Microwave and Millimeter Wave Nondestructive Testing and Evaluation

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Abstract

Microwave and millimeter wave NDE is an established method of evaluation with considerable advantages in areas that it applies. While mostly limited to lossy and lossless dielectrics, it has also found applications in surface analysis on conducting media. The number of applications is vast both in established areas of NDE and in emerging methods. The work and methods reported here are limited to the newer emerging methods but also to those that offer unique advantages such as microwave microscopy and in particular resonant methods where the emphasis is on open resonators and industrial scale testing and evaluation. Some common uses of microwaves for testing such as ground-penetrating radar and the

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use of microwaves in thermography are omitted since these are discussed elsewhere. A discussion of the emerging methods of ultra-wideband radar (UWB) testing and radiometry concludes the chapter.

Historical Perspective

From a historical point of view, microwave NDE can be traced back to about 1945 with its first known application to inspection of dielectric materials for their moisture content and foreign objects in sheet dielectrics (Liskow 1948). Although microwaves may be considered a latecomer in comparison with other methods, their use in NDE occurred only a few years after the first microwave systems and equipment came into being following the invention of the cavity magnetron in 1939 and klystron in 1937 (Ginzton 1975) (various types of microwave devices can be traced back to the early 1920s, but the klystron and the magnetron were the first that were produced commercially). Even the waveguide did not exist before 1932. However, the theory of microwaves goes back to at least 1887 (Lord Rayleigh 1897). The same year, Heinrich Hertz, in his experimental proof of propagation of electromagnetic waves, produced waves at 0.6 m (about 500 MHz), well within the microwave frequency range (Cassidy et al. 2002) (Hertz used a pulsed source, and although the fundamental frequency of the pulses is not known, it is estimated anywhere between 50 MHz and 1 GHz). As equipment became more widely available and the understanding of the interaction of microwaves with materials increased, so did applications of microwaves for nondestructive testing and evaluation. It is common to mark the beginning of this trend with a paper by Hochschild (Hochschild 1963), but it should be remembered that the progression was gradual with many applications and publications before 1963 (Leonard and Stropki 1961; Soohoo 1962).

Initial applications of microwave techniques to NDE came slowly and tentatively by taking advantage of the effects substances such as water and variations in properties such as density or thickness have on propagating waves. These attempts were a direct outcome from measurements and work on radar. Only later, starting in the early 1970s, was it recognized that microwaves could be used to detect flaws such as voids and delaminations in composites (Decreton and Gardiol 1974; Bachtiari et al. 1994; Ghodgaonkar and Ali 2000) and for testing of ceramics (Bahr 1978). With the increased acceptance of microwave testing came a new generation of researchers that advanced the science behind and the application of microwave NDE. The first microwave devices can be traced to the use of the crystal diode in the early 1930s, but the real impetus came in the 1960s with the development of negative resistance devices and field-effect transistors (*FETs*). The use of gallium arsenide (*GaAs*) and indium phosphide (*InP*) have also benefited this aspect of solid-state device development by advancing the frequencies at which these devices could operate and eventually lead to microwave integrated circuits.

Passive devices were developed in parallel with the development of microwave sources. These include a variety of antennas, couplers, filters, attenuators, waveguides, cavity resonators, absorbers, terminators, rotators, and many others.

Microwave circuit development followed steps similar to other circuits at lower frequencies. As examples, the idea of heterodyne receivers was used starting with the earliest radar equipment, while microwave integrated circuits find applications in many communication systems.

Developments in microwave equipment and in particular the availability of the network analyzer starting in the 1970s have also contributed greatly to this trend so that by the late 1970s the method was recognized as a viable and useful method for a wide array of tests and measurements in a variety of materials with emphasis on dielectrics (Hochschild 1963; Ash and Nichols 1972; Bachtiari et al. 1994).

A common thread in the development of microwaves for NDE is that much of that happened in conjunction with communication and the NDE/NDT community has gained considerably from this synergetic link. It meant that equipment as well as processing algorithms were largely available and could be adapted to the NDE environment. That is not to say that the adaptation is trivial. For example, ground-penetrating radar, a common NDT/NDE method for assessment of concrete, borrowed freely from radar principles and processing methods, but the method today resembles very little a classical radar system (Joongsuk and Nguyen 2005; Han and Nguyen 2007; Yang et al. 2017; Travassos 2007).

Overview

Microwave nondestructive evaluation is the art of testing of materials and quantifying the results of testing using microwaves as the source of energy. Unlike many other NDE methods, which were developed specifically for testing, microwave NDE is an extension and appropriation of techniques that have matured in disciplines as diverse as radar and communication but also in radiometry, antennas, and methods of analysis, processing, and imaging. As such the method's development is closely linked with developments in diverse areas of microwave work and with components, instrumentation, and methods associated with that work. That also means that often, a method of microwave NDE is simply an application of a measurement, sensing, or detection method for the purpose of testing and evaluation.

Testing with microwaves is dominated by the basic properties of microwaves. Since their penetration in conducting materials is minimal, they are mainly used to test nonconducting materials. This includes dielectric and lossy dielectric materials. Testing and measurements on conducting materials are limited to dimensional testing such as thickness gaging and surface measurements such as testing for surface-breaking flaws, effects on the surface such as corrosion, and surface roughness and surface flaws including those undercoatings. But microwaves are affected by a large number of material properties related to the basic electrical properties: conductivity, permittivity, and permeability. In lossless or lossy dielectrics, porosity, material composition, uniformity of the material, delamination of layers, moisture, and contamination content are only some of the properties that can be measured. The range of nonmetallic materials in which this is possible is extensive and growing steadily. This includes ceramics, plastics, polymers and composites, concretes, as well as organic materials such as wood products, foods, or biological materials. The spatial resolution that can be expected of microwave tests depends on the wavelength of the wave. For microwaves and millimeter waves, the wavelength ranges between 1 m for the lowest microwave frequency (300 MHz) and 1 mm for the highest microwave frequency (300 GHz). This resolution indicates the ability of the test to discern closely spaced discontinuities in the materials at its most basic level. However, more sensitive measurements are possible by correlating them with changes in amplitude or phase and through a variety of techniques that include microwave microscopy, evanescent waveguide methods, and a variety of resonant techniques. This is the case with dimensional measurements where variations in thickness of a few microns are measurable even at the lower end of the microwave spectrum. High-resolution testing can be achieved by scanning of the microwave field and by moving the source. This is similar to synthetic-aperture radar (SAR) methods and can be used for imaging. If this is done in the near field of the antenna, it may even be called "micrometry."

Another particular property of microwave testing is the means by which energy is coupled into the testing environment. This can be as simple as a horn antenna or an open microwave guide. In some other cases, an aperture is used for this purpose, or in the case of microwave cavities, a simple probe or loop serves the purpose. In all cases, the coupling can be done through air or a convenient dielectric, and typically no special treatment or coupling media are needed. While many tests are done in what may be termed the "near-field" environment (close to the antenna or source), measurements in the far field are also possible where the waves propagate through a medium such as air. This is particularly applicable to scattering methods, including radar testing applications.

Because of the influence of so many effects and properties on the wave, the testing environment can be, and often is, noisy. Reflections from near and far surfaces, edges, and other artifacts in the material are often encountered, resulting in noise and loss of resolution. Microwave radiation is highly directive, and, because of the short wavelengths involved, the devices used are often very compact. While many of the applications are in high power communication and radar system, low power applications are just as common.

Of primary interest in this work is the interaction of microwaves with materials and components. This takes the form of attenuation (scattering and absorption) in materials, reflection, and resonance. These effects are exploited in various testing arrangements to allow for quantitative measurements in materials. The absorption of microwaves in water is well known and widely used in microwave ovens. These ovens depend on this effect because it is typical of the whole microwave range. Thus, while most microwave ovens operate at specific frequency bands because of regulation, they can also operate at other frequencies. The absorption in water can be used either directly or indirectly for testing of moisture and related effects (e.g., curing, drying, or amount of substance). Other materials absorb radiation at specific frequencies. Often, these are narrowbands that allow chemical analysis of materials. These resonant frequencies are extremely useful for material characterization and identification.

Sometimes even traces of materials can alter the resonant frequency of a microwave cavity, leading to the detection of materials in trace amounts. This again may be used for testing or detection. Typical applications of this type are contamination tests and detection of explosives. Because microwaves border on the one hand the high-frequency radio range and on the other the low infrared range, they have properties of both. More than any other frequency range, the microwave range is sometimes analyzed using circuit theory and sometimes using wave theory. Transmission lines are almost always analyzed as distributed parameter circuits, while the aspects of refraction, transmission, and propagation in waveguides are analyzed using wave theory.

The methods that can be brought to bear for NDE in the microwave range are truly vast. The most obvious are those related to propagation of electromagnetic waves: reflection, transmission, and scattering of waves (Kharkovsky et al. 2002). These are often used for evaluation of material properties (Stuchly and Stuchly 1980; Arunachalam et al. 2006; Hughes and Zoughi 2005a, b; Mukherjee et al. 2016; Bois et al. 2000; Peer et al. 2003; Mukherjee et al. 2018) but also for dimensional measurements and detection (Caorsi et al. 2003; Bogosanovic et al. 2012). Scattering and absorption of electromagnetic waves can also be included in this group. Then there are various resonant methods that can and are being used. But there are others. Radar-like methods, including Doppler and SAR techniques, are also applicable. A particularly interesting method is the ground-penetrating radar (GPR), developed specifically for microwave assessment of dielectrics and lossy dielectrics such as soils and concrete (Joongsuk and Nguyen 2005; Han and Nguyen 2007; Yang et al. 2017; Travassos 2007). The heating effects of electromagnetic radiation, loading of open-ended waveguides, or simple probes (antennas) can also be used for various tests (Bakhtiari et al. 1993; Mazlumi et al. 2006; Qaddoumi et al. 2000; Kharkovsky et al. 2011; Jundi and Qaddoumi 2009). Testing and evaluation can be done in the near field (Ghasr 2004; Qaddoumi et al. 2007; Akuthota et al. 2004; Fear et al. 2002a, b), leading to methods that can be identified as microwave microscopy with resolutions well below a fraction of a wavelength (Tabib-Azar et al. 2002; Rosner and Van der Weide 2002; Joffe et al. 2017; Ash and Nichols 1972; Anlage et al. 2007; Ciocan 2000; Ciocan and Ida 2004; Chen et al. 2005) as well as in the far field (Arunachalam et al. 2006; Mukherjee et al. 2018, MTHUU-1). Detection and evaluation can be done on the surface of materials or in the bulk with low or high penetration depending on material properties and frequency (Xu et al.). Imaging, tomography (Broquetas et al.), and inversion (Mukherjee et al. 2016, 2018; Lerosey et al. 2004; De Rosny et al. 2010; Reyes-Rodríguez et al. 2014; Liu et al. 2005) are also possible in dielectrics and composites, and resonant methods are often used for material evaluation and moisture content studies (Ida 2008, 2018; Ida and Bhuyia 2008; Auld 1978; Li et al. 2011; Joffe et al. 2017). In terms of applications, microwaves are best suited for evaluation in dielectrics and low-loss dielectrics such as ceramics, rubber, and plastics (Ganchev et al. 1994; Decreton and Gardiol 1974; Bachtiari and Zoughi 1990) but also in higher loss materials such as concrete, composites, sands, and carbon fiber-based products (Kharkovsky et al. 2002; Bois et al. 2000; Trabelsi et al. 1997; Yang et al. 2017) and in biological media (Stuchly and Stuchly 1980; Fear et al. 2002a, b; Winters et al. 2006; Mehta et al. 2006).

