REVIEW OF NDT TECHNIQUES AT RADIO AND MICROWAVE FREQUENCIES

Reza Zoughi

Electrical Engineering department
Colorado State University
Ft. Collins, CO 80523

INTRODUCTION

Clearly the natural transition for NDT science is the use of higher frequencies, namely microwaves. The behavior of EM waves at these frequencies is well known and their interaction with material media has received a great deal of attention [1]. Moreover, making use of the coherency property of microwaves, images of objects and defects may be produced. Research in microwave NDT, with defect detection and classification in mind, has received minimal attention. However, microwaves show great promise in developing techniques and tools for NDT purposes. Some of the reasons for this are as follows:

a) Ability to penetrate material media (excluding conductors) to reasonable depths (penetration depth is a function of frequency and dielectric properties of the test material) [2].
b) Relatively small wavelengths at microwave frequencies make for small-sized probes (probe or antenna size is directly related to the size of the wavelength).
c) Relatively large signal bandwidths available at microwave frequencies make for fine-resolution measurements, thus increasing the ability and confidence in detection of defects in an object.
d) Ability to identify various boundary layers in an inhomogeneous (stratified) medium via detection of reflections from each layer.
e) Probe characteristics (center operating frequency, Q-factor, etc.) vary as they are operated in different media, thus rendering information about the characteristics of the media.
f) Signal analysis of probes in microwave region (radars, scatterometers, open-ended coaxial lines, cavity resonators, etc.) is a relatively easy task.

g) Coherency properties of microwaves make for production of images of objects and defects.

h) Movement of transmitter/receiver can provide very-fine-resolution images/data of a defect or an object (i.e. SAR).

i) Polarization properties can be used to detect flaw/inhomogeneity shape and orientation.

j) There is no need for the sensor (antenna) to be physically attached to the sample under test.

At least two classes of microwave NDT techniques and three types of probes can be utilized to evaluate properties and abnormalities of a medium:

a) Totally nondestructive technique.
   1) Scatterometers (radars that measure scattering properties of a target) and reflectometers [3,4,5].
   2) Near-field probes operating in very close proximity to a medium (open-ended coaxial lines, cavity resonators, microstrip/stripline patches/antennas, etc.) [6,7].

b) Semi-nondestructive technique.
   1) Small probes which are inserted into a medium (monopoles, microstrip/stripline patches, etc.) [8,9].

APPROACH

Each of the above techniques have shown to be effective in providing valuable information about various media and their characteristics. Scatterometers and reflectometers have been used to detect boundary layers, voids and buried objects in soils and other bulk media. This is accomplished by detecting echoes from different ranges (distances) and using echo amplitude, relative phase and range information to determine the characteristics of the target (defect, inhomogeneity, etc.).

Figure 1 shows the principle of a monostatic scatterometer (radar). Here amplitude of the echo signal vs. slant range (distance from the antenna) is used to identify the location of inhomogeneity in the material. The range resolution of this system depends on the transmitted signal bandwidth (pulse length in the case of pulse radar) and finer resolutions provide more accurate information. Moreover, the polarization characteristics of the transmitted and received signals can be used to determine the orientation of an object within the bulk material, such is the orientation of steel bars in concrete or asphalt layers. Zoughi, et. al. used a frequency modulated scatterometer operating at 10 GHz with a range resolution of 11 cm to obtain thickness profile of a concrete walkway as shown in Figure 2 [10]. The difference in the slant range between the echoes from the air-concrete and concrete-dirt boundaries was used to determine the thickness. Moore, et. al. used a similar scatterometer operating at L-band (1 GHz) to probe concrete structures for void detection with great success [11].

The phase information of the transmitted and the echo signal can also be used to determine thickness of layered media. This is especially a good technique for a metal plate covered with a dielectric material whose thickness is in question. The phase of these two signals are used to measure the coherent reflectivity due to the metal plate (i.e back interface) and the dielectric-air interface (Reflectometery). A swept frequency measurement provides peaks and nulls in the reflectivity vs. frequency characteristic and the location of any successive peak will depend on the thickness of the material. If the material is lossy, a damping effect is superimposed on the reflectivity vs. frequency characteristic. Figure 3 shows the simulation (theoretical) results for a metal plate covered with a 5 cm-thick material with permittivity of 5-j2 [12].

