Microwave and Millimeter Wave Sensors for Nondestructive Testing and Evaluation

Nathan Ida

Abstract Microwave nondestructive testing and the sensors required to affect the testing are less well known than other electromagnetic methods such as eddy currents techniques. Nevertheless, they occupy a critical role in testing as well as imaging of conditions and flaws in primarily nonmetallic structures including plastics, polymers, and ceramics as well as wood structures, various composites and concrete. It has also found uses in conductors for surface testing and for evaluations of coatings. The methods and sensors range from microscopy to industrial scale testing and from simple open-ended waveguides to complex radars. The frequency range covers the whole microwave range and down to mm waves. The present work discusses the use of microwave testing, its place in a nondestructive testing regime, and a sampling of sensors that are representative of the art and its present state, with emphasis on emerging methods.

Keywords Microwave sensors · mm-wave sensors · Nondestructive testing · Microwave microscopy · Resonant testing methods · Radar

1 Introduction

Microwave nondestructive testing (NDT) is a method of testing materials and structures that uses microwaves and millimeter waves as the source of energy. The method can be viewed, to some extent, as an extension and adaptation of methods that have been developed for other purposes including radar, communications, and even microwave heating. But there are also techniques that have evolved specifically for NDT.

Historically, microwaves use for NDT started shortly after its first use in radar in attempts to quantify moisture and detect foreign objects in dielectrics [1]. Soon

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it became an accepted method of testing of a variety of conditions and flaws in dielectrics, ceramics, and composite materials with applications to composite materials [2–4] and for testing of ceramics [5]. The main impetus for development of microwave methods of testing came in the 1970s with the increased availability of commercial microwave equipment and in particular the appearance of the network analyzer.

Testing with microwaves is defined and limited by properties of materials in the microwave field and the frequencies used for testing. The range of microwaves is formally defined between 300 MHz and 300 GHz. This corresponds to wavelengths between 1 m at 300 MHz and 1 mm at 300 GHz. Beyond this frequency range, formally it is the terahertz region and the methods of testing expected are different, having more to do with infrared radiation than classical electromagnetic waves. The range of microwaves defines the fundamental spatial resolutions that can be expected based on the wavelength. This resolution defines the smallest artifacts that can be discerned. However, there are many techniques that can be brought to bear to increase this resolution many fold. These include reliance on phase changes, which can vary rapidly, the use of evanescent waves, which decay within a fraction of a wavelength, testing with resonant structures, etc. Dimensional parameters such as thickness can be measured to well within a micrometer and scanning methods can easily improve resolutions. Methods borrowed from radar but on a much smaller scale, including SAR are also used for that purpose. Other methods include interferometric and microscopy methods which are not limited by the wavelength resolution. Microwave testing relies on the effects material properties have on electromagnetic waves. These include primarily effects of permittivity, conductivity, and permeability and any effect, property, or quantity that affects one or more of these. In addition, electromagnetic waves are affected by dimensional properties including volume and surface artifacts and interfaces. This makes for a large number of possible test responses. In lossless and lossy dielectrics, material composition, density and porosity, uniformity, delamination between layers and constituents, moisture content, contamination, etc. can be tested. In conductors, electromagnetic waves can only penetrate to very shallow depths and hence tests are limited to surface conditions such as roughness, scaling, and surface corrosion as well as surface-breaking flaws and dimensional variations of conductors. Unlike most testing methods, microwaves are also sensitive to properties of gases and hence can be used to detect and quantify the presence and density of gases including those emitted by explosives. Thus, the range of materials in which microwave NDT can be used is rather large and includes most plastics and polymers, ceramics, composite materials, concrete, biological and organic materials, many conducting media, wood and food products and, in fact, almost any medium in which electromagnetic waves of proper frequency can interact with its constituents.

A unique feature of microwave NDT is the fact that energy is usually coupled into the test medium through air and there is no need for contact. This is done through antennas of various types, open waveguides, and in some cases directly through the fields of transmission lines. Testing can also be done in microwave cavities or apertures in cavities can be used for this purpose. Testing is often done in the near fields of the sources because of the high gradient in the fields in that region but can also be done in the far field. Of course, like any other method of testing, microwave NDT has its problems. Signals can be noisy because of the many effects that influence it and results can be ambiguous for the same reasons. Reflections from structures near and far can affect tests and interference from a variety of electromagnetic sources can reduce sensitivity.

Microwave NDT relies on the interaction of high-frequency electromagnetic waves with materials, taking advantage of absorption in materials, scattering, attenuation, reflection, transmission, and resonance. These are fundamental effects and testing attempts to use these in various arrangements for quantitative evaluation of properties and conditions in materials.

There are many methods through which microwaves can be used for testing. The first that come to mind are those associated with propagation of electromagnetic waves and the reflection, transmission, and scattering of these waves due to the presence of flaws or material variations [6–9]. The same principles have been used for dimensional testing [10, 11]. Radar and radar-like methods are obvious applications that rely on reflection and scattering of electromagnetic waves. A particularly useful method of NDT is the ground penetrating radar (GPR) ([12–15]), but also related methods including newly developed ultra wide band (UWB) radars for low power, short range testing in dielectrics [16–23] and in biological media medical applications such as detection of tumors [24–27].