Applications in characterization of dielectric and magnetic properties can take various forms in dielectrics, magnetic materials, mixtures of solid or liquid forms, glasses, foams, resins, and others including concretes of various types. Properties can be monitored for a variety of conditions including moisture content (Ida 2008, 2018; Ida and Bhuyia 2008), porosity, and consistency (Ganchev et al. 1994; Bois et al. 2000; Hughes and Zoughi 2005a, b; Peer et al. 2003; Trabelsi et al. 1997; Mubarak et al. 2001; Decreton and Gardiol 1974). Microwave testing can be used for dimensional measurements (Bachtiari et al. 1994; Anderson 1997; Sayar and Ogawa 2009; Li et al. 2011; Ghasr et al. 2015; Zoughi et al. 2016) with resolutions down to micrometers (Bachtiari and Zoughi 1990; Ganchev et al. 1995; Qaddoumi et al. 2002), detection of conditions such as disbonds and delaminations (Bachtiari et al. 1994; Ganchev et al. 1995; Qaddoumi et al. 1996, 2002; Gray and Zoughi 1997), as well as flaws on surfaces of conductors (Mazlumi et al. 2006; Huber et al. 1997). Applications to metals also include detection of some fatigue flaws, surface roughness, and evaluations of coatings such as paint (Bahr 1981, 1982) as well as corrosion effects on surfaces or undercoatings (Qaddoumi et al. 1997, 2000; Hughes et al. 2001; Ghasr et al. 2005a, b; Mast 2001; Kharkovsky et al. 2006).

Although this would indicate a vast number of effects and applications, these are only a fraction of what is possible with microwave NDE. However in principle most tests can be summarized by the evaluation of permittivity, permeability, and conductivity and anything that affects these three properties, including dimensional parameters.

Energy and Safety Associated with Microwaves

The radiation energy associated with microwaves can be estimated considering the quantum equivalent photon. The energy of a photon is equal to hf where h is the Planck constant ($h = 4.14 \times 10^{-15} ev$). Thus the maximum energy of a photon in the microwave range is roughly $1.2 \times 10^{-3} ev$ (minimum is about $1.0 \times 10^{-6} ev$ at the lower frequency range). This energy is relatively low and is much lower than the energy needed for ionization, that is, the energy is much lower than the energy in molecular links. Thus, because it cannot break these links, it is considered a nonionizing form of radiation.

The danger, if any, from microwave radiation is considered to be primarily due to absorption (causing heating) rather than due to its intrinsic energy. For this reason, the safety levels of radiation are defined on the surface, in terms of power per unit area (W/m2) or (mW/cm^2), in terms of specific absorption rates (SAR) in W/kg, or in terms of electric field intensity [V/m]. Limits on exposure vary from country to country, but in general they follow standards set by various bodies including the World Health Organization (WHO) (WHO 2016), the International Commission on Non-Ionizing Radiation Protection (ICNIRP) (ICNIRP 1998), the International Electrotechnical Commission (IEC) (ITU K.52 2016), the European Committee for Electrotechnical Standardization (CENELEC), national regulatory bodies such as the Federal Communications Commission (FCC) in the US (OET Bulletin 65 1997) standards organizations (IEEE 2002, 2006), and other interested bodies

(International Commission on Non-Ionizing Radiation Protection 2016; ACGIH 2017; SCENIHR 2015). There is some evidence that nonthermal effects of microwave radiation also play a role in safety, but this issue is still controversial and not very well researched. The exposure levels allowed should serve as guidelines only. While there may be no harmful effects due to allowable levels of microwave radiation, as a matter of prudence, one should avoid all exposure to microwave radiation if only because of its absorption effects.

Basics

Some Theory

Microwave testing and evaluation is based on the properties of electromagnetic waves and their interaction with materials in the microwave frequency range. That covers the whole range of effects and interactions from simple propagation in lossless or lossy materials, reflection and transmission of waves across material boundaries, attenuation and phase changes, antennas, and many more including propagation in waveguides and transmission lines and resonance in microwave cavities or transmission line resonators. It is therefore impractical to discuss here the whole electromagnetic theory (Ida 2015). There are however a few concepts that are fundamental to testing, and these are summarized here, assuming the reader is either familiar with the concepts or will undertake their study as necessary. The main reason to discuss these here is to list the concepts that are being used in this chapter.

For a wave to exist and be able to carry power, it must exhibit an electric field intensity **E** [V/m] and a magnetic field intensity **H** [A/m]. Both **E** and **H** are vector quantities, and for a wave to carry power, their vector product must be nonzero. The time-averaged power density (real power density) in the wave is:

$$\mathbf{P}_{av} = \frac{1}{2}\mathrm{Re}\{\mathbf{E} \times \mathbf{H}^*\} \qquad \left[\frac{\mathrm{W}}{\mathrm{m}^2}\right] \tag{1}$$

Power density is a vector as well and indicates both the magnitude and direction of propagation of power. An equivalent relation for propagation of power on a transmission line replaces **E** and **H** by V and I and produces power on the line:

$$P_{av} = \frac{1}{2}\mathrm{Re}\{VI^*\} \qquad [\mathrm{W}] \tag{2}$$

The ratio between the magnitudes of **E** and **H** is called the wave impedance or the intrinsic impedance in which the wave propagates. For the common TEM modes of propagation (see below), the wave impedance is:

$$\eta = \frac{|\mathbf{E}|}{|\mathbf{H}|} \qquad [\Omega] \tag{3}$$

The characteristic impedance of transmission lines is defined using similar concepts and normally denoted as Z_0.

Waves propagate subject to a propagation constant $\gamma = \alpha + j\beta$ where α is the attenuation constant and β is the phase constant. Thus a wave propagating a distance d from the source will experience attenuation and a change in phase as follows (for TEM waves, see below):

$$E = E_0 e^{-\alpha d} \cos(\omega t - \beta d) \qquad or: \qquad E = E_0 e^{-\alpha d} e^{-j\beta d} \tag{4}$$

The first form is in the time domain; the second is written with phasors in the frequency domain. Identical forms apply to the magnetic field, and, in general, **E** can be a function of space. Attenuation is exponential whereas the phase is linear. Both depend on conductivity, permeability, permittivity, and frequency. The quantity βd is called the electric length.

Waves may be transverse electromagnetic (TEM, both **E** and **H** are perpendicular to each other and to the direction of propagation), transverse electric (TE, **E** is perpendicular to the direction of propagation, but **H** has components perpendicular and in the direction of propagation), or transverse magnetic (TM, **H** is perpendicular to the direction of propagation, but **E** has components perpendicular and in the direction of propagation). The type of wave has consequences on all properties of the wave. For example, the wave impedance of TM waves is lower than that of TEM waves, whereas the wave impedance for TE waves is higher than the TEM wave impedance. In general, waves propagating in unbounded space may be considered as TEM waves, whereas waves propagating in waveguides are either TE or TM waves.

The wave propagates at a finite speed called phase velocity, which depends on material properties and mode of propagation. In its simplest form, in a perfect dielectric, the phase velocity may be written as:

$$v_p = \frac{1}{\sqrt{\mu\varepsilon}} \qquad \left[\frac{\text{m}}{\text{s}}\right] \tag{5}$$

where μ is the permeability and ε is the dielectric constant of the medium in which the wave propagates. In most media, the dielectric constant is the real part of the permittivity of the material ε_c:

$$\varepsilon_c = \varepsilon' + j\varepsilon'' = \varepsilon\left(1 - j\frac{\sigma}{\omega\varepsilon}\right) \tag{6}$$

where σ is the conductivity of the medium and $\omega = 2\pi f$ where f is the frequency. The ratio between the imaginary and real part of permittivity is a measure of losses in the medium and is called the loss tangent:

$$\tan\theta = \frac{\sigma}{\omega\varepsilon} \tag{7}$$

In real materials, the dielectric constant in (5) is replaced with ε_c, and phase velocity depends on conductivity and becomes frequency dependent. It also depends on the type of wave supported in the medium of interest. Permeability is also in general complex.

The wavelength λ associated with the wave is often a convenient quantity to invoke in analysis. It is measured in meters and may be written simply as:

$$\lambda = \frac{v_p}{f} \qquad [\mathrm{m}] \tag{8}$$

At the interface between two media with different material properties, part of the wave reflects with a reflection coefficient Γ, and part of it transmits across the interface with transmission coefficient T. Given incident electric field intensity $E_{\mathrm{inc.}}$ propagating in medium 1, Γ and T are:

$$\Gamma_{12} = \frac{E_{ref.}}{E_{inc.}} \qquad \mathrm{T}_{12} = \frac{E_{trans.}}{E_{inc.}} \tag{9}$$

The reflection and transmission coefficients depend on the material properties of the two media, on the angle of incidence of the wave and on the polarization of the wave (direction of the electric field intensity) relative to the interface. In transmission lines, the reflection and transmission coefficients depend on the load and characteristic impedances, which in turn depend on material properties.

Propagation of waves in waveguides (hollow metallic structures of a defined cross-section) is governed by the basic relations, with the additional effects of conducting surfaces including reflections of these surfaces, attenuation due to losses in the walls, and geometry of the waveguide. The waves in waveguides are either TE or TM modes propagating with a phase and attenuation constant that again are different than propagation in unbounded space. Unlike propagation in unbounded space or on transmission line, TE or TM modes can only propagate above a certain frequency, called the cutoff frequency, which depends on the mode and structure of the waveguide. Below that frequency the waves are highly attenuated to the point that propagation is not possible.

