01 Mar 2008

Application of Frustrated Total Internal Reflection of Millimeter Waves for Detection and Evaluation of Disbonds in Dielectric Joints

Sergey Kharkovsky
Missouri University of Science and Technology

Emilio Alessandro Nanni

R. Zoughi
Missouri University of Science and Technology, zoughi@mst.edu

Recommended Citation

Application of frustrated total internal reflection of millimeter waves for detection and evaluation of disbonds in dielectric joints

Sergey Kharkovsky,[a)] Emilio Nanni, and Reza Zoughi

Applied Microwave Nondestructive Testing Laboratory (amntl), Missouri University of Science and Technology (formerly University of Missouri-Rolla), 214 Emerson Electric Company Hall, 301 W. 16th Street, Rolla, Missouri 65409-0040, USA

Millimeter waves penetrate inside of low loss dielectric materials and they are sensitive to the presence of internal interfaces and nonuniformities. This allows millimeter wave nondestructive inspection techniques to be utilized for inspecting dielectric composite structures. A disbond (a thin and extended airgap) in structures possessing adhesively bonded joints with complex geometries is commonly difficult to inspect. In this letter, we demonstrate the operational principle and the useful features of a millimeter wave technique, employing a frustrated total internal reflection of signals transmitted and received by dielectric waveguide probes for detecting and evaluating disbonds in such joints. © *2008 American Institute of Physics.* [DOI: 10.1063/1.2890054]

Microwave and millimeter wave nondestructive inspection (NDI) techniques have certain distinct advantages over other "standard" NDI techniques when detecting flaws (i.e., disbond, delamination, etc.) in dielectric composite structures. The utility of microwave and millimeter wave NDI techniques has been effectively demonstrated, in the past two decades, for a diverse array of applications.[1] Moreover, at these frequencies, inspection systems can be readily designed to accommodate complex geometries in many ways easier than other NDI techniques. To this end, a near-field millimeter wave NDI technique, utilizing dielectric waveguide (DW) probes, was developed for inspecting difficult-to-access bonded dielectric joints.[2] This technique was initially applied to interfaces made of polymer joints possessing subtle anomalies in the form of localized small air bubbles (i.e., localized disbonds).[2] However, for evaluation of disbond dimensions including thickness and spatial extent, the technique must be properly optimized. This letter presents the operational principle and the useful features of this technique utilizing the effect of frustrated total internal reflection[3–6] (FTIR) at millimeter wave frequencies.

For this purpose, the structure of interest is made of two identical dielectric sections forming a joint, which may include a disbond. The principle of the FTIR in this type of structures is schematically shown in Fig. 1(a). When the incidence angle θ is larger than the critical angle $\theta_c = \sin^{-1}(1/n)$, where n is the refractive index of the medium $n = (\varepsilon_r)^{1/2}$, ε_r is the relative dielectric constant of the medium, and the disbond thickness d is comparable to or smaller than the wavelength λ, then the signal partially penetrates through the disbond, as shown in Fig. 1(a). Monitoring the changes in the power reflection (ratio of reflected to incident signal power), R, and power transmission (ratio of transmitted to incident signal power), T, coefficients, where ($R=1\text{-}T$), which are sensitive to changes in d can yield the presence of a disbond and be used to estimate its thickness. Monitoring the changes in R is critically important from practical and measurement points of view for detecting and evaluating disbonds in dielectric joints since in such structures one does

not have access to the interior of the dielectric substrate for evaluating T or the transmitted signal.[2] Assuming an incident plane wave, the power reflection coefficient is given by[3]

$$R = 1 - \{a \sinh^2[2kd(n^2 \sin^2 \theta - 1)^{1/2}] + 1\}^{-1}, \quad (1)$$

where $k = 2\pi/\lambda$ and $\lambda = c/f$, c is the velocity of the electromagnetic wave in free space and f is the operating frequency. The "amplitude parameter" a, denoted by a_s and a_p, for perpendicular and parallel polarizations, respectively, is given by