Particularly useful are tests in which the resonant frequency of resonant structures such as cavity resonators or resonant transmission lines are affected by the effect that is measured. These include moisture content monitoring and evaluation of material properties [28–33]. Resonant methods are particularly useful when they apply because their sensitivity and resolution can be orders of magnitudes better than, for example, reflection methods and these are not related to the wavelength.

Another method that has been successfully used to circumvent the wavelength limitation is the use of open-ended waveguides. These near-field methods are often referred to as microwave microscopy to indicate their ability to resolve well below the wavelength. (See for example: [32, 34–41].)

As is well known, microwave testing is applicable mostly in dielectrics and low loss dielectrics including ceramics, plastics, and polymers [3, 42, 43]. Lossy materials such as concrete, composites, carbon fibers based composites and sands can also be tested successfully [7, 44]. Another area of successful use of microwaves is in biological media, including medical applications [9, 25, 26].

Material properties can be tested for moisture content [29–31], consistency, and porosity [3, 6, 43–45] and other properties including density changes.

One of the earliest uses of microwave was for dimensional measurements [33, 46–49]. Some of these tests allowed resolutions in the micrometer range [42, 43]. Other applications are in the detection of disbands, delamination, and corrosion [2, 35], as well as surface conditions on conductors [50].

In addition, microwaves can also be used to detect surface conditions such as roughness, evaluate coatings on metals and, to a limited extent, detect fatigue cracks.

The number of applications of microwaves for testing and evaluation is quite large but, in effect, these applications can be summarized to that of detection and evaluation of changes in the dielectric constant, in permeability and in conductivity and, naturally, anything else that affects the electric properties of the material.

The following sections expand on a few of the more advanced methods of microwave testing and evaluation including microwave microscopy, resonant methods, GPR, and UWB radar.

2 Microwave Microscopy

Microwave microscopy relies on the behavior of open waveguides or apertures in cavity resonators. These are near-field methods that take advantage of the fact that under these conditions the gradients in the fields are very large although they are of very short extent, that is, the fields of apertures or open waveguides can only be used over a very short distance. The resolution of these methods stems from the very high spatial frequency they afford [32, 36, 51]. This high spatial frequency is also at the root of the method's limitations—it requires scanning for the detection of features of any extent, it must be done in very close proximity to the effects, and necessarily only small samples or sections of structures can be tested. The method is usually associated with localized testing and very often used for evaluation of material properties [37, 52, 53], rather than for testing for defects, although it has been used for dimensional testing and flaws in conductors [40, 54].

Microwave microscopy instrumentation is relatively simple. In its simplest form it consists of an open waveguide or transmission line (Fig. 1a), sometimes supplemented by a sharp tip that helps in increasing spatial resolution around the tip (Fig. 2a). Better resolution is obtained by using a small aperture in a resonant cavity or a resonant probe as shown in Figs. 1b and 2b. The fields around the aperture or tip may be viewed as being generated by an antenna in the near field and are reflected and scattered by the sample's surface and any feature or condition in the test medium. The signal obtained from the non-resonant probe is either from the scattered or reflected field. Because the fields are very low, it is only practical to

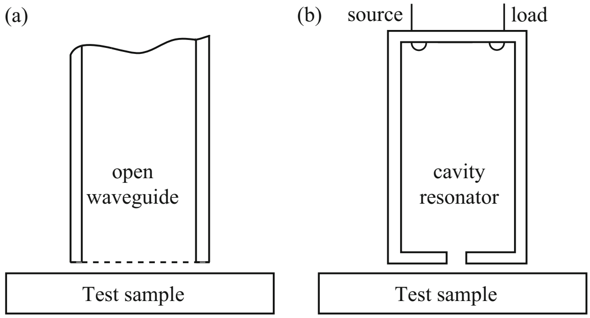


Fig. 1 Simple microwave microscopy probes. (**a**) Open waveguide. (**b**) Small aperture in cavity resonator

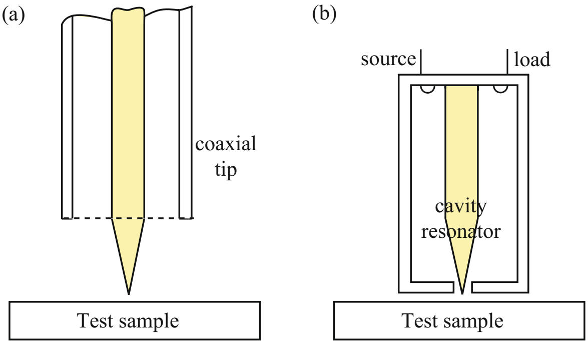


Fig. 2 Sensitive microwave microscopy probes (**a**) Tip in open coaxial probe. (**b**) Tip in cavity resonator aperture probe

monitor the impedance of the probe and extract the changes in material properties (complex permittivity or complex permeability) from the near-field impedance of the probe. The latter is approximated as [36]:

$$Z_{\mathrm{s}} \approx \frac{1}{j\omega\varepsilon_0\varepsilon_{\mathrm{s}}v} \tag{1}$$

Any deviation from this reference impedance is viewed as being due to change in material properties.