On most transmission lines, propagation is in TEM mode and can occur at all frequencies. Propagation properties on transmission line are defined similarly to those in space but are typically related to circuit parameters (resistance, capacitance, inductance, and conductance), all defined per unit length of the transmission line and dependent on dimensions and structure of the line and material properties of the line.

Waveguides and transmission lines can also oscillate by simply enclosing a waveguide to form a cavity or by shorting a transmission line. The enclosed structure causes reflections of the propagating waves, and these will interfere constructively to resonate at the frequencies at which such interference occurs. The resonant frequency depends on the dimensions and structure of the resonator and, most critically, on the properties of materials within the resonator.

One of the more common elements of most microwave system and, indeed, of many electromagnetic systems is the antenna. Its purpose is to generate a wave that can then propagate in a medium surrounding the antenna. In fact the concept is very simple – a conductor of a defined shape carrying a time-dependent current will generate around itself an electric and a magnetic field and hence, based on the relations above, a wave. The antenna can take the form of a cylindrical conductor or a loop. Of course, not all antennae are conductors carrying currents. An antenna can be an opening (an aperture) in a waveguide or a cavity resonator (an aperture antenna) or may be a flared termination of a waveguide (a horn antenna). What is important is that the antenna can generate an electric and magnetic field such that the vector product of the two is nonzero. The physical size of the antenna defines its frequency response. In general antennas are very efficient in transmitting power in spite of their simplicity.

In terms of operation, one distinguishes between the near field and the far field of antennas. In the near field, which is defined by distances smaller than a wavelength, antennas behave either as capacitive or inductive devices (depending on the type of antenna). As such, there is no radiation, but there is coupling of energy into the near field. In most cases therefore, the near field of antennas is of little interest except in applications where one needs to couple energy into a system. Examples of these are the coupling of energy into waveguides or cavity resonators. In such cases, a short wire or a loop serve the purpose although they are usually called probes rather than antennas. The far field of antennas is that region that is much further than a wavelength (at the frequency the antenna operates) and is characterized by radiation based on the relations above.

Antennas come into a bewildering variety of types, sizes, and shapes. They may be designed for specific applications or general purpose and may be directional or omnidirectional, low or high power, resonant or broadband, and so on. Antennas are often integral with circuits and may be no more than a trace on a printed circuit board or may be massive installations of reflectors and control machinery to track signals. However, they all operate on essentially the same principles. In addition, all antennas can serve as transmitting or receiving elements based on the duality principle in antenna theory (Stutzman and Thiele 2013; Balanis 2005; Ida 2018).

Instrumentation

One of the perennial issues associated with microwave NDE is that of instrumentation and circuits. When one thinks of a circuit, the classical electric circuits come to mind. But at microwave frequencies, electronic circuits are less useful than at lower frequencies. Often one deals with devices that are foreign to most test technicians. Signals are generated using microwave tubes or through harmonic generators and are propagated over transmission lines, over waveguides, or through air. Coupling of power into a test environment is done with an antenna (classical antennas or probes, horn antennas, apertures in waveguides, or cavity-backed apertures). Detection and quantification of power may be done with diode detectors, thermistors, bolometers, or, in some cases, using calorimetric methods, especially at higher power levels. Simple components such as attenuators, phase shifters, and couplers are likely to be made of various types of transmission line circuits. Then there are circuits and components unique to microwaves such as directional couplers, splitters, isolators, and circulators. All of these are available commercially and allow the practitioner to assemble the circuits required for useful tests. As a consequence, the resulting instruments tend to be bulky with little flexibility in construction and often quite expensive. Mechanical assembly of the various components is required and must be exact to eliminate losses and unwanted signals due to reflections of waves from discontinuities, poor connections, and cables. Mastering microwave devices is a rather specialized endeavor that takes time and resources and must be undertaken very carefully.

Fortunately one can lighten some of these issues through the use of network analyzers. A network analyzer is a specialized instrument of considerable complexity, but in its most fundamental form, it can be thought of as a microwave source that can be coupled to the test environment by some means, a detection mechanism that can detect and quantify signals received from the environment and a computer to drive the measurement and compute measurement parameters. In practice it is much more than that. The source itself can be scanned over a large frequency range and at exact and variable power levels with great accuracy. The measurement can be any of a number of different possibilities, some of which are pre-programmed into the onboard computer, but in most cases, it is based on the so-called S-parameters. The latter are the reflections from both ports of the network (S_{11} and S_{22}), transmission from the input to the output (S_{21}) and from the output to the input (S_{12}) (Rohde and Schwarz 2007; Wu 2007). These four parameters allow complete analysis of a linear two-port network connected to the analyzer. From these, one can obtain, again with the aid of the analyzer, other parameters and test results including resonant frequencies (Ida 2018; Das and Das 2000; Pozar 1998), frequency response, material properties (Weir 1974; Nicholson and Ross 1970; Kadaba 1984), and many more (Dunsmore 2012; Godgaonkar et al. 1990). Vector analyzers are either scalar (measure amplitudes only) or vector (measure amplitudes and phase) and in frequency ranges from sub-GHz to well in excess of 150 GHz. Although the typical measurement assumes a linear network, nonlinear measurements are also possible as are measurements in space, where the network is not clearly defined.

Interaction with Materials and General Setups

As mentioned in the introduction, some of the most common and most useful microwave methods rely on the reflection, transmission, or scattering of microwaves. These include simple arrangements of sources, antennas, and detectors or may be as complex as a radar system. In all cases, however, advantage is taken of the fact that the reflection, transmission, or scattering of electromagnetic waves is affected by the properties of the medium and hence may be used to evaluate its state including evaluation of material properties and conditions of the medium. The basic methods of reflection and transmission are shown in Fig. 1 in which both methods are used to analyze the complex permittivity of a medium. The incident wave is transmitted at an angle, and both the reflected and transmitted waves are used to evaluate the dielectric constant and the loss tangent of the medium through the use

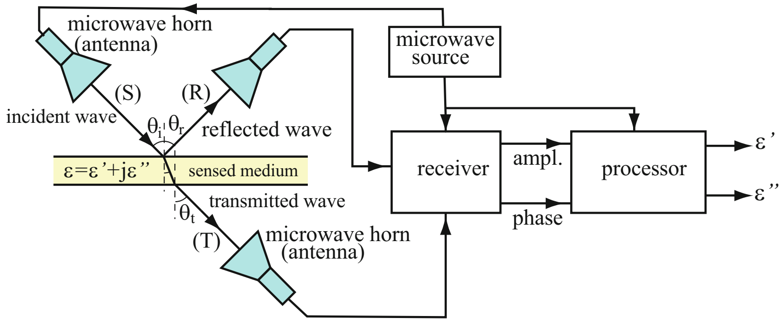


Fig. 1 A generic method of evaluation of the complex permittivity of a medium

of amplitude and phase measurements. The instrumentation shown can be and often is replaced by a network analyzer for simplified and accurate measurements. In many tests, only the reflected or only the transmitted waves are required, and these can be accomplished through a variety of arrangements as shown schematically in Figs. 3 and 7.

Reflection Tests

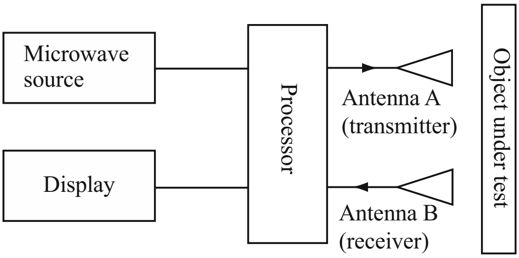
A basic reflection test is shown in Fig. 2. The incident wave is produced by a source and coupled through an antenna. The waves are reflected off the material either completely (as for conductors) or partially (as for dielectrics and lossy dielectrics). The reflected wave is received by an antenna (antenna *B* in this case). The processing module in Fig. 2 identifies the two parts of the wave and produces the required display. This may be any of the effects on which reflection depends. In most cases, the changes in the dielectric constant or changes in losses (loss tangent) are correlated to a particular property. This may be as simple as thickness of the material, variations in dielectric constant (e.g., delamination), moisture content, contamination, and a variety of other parameters. In fact, almost any material property can be identified with some change in the reflection coefficient. In many cases, the source processor and display are accomplished through the use of a network analyzer, in the present application operating in reflection mode.

For simplicity, we have used two antennas: one for transmission and the other for reception. However, any transmitting antenna can also be used for reception, and in pulsed mode, the same antenna can serve both functions. The separation of the two waves can be done by directional couplers or, in some cases, not done at all, and measurements are performed on the total wave. There are many variations on this simple test, but in all cases one can distinguish between an incident and a reflected wave.

Three practical methods of reflection tests on dielectrics are shown in Fig. 3. The configuration in Fig. 3a or a variation of this can also be used on conducting surfaces. Figure 3b shows the use of a reflection test for coating and undercoating effects.

A simple example of the use of reflected waves for the detection of dielectric inclusions in a lossy medium is shown in Fig. 4a. This particular application relates

Fig. 2 A basic reflection test



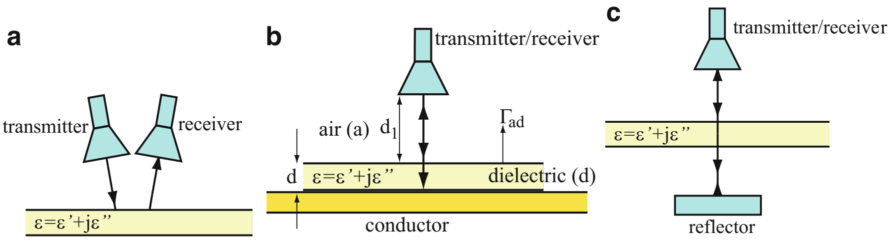


Fig. 3 Reflection tests on a dielectric. (**a**) Both antennas on one side, (**b**) reflection test on a conductor-backed dielectric, (**c**) the use of a reflector to reflect the signal

to detection of nonmetallic, antipersonnel mines buried in shallow soil. The central antenna transmits a 100 mW microwave at 10 GHz, from a height of 35 cm above the surface of the ground. The transmitted signal is partially reflected by the ground surface and partially transmitted into the ground and again partially reflected by the dielectric. The reflections are received by two antennas feeding two receivers after heterodyning. In this simple application, the output is simply the difference between the outputs of the two channels. The measurement in this case is greatly simplified by the fact that the primary function is detection rather than evaluation or imaging and by the fact that the measurement is differential and hence common mode effects such as ground clutter and noise are practically eliminated. The signal in Fig. 4 shows that the dielectric is approximately at the center of the 30 cm horizontal scan. The wavelength at 10 GHz is 3 cm, and one would expect to be able to detect the edges of the dielectric provided it is larger than a wavelength. That in fact is the case if the antennas are in much closer proximity (say at ground level). In this case, the need to clear obstacles on the ground dictated a higher clearance, and the edges can be seen as the broad dips on the two sides of the peak. The diameter of the dielectric is 12 cm corresponding well with the two dips even though they are not sharp.

