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HIGH-RESOLUTION MILLIMETER-WAVE IMAGING SYSTEM FOR DEFECT CHARACTERIZATION IN DIELECTRIC SLABS*

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High-resolution millimeter-wave imaging system for defect characterization in dielectric slabs

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ABSTRACT

Preliminary results are presented for a millimeter-wavelength free-space imaging system used to detect and characterize defects in layered dielectric composite slabs. Such systems throughout the microwave spectrum have shown great potential as alternative nondestructive evaluation tools for on-line, in-situ examination of low-loss dielectric materials such as plastics, ceramics, and various dielectric composites. Results of a fixed-frequency W-band imaging system operating in either through-transmission or reflection mode are presented here. Incorporation of focused-beam antennas allows high-resolution measurement of small variations within the sample under test. The results are based on measurement of the relative amplitude and phase of the reflected or transmitted wave in monostatic or bistatic configurations, respectively. With proper calibration, the measured parameters can be used to estimate dielectric property variations within the material media. A theoretical simulation for plane wave propagation in a multilayered media is used to interpret the measurement results.

Keywords: Nondestructive, Millimeter Waves, Composites, Defect, Dielectric Properties

INTRODUCTION

High-frequency electromagnetic nondestructive evaluation (NDE) in the microwave/millimeter wave region has shown great potential for examination of dielectric composite media.¹⁻⁴ The reason is that the transmitted radiation at these frequencies can penetrate dielectric media that often pose limitations to other conventional NDE techniques. With the sensor often consisting of a radiating antenna, the noncontact nature of such techniques allows examination of materials under hostile conditions such as stress or high

temperatures. Further, because the antenna beamwidth is directly proportional to the operating wavelength, higher frequencies offer finer resolutions, given that the depth of penetration in the material medium does not limit the sensitivity of the receiving system. Microwave sensors detect dielectric property variations within material media. These inhomogeneities within a layered medium result in reflection, refraction, attenuation, and scattering of the incident radiation, which may be detected and related to macroscopic or microscopic properties of the medium under test. The parameter often measured is the effective complex reflection or transmission coefficient of the medium.

Results of a fixed-frequency millimeter-wave (mm-wave) reflection/transmission imaging system operating in the WR-10 band are presented here. The system incorporates Gaussian beam antennas and offers high-resolution inspection of layered dielectric composite media. Electrically thick samples of Kevlar/epoxy composite with artificial defects have been used to demonstrate the system's capability. The measurement system may be used to generally examine low-loss dielectrics such as polymers, plastics, polymeric and ceramic composites, as well as dielectric-type coatings on conducting surfaces.

MEASUREMENT APPARATUS

Figure 1 depicts the monostatic reflection configuration of the mm-wave imaging system. Results are also presented for the bistatic configuration, in which separate antennas placed on either side of the sample are used for transmitting and receiving the continuous wave (CW) signal. The source is a wide-band, mechanically tuned Gunn-diode oscillator used in a frequency-locked arrangement via a square-wave modulator/regulator unit and a crystal-tuned phase-locking frequency counter. This allows precise frequency stabilization of the cavity-tuned source, which can drift over a period of time. To enhance spatial (lateral) resolution, focused-beam conical horn antennas are incorporated into the system. The antennas are fitted with bi-convex lenses having diameter $D = 12$ in. and a focal length f of 12 in. (i.e. $f/D = 1$). The spot size of the beam at the focal point is about one wavelength and has an approximate depth of focus of 10λ . The sample under test is positioned in a plane perpendicular to the antenna symmetry axis

and within the focal depth. For the reflection setup, the signal is separated into transmitted and received components with a matched hybrid coupler and a conducting plate is placed behind the sample within the focal depth of the antenna. In the bistatic transmission case, a directional coupler separates the RF and LO signals. A variable attenuator and phase shifter are also inserted in the RF arm for calibration of the system. To measure both the relative amplitude and phase variations of the reflected or through-transmitted radiation, a quadrature IF mixer is used. The two outputs of the mixer are DC signals proportional to in-phase and quadrature components of the difference signal between the RF and LO ports. This allows simultaneous measurement of the amplitude and phase of the reflected or transmitted wave. Outputs from the detector are amplified and subsequently digitized with a 12-bit A/D board. Incorporation of a balanced amplifier facilitates large DC offset adjustment and amplification of the received signal, greatly enhancing sensitivity and dynamic range. The computer also controls a two-axis translation stage that facilitates continuous scanning of the sample.

Figure 1 : Reflectometer imaging apparatus used at 94 GHz. GDO = Gunn Diode Oscillator, GMR = Gunn Modulator Regulator, and QIFM = Quadrature IF Mixer.

THEORETICAL MODEL

With the radiation from a Gaussian beam having an approximately parallel phase front within the focal depth, a model based on plane-wave incidence on a layered lossy dielectric medium may be used to examine the significance of various parameters such as permittivity, frequency and thickness variations on the measured amplitude and phase components. Only the initial steps in construction of the solutions are presented here, with a more detailed explanation given in refs. 4 and 5. A slablike sample with planar defects was modeled as a multilayer geometry backed by a conducting sheet or terminated into an infinite half-space. Figure 2 shows cross sections of the two multilayered geometries considered for the reflection measurement setup. The model was developed by constructing general forward and backward traveling field components in a multilayer media. In general form, these fields may be written as:

$$\bar{E}_n(z) = E_n^+ \left(e^{-jk_n z} + \rho_n e^{jk_n z} \right) \hat{a}_x \quad (1)$$

$$\bar{H}_n(z) = \frac{\sqrt{\epsilon_{r_n}}}{\eta_0} E_n^+ \left(e^{-jk_n z} - \rho_n e^{jk_n z} \right) \hat{a}_y \quad (2)$$

where,

$$k_n = k_0 \sqrt{\epsilon_{r_n}} \quad (3)$$

is the complex propagation factor in each layer and ϵ_{r_n} is the complex relative dielectric constant. E_n^+ denotes the amplitude of the forward traveling E-field of the n^{th} layer, and $\hat{a}_x$ and $\hat{a}_y$ are the unit vectors in the x and y direction respectively. ρ_n represents the ratio of the reflected and transmitted wave amplitudes, and k_0 and η_0 are the free-space propagation factor and intrinsic impedance, respectively. Enforcement of the boundary conditions at each planar boundary interface allows construction of the solution for the effective complex reflection coefficient, $\rho_0 = \Gamma e^{j\Phi}$, of the medium. The numerical results presented here are based on the normalized amplitude and phase of the reflection coefficient.

