Surface Electromagnetic Wave Characterization Using Non-Invasive Photonic Electric Field Sensors

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Abstract— Electromagnetic properties of aircraft and missile skins have a large effect on radar cross sections and determine the level of stealth that is achieved over the various RF bands currently in use. RF absorption, reflection, and propagation along the skin surface all serve as important measures of the electromagnetic performance of the coated surfaces. Non-invasive probing of the electromagnetic field just above the propagating wave at multiple spots along the propagation direction can be used to determine and measure wave propagation parameters, including effective RF index, loss per length, wave impedance, and frequency dependent material properties of the coatings. Wide-band photonic electric field sensors have been demonstrated for probing of dielectric layers by measuring the traveling waves along the coated aircraft surface. The photonic E-field sensors are extremely linear and produce an exact real time analog RF representation of the electric field, including phase information. These ultra-wideband (UWB) photonic RF sensors are very small and contain negligible metal content, allowing them to be placed at close proximity without perturbing the RF surface waves. This is very important in accurately characterizing highly damped surface waves on absorber layers. This paper discusses the linearity, bandwidth, polarization, and sensitivity of the unique UWB photonic E-field sensor design. Experimental results are presented on surface-wave characterization measurements using these sensors.

I. INTRODUCTION

Near-field probing of traveling waves at the surface of a dielectric layer is a potentially reliable and accurate method of characterization of RF properties. RF material properties of the dielectric can be extracted over a desired frequency band from the measured wave propagation parameters, including effective RF index, loss per length and wave impedance RF energy can be launched off axis at an angle and polarization that can allow coupling into the dielectric layer. Specifically, this coupling angle is such that the momentum vector component of the launch beam parallel to the skin surface is equal to that of the traveling mode. Non-invasive probing of the electromagnetic field just above the propagating wave at multiple spots along the propagation direction can be used to determine the RF index and loss characteristics of the coated surface.

Photonic E-field sensor technology makes non-intrusive RF field mapping possible, thereby ensuring minimal cross talk between arrayed sensor elements for highly accurate near-field RF measurements. The sensor technology is highly compact, has high sensitivity, and is coupled to RF instrumentation via EMI immune fiber optics. The fiber optic-coupled RF Photonic probes are wide-band and can support the entire frequency range from near DC to over 20 GHz, accommodating both S and X bands. The sensors are extremely linear and produce an exact real time analog RF representation of the electric field, including phase information.

II. PHOTONIC SENSOR CHARACTERISTICS

Electric field sensors operating from near DC to 20 GHz based on the electro-optic effect in lithium niobate and similar materials have been demonstrated [1-4]. A sensor system consists of an electro-optic chip connected to a remote optical source/receiver unit via fiber optics. From an application perspective, it is an RF-in / RF-out device, in which the sensor head is tethered by a compact, light-weight fiber optic rather than a coaxial cable.

The fundamental principle of a photonic electric field sensor is that the refractive index in the sensor chip changes in proportion to the external electric field. The most effective device structure to translate the refractive index change into an intensity change is the Mach Zehnder interferometer (MZI). Light from a laser is passed through the chip via fiber optics, and changes in intensity of the returning light are detected using a photoreceiver that is connected to an RF spectrum analyzer, network analyzer or high-speed oscilloscope. The sensor small-signal response is highly linear with respect to the E-field amplitude.

The sensors used in this work are MZI-based devices in bulk, x-cut lithium niobate. A thin integrated electrode structure on one face of the crystal is used to translate the external electric field into an internal field along the crystal’s z axis, which gives the maximum electro-optic effect.

A. Sensitivity Measurement

The minimum detectable field amplitude, or sensitivity, of a sensor is measured in the laboratory by placing the sensor in a transverse electromagnetic mode (TEM) cell [5]. The TEM cell produces a known field amplitude for a given RF input power. The test setup is illustrated in Figure 1. The sensor is placed in the TEM cell with its preferred axis at a known
orientation relative to the applied field. A 1550 nm diode laser is connected to the sensor input, and the sensor output is connected to a high-speed photodetector. The photodetector output is connected to an RF spectrum analyzer. A 300 MHz calibration tone from the spectrum analyzer is amplified and connected to the TEM cell’s RF input.

From the measured output power, $P_0$, and noise power spectral density, $P_n$, the minimum detectable field in a 1 Hz bandwidth can be calculated as:

$$E_{\text{min}} = E_0 10^{-(P_0 - P_n)/20}$$  \hspace{1cm} (1)

where $E_0$ is the electric field amplitude at which the measurement was made.

Several sensors were characterized at 300 MHz, with the results summarized in Table I. In all cases the minimum detectable field is less than 10 mV/m/Hz$^{1/2}$.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>SNR @ 300 MHz, $E_0 = 3.4$ V/m</th>
<th>$E_{\text{min}}$ @ 300 MHz (mV/m/Hz$^{1/2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>51.8</td>
<td>9</td>
</tr>
<tr>
<td>2</td>
<td>52.7</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>52.5</td>
<td>8</td>
</tr>
<tr>
<td>4</td>
<td>60.5</td>
<td>3</td>
</tr>
</tbody>
</table>

**TABLE I. MEASURED SIGNAL-TO-NOISE RATIO (SNR) AND MINIMUM DETECTABLE E-FIELD FOR SEVERAL SENSORS**

**B. Compact Range Measurements**

The ability of the photonic sensor to measure RF waves with high time resolution has been demonstrated by measurements in the compact electromagnetic range at The Ohio State University ElectroScience Laboratory. The test setup is shown in Figure 2. The sensor was placed at a distance of 8 feet from a wide-band (2-18 GHz) horn that was driven by one port of a vector network analyzer (VNA). The output of the sensor system was connected to the second port of the VNA, or alternatively to an RF spectrum analyzer for single-frequency measurements.