In most testing applications, a more robust method is needed, that is, one requires exact values and correlation of these values with a property or condition in the material. In such cases, a network analyzer is likely to be used for both the transmitter and receiver, and the correlation is done through the measurement of the S-parameters. A schematic example is shown in Fig. 5, which shows a free-space measurement of permittivity using either a reflection test or, for that matter,

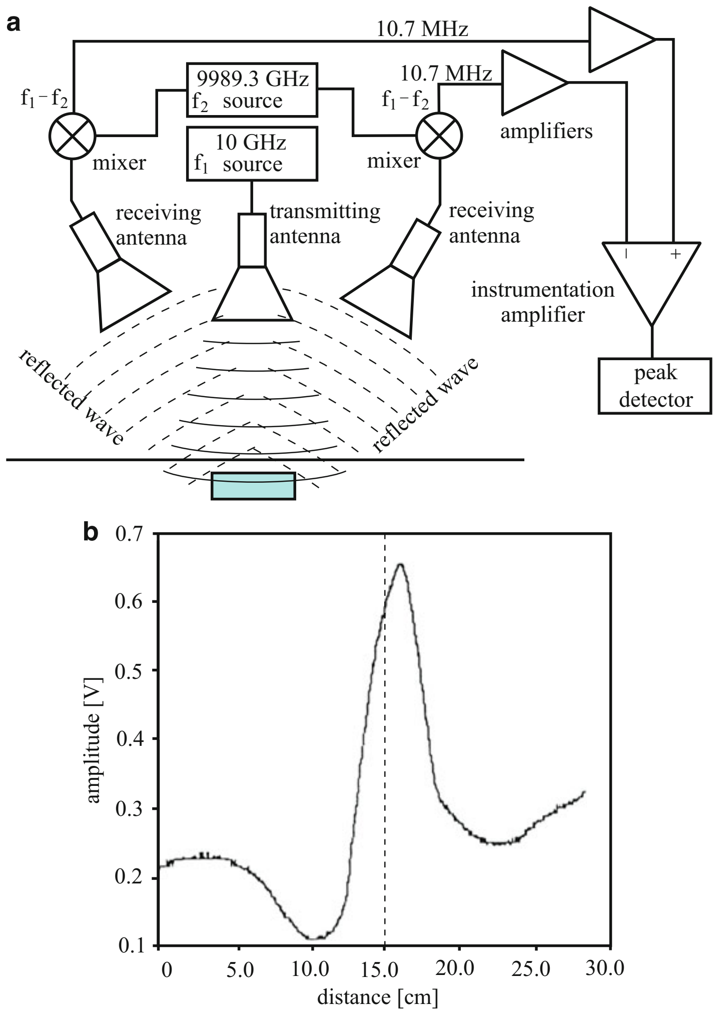


Fig. 4 (**a**) Detection of buried objects using a differential reflection method. (**b**) The signal obtained shows a peak at the center of the dielectric and two dips indicating its corners

a transmission test. The network analyzer measures all four S-parameters from which the reflection and transmission coefficients are calculated, and these correlated with (primarily) material properties. This approach can be used in many configurations, and because the network analyzer can remove undesirable effects such as those caused by the sample holder, measurements can be very accurate.

Transmission Tests

Transmission tests rely on measurements on the transmitted wave. This is shown schematically in Fig. 6 (see also Figs. 1 and 5). The transmission coefficient also

Fig. 5 Transmission test

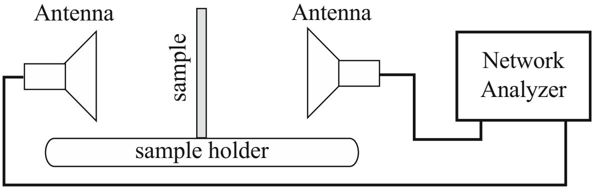
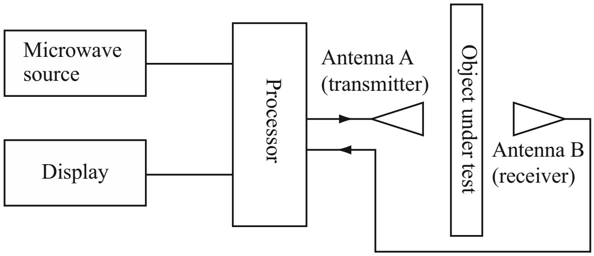


Fig. 6 A basic transmission test



depends on material properties as the reflection coefficient. However, transmission tests are sometimes easier to perform or to correlate to material conditions. Attenuation measurements are also transmission tests and are often used for evaluation of lossy dielectrics. The basic modules of the test are the transmitting and receiving antennas and associated instrumentation. Processing is similar to that done for reflection tests. There are some cases for which only one of the tests is practical. For tests on conductors (such as thickness gaging), only reflection tests are possible. Since the transmission is negligible, it is not possible to use it for testing. Similarly, if the reflection coefficient is very small, especially for low-loss dielectrics, the transmission test might be more effective (Fig. 7).

An example of a transmission test to sense a variety of effects including thickness, water content, losses, and variations in permittivity caused, say, by density variations, delamination, or bulk inclusions is shown in Fig. 1 with only the source (S) and transmitted (T) antennas present. In this configuration, amplitude and phase of the received signal are compared with a reference signal from which the transmission coefficient can be calculated leading to information on the material under test. With proper calibration accurate measurements are possible although, as was the case with transmission tests, only bulk properties can be analyzed.

Scattering Tests

Both reflection and transmission are properties associated with the bulk of the material. Scattering, as understood in the context of testing of material, on the other hand, is associated with local conditions in the material. While any variation in the material will affect both the reflection and transmission, we will view scattering as an indication of local effects such as flaws, inclusions, delaminations, surface roughness, etc. We also include radar and similar effects with scattering. The two basic tests associated with scattering are shown in Figs. 8 and 9. In Fig. 9, the scattered field is picked up by antenna *C*. This antenna will pick little or nothing

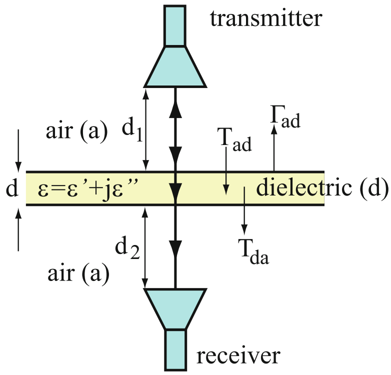


Fig. 7 Transmission test on a dielectric

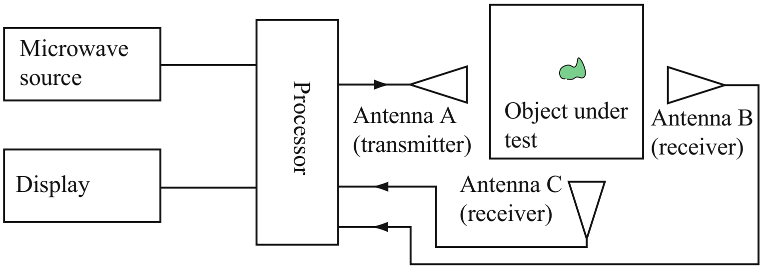


Fig. 8 Scattering test for inclusions or flaws in dielectrics

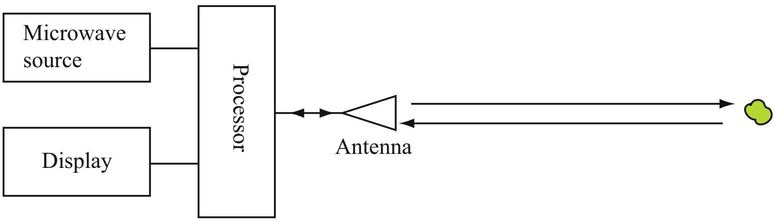


Fig. 9 Scattering test using a monostatic radar method

unless there is scattering within the test sample. Normally, only reflection and transmission will exist. Transmission is detected by antenna *B*, while reflection can be detected by antenna *A* or, perhaps, a separate antenna as in Fig. 1. This type of measurement can be used to detect scattering by foreign objects or sharp variations in material properties such as delaminations inclusions or interfaces between different materials. The second type is the basic radar system and is shown in Fig. 9. Here the pulsed radar method is shown although other radar methods can be used. In *NDT*, the pulses as scattered and picked up by the antenna are correlated with the location, size, or properties of the material.

Scattering methods of particular interest are those associated with radar. Probably the best known of these methods is the ground-penetrating radar (GPR) which was mentioned in the introduction. This will not be discussed here, but it and its use in NDE is the subject of a separate chapter in this handbook. Nevertheless, it should be noted here that GPR is a common method of assessment of concrete structures whereby rebars, inclusions, cracks, delaminations, and other effects can be detected and imaged in near real time and over large areas. There are however uses of radar in NDE which, although similar or related to GPR, are nevertheless sufficiently different to be discussed here. One relatively new and useful radar in some applications is the ultra-wideband (UWB) radar, as discussed below.

Microwave Microscopy

Microwave microscopy allows the quantitative measurement of properties below the scale of the wavelength expected from the wavelength. In most microwave systems, one can only detect variations in, say, material properties or dimensions of artifacts that are of the order of the wavelength, as was discussed in the introduction. However there are two methods that allow, under certain conditions, the detection and quantitative evaluation of properties well below the wavelength limit. One is to test the material in resonant cavities. In this approach, the shift in resonant frequency, especially when measured with high precision instruments such as network analyzers, can detect variations in dimensions of the order of micrometers at test wavelengths of the order of 1 m. This will be discussed in the following section. A second method, which is usually called microwave microscopy, involves the interaction of the microwave probing energy in the near field of the source where the spatial frequency is high (Anlage et al. 2007; Rosner and Van der Weide 2002; Joffe et al. 2017). In many cases this involves evanescent waves that interact with the material under test in a highly localized manner. There are a few additional conditions that must be satisfied. First, it is implicit that evaluation is done at relatively high frequencies. Second, because the very localized interaction, the test sample must be scanned in some pattern. Related to that, it is also clear that only small sections of a sample can be realistically scanned. Therefore the method is useful for localized testing and for that reason has been in the past limited to laboratory use and to specialized tests. Although the original development of microwave microscopy was to allow evaluation of material properties, especially permeability (Acher et al. 1996; Ustinov et al. 1999; Ciocan 2000), it can be used as well for dimensional tests such as surface flaws in conductors (Ash and Nicholls 1972; Tabib-Azar et al. 2002).