More sensitive measurements are affected through use of a resonant probe such as that in Fig. 1b or 2b. In these cases it is not the impedance that is monitored but, rather, the resonant frequency. In essence, the cavity is perturbed by the external loading due to the material properties and its resonant frequency changes due to the external conditions. This shift in resonant frequency may be written as [30]

$$\frac{f-f_0}{f} = -\frac{\int_v \Delta\varepsilon \mathbf{E}\cdot\mathbf{E_0}^* \, dv + \int_v \Delta\mu \mathbf{H}\cdot\mathbf{H_0}^* \, dv}{\int_v \mu \mathbf{H}\cdot\mathbf{H_0}^* \, dv + \int_v \varepsilon \mathbf{E_0}^* \cdot \mathbf{E} \, dv} \tag{2}$$

E and **H** in Eq. (2) are the perturbed fields, $\mathbf{E_0}$, $\mathbf{H_0}$ are the unperturbed fields, and $\Delta\varepsilon$, $\Delta\mu$ are the effective changes in the permittivity and permeability of the cavity caused by the external effects. This expression is only a simplistic representation but it serves to explain the behavior. In some applications including thin films, the expression in Eq. (2) can be simplified, especially if the relative permeability is 1 [30, 36]:

$$\frac{f-f_0}{f} \approx -(\varepsilon_{\mathrm{rf}}-1)\frac{\varepsilon_0\int_{v_{\mathrm{f}}} \Delta\varepsilon \mathbf{E}\cdot\mathbf{E_0}^* dv}{\int_v \mu_0 H_0{}^2 dv + \int_v \varepsilon_0 E_0{}^2 dv} \tag{3}$$

where v_{f} and $\varepsilon_{\mathrm{rf}}$ are the volume and permittivity of the film under the influence of the aperture, whereas the denominator is the total energy stored in the cavity. Similar expressions may be obtained for testing on conducting surfaces and other conditions.

Microwave microscopy was first developed for material characterization in thin films using ferromagnetic resonance [36] but has been adapted to application in NDT [37, 55, Zoughi 2000].

A simple demonstration of the possibility of microwave testing can be found in [37, 56]. In this application, the permeability of a thin film ferromagnetic CO-NETIC alloy is tested with the probe in Fig. 2b under the effect of an external magnetizing field and without the field. The basic configuration is shown in Fig. 3. The probe is stationary but the sample is scanned under the probe and the frequency response of the probe is recorded using a network analyzer. The microwave probe operated in reflection mode [55] and the frequency response was obtained from the S_{11} parameter. The test configuration was also simulated using commercial computational electromagnetic software.

As an example of the type of results can be obtained, consider Fig. 4. The figure compares numerical and experimental resonance data for an alloy sample. In this case the relative permeability is 1 and no external magnetic field is applied [56]. The numerical data was obtained using the transmission line modeling method (TLM) as described in [34]. Although relatively lengthy, modeling of microwave microscopy is quite practical. The simulation and experiment were repeated after application of an external magnetic field on a sample with relative permeability of 1000. The net effect of the higher permeability material is to shift the resonant frequency by approximately 180 kHz.

In another test, the values of the S_{11} parameter obtained at 889.61 MHz was used to sense and quantify changes in relative permittivity by scanning across a small 2-mm sample of relative permittivity of 1000. The results are shown in Fig. 5.

Although the result in Fig. 5 is excellent as is the comparison with the numerical simulation, the sample is very small and thin and the scan was done very slowly to

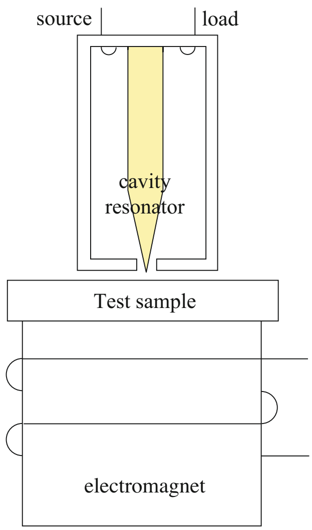


Fig. 3 Block-diagram of the experimental set-up: The sample moves during the scan whereas the probe is stationary. The electromagnet is used to bias the sample with a given magnetic flux density

