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by

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MILLIMETER-WAVE IMAGING OF COMPOSITE MATERIALS

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INTRODUCTION

The use of microwave electromagnetic radiation which roughly covers the frequency range of 0.3-300 GHz, with wavelengths below cm called millimeter wavelengths (mm-waves), for Nondestructive Evaluation (NDE) of materials is recently gaining more recognition.¹⁻² This is due to various reasons such as:

- Inherently noncontact nature of the technique allowing for *in situ* measurements
- Reasonable depth of penetration for low-loss dielectrics
- Small size of components, wider bandwidths, and finer resolutions
- Availability of mm-wave source and components at reduced cost with the advancements in solid-state monolithic integrated circuit technology
- Emergence of advanced, unconventional materials such as polymeric and ceramic composites posing new NDE challenges and demanding new approaches.

Only limited work has been done on the use of mm waves in the past as a technique for materials evaluation, mainly due to technological barriers such as unstable sources and unavailability and high cost of mm-wave components.³ The types of materials suitable for mm-wave interrogation include polymers, ceramics, plastics, polymeric and ceramic composites, wood, and nonmetal-over-metal type coatings. For highly conductive and metallic media microwaves may only be used to examine surface features. The major contrast mechanism detected at microwave frequencies is the change in dielectric properties of the material (the permittivity and loss factor) due to inhomogeneities in the medium. This work addresses the application and evaluates the potential of mm-wave imaging in the W band (75-110 GHz) using samples of low-loss dielectric and composite materials with artificial defects. The initial focus is on the measurement of amplitude changes in the back scattered and forward-scattered fields. The c-scan system developed employs a focused beam antenna to provide spatial resolution of about one wavelength. A plane-wave model is used to calculate the effective reflection (or transmission) coefficient of multilayer test sample geometry. Theoretical analysis is used to optimize the measurement frequency for higher image contrast and to interpret the experimental results. Both

reflection and transmission images, based on back scattered and forward-scattered powers, were made with Plexiglas and Kevlar/epoxy samples containing artificially introduced defects such as subsurface voids and disbonds. The results clearly indicate that mm-wave imaging has high potential for non contact interrogation of low-loss materials.

MEASUREMENT APPARATUS

The W band c-scan imaging system developed is shown in Figure 1. The system employs both monostatic and bistatic radar configurations. A backward wave oscillator source allows frequency sweep over the entire band. Antennas used are high gain, spot focusing, conical horns which incorporate two back to back mounted plano-convex dielectric lenses for resolution enhancement. Focal length of the antennas are approximately equal to the aperture diameter (i.e. 1') and the depth of focus is about $10\lambda_0$. The spot size, based on E-plane and H-plane 3-dB antenna beam widths, are approximately $1.1\lambda_0$ and $1.6\lambda_0$, respectively, at 94 GHz. A computer controlled positioner allows for precise adjustment of scanning steps in two horizontal orthogonal directions.

Figure 1: W-band measurement apparatus showing both the bistatic-forward-scatter and monostatic-backscatter configurations. The dashed lines represent the required system modifications from the former configuration to the latter. Component abbreviations; SLMC: Source Locking Microwave Counter, W-SG: W-band Sweep Generator, HM: Harmonic Mixer, TDD: Tunable Diode Detector, DO: Digital Oscilloscope. CNT: Controller, TS: Translation Stage, SH: Sample Holder, AP: Absorbing Panel.

The test sample is mounted in a plane perpendicular to the incident beam within the focal depth of the lenses. In the monostatic case, a circulator or a hybrid junction separates the transmitted and reflected waves. The amplitude of the backscattered or forward-scattered radiation (i.e., the received power) is measured via a crystal-diode detector. Output from the detector is retrieved and analyzed by a personal computer which is also interfaced with a two-axis translation stage. The preliminary experimental results presented here are based on the measurement of the amplitude of the scattered (transmitted/reflected) signal only, although with minimal modifications multiparameter measurements such as amplitude and phase information as well as swept frequency measurements are also possible.

