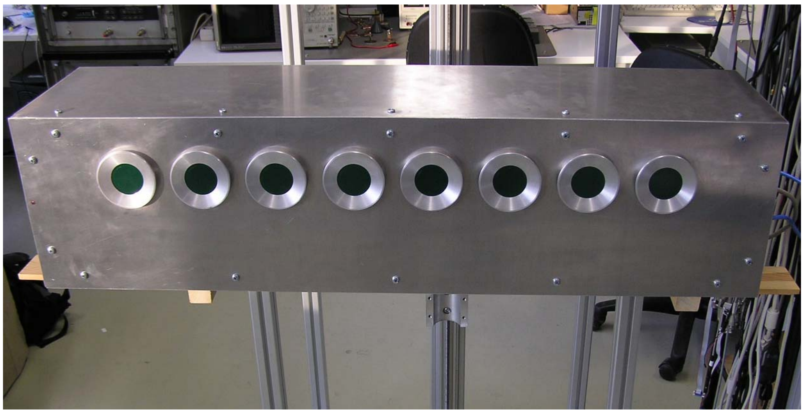


Fig. 6. Microwave Process Scanner Module EM VISION PROCESS 8P

Fig. 6 shows the microwave process scanner module EM VISION PROCESS 8P, which is one of many possible configurations for microwave process scanner modules. EM VISION PROCESS scanner modules can be delivered with up to 64 microwave sensors of one type and a maximum track width of 2 m.

2.3 Image Processing with Microwave Scanners

The high amount of data generated with a microwave scanner increases the meaning of data processing for the desired applications. In many cases certain morphological features of the test object like density variations caused by the manufacturing process are superimposed the desired structure information. Therefore filtering of the generated images becomes a very important part of post-processing.

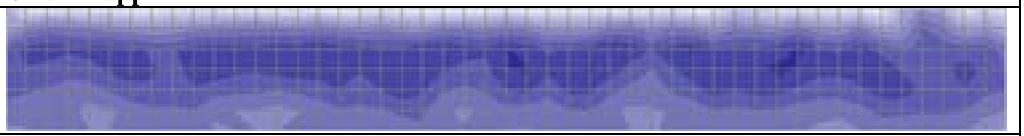
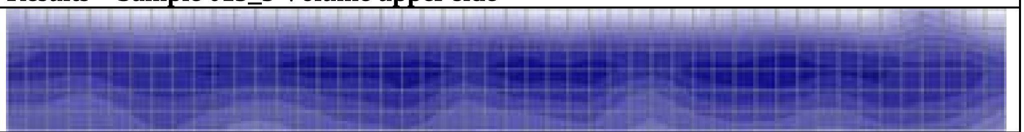
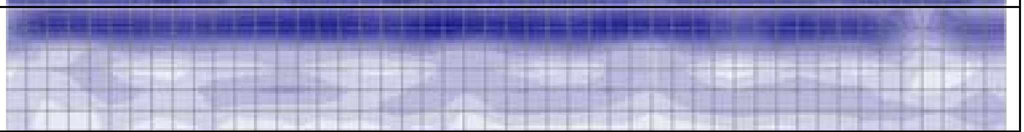
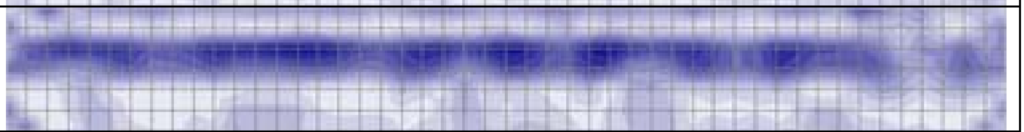
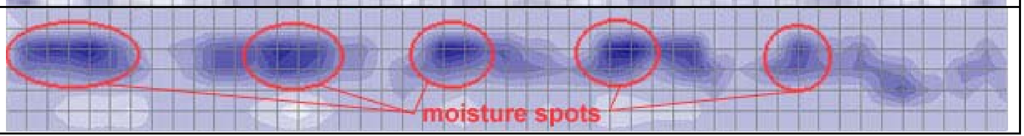
Sample **013_3**	**Volume upper side**
Rough data Moisture disturbances included	
Filter type	**Results – Sample 013_3 Volume upper side**
3x3default	
Sobel	
5x5_loc.Max_ normal	
5x5_P-Median_y (best filtering results)	

Fig. 7. Rough data of wet material web and results of different filter algorithms

Figure 7 shows a typical volume scan at a test object with moisture disturbances included. From rough data it is not possible to decide which part of the image changes due to structural changes and what is moisture caused. For being able to make a clear decision it is necessary to have one ore more filtering steps.

Solving such a problem the first step will be to observe the basic structure of the non-disturbed material in order to characterize it's special morphological features. If it's possible to find filter algorithms that identify this basic structure cracks and disturbances can be found with high probability. Figure 7 gives the results of some filter algorithms. Only some of them give a good differentiation between moisture and material structure.

