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Single Sided, Segmented Field Dielectrometry and Dielectric Spectroscopy

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KEYNOTE PRESENTATION

Abstract. The Interdigitated Electrode Dielectrometer (IDED™) is suitable for measurements on insulating or slightly conducting dielectric materials. The JENTEK team is now developing solutions for several practical applications:

- Quality control and degradation monitoring in ceramic matrix (CMC) and glass fiber composites.
- Cure monitoring of polymers, epoxy, sealants, etc.
- Measurement of porosity and thermal conductivity in ceramic thermal barrier coatings.
- Moisture measurement in transformer oil and pressboard.
- Asphalt porosity measurement
- Thin film characterization.

Keywords. Dielectrometry, Dielectric Spectroscopy, IDED, Sensors

Technical Discussion.

The layout for a typical single-wavelength IDED is shown in Figure 1(a). There are two interdigitated comb electrodes on a dielectric substrate. A driving voltage V_D is applied to one electrode, the drive, whereas the second electrode, the sense, is kept at ground potential. In the electroquasistatic mode, a spatially periodic electric field is generated, which penetrates the material under test. The electric field lines originate on the drive electrode and terminate on the sense electrodes. The IDED transadmittance, which is the quantity measured by an impedance analyzer, is defined as $Y_{21} = I_S / V_D$, where I_S is the current in the sense electrode. Typical excitation frequencies range from 0.005 Hz for highly insulating materials to 10 MHz for semiconducting materials. The frequency of excitation does not affect this depth of sensitivity for low loss dielectrics.

The spatially periodic quasistatic sensors have several advantages over alternative sensing technologies:

- Control over the depth of sensitivity allows for measuring profiles of material properties by combining the results of measurements at varying depths, controlled by varying sensor wavelength (i.e., electrode spacing).
- The layout allows for a good match between simulated and measured sensor response with the simulations carried out with efficient collocation point methods. This reduces the need for elaborate calibration standards and procedures.
- The flexible substrate makes it possible to measure on curved surfaces, with the curvature having no appreciable effect on sensor response.
- The sensor geometry allows for the creation of sensor arrays, to allow scanning over large areas with good uniformity between individual array elements. The simulation methods remain valid for arrays.
- The Fourier series analysis together with collocation point numerical techniques offers greater insight on the effects of material dielectric and conduction properties, layer thicknesses, and frequency and is usually much faster and more accurate than finite element methods [2].

A side view of the interdigitated dielectrometer in contact with a material structure that consists of several layers of homogeneous dielectric materials is shown in Figure 1(d). On the side opposite to the sensor electrodes the substrate is bounded from below by a metal plane electrode kept at ground potential.

A JENTEK IDED GridStation measuring system and a selection of IDED sensors are shown in Figure 2.