**Figure 2. Arrangement for compact range testing.**

1) **Linearity Measurement**

The linearity of sensor 4 was measured at 2 and 10 GHz by varying the horn input power from -10 to +5 dBm. The results, plotted in Figure 3, show that the sensor response is highly linear over this range.

**Figure 3. Linearity of sensor 4 response at 2 GHz (red) and 10 GHz (blue).**

2) **RF Polarization Extinction**

To determine the polarization dependence, the horn was rotated in steps from 0 to 90°. The measured signal power vs. angle is plotted in Figure 4, along with the expected value based on a cosine-squared dependence. The latter is what one would expect with complete polarization extinction. Based on the test data, the photonic E-field sensor exhibits a strong dependence on the polarization of the RF wave, with an extinction ratio of approximately 20 dB.

Also shown in Figure 4 is the signal in the cross-polarization configuration (90°) with a three-dimensional...
corner reflector placed behind the sensor (green triangle). Due to the polarization rotation upon reflection, the sensor responds to the reflected wave at a level of more than 15 dB above the incident wave.

3) Time Domain Response

Figure 5 shows a representative frequency response from 2 to 14 GHz for a SRICO sensor in the far-field of the horn antenna, with a reflector placed one foot behind the sensor. Figure 6 shows the corresponding time domain response, calculated by an inverse fast Fourier transform. The frequency domain response shows interference fringes from the incident and reflected RF waves. In the time domain response, two peaks separated by approximately 2 ns can be seen, corresponding to the incident and reflected waves. The round trip separation between the sensor and the reflector can be inferred from the time delay as approximately 2 ft. The sharpness of the peaks in the time-domain plot confirms that the sensor response has low dispersion.

One advantage of fiber optic sensors is that they can be arrayed in a compact, multi-sensor configuration more easily than devices that require coaxial cable connections. By arraying sensors appropriately, it is possible to extract a full vectorial representation of the propagating EM wave. Figure 7 illustrates the proposed surface-wave sensor head design concept, which includes three small SRICO electro-optic (EO) sensors in a planar delta formation. Each EO sensor records the amplitude and phase of the electric field passing through the sensor. The propagation constant and attenuation factor can then be derived from sensor outputs of A-C and A-B pairs. The direction of propagation (in case of misalignment) can be derived from the difference in phase or time delay between sensor B and C outputs.

III. MEASUREMENT OF DIELECTRIC LAYER PROPERTIES

To demonstrate how photonic E-field sensors can be used to probe surface waves, we conducted a simple measurement using the setup shown in Figure 8. A commercial microwave absorber layer was laid on top of a conducting plane. A wideband horn was used to launch EM fields from 2 to 18 GHz at approximately 75 degrees depression angle from the right hand side of Figure 8. A SRICO sensor was then placed
directly on the absorber at different down range positions at 2 cm increments toward the left (i.e. away from the source). Note that the actual EO sensor is less than 1 cm² and was placed inside a plastic housing for mechanical protection. S₂₁ data were then collected from 2 to 18 GHz by connecting the horn to Port 1 and the sensor output to Port 2 of a vector network analyzer.

Figure 8. Measurement of traveling wave in a dielectric layer.

Figure 9 plots the time-domain response obtained from inverse Fourier transforming the measured frequency-domain data at different downrange positions. The amplitudes of the time-domain responses are normalized to the peak amplitude of response obtained at zero offset. Two sets of curves were included in Figure 9: one with the absorber coating (dashed lines) and the other without absorber (solid lines). It is observed that the peak amplitude decreases as the probe moves away from the source in the no-absorber case as expected from spherical wave spreading. The photonic E-field sensor can accurately measure the time delay associated with the 2 cm distance increments. In the absorber-coated case (dashed lines), it is interesting to observe that the rate of peak amplitude decreasing is faster compared to the no-absorber case (solid lines), indicating additional surface-wave attenuation introduced by the absorber coating. It is also interesting to observe that the shorter time delays between adjacent probe positions compared to the no-absorber case, indicating the presence of fast wave, i.e. phase velocity faster than speed of light. This is related to the presence of magnetic contents. With further processing and calibration, the propagation constant and attenuation factor information can be extracted from the time delays and amplitude decay.

Figure 9. Time domain response of sensor at 2 cm distance increments with and without dielectric absorber.

IV. CONCLUSION

Lithium niobate photonic electric field sensors have been shown to be a viable tool for near-field measurement of traveling waves in dielectric layers. The wide bandwidth, high sensitivity and low dispersion of the sensors enable accurate determination of RF propagation constants, which can be used to extract material properties of the dielectric layer.

REFERENCES