In most cases, microwave microscopy instruments consist of a sub-wavelength sensor or antenna that constitutes the microscopy in the instrument. This can something be as simple as an open waveguide, an open-ended transmission line, or a tip as shown in Fig. 10. In all three cases shown, use is being made of the fact that fields at an open waveguide or transmission line decay rapidly generating the required high spatial frequency. These features may be viewed as very small antennae. The fields from the aperture or tip interact with the sample. Some of the

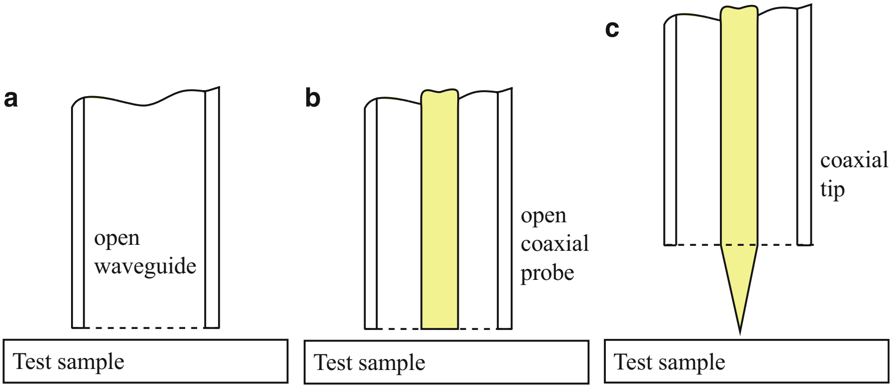


Fig. 10 Simple microwave microscopy probes. (**a**) Open waveguide. (**b**) Open coaxial probe. (**c**) Coaxial tip

energy in the fields is reflected; some is scattered. One monitors either the reflected fields or the scattered fields as a function of probe position to generate a measurement or an image of the sample properties. This type of probe is called a nonresonant probe. The analysis of the fields due to any of the probes in Fig. 10 can be done numerically using appropriate simulation software. Approximate analysis (Anlage et al. 2007) relies on a passive network that attempts to replace the probe by capacitances to account for the coupling with the sample and impedances to account for stored and dissipated energy. The near-field impedance of the probe due to the presence of a homogeneous sample can then be approximated as:

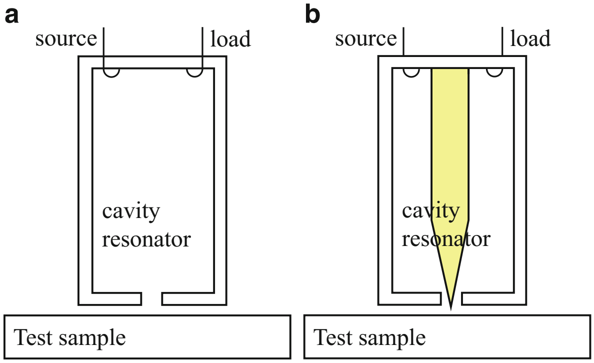
$$Z_s \approx \frac{1}{j\omega\varepsilon_0\varepsilon_s v} \tag{10}$$

where ε_s is the complex permittivity of the sample and v is the volume of the sample in the near field of the probe.

More sensitive instruments use either an aperture in a cavity resonator or a tip in conjunction with a cavity resonator. Figure 11a shows an aperture in a cavity resonator which can be scanned over the sample. Since the cavity is open to the outside, the interaction is through perturbation of the cavity and the resulting shift in the resonant frequency of the cavity. Figure 11b is a modified rectangular resonator (coaxial resonators can also be modified), in which the central conductor extends into a tip outside the cavity to interact with the material. Its operation is similar to that of Fig. 11a, but it is usually more sensitive because of the more localized effect of the tip. In either case, the shift in resonant frequency is due to the perturbation of the cavity. This shift may be written as:

$$\frac{f - f_0}{f} = -\frac{\int_v \Delta\varepsilon \mathbf{E}\cdot\mathbf{E}_0^* dv + \int_v \Delta\mu \mathbf{H}\cdot\mathbf{H}_0^* dv}{\int_v \mu\mathbf{H}\cdot\mathbf{H}_0^* dv + \int_v \varepsilon\mathbf{E}_0^*\cdot\mathbf{E} dv} \tag{11}$$

Fig. 11 Resonant microwave microscopy probes. (**a**) Aperture in cavity probe. (**b**) Tip in aperture probe



where **E and H** are the perturbed fields, $\mathbf{E}_0$ and $\mathbf{H}_0$ are the unperturbed fields, and Δε and,Δμ represent the equivalent change in cavity permittivity and permeability due to the perturbation by the external effects. Although this is a simplistic explanation, it is useful in understanding the shift in resonant frequency of the cavity. In specific cases this can be simplified considerably. For example, in thin films with relative permeability of 1, the shift in resonant frequency can be approximated as (Anlage et al. 2007; Ida 2018):

$$\frac{f - f_0}{f} \approx -\left(\varepsilon_{rf} - 1\right) \frac{\varepsilon_0 \int_{v_f} \Delta\varepsilon \mathbf{E} \cdot \mathbf{E}_{\mathbf{0}}^{*} dv}{\int_v \mu_0 H_{\mathbf{0}}^2 dv + \int_v \varepsilon_0 E_{\mathbf{0}}^2 dv} \tag{12}$$

where v_f is the volume of the film under the influence of the aperture, ε_{rf} is the relative permittivity of the film, and the denominator is the total energy stored in the cavity. Similar expressions can be obtained for other conditions, but it should be noted that these relations could only be used if the fields and volumes can be identified. In practice they serve to understand the behavior rather than to calculate exact resonant frequencies. If calculations are called for, a full-wave simulation is usually necessary.

The first attempts in near-field microwave microscopy came from the Physics community in attempts to characterize permittivity of thin film materials using ferromagnetic resonance (FMR) (Frait et al. 1960) based on even earlier ideas (Synge 1928). The first microwave probe capable of measuring the spatial variation of magnetic properties was proposed in 1962 (Soohoo 1962). The possibility to perform microwave measurements on thin ferromagnetic layers in a magnetic field was demonstrated more recently (Anlage et al. 2007; Acher et al. 1996; Ustinov et al., 1999). Other applications followed, and recently, the method has found applications in NDE (Ciocan 2000; Zoughi 2000; Ida 1992). A thorough review and analysis of the general method can be found in Anlage et al. (2007).

To demonstrate the possibilities in the use of microwave microscopy, consider the simple experimental setup shown in Fig. 12 (Ciocan 2000; Ciocan et al. 2004). In this setup, the magnetic sample (6) was placed over an electromagnet (7) that was

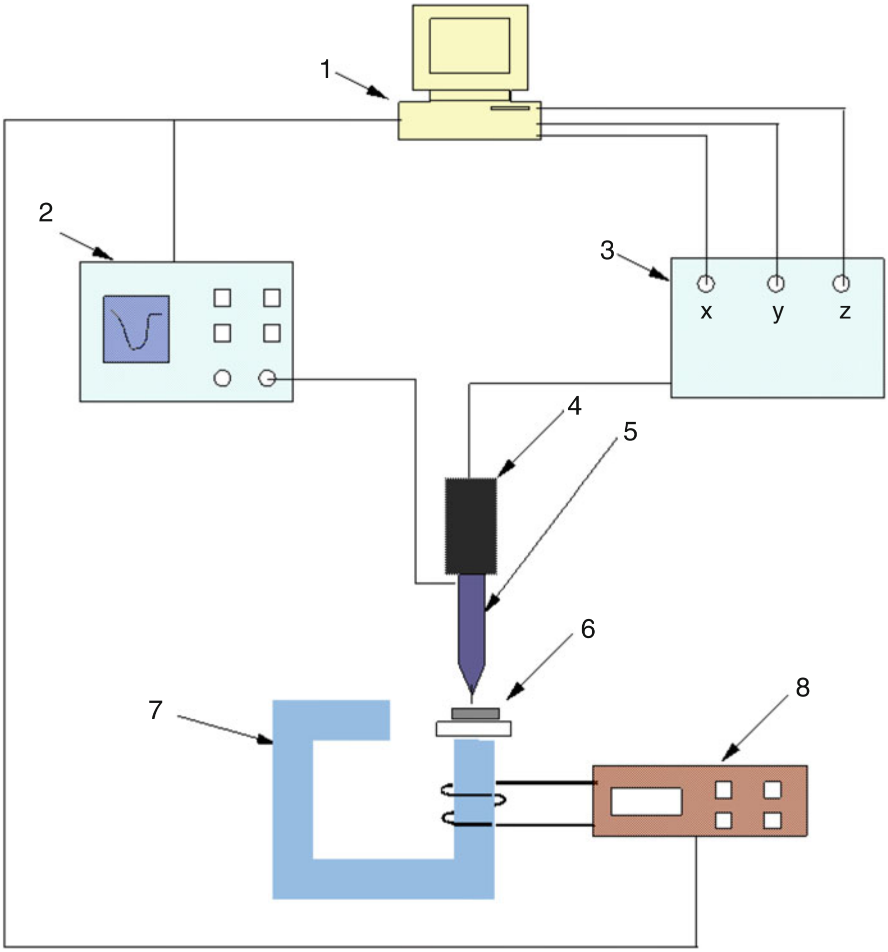


Fig. 12 Block diagram of the experimental setup: 1, computer; 2, network analyzer; 3, stepper motor controller; 4, port-probe assembly; 5, microwave probe; 6, sample; 7, electromagnet; 8, voltage source. (Reproduced with permission from Ciocan and Ida 2004. © 2004 IEEE)

energized by a dc current from voltage source (8). The sample and the electromagnet assembly were located underneath the microwave probe (5). The personal computer (1) controlled the movement of the microwave probe via a stepper motor controller (3). The network analyzer (2) and voltage source were controlled by the computer. The electromagnet used in this work produced 250 Gauss, and its *B* versus *I* characteristics were approximately linear in that range as determined with a Gauss meter.

The microwave probe operated in reflection mode (Ida 1992) whereby its S_{11} parameter was measured by the network analyzer to determine the frequency response of the probe as a function of position over the sample. The probe position over the sample was controlled using micrometers and stepping motors.