3. Examples for Applications

There are manifold applications for such a technology in production processes, civil engineering, test of packagings and even in automotive applications like scanning of car seats. One main application is concerning structural, moisture or density investigations at moving webs. Such materials (chip board, laminates, composites, rubber, mineral wool) show similar problems in most cases.

3.1 Microwave Scanning for Structural Investigations of Moving Webs

In case of structural investigations of moving webs either moisture distribution is to detect, or a detection of cracks in the material is seeked for, which can be derived from density or moisture distributions.

An example for this is the detection of wet spots in insulating materials. Wet spots can be located on the surface, but also be buried. While surface spots can be detected by optical imaging too, it is not possible to find buried spots by this method. A broad variety of experiments under lab and production conditions has shown, that microwave scanning is an excellent choice to find wet spots in the kernel or at the surface of the material.

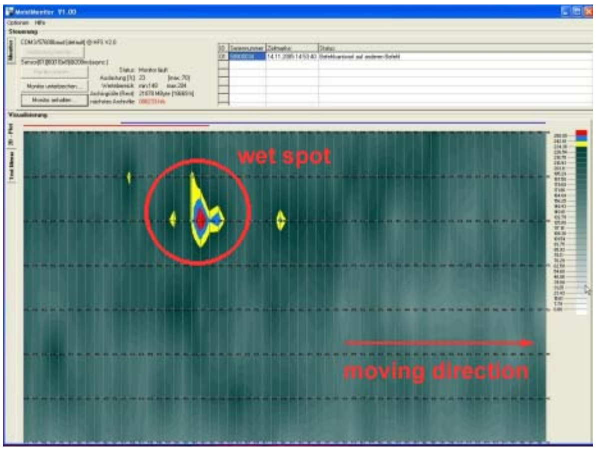


Fig. 8. Microwave online scan of insulating material during production

Fig. 8 shows part of an online scan during the production of insulating material. A wet spot can be located very clearly, which was found after destroying the material at a depth of approximately 50 mm.

3.2 Microwave Scanning Technology in Packaging Industry

Another field of application is packaging technology. The questions to be answered there are position or completeness of goods in closed non-metallic packages or the detection of leakages in bags filled with aqueous liquids packed in cartons. In medicine technology such bags are used for the transport of saline water. In some cases small leakages occur at the port system of such bags leading to rejection of the whole carton. Imaging the closed cartons with a microwave scanner from the bottom side while moving along a conveyor belt finds small leakages as shown in fig. 9.

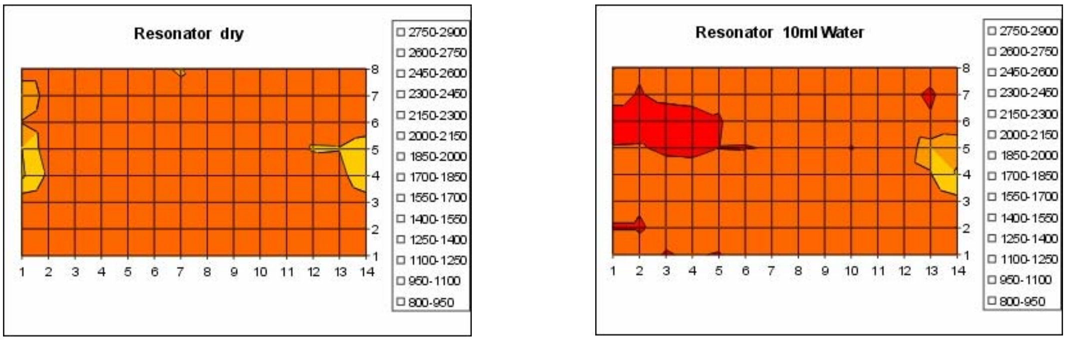


Fig. 9. Comparison of Microwave scans without leakage and with small leakage

3.3 Other applications for microwave scanners

For structural imaging of moisture and density distribution in ceramics and glasses the laboratory scanners are a good solution.

Microwave scanners can also be used for tasks which seem to have nothing in common with the measurement of permittivity distributions, like moisture measurements in car seats. A non-destructive moisture measurement is difficult because of the metallic bottom of the seat. Microwave Imaging generates typical reflection patterns for the seat. A change in these patterns can be correlated with moisture content.

4. Conclusion

Microwave scanners are imaging systems which allow non-destructive two-dimensional and quasi-three-dimensional structure investigations. Microwave scanners act like microwave cameras with volume interaction and multidimensional spatial resolution. Because of the outstanding features of this technology a very broad variety of applications can be expected. For different kinds of applications a selection of ready-to-run configured scanners is already available.

References

[1] Moisture Mapping – Getting 2D and 3D Moisture Distribution by Microwave Measurements. Göller, A. in Proc. 4th International Conference on Electromagnetic Wave Interaction with Water and Moist Substances. May, 13–16, Weimar, 2001