THEORETICAL IMPLEMENTATIONS

Interaction of electromagnetic radiation with layered media is a complex phenomenon. An understanding of the nature of this interaction is important in optimizing the measurement parameters (e.g., operating frequency based on sample thickness and dielectric properties) and analyzing the experimental results. Figure 2 shows cross section of the multilayered geometry considered in the analysis. Because the radiation beam approximates plane waves within the focal depth of the lenses, a plane-wave model is used in this analysis to calculate the effective reflection coefficient. The final results are given as a set of recurrence relations for general N-layer media backed or unbacked with a conducting plate.⁴ The solution of the source-free Helmholtz wave equation as a function of position in the z-direction for the field components in conjunction with the enforcement of the boundary conditions at each planar boundary interface results in the following recurrence relations for calculation of the complex reflection coefficient:

Figure 2: Cross section of the multilayered media. For the case of termination into infinite half-space the conducting plate interface does not exist.

$$\rho_i = \left(\frac{\rho_g^i - 1}{\rho_g^i + 1} \right) e^{-j2k_0 z_i \sqrt{\epsilon_{r_i}}} \quad (1)$$

where

$$\rho_g^i = \sqrt{\frac{\epsilon_{r_i}}{\epsilon_{r_{i+1}}}} \frac{1 + \rho_{i+1} e^{j2k_0 z_i \sqrt{\epsilon_{r_{i+1}}}}}{1 - \rho_{i+1} e^{j2k_0 z_i \sqrt{\epsilon_{r_{i+1}}}}} \quad (2)$$

and for the terminating N^{th} layer

$$\rho_N = \begin{cases} 0 & N^{\text{th}} \text{ layer infinite in } +z \text{ direction} \\ e^{-j2k_0 z_N \sqrt{\epsilon_{r_N}}} & N^{\text{th}} \text{ layer terminated into a conducting sheet} \end{cases} \quad (3)$$

$$\text{with, } z_n = \sum_{i=1}^n d_i, \begin{cases} 1 \leq n \leq N-1 & N^{\text{th}} \text{ layer unbounded in } +z \text{ direction} \\ 1 \leq n \leq N & N^{\text{th}} \text{ layer backed by a perfectly conducting sheet} \end{cases} \quad (4)$$

$k_n = k_0 \sqrt{\epsilon_{r_n}}$ is the complex propagation factor, and ϵ_{r_n} is the relative complex dielectric constant of the n^{th} layer. r_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. The above calculations must start from $i = N - 1$ and be carried out backward to $i = 0$. The value of r_N is chosen from Equation 3, depending on whether the N^{th} medium is an infinite half-space or is of finite thickness terminated into a conducting sheet.

In the numerical simulation results presented here, the calculated parameter is an experimentally measurable value of the magnitude, Γ , of the complex reflection coefficient $R = \rho_0 = \Gamma e^{j\Phi}$. The parameter Γ is 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. The purpose of the two numerical-simulation cases presented here is to gain a better understanding of the nature of the scattering involved and to stress the importance of theoretical models for optimizing different parameters (e.g., frequency) on the basis of sample/defect dimensions and dielectric properties. For simulation, a slab of low-loss dielectric material (Plexiglas) with a thickness of 25 mm and complex dielectric constant $\epsilon_r = (2.61, -0.03)$ was chosen. The dielectric constant at the W-band was taken from values reported in the literature.⁵ The defect was taken as a 1-mm layer of air bounded by Plexiglas on both sides. Total layer thickness was kept constant as the position of the defect within the slab was varied. Figure 3 shows the numerical results in the frequency range of 90-94 GHz, where the three-layer sample (Plexiglas-air-Plexiglas) is either

terminated into free space or a conducting sheet. The results show that the intensity of the scattered field is dependent on the position of the defect in the standing wave within the medium. This in turn is dictated by the operating frequency and the dielectric property of the material medium. Further, one must find the equivalent infinite half-space thickness of material media to ensure adequate depth of penetration through the material. Other important parameters that should be examined by such theoretical models are size of the defect to be detected (i.e., resolution of the measurement system) and defect orientation relative to the polarized incident field.