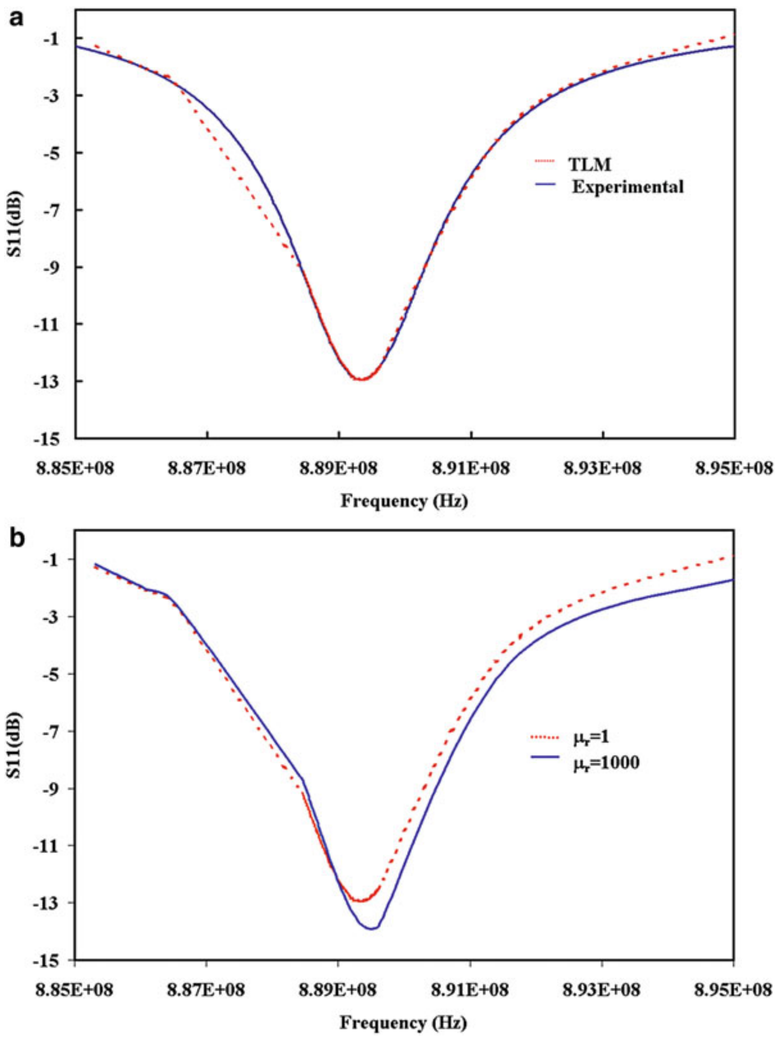


Fig. 13 (**a**) Comparison between numerical (dashed line) and experimental frequency responses obtained in the absence of an external magnetic field. (**b**) Numerical frequency responses obtained in the absence of magnetic field ($\mu r = 1$, dashed line) and in the presence of magnetic field ($\mu r = 1000$ solid line). (Reproduced with permission from Ciocan and Ida 2004. © 2004 IEEE)

Figure 13a shows a comparison between numerical and experimental resonance curves obtained for a CO-NETIC alloy sample in the absence of the external magnetic field (Ciocan et al. 2004). The graph shows good agreement between experimental and numerical data, which was obtained with a transmission line method (TLM) (Ciocan and Ida 2004) indicating that simulation of microwave microscopy is a valid endeavor. To further this point, Fig. 3b and Table 1 show simulated responses for the same configuration showing a shift in resonant frequency

Table 1 Comparison between numerical and experimental data

Type of data	μ_r	Frequency (MHz)	S_{11} (dB)
Numerical	1	889.32	−12.94
Numerical	1000	889.51	−13.91
Experimental	1	889.31	−12.93
Experimental	1000	889.49	−13.90

Table 1 reproduced with permission from Ciocan and Ida 2004. © 2004 IEEE.

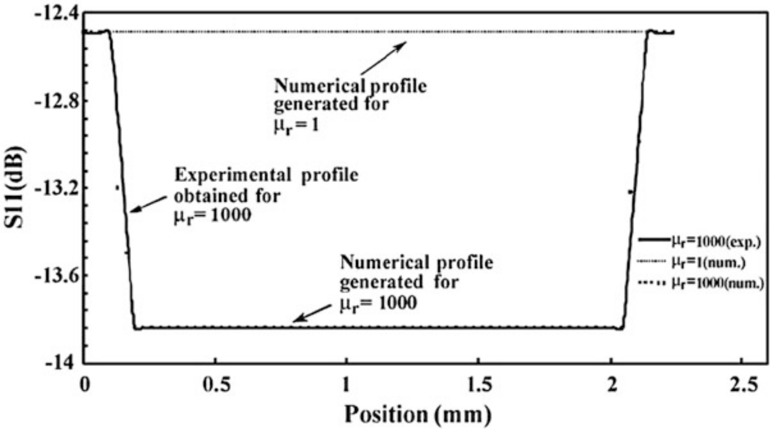


Fig. 14 Numerical and experimental profiles obtained by scanning over a 2 mm sample. Comparison of simulated and experimental results. (Reproduced with permission from Ciocan and Ida 2004. © 2004 IEEE)

of approximately 190 kHz and a 1 dB difference between the tests with the sample present and absent. The experimental data in Table 1 shows very close values – 180 kHz and 1 dB.

To show that the system can detect nonuniformity in magnetization, the values of the S_{11} parameter obtained at 889.61 MHz, when the microwave probe was scanned over a 2 mm sample, are plotted in Fig. 14. The comparison with experimental measurements shows indistinguishable values, an indication of the accuracy of the method. It should however be noted that the scan is over a 2 mm sample. Larger samples can be used, but the scan can take considerable time to perform since it is assumed that measurements are taken with the probe stationary or moving very slowly to avoid distortions in the fields.

Resonant Testing Methods

Resonant methods of testing offer, perhaps, the highest sensitivity of all microwave methods as was also discussed in the previous section. Because what is usually measured is the resonant frequency and the quality factor of the cavity, and the

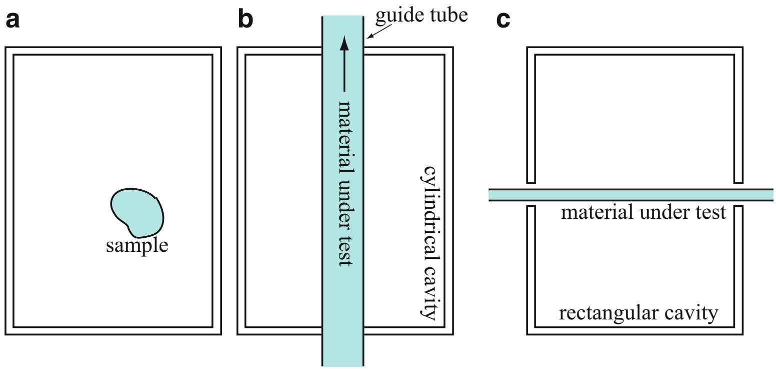


Fig. 15 Testing in resonant cavities. (**a**) A small sample introduced into the cavity. (**b**) A tubular material flowing through a cylindrical cavity. (**c**) Testing of flat sample in a partially open rectangular cavity

quality factor itself can be obtained from frequency measurements, resonant methods of testing can also be quantitatively accurate and mostly noise free. With the use of a network analyzer as the basic instrument in the test, high-resolution tests are the norm. The classical approach is to introduce the test sample in the cavity and measure the shift in resonant frequency due to the sample dimensions and its electric properties from which one or more parameters may be monitored. This is shown in Fig. 15a. That of course is also the limitation of resonant methods – what is being measured are the effective properties of the cavity, and it is rather difficult to distinguish between a flaw in the material and a change in dimensions of the sample from measurements of frequency alone. For that reason, resonant methods should be viewed as measuring the real and imaginary part of permittivity (dielectric constant and loss tangent) and/or the real and imaginary part of permeability. Anything that can be correlated to these properties can then be the subject of testing. One can envision testing for diverse properties from dimensional changes to density, but the most common use is in monitoring of moisture content and properties that can be related to moisture content such as curing or drying of substances.

Of course, the configuration in Fig. 15a is limited to small samples that can fit in a cavity. It also suffers from limitations in access to the cavity and positioning of the sample in the cavity reducing its usefulness as a practical test method to a limited number of applications. However, cavities do not have to be closed entirely. Figure 15b and c show possible ways by which test material may be introduced into cavities either for testing of samples or for continuous monitoring on a production line. In Fig. 15b the material is introduced through appropriate openings in the cavity, such as a thin dielectric tube to allow movement of the material in the cavity. The cavity shown is cylindrical, assuming the material under test is itself cylindrical, but other arrangements and cavities are possible. In Fig. 15c, the cavity is split in two forming a small gap between the lower and upper halves to allow insertion and movement of the test material, in this case thin flat samples such as sheet products (wood, plastics, or fabrics). Resonators may also be made with transmission lines so that they are open (Ida 2015, 2018; Pozar 1998) in many useful configurations. However, the configuration in Fig. 15a is the simplest to analyze using the perturbation method mentioned above and hence affords understanding of what one can expect from resonant methods. Eq. (11) shows the shift in resonant frequency of a cavity if the permeability and permittivity in the cavity change by $\Delta\mu$ and $\Delta\varepsilon$ assuming the change occurs throughout the cavity (Fig. 16b). This would be the case, for example, where the cavity is used to sense a gas or monitor humidity. The permittivity in Eq. (10) may be replaced with a complex permittivity ε_c to take into account lossy materials:

$$\varepsilon_c = \varepsilon' + j\varepsilon'' = \varepsilon' - j\frac{\sigma_s}{\omega} \tag{13}$$

Equation (10) now becomes (Ida 2018):

$$\frac{f - f_0}{f_0} = -\frac{\int_v \left[\left(\Delta\varepsilon' - j\dfrac{\Delta\sigma}{\omega}\right)\mathbf{E}\cdot\mathbf{E}_0 - \Delta\mu\mathbf{H}\cdot\mathbf{H}_0\right]dv}{\int_v [\varepsilon_0\mathbf{E}\cdot\mathbf{E}_0 - \mu_0\mathbf{H}\cdot\mathbf{H}_0]dv} \tag{14}$$

where, again, the change in permeability may be null or it may be complex. In the denominator, ε_0 and μ_0 are the properties of the empty cavity.