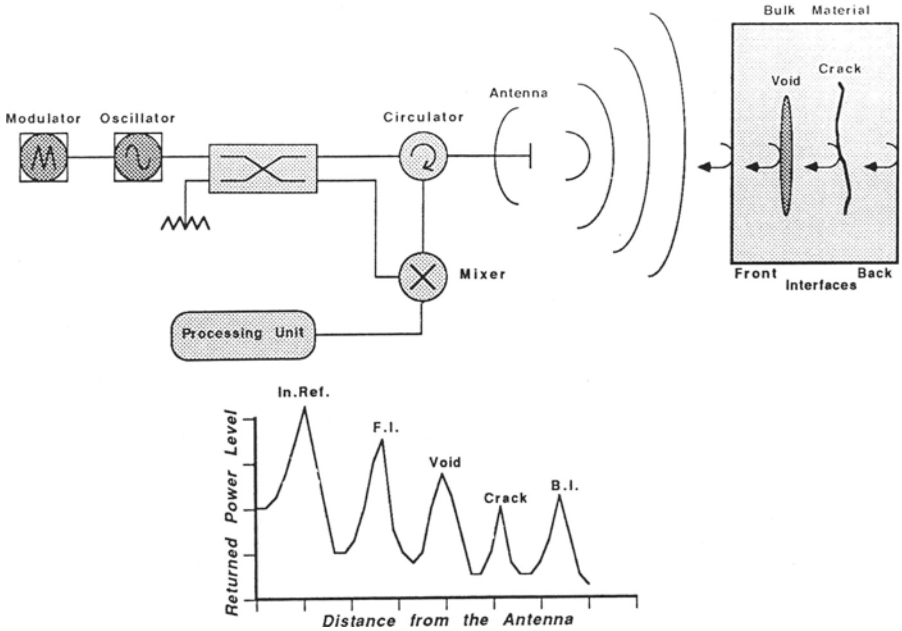

Fig. 1. Illustration of the principle of monostatic scatterometer.

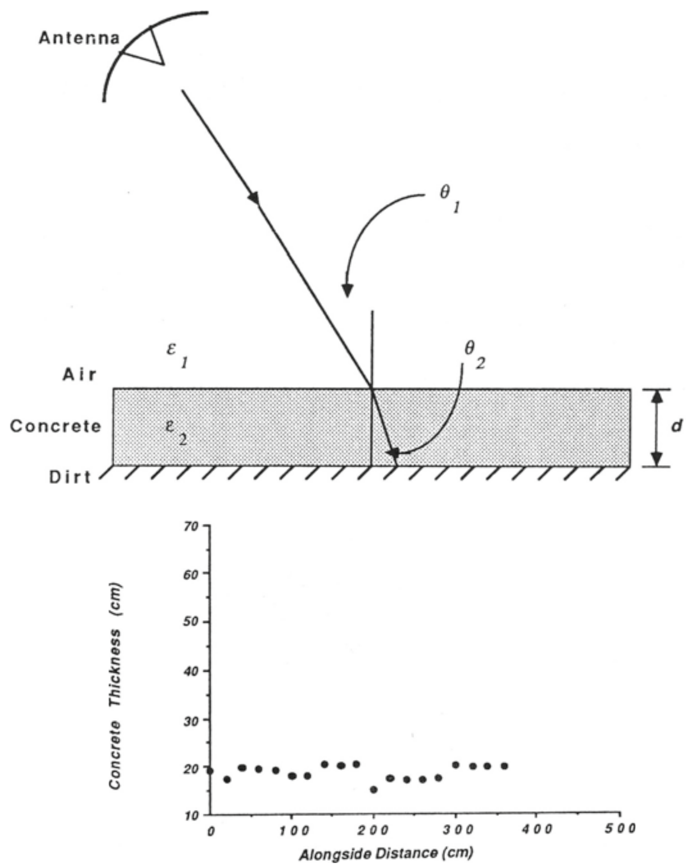

Fig. 2. Measured concrete thickness profile (Zoughi, et. al., 1985).