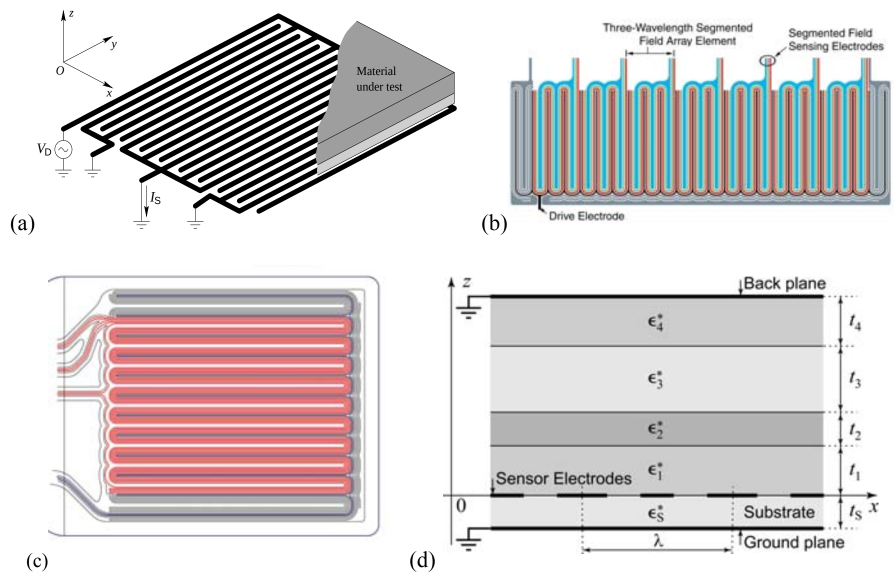


Figure 1. (a) Schematic layout for an IDED™ sensor in contact with a test material; (b) a segmented field IDED Array schematic; (c) a photo and schematic of a segmented field IDED; (d) side view of an IDED sensor in contact with a material structure having several homogeneous, lossy dielectric layers. Patents issued and pending.

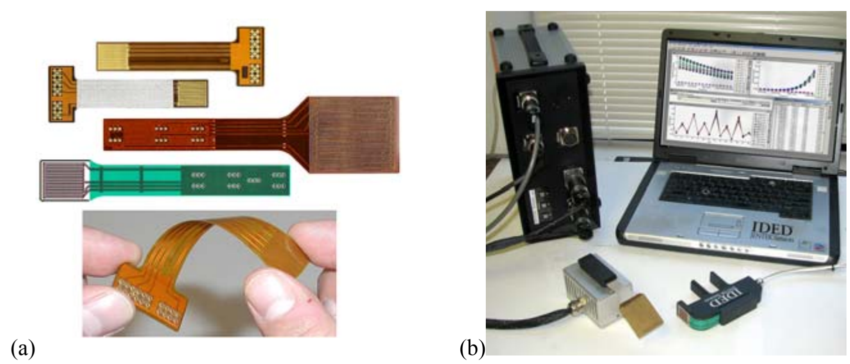


Figure 2. (a) A selection of dielectric sensors along with an image showing the flexibility of the JENTEK DS04, and, (b) a complete IDED system recently used for imaging density and thickness of asphalt samples in a program for the Transportation Research Board.

An interdigitated dielectrometer, such as that shown in Figure 1(a), produces a spatially periodic electric potential along the surface and an exponentially decaying electric field that penetrates into the material under test. The depth of penetration of the electric field produced by the IDED is proportional to the spatial wavelength of the periodic electrodes. The depth of sensitivity is considered to be approximately ⅓ of the fundamental spatial wavelength. This implies that small wavelength sensors will primarily respond to changes of material properties near the sensor-material interface, while larger wavelength sensors respond to changes farther from the sensor interface. As shown in Figure 3, multiple wavelength (segmented field) sensors and arrays can provide multiple penetration depths within the same sensor footprint. **Multiple wavelength data are needed for the simultaneous independent estimation of the several unknown properties that typically need to be estimated in a practical problem.** For example, the simplest two-unknown practical problem of lift-off (proximity) and dielectric constant (permittivity) requires two electrical spacings (wavelengths) for a nonconducting material (e.g., ceramic). Alternative dielectric techniques, e.g., parallel-plate, cannot accomplish this independence and must make assumptions that incidental variables, such as lift-off (air gap between senor and material), are known and constant, which is rarely justified in a typical single-sided NDE measurement, especially on a curved part.

Several types of segmented field sensors have been developed by JENTEK [1, 2, 3]. Some of these sensors are shown in Figures 1(c) and 2(a). A schematic of a segmented-field IDED-Array is shown in Figure 1(b). These sensors integrate multiple sensing elements into a single sensing structure so that all of the sensing elements interrogate the same region of the material under test. A schematic for the electric field distribution is shown in Figure 3, where three sensing electrodes are placed within each interdigitated electrode period and respond to different effective wavelength modes (near, mid, or far) of the electric field.

Thus, segmented-field sensors provide estimates of the absolute dielectric properties (conductivity, permittivity) of the material at any given frequency (in addition to layer thickness measurement). This enables dielectric spectroscopy, where the dielectric propertied of the materials are measured over a wide frequency range. This allows characterization of dispersive materials (such as asphalt and CMCs). The bulk (average) dielectric properties of composite materials typically manifest such frequency-dependent (dispersive) behavior; thus dielectric spectroscopy is particularly useful in quality control and degradation monitoring of such materials.