The quality factor may be equally computed from its definition as the peak stored energy divided by the energy dissipated per period:

$$Q = 2\pi\frac{\textit{Peak stored energy}}{\textit{Energy dissipated/per period}} \tag{15}$$

Assuming power is lost only in the dielectric, the Q-factor is:

$$Q = \frac{\int_v \varepsilon_0 {E_0}^2 dv}{\int_v [\varepsilon''\mathbf{E}\cdot\mathbf{E}_0]dv} \tag{16}$$

The Q-factor may in fact be measured by measuring the bandwidth of the cavity:

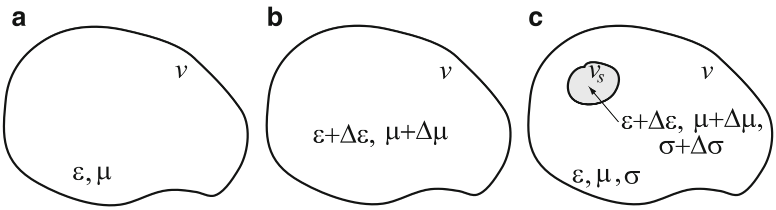


Fig. 16 The concept of cavity perturbation. (**a**) Unperturbed cavity. (**b**) Whole cavity perturbation, lossless material. (**c**) Perturbation by small sample of lossy material

$$Q = \frac{2\pi f_0}{BW} = \frac{f_0}{f_u - f_l} \tag{17}$$

where f_u is the upper half power frequency and f_l is the lower half power frequency of the cavity. Clearly then all that is necessary is to measure the frequency response of the loaded cavity w and empty cavity f_0 to obtain the shift in resonant frequency and the Q-factor. Measurements of the shift in resonant frequency $(f - f_0)$ then provide a measure of the change in material properties, whereas measurement of the Q-factor is a measure of losses in the cavity. From these one may infer the change in properties due to introduction of the material in the cavity.

So far it was assumed that the sample fills the cavity. This is not necessarily the case as can be seen in Fig. 15b and c. If the sample only fills a small section of the cavity (see Fig. 16c), the integral in the nominator in Eq. (14) and in the denominator in Eq. (16) only extends over the volume of the small sample. Although calculations using these equations are obviously difficult, from a testing point of view, they show what changes as material properties change.

Testing in Microwave Cavities

The testing configuration in Fig. 16a is perhaps not as common as other microwave methods, but it can afford as simple method of evaluation of material properties of samples of materials as these depend on frequency, especially when these materials are lossy, mixtures, anisotropic, or nonlinear and a bulk equivalent permittivity is needed, perhaps as a means of verification of other tests. To see the utility of this method, the following shows some simulations of lossy samples in cavities.

Monitoring of Moisture

Because the resonant frequency of the cavity is due to the whole volume of the cavity, the method is particularly useful in testing and monitoring of material parameters rather than, say, flaws or individual inclusions. The latter will also change the resonant frequency, but localization of defects cannot be done directly, and flaws cannot be distinguished from changes in material properties unless additional testing is done, often using other methods. However, the method is particularly useful in detecting or monitoring changes in material properties over the whole sample or over the whole volume of the cavity. Consider as an example the monitoring of moisture content in a fabric coated with latex on the production line (producing tire belts). The fabric is nylon, polyester, or aramid and is coated with latex in a water solution. The purpose of monitoring is twofold. First it monitors the drying process. More importantly it monitors the amount of solids left as a coating on the fabric after drying to ensure proper coating and hence the performance of the fabric in tires. In the application described here, the resonant sensor was used to control the amount of latex during production. The resonant sensor is shown in Fig. 17. It consists of two

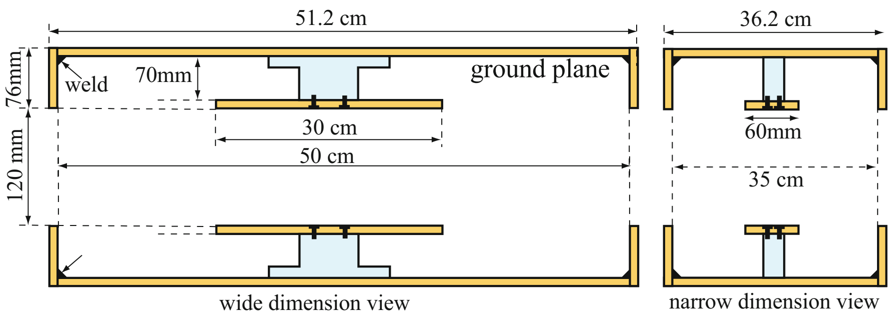


Fig. 17 Final dimensions of the sensor with internal dimensions of 50 cm by 35 cm. The center plates are 30 cm by 6 cm and are flush with the shield. The separation between the two halves is 120 mm to allow ample space for the fabric. The two probes are used for reflection and transmission measurements. (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)

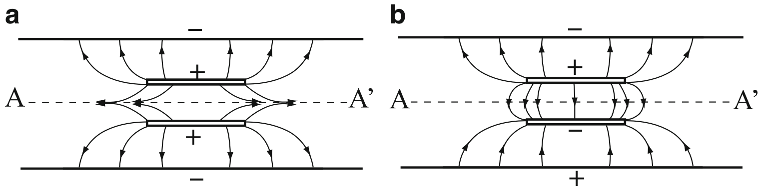


Fig. 18 Fields in broadside-coupled striplines. (**a**) Even mode. (**b**) Odd mode. (Reproduced with permission from Open Resonator Microwave Sensor System for Industrial Gauging, N. Ida, The Institution of Engineering and Technology, 2018, ISBN 978-1-78561-140-7)

open metal shields 50 cm by 35 cm by 7 cm and two center plates 30 cm by 6 cm isolated from the shields using Teflon blocks. Two probes (short antennas) penetrate through the upper shield to couple to the upper central plate. These are connected to a network analyzer to the source and load ports so that both the reflection and transmission properties may be monitored using *S*-parameters. The fabric shown at the center of the sensor is between 0.3 mm and 0.8 mm thick and absorbs up to 35% of a solution of latex in water with the latex being about 20% by volume. The target is 5% solids coating (after drying) on the fabric. The sensor described here is a broadside-coupled stripline resonator (Ida 2018; Garg et al. 2013). Its value in this application is that it is wide open allowing free movement of the fabric and in the fact that it resonates in two modes as shown in Fig. 18. The even mode electric fields are parallel to the fabric and hence sensitive to the properties of the fabric (primarily the solution), whereas the odd mode is more sensitive to the bulk between the center plates rather than the fabric. The even mode is used to monitor the properties of the fabric, whereas the odd mode is used to compensate for bulk effects such as temperature and humidity. Figure 19 shows the upper half of the sensor without the fabric. The upper center plate and its Teflon block can be seen as well as one of the probes. The sensor is designed so it can move across the fabric to evaluate the whole width of the fabric as it moves. Figure 20 shows the performance of the sensor for two fabrics. The left part is for a fabric with higher permittivity (or more solution

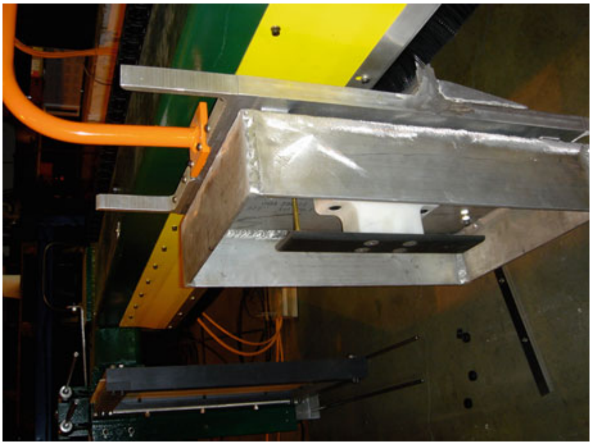


Fig. 19 The upper half sensor and its attachment to the motion mechanism. Note the construction of the ground plane and partial shield afforded by the bent plates. The second half shell has been moved away for a better view. The Delrin calibration frame can be seen in the lower part of the picture away from the half shell. (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)

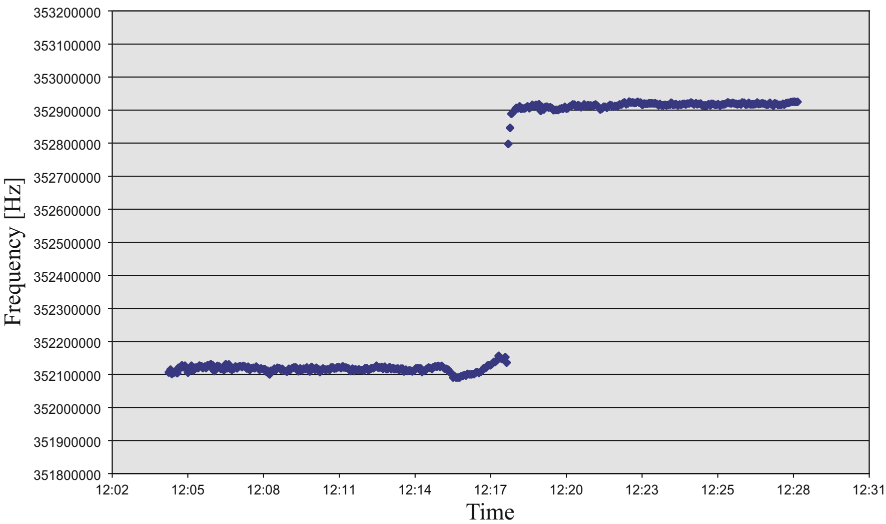


Fig. 20 Resonant frequency versus time for fabric code (type) and speed change. (Reproduced with permission from Open Resonator Microwave Sensor System for Industrial Gauging, N. Ida, The Institution of Engineering and Technology, 2018, ISBN 978-1-78561-140-7)

on the fabric), whereas the right part is for a lower permittivity fabric (or less solution on the fabric). The sensor is capable of measuring a resolution of 0.014% dry latex on the fabric assuming a 10 kHz resolution at the network analyzer. In principle the resolution can be increased by a factor of 10 (to 0.0014%) for a network analyzer capable of resolving down to 1 kHz, which is not unusual for modern vector network analyzers. Measurements are in real time, that is, the fabric moves continuously, and the sensor moves back and forth across the fabric. Each point in Fig. 20 is the average of five individual measurements of the network analyzer, recorded on a computer (with a time and position stamp). Separately (not shown) the sensor also records temperature and humidity to compensate for errors in the measurements using the odd-mode resonant frequency (Ida 2018; Ida and Bhuyia 2008). The measurements were taken unattended remotely with the operation of the system and transfer of data being done over the Internet.