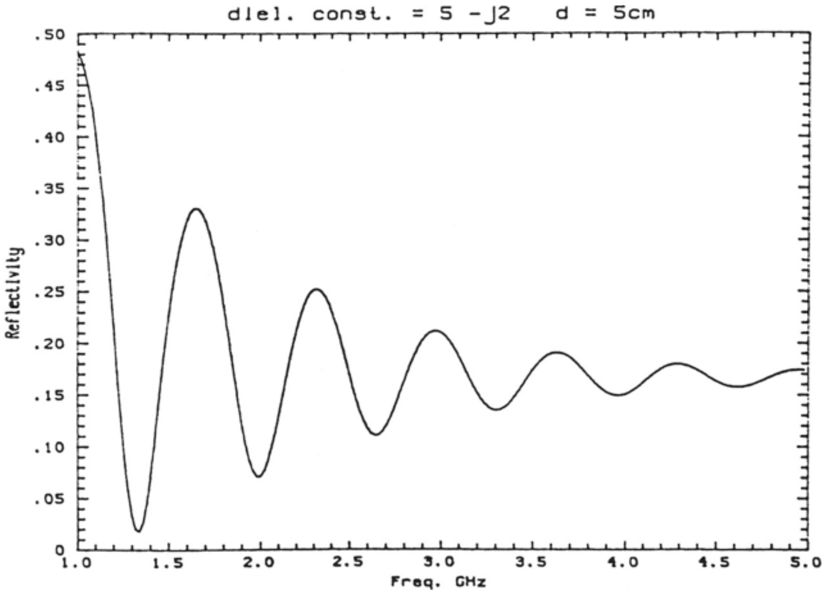

Fig. 3. Coherent reflectivity vs. frequency for thickness measurements.

Another technique for thickness measurement of thin film or slabs is shown in Figure 4 [13]. An open transmission line is filled with the film and the phase difference between the reference and the test channels is used to determine the thickness. There are various types of transmission lines available which can accommodate many types of slab geometries.

Near-field probes have also been effectively used to determine dielectric properties of various martial media. Permittivity measurements reveal a great deal of information about the composition of a material. There are various techniques available to measure dielectric constant of material nondestructively. Figure 5 shows a technique by which the VSWR of standing waves in a slotted waveguide due

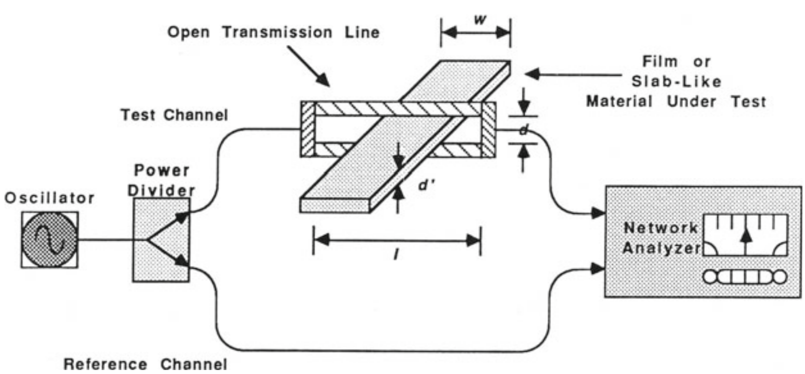

Fig. 4. Configuration of CW Thickness/dielectric measurement (Chudobiak, et. al., 1986).

to a metal plate (reference) and a snow layer are used to measure reflection coefficient due to the layer and thus its permittivity [14]. Figure 6 shows a microstrip line covered with a dielectric sheet. The changes in the impedance, phase velocity and Q-factor of the line when covered with a material are used to determine its complex permittivity [7]. An open-ended coaxial line can also provide the same information. Changes in the coax's characteristics when operating adjacent to a dielectric medium is directly related to the medium's permittivity, as shown in Figure 7 [6].