$$a_s = (n^2 - 1)^2[4n^2 \cos^2 \theta(n^2 \sin^2 \theta - 1)]^{-1}, \quad (2)$$

$$a_p = a_s[(n^2 + 1)\sin^2 \theta - 1]^{1/2}. \quad (3)$$

Initially, using Eqs. (1)–(3), numerical simulations were performed in the millimeter wave spectrum (30–300 GHz) corresponding to the wavelength range of 10–1 mm for a dielectric polymer with $\varepsilon_r = 2.5$ and for different values of d and θ. The results showed that the millimeter wave signals
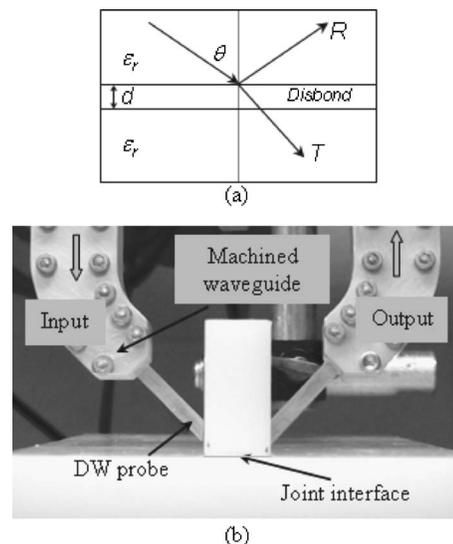
FIG. 1. (a) Schematic of FTIR of a signal incident upon disbond in a dielectric joint (not-to-scale) and (b) picture of the measurement apparatus inspecting a joint.

a)Electronic mail: sergiy@mst.edu.
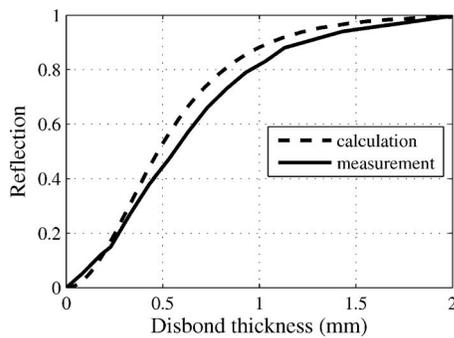
FIG. 2. Normalized measured output voltage and the calculated reflection coefficient as a function of disbond thickness ($f=67$ GHz, $\varepsilon_r=2.5$, $\theta=45°$, and perpendicular polarization).

FIG. 3. (a) Picture of the interface with five disbonds and (b) measured output voltage vs distance along the joint for two disbond thicknesses (schematic of the interface with disbonds is shown in the inset).

are suitable for detecting a disbond and estimating its thickness. For instance, at $f=100$ GHz, a 20 μm change in d (from 0.18 to 0.2 mm) yields a correspondingly detectable change in R from 0.37 to 0.43.

Based on the simulation results, a bistatic millimeter wave measurement system, similar to that used in Ref. 2, but using an optimal FTIR, was designed to provide maximum sensitivity to the presence of a disbond while being relatively insensitive to changes in θ (in the range of 40°–60°) and polarization for a material with $\varepsilon_r=2.0-2.5$ [polymers used for the experiments using configuration shown in Fig. 1(b)]. The system consisted of a millimeter wave transmitter (Gunn oscillator with an isolator), an air-filled machined rectangular waveguide assembly, two straight DW probes (each DW probe had cross section of 3.8×1.9 mm^2), and a detector while operating at a frequency of 67 GHz. The system was designed and built for $\theta=45°$ and for operation at perpendicular polarization. A signal from the transmitter is applied to the input port of the machined waveguide assembly. The machined waveguide using the DW probes launches this incident signal and receives the reflected signal from the joint interface. The magnitude (power level) of the reflected signal is subsequently measured via a crystal detector producing a corresponding dc output voltage. The main features of this technique are that the ends of the DW probes are particularly shaped to provide effective signal coupling into the sample under test, minimize the reflections from the air-dielectric interface, while the transmitted signal *locally* illuminates the desired joint interface.