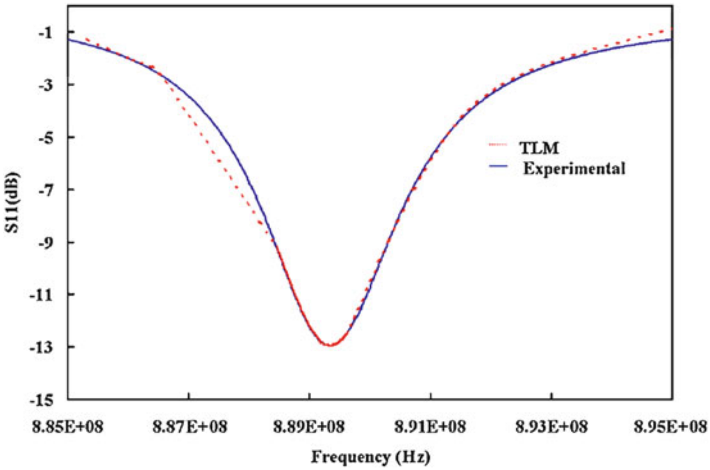


Fig. 4 Comparison between numerical (dashed line) and experimental frequency responses obtained in the absence of an external magnetic field. (Reproduced with permission from R. Ciocan and N. Ida, "Transmission line matrix model for detection of local changes in permeability using a microwave technique," in *IEEE Transactions on Magnetics*, vol. 40, no. 2, pp. 651–654, March 2004. doi: 10.1109/TMAG.2004.824883. © 2004 IEEE)

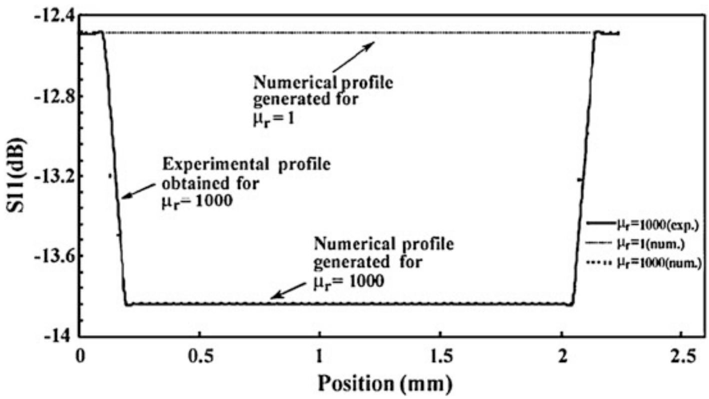


Fig. 5 Experimental and numerical results for a 2-mm sample produced by scanning across the sample. (Reproduced with permission from R. Ciocan and N. Ida, "Transmission line matrix model for detection of local changes in permeability using a microwave technique," in *IEEE Transactions on Magnetics*, vol. 40, no. 2, pp. 651–654, March 2004. doi: 10.1109/TMAG.2004.824883. © 2004 IEEE)

avoid distortions in the field. Large samples require considerable time for scanning especially if two-dimensional scans are called for, pointing to a serious limitation of the method. Nevertheless, under the right conditions this method is very accurate and the resolution extremely high.

3 Resonant Testing Methods

For production-level high sensitivity testing, the use of resonant methods is one of the best approaches, provided that the conditions of testing and the samples being tested lend themselves to this type of test. When resonant methods can be used for testing, they offer high resolution, high sensitivity, and an ease of signal analysis that cannot be matched in other methods. In most cases what is measured is the resonant frequency that is essentially noise free and extremely easy to measure by digital means. In the process of measuring the resonant frequency, scanning is done over a range of frequencies and therefore the frequency response of the resonator over the range is obtained. This then allows the calculation of the quality factor of the cavity. In a resonator, regardless of its physical construction, the resonant frequency is primarily a function of the physical dimensions and the real part of permittivity and permeability of the medium within the resonator. The quality factor is directly related to the losses in the cavity and therefore the quality factor is a measure of these losses through the imaginary parts of the complex permittivity and permeability. By measuring both the resonant frequency and the quality factor, a complete characterization of the material properties can be obtained and through that the condition of the test sample, including effects such as cracks, stresses in materials, delaminations, inclusions, and the like. In effect what is measured is the effective complex permittivity and the effective complex permeability. There are a variety of resonant structures that can be used for testing. The most obvious is the cavity resonator in which the sample is either inserted in the cavity (Fig. 6a) or the cavity is partially opened to allow samples either to pass through the cavity or the cavity to pass over the sample (Fig. 6b). The configuration in Fig. 6a is limited to small samples that can be inserted in the cavity and hence it is used mostly for evaluation of material properties under specific, controlled conditions. This may mean, for example, that the sample must have a certain size or shape or that it fills a portion of the cavity in which conditions are appropriate for the test. In general this is a limitation both in terms of the types of materials and conditions that can be evaluated and in terms of the speed and accuracy of the test. In partially open cavities, the range of materials and structures can be extended to flat samples, tubes and bars or even to continuous testing of fabrics and polymers on the production

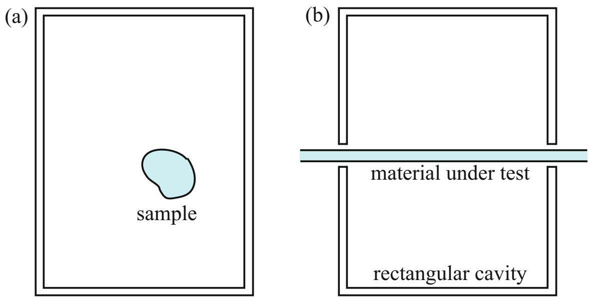


Fig. 6 Testing in resonant cavities. (**a**) A small sample introduced into the cavity. (**b**) Testing of flat sample in a partially open rectangular cavity

line. In that respect, the most commonly measured quantity is moisture content but also density, permittivity, dimensions and any condition related to these.

