MAPPING THE DIELECTRIC PROPERTIES OF LOSSY MATERIALS IN SITU

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INTRODUCTION

Microwave sensors have been adapted to measure and create an image of the complex permittivity of lossy sheet materials non-destructively. The intended application is a portable probe which can map near-surface dielectric anomalies in various types of partially conductive sheet materials commonly found in aerospace equipment. Examples abound: radar-camouflage panels and textiles, coated canopies and moisture in non-conducting composites. The need for such a probe originates in a number of different ways:

The radar signature of low-observable panels may be altered by any one of a number of different types of damage occurring in flight or otherwise.

A canopy has an encapsulated thin metal film which is not accessible to a 4 point probe for quality assurance.

The surface temperature of a high-performance aircraft can rise above 300 °F in flight. Therefore, absorbed moisture in sufficient quantity can vaporize and cause structural damage and/or degraded radome performance. In general, moisture in composites can cause swelling, blistering, microcracking, reduced glass transition temperature, exacerbated repair problems, and increased weight and possible imbalance of the aircraft.

RECAPITULATION OF SENSOR BEHAVIOR

Reflection-mode open microwave resonator sensors [1] of various types are used to generate the maps. One such resonator is a quarter-wave section of coaxial transmission line. One end of the line is terminated in a short circuit, the other is open-circuited. For a resonant frequency of about 1 GHz the overall length is about 7.5 cm using air as a dielectric insulator. The transmission line supports a standing wave electric field when excited via the coupler at its input port. In use, the open end is pressed against some piece of dielectric material, perhaps the wing of an aircraft. The near field of the resonant structure fringes into the test material. The complex dielectric properties of the test material \( \varepsilon^* = \varepsilon' - j\varepsilon" \) thereby affect the resonance in a way that can be detected at the input port.

Mapping is accomplished by rastering the sensor over the surface of the test piece, meanwhile recording an image of the dielectric properties at each location. An encoder or scanning mechanism attached to the sensor keeps track of the location.

The coaxial resonator has the advantage of symmetry and a very small footprint. The coaxial sensor data is independent of the sensor's orientation or the degree of anisotropy, and the size of the footprint is independent of the operating baseband. On the other hand the sensitivity leaves something to be desired since only the end-admittance is
affected by the test material. Also, as will be seen, this type of sensor does not have a linear response to the loss factor ($\varepsilon''$) of a lossy test material.

Another class of resonator is based on the microstrip transmission line. For instance, a linear half-wave dipole resonator consists of a narrow strip of metal tape about 8 1/2 cm long, separated from a ground plane by a sheet of Duroid™. In use, the metal strip is exposed to the test material along its entire length. The sensitivity is much higher than that of the coaxial resonator, because the distributed admittance as well as the end-admittance of the transmission line are affected by the test material. The sensitivity tends to increase as the Duroid thickness increases, and as the linewidth of the metal strip decreases.

On the other hand, the footprint of the linear dipole is correspondingly much larger than that of the coaxial resonator. Also, the linear dipole "sees double"; being open-circuited on both ends, there is a high-field point at each end. One way to shrink the footprint is to shape the resonator [2]. In the "split-ring" resonator the linear dipole has been bent around in a circle until the ends almost touch. This approach puts the high-field points next to each other, eliminating the "double vision". The footprint can be reduced further, for instance by putting capacitor-like plates at each end or by increasing the baseband frequency of operation.

RECENT EXAMPLE OF DIELECTRIC CARTOGRAPHY: RADAR-CAMOUFLAGE HONEYCOMB PANELS

Fig. 1 resembles maps that have been described on other occasions, but it was not possible to map this particular test material until recently because the material is so lossy it would have damped out the resonance of the sensors in use then.

![Fig. 1.](image)

(a) Sketch of lossy panel with two subsurface burned spots. (b) Sensor map of the panel, using $R_o$ as the dependent variable.
The Air Force supplied a pair of wedge shaped lossy honeycomb panels which are surrogates for airfoils in use. As sketched in Fig. 1(a), one of the panels' core was burned with a torch in two places prior to assembly. The burn simulates a type of realistic damage (removing the matrix next to the skin) producing an air gap, without affecting the visual appearance of the skin. The location of the burns was not revealed until after the test. The materials of the honeycomb and skin are known only to the Air Force.