In one of the experiments, the two polymer pieces, comprising the joint, were not adhesively bonded. The lower piece remained stationary, while the top piece and the millimeter wave section of the measurement system [see Fig. 1(b)] were attached to the same holder and could easily and precisely be moved up and down in tandem (i.e., producing disbonds with varying thickness). Figure 2 shows the normalized measured detector output voltage and the calculated R as a function of disbond thickness d, and for the joint constructed from two dielectric sections with $\varepsilon_r=2.5$ The power reflection coefficient R was calculated using Eq. (1), which is based on a plane wave approximation, while the experimental measurement of the reflected signal was conducted in the near-field region of the DW probes of complex shape. Therefore, one does not expect to achieve a perfect match between the calculated and the measured results. Nevertheless, the results shown in Fig. 2 indicate a good agreement between the calculated and measured results. In another
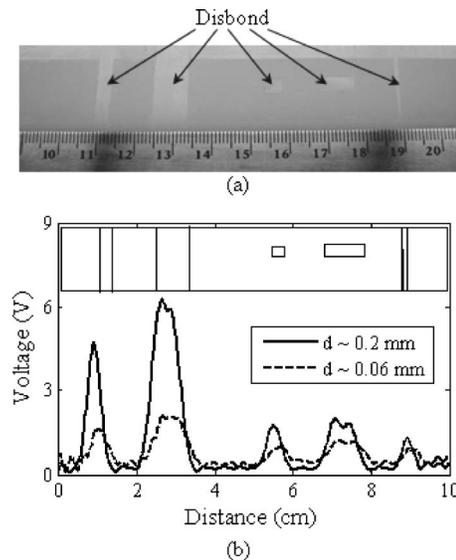
experiment, a bond was created between the same two polymer sections using a double-sided tape with a uniform thickness of ~0.06 mm. The relative dielectric constant of tape is very close to that of the dielectric polymer sections. Disbonded areas of different dimensions were produced in the interface. Figure 3(a) shows the picture of the lower (horizontal) joint section with one layer of tape and five disbonded areas created by removing specific portions of the tape. Subsequently, the top section was tightly placed at the bottom section and all were placed on a computer-controlled scanning table. The millimeter wave measurement system with DW probes was then held above the structure in the same manner as that shown in Fig. 1(b). The motion of the scanning table along the joint provided a linear scan (inspection) of the interface. The computer then synchronized the measured output voltage from the detector with the location of the scanning table (i.e., location of the DW probes). Figure 3(b) shows the scan results for two disbond thicknesses (the thicker disbond was produced by placing three layers of double-sided tape). The results show noticeable perturbations in the measured output voltage, corresponding exactly with the locations of the disbonded areas including very thin (~0.06 mm thick) disbond of different shapes. Moreover, the relative magnitude and the corresponding widths of these perturbations are proportional to the dimensions/widths of the disbond areas. It should be noted that the DW probes have a certain "footprint" over which the millimeter wave signal is reflected from the interface. Therefore, at each position the probes sense a slightly wider area compared to the actual DW aperture area. In order to directly compare the measurement results to the dimensions of disbonds, the footprint of the DW probes on the interface was taken into account. The first order approximation of the footprint with a uniform millimeter wave field distribution on the inspected interface is a rectangle, which covers the entire width of the interface and has an extent along the joint that was determined experimentally to be about 5 mm. Then, the dimensions of disbonds were convolved by a rectangular function representing the footprint of the DW probes, taking into account percent coverage of the footprint over the disbond
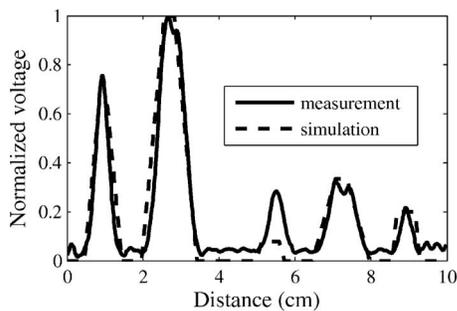
FIG. 4. Normalized measured and the simulated scan results as a function of distance along the joint for $d \sim 0.2$ mm.

area, and the results were normalized. The rectangular (footprint) function was simply defined as a unit step function from 0 to 5 mm. Figure 4 shows the normalized measured and the simulated results for a disbond thickness of 0.2 mm, indicating a good correlation between the measurement and simulation results.

In conclusion, the ability of a near-field millimeter wave NDI technique, using DW probes and employing the effect of FTIR, to detect thin disbonds in complex-shaped dielectric joints, was demonstrated. Moreover, this method was shown to be capable of closely estimating disbond thickness and spatial extent, which are important parameters in practical applications for manufacturing and repair considerations.

[1] R. Zoughi, *Microwave Non-Destructive Testing and Evaluation* (Kluwer, Dordrecht, 2000), Chap. 3, p. 82 and Chap. 5, p. 225.

[2] S. Kharkovsky, E. A. Nanni, R. Zoughi, J. Yu, and R. Wilson, Proceedings of the Third International Conference on Electromagnetic Near-Field Characterization and Imaging (ICONIC 2007) (Omni Press, Rolla, MO, 2007), p. 375.

[3] I. N. Court and F. K. Willisen, Appl. Opt. **3**, 719 (1964).

[4] S. Zhu, A. W. Yu, D. Hawley, and R. Roy, Am. J. Phys. **54**, 601 (1986).

[5] D. C. S. Beddows, B. C. Griffiths, O. Samek, and H. H. Telle, Appl. Opt. **42**, 6006 (2003).

[6] M. A. C. Potenza, D. Brogioli, and M. Giglio, Appl. Phys. Lett. **85**, 2730 (2004).