Resonators can also be made of transmission lines, which are often open [30, 57, Pozar 1998] and can therefore easily sense conditions in their proximity. An application of this type resonator to online industrial testing and monitoring will be given in the following section.

Equation (2) describes the shift in resonant frequency for a cavity in which the permeability and permittivity are uniform throughout the cavity and the change $\Delta\mu$ and $\Delta\varepsilon$ is also uniform (Fig. 6b). This occurs in testing of fluids or gases that fill the cavity, such as in monitoring of humidity or for detection of gaseous emissions from explosives. Although Eqs. (1) and (2) simply indicate permittivity and permeability, both can be complex to allow for modeling of complex media:

$$\varepsilon_c = \varepsilon' + j\varepsilon'' = \varepsilon' - j\frac{\sigma_s}{\omega} \tag{4}$$

Equation (1) now becomes [30]

$$\frac{f - f_0}{f_0} = -\frac{\int_v \left[\left(\Delta\varepsilon' - j\frac{\Delta\sigma}{\omega}\right)\mathbf{E}\cdot\mathbf{E}_0 - \Delta\mu\mathbf{H}\cdot\mathbf{H}_0\right]dv}{\int_v \left[\varepsilon_0\mathbf{E}\cdot\mathbf{E}_0 - \mu_0\mathbf{H}\cdot\mathbf{H}_0\right]dv} \tag{5}$$

The change in permeability may be real or complex or may be zero. ε_0 and μ_0 are the properties of the empty cavity.

A quality factor is defined as the peak stored energy divided by the energy dissipated per period as an indication of performance of the cavity:

$$Q = 2\pi\frac{\text{Peak stored energy}}{\text{Energy loss per period}} \tag{6}$$

If we assume for simplicity that power loss occurs only in the volume of the cavity (none in its walls), the Q-factor is:

$$Q = \frac{\int_v \varepsilon_0\mathbf{E}_0{}^2 dv}{\int_v \left[\varepsilon''\mathbf{E}\cdot\mathbf{E}_0\right]dv} \tag{7}$$

This shows the physical properties that affect the Q-factor but in practice the Q-factor is calculated from the half-power points of the frequency response as:

$$Q = \frac{2\pi f_0}{BW} = \frac{f_0}{f_u - f_l} \tag{8}$$

f_u is the upper half power frequency and f_l the lower half power frequency of the resonating cavity. In a practical test, the frequency response is obtained by measuring the S_{11} parameter using a network analyzer, and by measuring the amplitude of the response, the upper and lower half-power frequencies are obtained.

The relations above apply to closed, partially open, or entirely open resonator of any kind. The methods based on perturbation are most easily applied to closed cavities whereas those based on measurement of resonant frequency and Q-factor are universal since they do not actually depend on the physical attributes of the structure—only on their frequency response.

4 Testing Through Monitoring of Moisture Content

As an example of the use of open transmission line resonators for testing of moisture content, the monitoring of moisture in production of latex-coated fabrics for the production of tires is considered. Fabrics such as nylon, polyester, or aramid are coated with latex for the production of tire belts. The amount of latex is critical. Too much or too little and the bonding process suffers. In addition, during the coating process, streaking, dry patches, and breaks in the fabric must be detected to prevent failure of tires. A resonant sensor suitable for this purpose is shown in Fig. 7. The sensor consists of two metal shields and two center plates (dimensions shown in the figure). Two short probes penetrate through the shield to couple energy to the center plates and drive the resonator. These are connected to a network analyzer, which supplies the power needed and measures the response by measuring the reflection (S_{11}) and transmission (S_{21}) parameters of the resonator to obtain the resonant frequency and the Q-factor continuously while the fabric moves at production speeds. The fabric is thin (ranging in thickness from 0.3 to 0.8 mm. Production requirements are typically for about 5% solid latex (measured after drying) while in the wet stage the latex is 20% of the solution by volume. The sensor measures the permittivity in the wet stage.