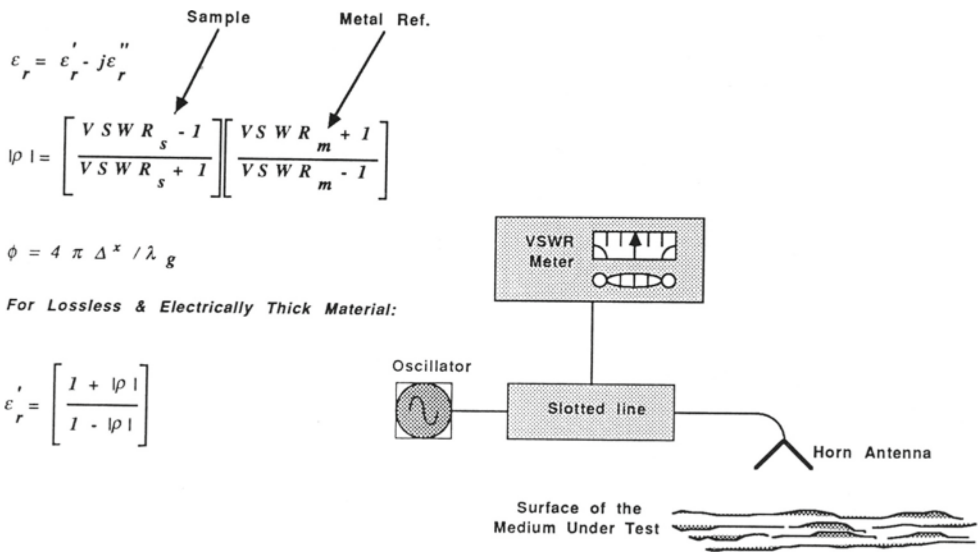

Fig. 5. In-situ reflectometer measurement of permittivity (Arcone, et. al., 1988).

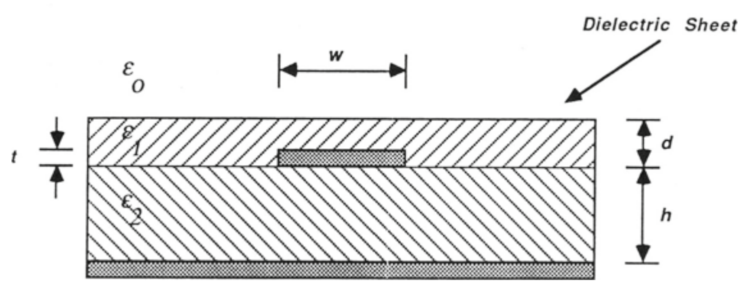

Fig. 6. Microstrip covered with dielectric material (Bahl, et. al., 1980).

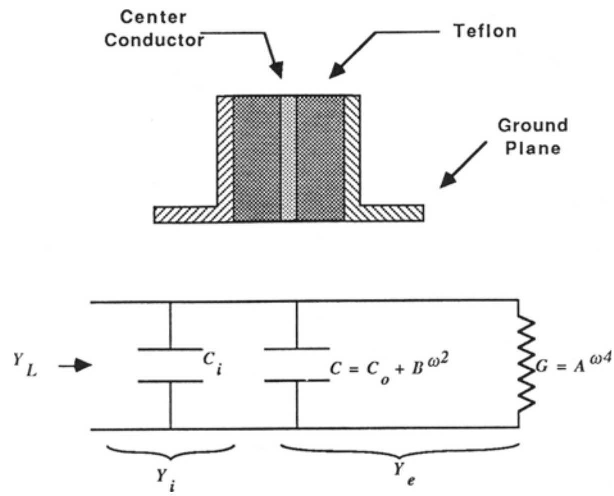

Fig. 7. Coaxial probe for permittivity measurements (El-Rayes, et. al., 1987).

Semi-nondestructive probes which measure dielectric properties of layered media such as snow and soils vs. depth have been developed and tested successfully. By inserting such a probe (e.g. a monopole) into the snow medium its dielectric properties can be measured by the measured variations in the probe characteristics. Insertion of the probe to various depths provides a permittivity profile of the snow medium. Consequently, the measured permittivity values are related to the snow temperature, density and moisture and as a result weak snow layers are identified and avalanches are predicted (see Figure 8) [9].

For all of the cases discussed above, it is very important to note that by moving the position of the transmitter (source) which could be one of many types, an image of a defect, void, buried object, etc. can be produced. This can be further enhanced by varying the resolution of the probe to obtain a very accurate estimate of the size of the defect. The ability to produce images stems from the coherency of microwaves. A Synthetic Aperture Radar (SAR) also makes use of this property and as a result radar imaging has been revolutionized.

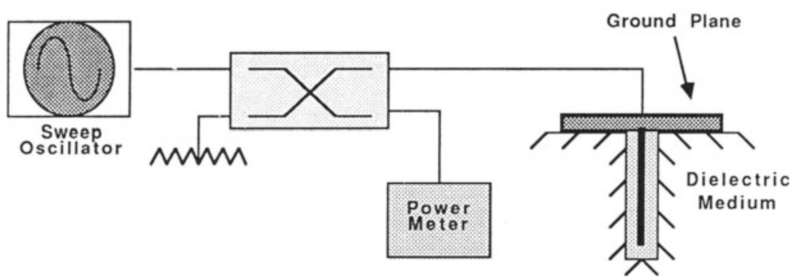

Fig. 8. In-situ semi-nondestructive permittivity measurement (Jiang, et. al., 1982).