An example of the use of the same basic sensor for dimensional measurements on rubber is shown in Fig. 21. The rubber is backed by a conductor, and the sensor is made of only one, modified section of the sensor in Fig. 17. The resonator now is between the center plate and the conducting drum, which moves the rubber sheet. The minimum separation between the plate and the drum is 35 mm. The first (lower) and second (higher) resonant frequencies as a function of rubber thickness are shown in Fig. 22, resulting in a frequency shift of 2.4 MHz/mm of rubber at the lower resonant frequency (Fig. 22a). The net effect is a sub-micrometer resolution with a linear response to rubber thickness. At a network analyzer resolution of 1 kHz, the sensor can reliably measure variations in rubber thickness of 0.4 micrometers. Higher resolution can be obtained using the second resonant mode (about twice as high) although in this application the higher resolution was not necessary and work at the lower frequency proved to be easier.

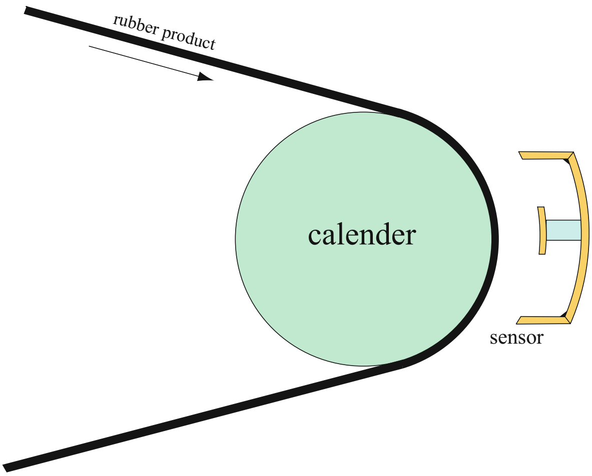


Fig. 21 Monitoring of rubber thickness on the production line using the open transmission line resonant sensor. (Reproduced with permission from Open Resonator Microwave Sensor System for Industrial Gauging, N. Ida, The Institution of Engineering and Technology, 2018, ISBN 978-1-78561-140-7)

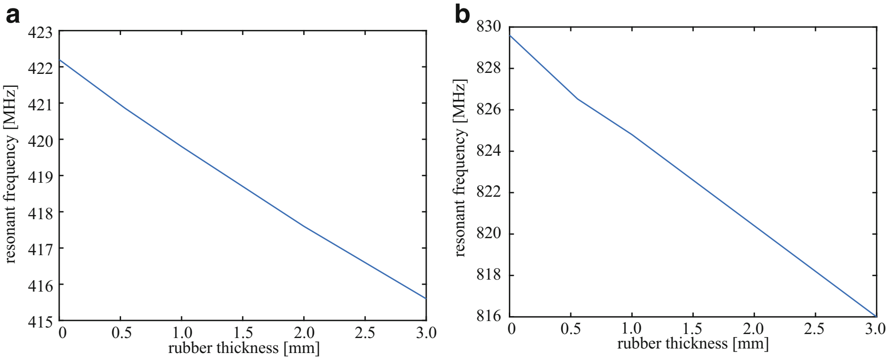


Fig. 22 Resonant frequency as a function of rubber thickness. (**a**) For the first resonant frequency. (**b**) For the second resonant modes

Either implementation of the sensor can be used for other purposes including in situ testing of coatings, concrete, composites, gasses, liquids, and others with similar sensitivities.

Other Methods

UWB Radar

An ultra-wideband (UWB) radar is characterized by a much wider bandwidth coupled with low power transmission. This is achieved by transmitting a very narrow pulse, typically around 1 ns wide, thus generating a wide-spectrum transmission. Power transmitted is typically under 10 mW. The bandwidth is very wide but typically is taken to be about 25% of the center frequency. As a result of these properties, UWB radars are very compact, intended for relatively short ranges. For NDE purposes, UWB radars offer some exciting possibilities without some of the issues associated with conventional radars. First and foremost, the wideband allows interaction with flaws on the whole spectrum, something that is akin to multi-frequency testing. This means that one can hope to detect and possibly image flaws with much more detail and higher resolution possible with other methods. Second, because of the very low power and its spread over a wide spectrum, there are fewer regulatory constraints and little concern to radiation safety. In addition, there is virtually no concern to interference with or from the system and a typical decrease in the dead zone exhibited by pulsed radars. The main trade-off associated with the wider bandwidth is a reduction in the signal-to-noise ratio. UAB radars can transmit in narrow patterns (high directivity) for increased detectability and resolution through the use of antenna arrays. In spite of what may seem as a complex system, commercial UAB radars are small and highly integrated and often come on a small board with all electronics needed for operation. Single-chip radars are available as well. The cost is also very low in comparison to most microwave systems. In most NDE applications, the UAB radar is used to scan the object under test and obtain a signal not unlike the A-scans obtained in ultrasound testing. Imaging is much more complex than that and requires both additional equipment and appropriate software. UAB radars come in various center frequencies ranging from a few hundred MHz to the high GHz region. For example, the FCC allows unlicensed use of UWB devices in the frequency range from 3.1 GHz to 10.6 GHz and a maximum equivalent isotropic radiated power (EIRP) spectral density of −41.3 dBm/MHz. Although the band is used for other applications as well, including cell communication and Wi-Fi routing, the fact that UWB applications under these conditions do not interfere with other services allows their use on the same band. Other frequencies and other power levels require licenses.

Some Applications of UWB Radar

UWB radars are not new – the first were developed in the late 1960s but only recently have they become small enough and inexpensive enough to allow their use in common applications. One of the more common general applications is what is sometimes called "see-through-wall systems" (Yang 2008; Gubinelli et al. 2014; Pochanin et al. 2016). In these, as in GPR one attempts to detect, quantify, and image objects and conditions buried in or located behind lossy dielectrics in a manner similar to GPR, often without making contact with the surface. Examples abound. Gubinelli et al. (2014) used a comparative method to detect surface defects in carbon fiber composites by measuring the mismatch between the reflected waveform from sound sample flawed samples. Cristofani et al. (2017) discuss the use, advantages, and limitations of UWB radar in testing of aeronautic components as well as variations of UWB and the use of synthetic-aperture radar (SAR) algorithms to enhance performance. Imaging and applications to testing of composite materials are also discussed. Xu et al. (2013) show that detection of rebar in concrete using essentially GPR methods in conjunction with UWB and B-scans results in high-resolution images as well as the possibility of estimation of rebar depth in pavements at vehicle road speeds. UWB radar can also be applied on a larger scale in evaluation of conditions of walls and tunnels. Herrmann R (2011) discusses methods and measurements of walls in tunnels in salt mines. 2D and 3D images of conditions as deep as 2 m in the walls show flaws and cracks of various sizes. Other applications can be found in Gubinelli et al. (2014), Zhong et al. (2014), Xie et al. (2006), and Xu et al. (2004). Another promising area of application is in biomaterials and in medicine. The low power and high resolution offered by UWB systems lend themselves naturally to diagnostics in the body and in particular for breast cancer applications (Bidhendi et al. 2014; Fear et al. 2002a, b; Joines et al. 1994). The main impetus for this work is the high contrast between tumors and healthy tissue at microwave frequencies both in terms of permittivity and conductivity. Multiple antennas around the breast allows detection and reconstruction of tumors with minimum discomfort and practically no risk.

UWB radar is rather new in NDE, and many applications are still in the development stage. For that reason, much of the work is done by scanning over the surface of the test object to produce A-type scans. However, both commercial and experimental devices that incorporate imaging for high-resolution testing have been developed (Shin et al. 2016; Pochanin et al. 2016; Yang et al. 2017; Kidera et al. 2010; Li and Meng 2016).

Microwave Radiometry

In a radiometric method one measures the electromagnetic radiation and characterizes the distribution of the radiation power by means of a radiometer – a device that measures the radiant flux of the electromagnetic wave. Radiometry is commonly used in optics and in communication (e.g., in the evaluation of antennas and of communication links). In that context, the radiated power is measured using any of a number of sensors such as bolometers, diodes, or even calorimetric methods which respond to the power (or power density) being measured by a rise in their temperature which in turn changes some parameter of the sensor such as resistance or the direct output of thermocouples (Grant 2011; McCluney 2014). These measurements can be correlated with a variety of conditions. It is rather simple, for example, to measure the radiation pattern of an antenna or the power distribution from a distant star. In communication, radiometry is often used to characterize the path of communication and quantify the effects of scatterers such as clouds, dust, or even insect swarms in the path on the communication link. In this type of measurement, one measures the transmitted power through the scatterers (Feliciano 2009; Sweet 2013; Nessel 2015). Radiometry can be active (in which a source of radiation is provided), or it can be passive (in which the natural radiation from objects is measured) (Ulaby et al. 1981; Appleby et al. 2004). In general, passive radiometric methods are used for remote sensing taking advantage of naturally emitted microwave radiation, a method not unlike remote thermal sensing. In NDE however the active radiography is more practical using either a transmission or reflection method. The use of radiometric methods in microwave and mm-wave NDE is but a natural extension of the method to characterize materials and conditions based on the effect they have on the radiated energy. The sample to be tested is irradiated from a source at an appropriate frequency and power density. The wave transmitted through the sample is attenuated by the material, and any discontinuity within the sample scatters the wave. The transmitted wave's power density is measured either by an array of sensors or by a scanning sensor to obtain an image of the transmitted power density (Viegas et al. 2017; Shibuya et al. 2007; Bakhtiari et al. 1997). Alternatively, the wave is reflected off the sample to detect primarily surface and near-surface features (Clancy et al. 2000; Seah et al. 2012; Harmer et al. 2016; Smulders 2012). Typically, the source is broadband (often characterized as "noise"), but there are no specific limitations on the sources other than availability and quality of the waves generated. Nevertheless, higher frequency content is useful since resolution is related to the wavelength, and as in any microwave method, the higher the frequency, the higher the resolution and, often, the signal-to-noise ratio. In the microwave and mm-wave range, this is a particularly difficult issue because sources are not easy to come by beyond about 100 GHz (free-space wavelength of 3 mm). Nevertheless, applications in the W band (94 GHz) have been reported in NDE of materials and products and in medical applications (Appleby et al. 2004; Clancy et al. 2000; Seah et al. 2012; Harmer et al. 2016; Bardati et al. 1992; Bakhtiari et al. 2012; Shibuya et al. 2007).

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