This sensor is called a broadside coupled stripline resonator [30, 58]. It is particularly useful since it resonates in two distinct modes. The even mode is sensitive to axial variations in permittivity and is used in this application to measure

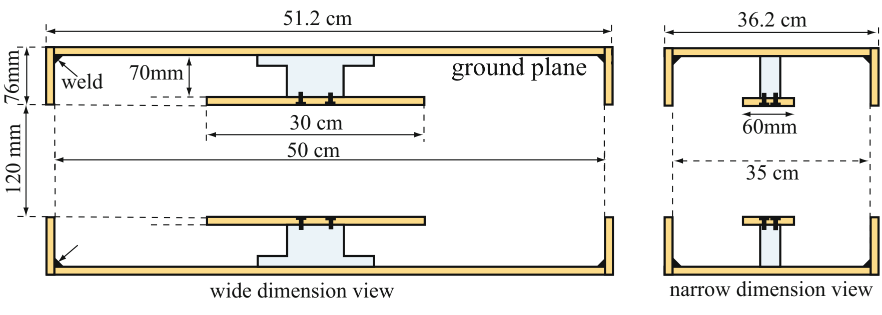


Fig. 7 Open transmission line sensor with dimensions. (Reproduced with permission from Open Resonator Microwave Sensor System for Industrial Gauging, N. Ida, The Institution of Engineering and Technology, 2018, ISBN 978-1-78561-140-7)

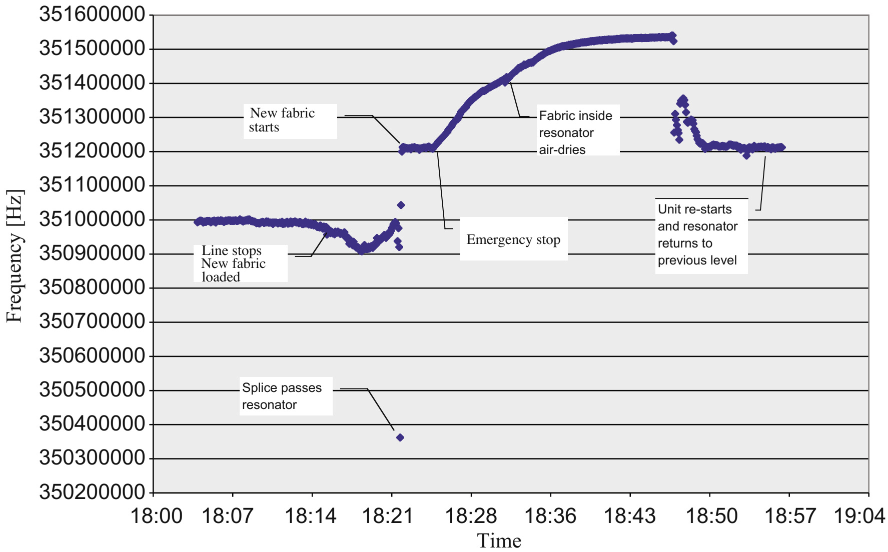


Fig. 8 Resonant frequency measured over time. (Reproduced with permission from Open Resonator Microwave Sensor System for Industrial Gauging, N. Ida, The Institution of Engineering and Technology, 2018, ISBN 978-1-78561-140-7)

moisture content. The odd mode is sensitive to variations in directions vertical to the axis of motion of the fabric and is used for compensation of variations in resonant frequency due to temperature and moisture in the sensor.

Figure 8 shows some of the capabilities of the sensor as recorded by the network analyzer on the production line. On the left, the production line is stopped to introduce a different fabric. The lowering of the resonant frequency indicates that during the changeover process the two fabrics, which are attached to each other, present a higher resonant frequency. As the line starts after the changeover, the passing of the stitch is seen as a dot at a much lower resonant frequency (the stitch is an overlap of the two fabrics). Then the new fabric, that either has a lower permittivity or absorbs less of the latex solution shows a higher frequency than the first fabric. Some time after, the line stops and the fabric dries in air. While stopped, the resonant frequency increases (lower permittivity). As soon as the line starts, the resonant frequency returns to the previous value indicating the permittivity of the fabric.

A sensor is only as good as its sensitivity and resolution. The sensor described here has a resolution below 0.02% (for dry latex) given a 10 kHz resolution of the network analyzer. This can be increased at lest by a factor of 10 since the network analyzer is capable of resolving frequencies below 100 Hz but the figure of approximately 0.1% is more than sufficient in this application.

5 Reflection, Transmission, and Scattering Testing Methods

Although the focus of this work is on the more sensitive, more advanced methods of testing, reflection, transmission, and scattering methods form a large part of the available methods [30, 55]. These rely on the basic propagation properties of materials including attenuation, phase delays, and interactions at interfaces. The testing arrangements are simple combinations of antennas and detectors, recording changes in amplitude, phase, and propagation angles. The fundamentals of these tests are shown in Fig. 9. The instrumentation shown is often replaced by a network analyzer used either in reflective or transmission mode. Reflection depends on the properties of the medium and on its surface conditions. In dielectrics, the bulk of the material as well is analyzed although that is better done with a transmission test. In either case, the changes in material properties (dielectric constant, permeability, or conductivity) are related to specific properties of the test environment. The properties tested for may range from simple dimensional quantities to delamination, humidity, contamination, and a host of other conditions. In practice, almost any material property may be related to a change in its electrical properties and hence detectable through transmission or reflection tests. In some tests, a single antenna is used in pulsed mode and serves both for transmission and for reception of the signal in a method akin to pulsed radar although reflection tests are often done at short range. Reflection and transmission can be combined by using a reflector on the opposite side of the sample and recording both the directly reflected signal and the signal that passes twice through the sample. This is particularly useful in cases the reflection coefficient is small.