Databases of precomputed sensor responses (Figure 4), known as measurement grids, lattices, and hyperlattices, are used with a patented algorithm to convert complex transimpedance data into two or more unknown property estimates at each sensing element location. In the case of three unknowns, 3-D lattices (Figure 5), which can be visualized as a collection of 2-D measurement grids, are used.

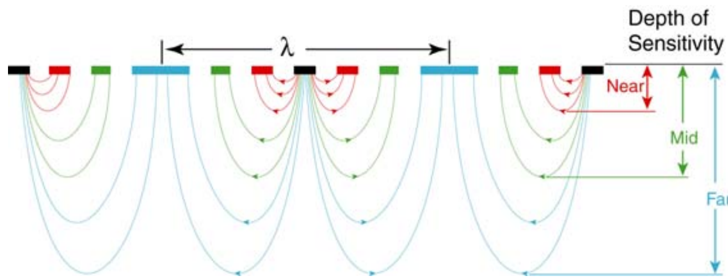


Figure 3. Electric field lines of a three-wavelength IDED. The three electrodes are shown to sense different depths within the test material and share the same sensor lift-off.

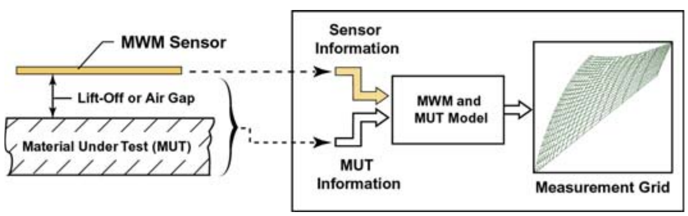


Figure 4. JENTEK measurement grid generation.

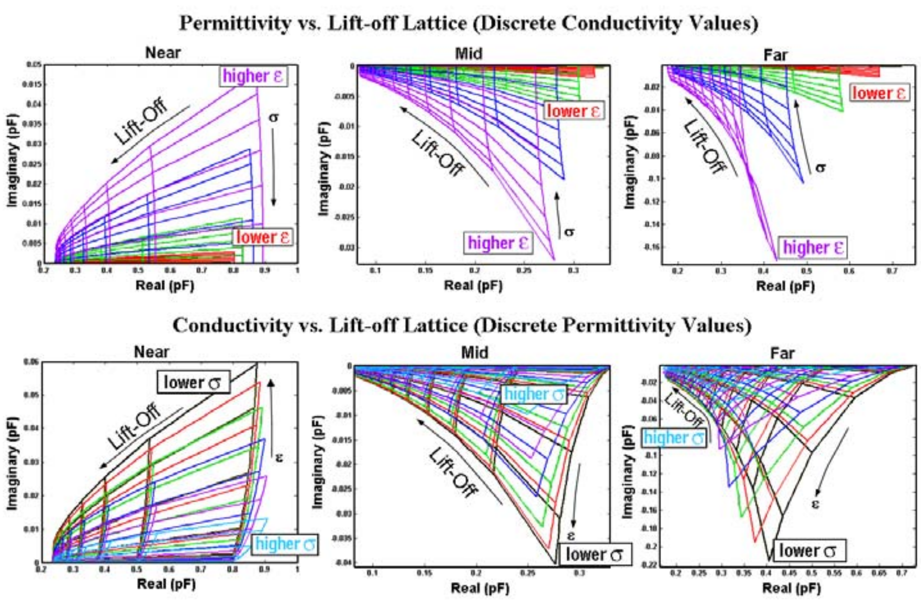


Figure 5. Visualization of three IDED measurement grid lattices for 3 unknowns (patents issued and pending). The lattices correspond to the IDED sensor's near, mid, and far sensing electrodes. The two rows represent different 2D visualizations of the same 3D lattices.