Figure 2: Cross section of geometry used in theoretical model for reflection setup.

Numerical results are presented for the case of a multilayered medium that terminates into a conducting plate; this situation resembles one of the measurement cases. A slab of low-loss dielectric material (Kevlar) with a total thickness of 5.0 mm and containing subsurface air defects that were 3.3 to 4.8 mm from the back surface was modeled as a two-layer medium. A complex dielectric constant of $\epsilon_r = (3.5, -0.1)$ was used for Kevlar at the W-band; this was inferred from values reported in the literature at lower frequencies.^{2,6} For simulation, the total layer thickness (sample with defect plus air-gap between the back of the sample and the metal plate) was kept constant as the thickness of the material layer was varied. The parameter Γ was normalized and plotted as the difference in decibels between the effective reflection coefficient when a defect exists within the layered media and that of defect-free media. Figure 3 shows the results of this simulation for three different air-gap values. Clearly, the air-gap has a substantial effect on both the phase and magnitude of the reflection coefficient. Further, for a fixed air gap and varying material thickness, the phase variation within a wavelength should result in less ambiguity in measurement than that of the amplitude variations. This was later justified by experimental results.

Figure 3: Theoretical results of normalized amplitude (a) and phase (b) for two-layer media terminated into conducting sheet. $f = 94$ GHz, $\epsilon_{r1} = (3.5, -0.1)$, $\epsilon_{r2} = (1.0, 0)$.

EXPERIMENTAL RESULTS

Several measurements were performed at a frequency of 94 GHz on plates of Kevlar-fiber-reinforced/epoxy composite (Kevlar 49 with HBRF55A epoxy from Hercules). Fabricated defects in the first sample consisted of subsurface voids of 6 mm in diameter at various depths from the front surface on a 50 x 50 x 5 mm sample plate. The second sample had artificial disbonds created by gluing two 50 x 50 x 2.92 mm plates at four corners and the center. The samples were scanned with resolutions of either 12 or 25 lines/cm. For the transmission images the two antennas were copolarized, while for the reflection images the sample was placed at some arbitrary air gap, within the focal depth of the antenna, from a metal plate.

Figures 4 shows the reflection images constructed from amplitude and phase variations for the first sample, which contained six subsurface holes. The image was scanned with a spatial resolution of 25 lines/cm. For all cases, results are displayed on each figure as a planar image and a surface plot to indicate the defect boundaries as well as the measured intensities. Although both amplitude and phase result display clear contrast for detection of defects, only the phase information in Figure 4 provides

unambiguous measurement of thickness variations. The phase image displays a linear dependence between the measured intensity and defect depth. This does not hold for the amplitude image. Since the measured intensity, among other factors, depends also on the position of the defect within the standing wave pattern, single parameter measurements of layered media can lead to ambiguous measurements. Figures 5 shows the amplitude and phase image of the same sample measured by the through-transmission setup and scanned with a resolution of 12 lines/cm. Once more, all of the six subsurface defects are visible in both the amplitude and phase image.

Figures 6 and 7 show amplitude and phase variations for the reflection and transmission images, respectively, of the second sample with debond. Figure 6 was constructed with resolution of 25 lines/cm and Figure 7 with 12 lines/cm. Because of the difference in dielectric properties of bonded and debonded areas, these regions appear distinctly different in the image. The planer images in all cases clearly indicate the boundaries of all five spots where the epoxy was applied.

Figure 4: Reflection measurement results of normalized amplitude (a) and phase (b) images of first Kevlar/epoxy sample with six subsurface holes at $f = 94$ GHz.

Figure 5: Through-transmission measurement results of normalized amplitude (a) and phase (b) images of first Kevlar/epoxy sample with six subsurface holes at $f = 94$ GHz.

Figure 6: Reflection measurement results of normalized amplitude (a) and phase (b) images of second Kevlar/epoxy sample with disbond at $f = 94$ GHz.

Figure 7: Through-transmission measurement results of normalized amplitude (a) and phase (b) images of first Kevlar/epoxy sample with disbond at $f = 94$ GHz.

CONCLUSIONS

A high resolution millimeter-wavelength free space imaging system was used to measure relative amplitude and phase variations in layered, low-loss dielectric composite sheet samples. Both monostatic backscatter and bistatic forward-scatter configurations were used. Results clearly indicate the capability of such a system for noncontact, in-situ NDE of generally lossy dielectric materials. Although single-parameter measurement of amplitude or phase variations may be used to detect defects within the material media, the results indicate that ambiguities in terms of defect depth within the electrical length of the sample may be avoided by simultaneous measurement of both relative amplitude and phase.

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Note: The clearance is pending for the above paper titled "*High Resolution Millimeter Wave Imaging System for Defect Characterization in Dielectric Slabs*" submitted to SPIE'94 conference. The clearance is expected to be awarded within two weeks.

Sincerely,

SASAN BAKHTIARI

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