Fig. 3 : Normalized effective reflection coefficient as a function of frequency and depth of void for three-layer media (Plexiglas-air-Plexiglas): (Left) terminated into free space, (Right) backed by conducting plate. Total layer thickness = 25 mm; void thickness = 1 mm; $\epsilon_r^{Plex} = (2.61, -0.03)$; $\epsilon_r^{Void} = (1.0, 0.0)$.

PRELIMINARY RESULTS OF C-SCAN IMAGING SYSTEM

A Plexiglas plate was first used with air inclusions at varying depths as a calibration sample (Fig. 4). The actual test samples considered were plates of Kevlar-fiber-reinforced-epoxy composite (Fig.'s 5 and 6); Kevlar 49 with HBRF55A epoxy from Hercules with dimensions 50.8x50.8x4.8 mm, with subsurface voids and disbonds. The mm-wave source frequency was chosen on the basis of defect contrast. To avoid jitters, the source frequency was phase-locked by a source-locking counter. The samples were scanned with a pixel size of 0.423 mm, and the resulting received signals were digitized using a 12-bit A/D board. Except for the Plexiglas sample, the transmitting and receiving antennas were always copolarized (i.e. the E-fields aligned parallel). For reflection images, the back of the sample was fixed to a metallic plate.

Figures 7(a) and (b) show the transmission mode c-scan images of Plexiglas sample of Figure 4 in copolarized and cross-polarized (i.e. E-field of the two antennas aligned perpendicular)

arrangements. Due to high resolution of the antennas the air inclusions appear clearly in either mode of transmission. The polarization factor plays a much more important role when small defects display certain orientations. Figures 8(a) and (b) display the reflection and transmission images of kevlar/epoxy sample of Figure 5, including all six voids. However, as explained in the theoretical section, the image intensities of voids at different depths from the front surface are not in direct proportion to the depths, but depend on the relative positions of the defects within the standing waves in the sample. Finally, figures 9(a) and (b) show the reflection and transmission images of Figure 6 with disbonds. Because the dielectric properties of the bonded (solid) area and disbonded (air) area are distinctly different, these regions appear with different intensities. The shades within the bonded area indicate the strength of the bonding because bond quality affects the effective impedance of the media. The ability to measure bond strength has great significance for fiber-reinforced composites.

CONCLUSIONS AND COMMENTS

The potential of mm-wave imaging is addressed for nondestructive testing of low-loss materials. Based on the amplitude (power) measurements of back scattered and forward scattered radiation, the technique was evaluated for detection of subsurface defects such as voids and disbonds in Kevlar/epoxy composite samples. The use of theoretical models suggests the importance of suitable source frequencies based on defect depth and equivalent infinite half-space length of the tested material. Although preliminary results clearly indicate the successful detection of small defects on the basis of amplitude measurement, accurate characterization (defect size and depth) will require multiparameter measurements, e.g., amplitude and phase or swept frequency. Moreover, polarization properties of the fields may be utilized to enhance detection of small defects and their orientations. For instance, in forward-scatter or bistatic-backscatter measurement, a cross-polarized arrangement will enhance defect contrast with respect to background clutter. Detection sensitivity will depend on the ability to discriminate defect-scattered signals from the background of specularly-reflected (surface reflection) or through-transmitted signals.

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Fig. 4 : Plexiglas sample with artificial inclusions at various depths from top surface.

Fig. 5: Kevlar/epoxy sample with six subsurface voids at various depths.

Fig. 6 : Kevlar/epoxy plates bonded at five spots with a thin layer of glue.

Fig. 7: c-scan through transmission images of Plexiglas sample with air inclusions shown in Figure 4 : (a) copolarized scan, (b) cross-polarized scan. $f = 94$ GHz.

Fig. 8 : c-scan images of Kevlar-epoxy sample of Figure 5 : (a) reflection measurement (Conductor backed) at $f = 90$ GHz, (b) transmission measurement at $f = 94$ GHz.

Fig. 9 : c-scan images of disbonded Kevlar-epoxy sample of Figure 6 : (a) reflection measurement (Conductor backed) at $f = 90$ GHz, (b) transmission measurement at $f = 94$ GHz.

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