Figure 6 shows the effect of tensile loading of a glass fiber composite on the relative permittivity, as measured by an IDED. These measurements were made at a single frequency and the decrease in permittivity is consistent with a reduction in the local density of the material, expansion of voids, or degradation (microcracking) of the fiber or matrix.

To illustrate the use of an embedded sensor in a joint, a permanently mounted IDED sensor was used to monitor the cure state of a sealant and to detect moisture ingress at the bondline in a laboratory demonstration [4]. The experimental set-up is shown in Figure 7. The outer layer was a two-part, epoxy cured polythioether compound used for aircraft fuel tanks and structures. Below the sealant is a 0.005 in. thick micro-porous layer sandwiched between two 0.0005 in. thick plastic sheets. The end of the porous layer extends well beyond the sensor in order to act as a channel for the introduction of moisture. Immediately below the plastic film, the segmented field IDED sensor was mounted on a 0.250 in. aluminum alloy plate.

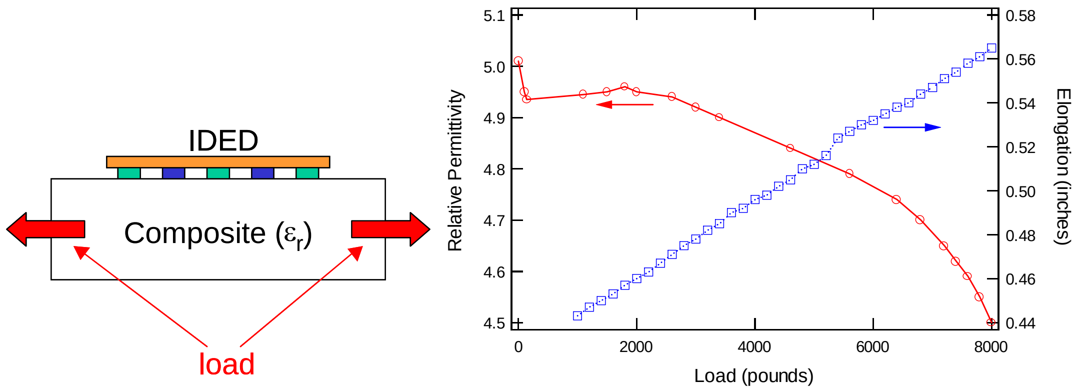


Figure 6. The effect of tensile loading of a glass fiber composite on the relative permittivity, as measured by an IDED. These measurements were made at a single frequency and the decrease in permittivity is consistent with a reduction in the local density of the material, expansion of voids, or degradation (microcracking) of the fiber or matrix.

After calibration in air using a model-based method, the sensor response was monitored using a 3-unknown Grid Method for three days from the initial application of the sealant through multiple wetting and drying cycles. During this time, the effective sealant permittivity, sealant conductivity and sensor lift-off were measured at intervals of 150 seconds. Figure 6 (left) shows the sealant property measurements for the first 30 hours following application of the sealant. Once the sealant cure was complete, water droplets were applied to the portion of the porous layer that extended beyond the sealant. Figure 6 (right) shows the permittivity response to the wetting and drying processes. While the introduction of the water was an abrupt event, the sensor response during the drying process better indicates the high sensitivity of this sensing modality to smaller changes in moisture content. This ability to sense minute quantities of moisture was subsequently displayed a second time by a rise and fall in permittivity corresponding with a passing rainstorm.

As a simple illustration of the use of measurement grids, Figure 9(a) shows an example measurement grid for monitoring the cure state of a thick layer of epoxy placed over an IDED sensor [5]. To permit reuse of the sensor, the epoxy is placed on top of a disposable polymer layer. The thickness of the epoxy layer (Δc) is large compared to the sensor wavelength so that the epoxy can be modeled as an infinitely thick layer. As the epoxy cures, the magnitude and phase of the sensor transadmittance change as illustrated on the measurement grid. Interpolation of these data points on the grid then provides the transient measurements and independent estimates of the permittivity and conductivity for the curing epoxy. The time and value of the peak in the permittivity and conductivity are dependent upon the chemistry of the epoxy and reflect the cure state of the material. Figure 9(b) shows, for these chemistries, that the nominal cure time is reflected in the time transient variation in the conductivity, rather than the permittivity.