An example of the use of reflections from an inclusion in a lossy dielectric medium is shown in Fig. 10. This is yet another variation on reflection methods in that use is made of two receivers and the signal of one is subtracted from the other

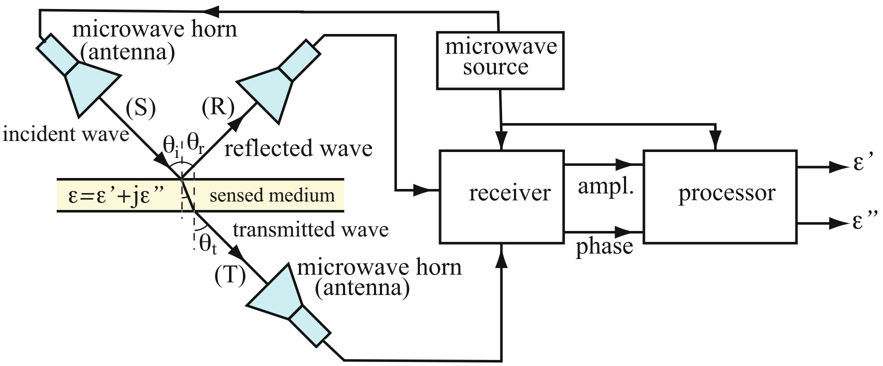


Fig. 9 Test method for the complex permittivity of a medium. Either the reflection or transmission method may be used

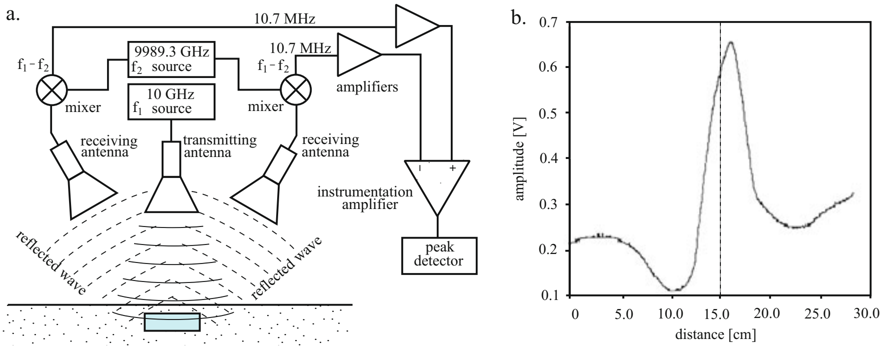


Fig. 10 (**a**) Detection of buried plastic (dielectric) mines using a differential reflection method. (**b**) The signal obtained from a scan across the dielectric shows a peak at the center of the dielectric and two dips indicating its corners

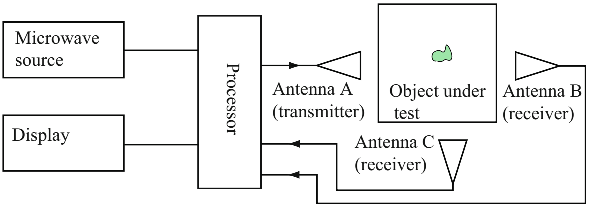
to obtain a differential sesor. This results in reduced noise levels and in emphasis on changes in permittivity. It therefore is more sensitive to the edges of the inclusion.

The configuration in Fig. 10 has been used as a simple, near-surface ground penetrating radar (GPR) but the basic idea also has applications in mine detection or buried pipelines and other utility structures or in archaeology. The transmitted (center) signal is low (about 100 mW) at approximately 10 GHz. The transmitter and receiver are at the same height from the surface and can vary according to needs. The signal in Fig. 10b was obtained from a height of 30 cm but higher resolution may be obtained at closer range. The transmitted signal penetrates into the groung and is reflected off any discontinuity such as buried objects. A large reflection due to the surface of the ground is also present. The two receivers receive the signals and these are subtracted to eliminate common mode features such as the reflection due to the ground surface. For this reason, the edges of the object in Fig. 10a can be seen as large dips in Fig. 10b whereas away from the object the signal is low. In this particular case, the wavelength is approximately 3 cm hence the expected resolution is of this order.

6 Radar Methods

Radar and radar-like methods in NDT can be traced to the first use of scattered fields for testing. An early use can be seen in Fig. 11. In an attempt to increase sensitivity to small defects and delaminations in composites and dielectrics, which provide little changes in either reflection or transmission, the scattered field at right angle is used for detection. Although this field is also small it only exists if a flaw exists and hence its detection is improved. In Fig. 11, antenna B can be used for a transmission test whereas antenna C is used for scattering text. If the signal is pulsed, antenna A can also be used for reflection testing.