CONCLUSIONS

The preceding discussions illustrate the potential of microwaves for NDT. A sample list of of areas which can benefit from this are listed below:

a) Detection of cracks in various types of bodies (ceramics, metals, composite materials)..
b) Detection of voids in concrete columns (bridges and other structures).
c) Detection of steel bars in frames of structures and bridge columns.
d) Detection of buried objects and production of their images.
e) Detection of excess moisture in bodies such as wooden structures.
f) Detection of rotted pieces of wooden structures.
g) Image production of various defects.
h) Development of new probes for characteristic property evaluation of materials.
i) Thickness measurements of concrete, ceramics, plastics and material covering metallic surfaces.
j) Detection of flaw size using swept frequency probes (a very important feature).

However, there are two major limitations in using high frequencies for NDT, as follows:

a) Inability to penetrate conductors and highly lossy material as skin depth shrinks when frequency increases.
b) Flaw/inhomogeneity size vs. wavelength. Operating at low frequencies (long wavelengths) relatively small-sized flaws will not be detected. This is one of the major reasons for developing techniques and probes at millimeter wavelengths.

It is very clear that the use of high frequencies for NDT has fantastic potential and promise and should receive much greater attention.

REFERENCES

1 Ruck, G.T., et. al., "Radar Cross-Section Handbook, Vol. I & II," Plenum Press, New York, 1970.
2 Ulaby, F.T., R.K. Moore and A.K. Fung, "Microwave Remote Sensing, Active and Passive, Vol. III," Artech House, Dedham, MA, 1986.
3 Zoughi, et. al., SOURCESCAT: A Very Fine-Resolution Radar Scatterometer," Microwave Journal, vol. 28, no. 11, pp. 183-196, Nov. 1985.
4 Culshaw, W., "High Resolution Millimeter Wave Ferby-Perot Interferometer," IRE Tarns. on Microwave Theory and Techniques, pp. 182-189, 1960.
5 Bahr, A.J., "Nondestructive Microwave Evaluation of Ceramics," IEEE Trans. on Microwave Theory and Techniques, vol. MTT-26, no. 9, pp. 676-683, Sept. 1978.
6 El-Rayes, et. al., "Microwave Dielectric spectrum of Vegetation," IEEE Trans. an Geoscience and Remote Sensing, vol. GE-25, no. 5, pp. 541-549, Sept. 1987.
7 Bahl, I.J., et. al., "Analysis of a Microstrip Covered with a Lossy Dielectric," IEEE Trans. on Microwave Theory and Techniques, vol. MTT-28, no. 2, pp. 104-109, Feb. 1980.
8 Denoth, A., et. al., "A Comparative Study of Instruments for Measuring the Liquid Water Content of snow," J. Appl. Phys., vol. 56, no. 7, pp. 2154-2161, Oct. 1984.

9 Jiang, J., et.al., "Dielectric Constant of Rocks from Bluff Utah at Microwave Frequencies," RSL TR #562-1, the University of Kansas, Lawrence, KS 66045, Oct. 1982.

1 Zoughi, R., et. al., "Determination of Backscattering Sources in Surface Type Targets," Inter. J. of Remote Sensing, vol. 6, no. 2, pp. 285-297, Feb. 1985.

1 Moore, R.K., et. al., "Probing of Concrete for Void Detection Using an L-band FM Radar," RSL TR #3488-0038-2, The University of Kansas, Lawrence, KS 66045, Nov. 1981.

1 Zoughi, R., "Nondestructive Material Evaluation and Flaw Detection at Radio, Microwave and Millimeter Wave Frequencies," In Preparation fro submission to the Materials Evaluation, 1988.

1 Chudbiak, W.J., et. al., "An Open Transmission Line UHF CW Phase Technique for Thickness/Dielectric Constant Measurement," IEEE Trans. on Instrumentation and Measurements, vol. IM-28, no. 1, pp. 18-25, March 1979.

14 Arcone, S.A., et. al., "Single-Horn Reflectometry for In Situ Dielectric Measurements at Microwave Frequencies," IEEE Trans. on Geoscience and Remote Sensing, vol. GE-26, no. 1, pp. 89-92, Jan. 1988.