A split ring resonator mapped the panel as shown, taking data every 10 mm. The shade of grey of the dark areas of Fig. 1(b) represents the $R_o$, a variable related to the microwave loss factor of the honeycomb. The air gaps cause a high value of $R_o$. In addition to revealing the burns, the sensor reveals an air gap where the lossy honeycomb wouldn't fit into the corner of the wedge. A smaller pixel size generally improves the image fidelity, with a corresponding reduction in the speed of data acquisition.

The $R_o$

The resonator can be modelled as a parallel lumped-element RLC tank circuit with an $n$:1 transformer as coupler [Fig. 1 of [2]]. As the source frequency is stepped through the sensor's resonance, a reflectometer is used to detect the return signal. The raw data as seen by a network analyzer is the spectrum of the absolute value of the complex reflection coefficient $S_{11}$. The resonant frequency $f_r$ is the minimum of $|S_{11}|$. The $R_o=n^2R_o$ or input resistance at resonance, is related to the amplitude of the minimum $|S_{11}|$ [3,4]. In the RLC model, the ($\varepsilon'$) of the test material affects mainly the resonant frequency $f_r$, and the loss factor ($\varepsilon''$) of the test material (as well as the turns ratio $n$) affects the input resistance $R_o$.

The occasion for this paper is the recent progress we have made in increasing the range of "turns ratio" $n$ of the field-adjustable coupler. When confronted with a very lossy test material, the user can increase the $n$ by means of a single adjustment, thereby preventing a serious mismatch between sensor and feed cable ($R_o \neq R_c$, the characteristic impedance of the feed cable) which would otherwise have damped out the resonance.

As the incident wave which is swept through a band of frequencies all of the energy in the incident wave is reflected back to the reflectometer or network analyzer above and below the resonant frequency. At the resonant frequency, most of the incident wave is absorbed by the sensor and material under test. The result is a sharp dip or spike in the spectrum. The spike is more pronounced or 'spiky' if there is little or no mismatch.

WHICH IS THE BEST SENSOR?

The choice of sensor depends on the application. The sensors we have experimented with to date have generally non-overlapping plusses and minusses when judged by various criteria: sensitivity, footprint size, linearity, image fidelity, dynamic range and so on. For the balance of this paper the criteria of linearity and footprint size are singled out.

LINEARITY

In certain applications it is desirable that the sensor's response parameters be linear functions of some material properties.

Example: Quality Control in Canopy Fabrication

A canopy manufacturer provided a sheet of plastic covered with an almost-transparent gold film, together with data of the distribution of 4 point probe DC sheet resistance. In the course of manufacturing a canopy, the gold films are laminated after deposition, rendering 4-point probe measurements of the finished product impossible. In order to monitor canopy quality it is important to find a sensor whose output is a linear or at least a monotonic function of the film thickness. In one corner of the plastic sheet (where $R_o \sim 26$ ohms/square) the film was thick enough to be plainly visible, tapering...
off toward the opposite edge ($R_Q \sim 130$ to 150 ohms/square). Fig. 3 (a) shows a three dimensional map of the film's sheet resistance.

A 1 GHz. linear dipole sensor was scanned over the film as in Fig. 2(b), taking data automatically every 5 cm over a 4 x 5 grid. Fig. 3(b) shows a map of the microwave data, $R_Q$ (in ohms, proportional to $1/e''$); chosen rather than $e''$ for ease of comparison to $R_Q$. The resemblance is evident.

In Fig. 4 the microwave is plotted against the DC data. The input resistance $R_Q$ is a fairly linear function of the logarithm of $R_Q$, but with considerable variance about the linear fit. The variance may be attributed to the poor spatial resolution caused by the large footprint of this sensor.

The curious dependence on log($R_Q$) is at present unexplained. From elementary electromagnetic theory we would have expected $R_Q$ to be proportional to $\sqrt{R_Q}$. We do not have a model of the microstrip resonator sensor because, owing to the laminar geometry, it is difficult to simulate the field distributions of these sensors in closed form. In order to corroborate Fig. 4 to some degree, we resolved to determine whether other types of microwave sensor, confronted with this test material, also responded with the same proportionality to log($R_Q$); and whether this resonant sensor, confronted with other types of sheet conductor with wider variation in $R_Q$, responded according to log($R_Q$).
Radar-Camouflage Cloth: Split-Ring Dipole Resonator

A greater sample population of $R_o$ was required to adequately test the dynamic range of the resonant sensor. Rather than trying to extend the range of $R_o$ with thin metal films, we acquired fifteen 20 x 28 x 0.15 cm sheets of conductive cloth from a textile manufacturer. The sheets are coated with doped polypyrrole, a conducting polymer. The nominal DC sheet resistivity as measured by the manufacturer using a 2-point resistivity meter ranged well over three orders of magnitude, from 27 to 10,000 ohms/square. The cloths are useful to the military as a type of camouflage.