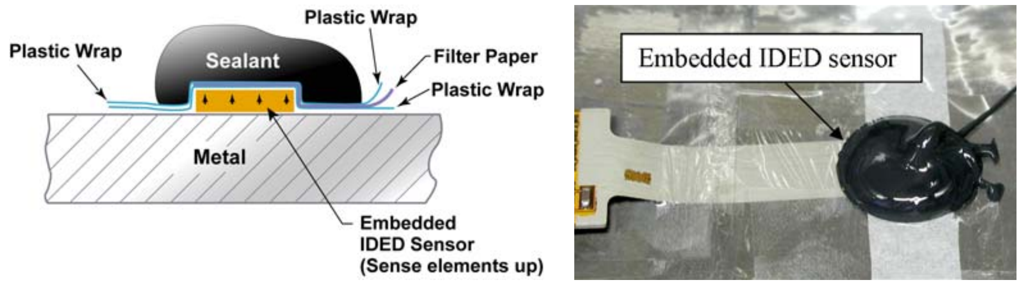


Figure 7. An embedded sealant construct used for cure monitoring and simulated water intrusion.

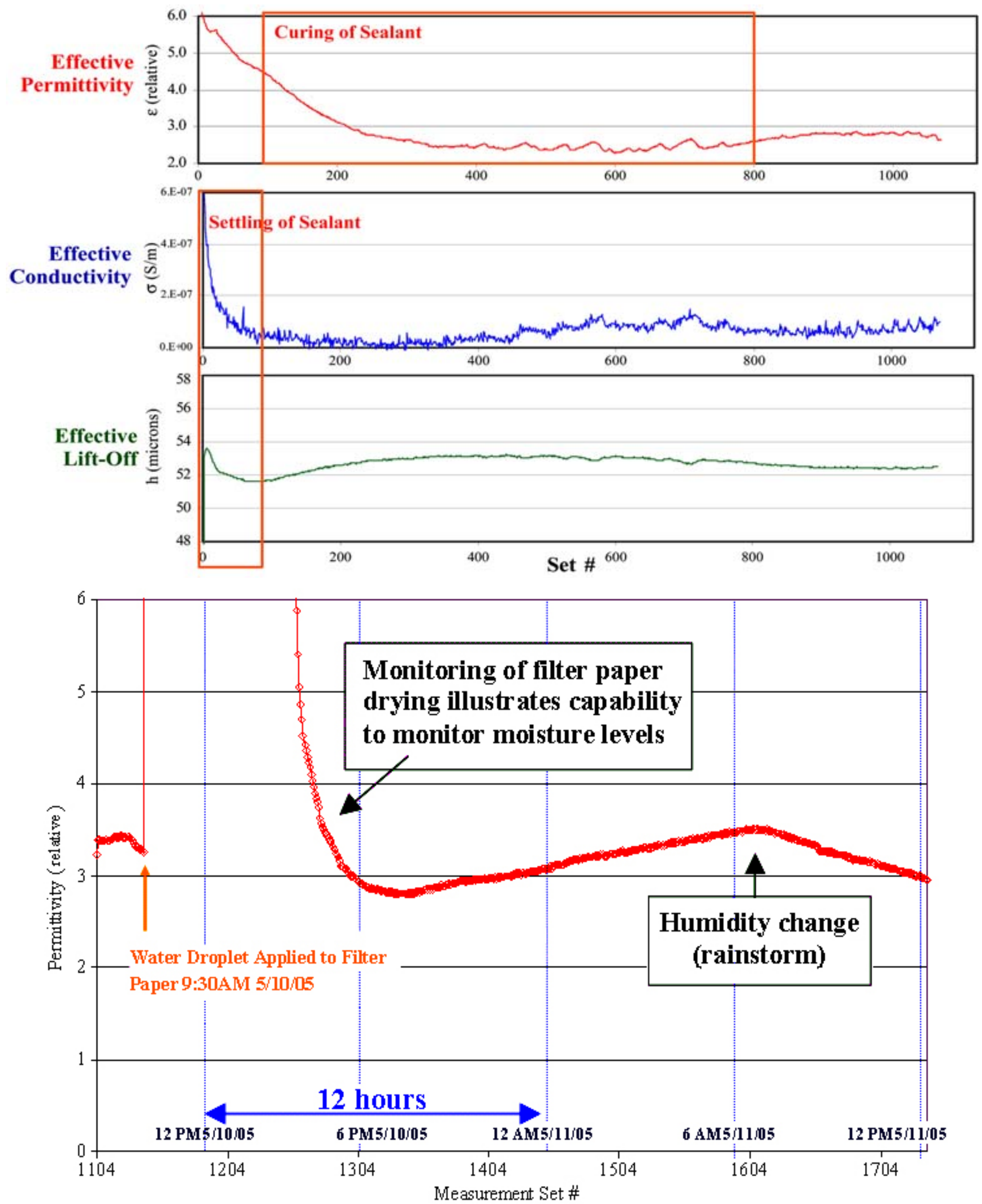
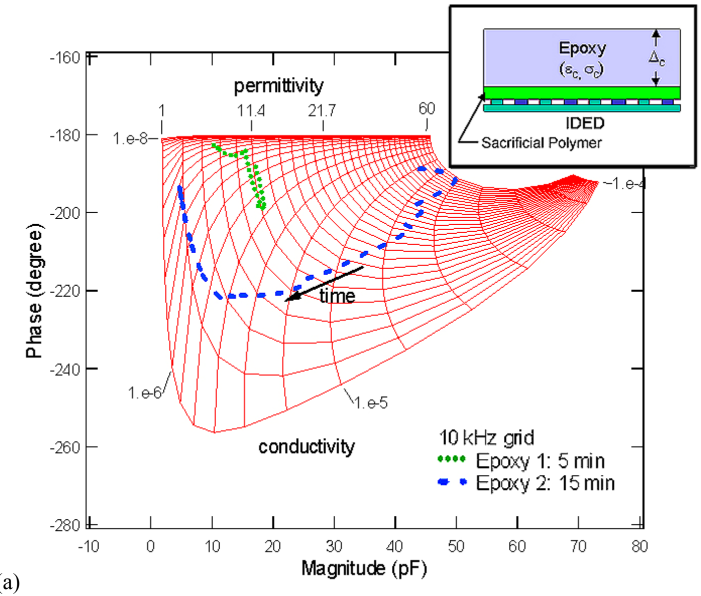
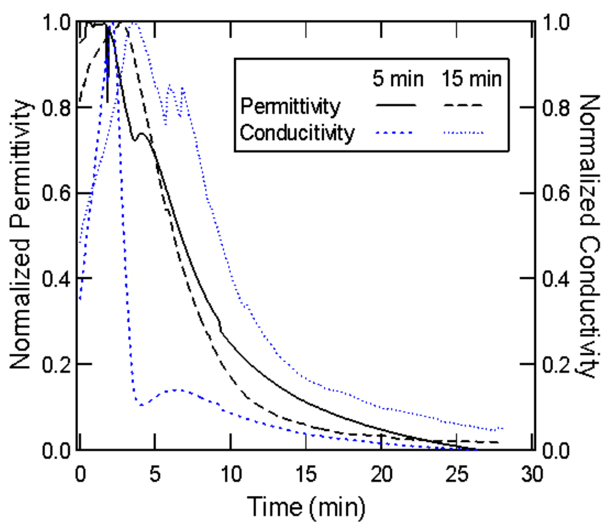


Figure 8. (top) In-situ sealant cure monitoring; (bottom) sealant permittivity during water exposure.



(a)



(b)

Figure 9. (a) A permittivity/conductivity grid for independent conductivity and permittivity estimation for two epoxies during curing, (b) effective property estimates normalized by the peak value.

References

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