Fig. 11 Detection of defects or inclusions by a scattering method



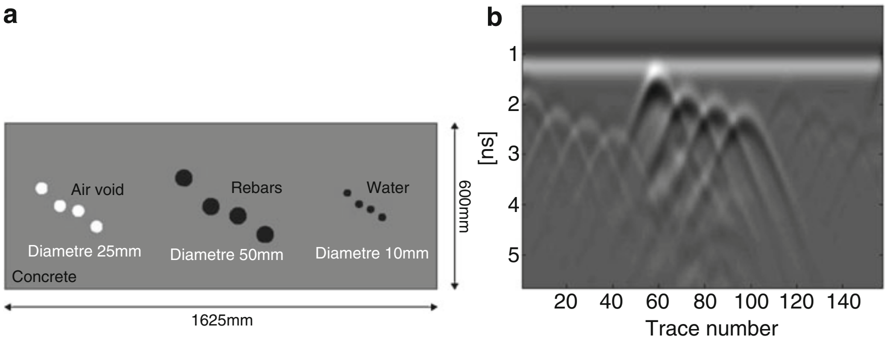


Fig. 12 Simulation of GPR scanning of concrete. (**a**) Various conditions at varying depts. From the surface. (**b**) Signal map of the interaction of waves in the concrete. The thick dark bar is the surface of the concrete [14]

True radar testing has been applied to evaluation of concrete using GPR equipment and techniques. The purpose is detection and evaluation of conditions such as inclusions and cracking but primarily evaluation of the condition of reinforcement steel. This is an important aspect of testing since deterioration of reinforcement bars due to corrosion leads to weakening of the concrete structure and even failure. A simulation of conditions in concrete and the results that can be obtained using a GPR scan can be seen in Fig. 12. It is clear that rebars, being made of steel, will result in large reflections but water inclusions or air pockets are equally detectable in spite of the relatively high loss of concrete. The advantage of using GPR for this type of testing is the speed with which large areas of concrete can be covered. Considering the amount of concrete in infrastructures, this is an overriding condition.

A promising newer approach to radar for use in NDT is the ultra wide band (UWB). UWB refers to the use of a wide bandwidth with reduced power and power density. Typically, a very narrow pulse is transmitted generating the wide spectrum typical of the method. The bandwidth is normally about 25% of the center frequency. UWB radars are very compact, transmit an effective radiated isotropic power (ERIP) of less than –41.3 dB/MHz in the range between 3.1 and 10.6 GHz. The wide bandwidth allows interaction with flaws and material properties over a wide range of frequency, akin to multifrequency testing. Because of the low power and the spread in spectrum, regulatory constraints are minimal, interference is almost nonexistent and resolution increases. The main problem with this type of radar is worsening of the signal–to-noise ratio. From the operational point of view, these radars are inexpensive, available as single-board systems, and some of the signal processing algorithms are also available. Although UWB radars are not new, they have only become small enough and practical in the last few years.

The uses of these radars are still evolving. A common application is colloquially called "see through wall" [16, 59, Pochanin et al. 2024]. Just as in GPR, the idea is to obtain and quantify signals from objects and conditions located behind or within lossy dielectrics. Surface defects have similarly been analyzed using comparative signals [16]. The method has also been applied to aeronautic component testing [60] as well as detection of rebar in concrete (Xu et al. 2013). Other applications include measurement of conditions of walls in salt mines [61] in which depths up to 2 m could be analyzed, as well as others [16, Zhang et al. 2014]. UWB radars operate at low powers and offer high resolution consistent with the high-frequency content of the signals. As such, forms of UWB radars have been applied to medical diagnostics, with particular preference to breast cancer [24–27]. In this particular application, the UWB radar takes advantage of the relatively high contrast between healthy and malignant tissue.

In NDE proper, UWB radar is still in the experimental stages. These attempts use mostly experimental devices [20, 23, Shi et al. 2016, Kidera et al. 2014, Yang et al. 2008].

7 Other Methods

Microwave application in NDT are not limited to those described above. Another method that is used, to a much smaller extent, is microwave radiometry whereby either the background microwave radiation is used (passive radiography) or a source is available (active radiography) [62, 63]. In either case, a radiometer (a device that measure the radiant flux of the source after it passes through the sample) is used. Here too, the types of sensors that can be employed vary and may include bolometers, diodes, or calorimeters to measure the radiant flux [64]. In radiometric microwave methods, the radiated power and its distribution is measured after the radiant flux passes through the test sample. This power is measured by common methods such as bolometers (or bolometer arrays) or diodes. In some cases, calorimetric methods are used. In bolometers and calorimeters, the rise in temperature is measured whereas diodes measure power (or power density) directly.

Although active or passive radiometry may be used, the preference in NDE is for active methods in which the sources can be accurately controlled. In applications where imaging is preferred, either an array of sensors or a scanning sensor is used [65–67]. For surface effects such as surface roughness or flaws, including surface-breaking and near subsurface effect, reflective methods can also be used [68–71]. In general, the higher-frequency ranges are preferred for improved resolution but this is somewhat difficult to attain at present because of the limited availability of sources above about 100 GHz [62, 72, Bakhtiari et al. 2012].

Microwaves are also used as sources of power for other methods of NDT. One common example of this type of use is for pulsed thermography in which the heat is provided by microwave pulses.

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