Tests were performed by taking a single data point of $R_o$ for each sheet of cloth, using an 0.3 cm foam spacer between the microstrip resonant sensor and the cloth to avoid damping out the sensor's electromagnetic wave completely. The use of foam rather than plastic for the spacer material increased the sensitivity of $R_o$ to $R_o$ appreciably.

In Fig. 5 it is seen that $R_o$ is again linear in log($R_o$) over a wide dynamic range. A different resonator shape was used--split ring rather than linear dipole--so the results are not numerically the same as in Fig. 4 (the canopy data). The data fits a straight line better than Fig. 4, probably because the sensor footprint is much smaller than any variation in $R_o$. Errors may be attributed to deviation of $R_o$ from the nominal value; the manufacturer only measured samples in a large batch.

Radar-Camouflage Cloth: Coaxial Resonator

The thought occurred that the dependence on log($R_o$) might be due to the geometry of the microstrip resonator. The microstrip resonator is inductively coupled to the feed cable in such a way that the feed cable can "see" the test material directly. In order to remove this effect, we repeated the experiment with a coaxial resonator sensor. The coaxial resonator differs from the microstrip resonator in that the standing wave propagates back and forth in air, in a direction normal to the plane of the test material, rather than in that plane. In consequence, the coaxial sensor's coupling mechanism is not directly affected by the test material, because the feed cable is on one end of the sensor, and the test material is on the other end.

Upon testing the conductive cloth of various sheet resistivities with the coaxial resonator, Fig. 6 was obtained. It is seen that $R_o$ is now a nearly parabolic function of the

![Graph](image-url)
Fig. 5. Microwave vs. 4 point probe DC data taken on radar-camouflage cloth, using a split-ring dipole resonator in microstrip. $R_0$ appears to track $\log(R_\text{DC})$ linearly over more than three decades.

The logarithm of the cloth's sheet resistivity. The existence of a minimum in $R_0$ accords with physical intuition. The ratio of $E/H$ (the electric field intensity divided by the magnetic field intensity) inside a coaxial cable is 377 ohms, the intrinsic impedance ($\eta_0$) of free space. If the wave travelling down the coaxial transmission line encounters an object with the same impedance as the intrinsic impedance of the wave, then the reflection from the object would be zero, and therefore $R_0$ would be zero; that is, the resonance would be entirely damped out.

This effect could be used to advantage in the testing of "space cloth", used for military camouflage purposes. In Fig. 6 $R_0$ falls to a very broad minimum centered at a sheet resistance of about 600, rather than 377 ohms/square. Presumably the laminar structure of the test material is to blame: the sheet resistance of the spacer layer combines with the sheet resistance of the conductive cloth to form an effective impedance, but we have not yet quantified the relationship.

Fig. 6. Microwave vs. 4 point probe DC data taken on radar-camouflage cloth, using a coaxial resonator sensor. The dashed line is a parabola fitted to all but the two outliers at either end.
FOOTPRINT

If the footprint is reduced, performance can improve in a number of respects:

- the image fidelity improves
- the sensor can follow surface contours, get into tighter spaces
- less pressure is required to eliminate air gaps, so in situ use becomes feasible

The image fidelity improves because the sensor image is related to the convolution of the anomaly with the footprint. One could shrink the footprint by increasing the operating frequency band, but it is better not to operate above 1 GHz for practical reasons related to the controller.

3-Dimensional (3D) Microstrip Resonators

As depicted in Fig. 7 little projections have been added to the open circuited (high-field) ends of various types of microstrip resonator, normal to the plane of the resonator. Also, we have shaped the ground planes to make it easier to follow the bulges, valleys and wrinkles which may be associated with anomalies in the composite material.

Fig. 8(a) is the template of another surrogate radar-camouflage (lossy) honeycomb panel, again with burns deliberately added. Fig. 8(b) is a 3D quarter-wave dipole sensor image of the lossy honeycomb. Note that this resonator can distinctly image a 1.25 by 1.25 cm burn, and the 0.6 by 0.6 cm burn is vague but still visible. None of the other (2D) resonators we have tested can see a low-contrast feature that is as small as 1.25 by 1.25 cm.

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Fig. 8. (a) Template of deliberate burns in surrogate LO panel. (b) Image of the panel made by a 3D sensor in microstrip.

REFERENCES