MEASURING NEAR AND FAR FIELDS OF ANTENNA SYSTEMS USING A NOVEL ELECTRO-OPTIC PROBE SYSTEM

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ABSTRACT

In this paper, we will introduce a novel near field measurement system that uses an electro-optic (EO) crystal probe mounted at the tip of an optical fiber to sample electric fields at the surface of a radiating aperture. The cross section of the probe has dimensions 1 mm × 1 mm and its depth may vary from 100 μm to 1 mm. Since the fiber-based probe does not involve any metallic parts or interconnects at the signal pickup area and due to its very small physical size, it operates in a non-invasive, RF-transparent manner with respect to the antenna under test (AUT). As a result, the probe can scan fields at a plane as close as 200 μm above the antenna surface. Tangential and normal probes are used to measure all the three components of the electric field with cross polarization suppression better than 25 dB. Both amplitude and phase of the field components are measured in each scan. Due to the optical nature of the probes, very wideband measurements can be performed up to 20 GHz using the same probes. From the scanned near field maps, the radiation pattern of the AUT is estimated using a near-to-far-field transformation. Measured data will be presented for the near and far fields of a number of antennas, and the results will be compared with full-wave simulation data as well as measured pattern data collected in an anechoic chamber.

I. INTRODUCTION

The measurement of far field radiation patterns of antennas, arrays and other radiating structures typically requires the use of an anechoic chamber. Chamber measurements are carried out in the far (Fraunhofer) zone of a radiating structure defined by

\[ r \ll \frac{2D^2}{\lambda_0} \]

(1)

where \( r \) is the distance between the antenna and the observation point, \( D \) is the largest linear dimension of the antenna, and \( \lambda_0 = 2\pi/k_0 = c/f \) is the free-space wavelength, \( k_0 \) is the free-space wavenumber, \( f \) is the operational frequency in Hz, and \( c = 3 \times 10^8 \) m/s is the speed of light. Depending on the operational frequency, the size of the required chamber may vary drastically. At lower frequencies when the wavelength increases to a meter or more, very large dimensions are required for an accurately calibrated anechoic chamber. This leads to very costly chamber constructions given the high cost of absorbing foam cones or other lossy materials like ferrites.
Compact near-field test ranges have been developed and exploited to address the above problem [1]-[2]. Conventional near-field ranges measure the near-zone fields radiated by the AUT either on a cylindrical or spherical surface surrounding the device. Reference [3] reports a more recent development using a photonic probe for near-field measurement that can be placed closer to the AUT up to a wavelength away. The proposed photonic probe is indeed a printed metallic dipole array deposited on an optical substrate.

During the last two decades, the researchers at the University of Michigan and EMAG Technologies Inc. have developed a unique novel technology for near field mapping using electro-optic (EO) crystals [4]-[5]. Unlike the photonic antenna probes of Reference [3], the EO probes are completely made of non-metallic parts. As a result, they are non-intrusive and virtually transparent to the RF at frequencies up to 20GHz. In this paper, we will demonstrate how the far field radiation patterns of an antenna can be estimated accurately from a knowledge of near-field scan maps extremely close to the surface of the antenna. First, we will describe the electro-optic probes. Then, we will lay the theoretical foundation for such a measurement methodology, which relies on the near-to-far-field transformation and the concept of Huygens surfaces. Finally, we will present some measured and simulated data.

II. ELECTRO-OPTIC FIELD PROBES

Our electric field probes utilize the Pockels effect for direct measurement of electric fields [6]. Imposing an external electric field on an electro-optic (EO) crystal induces a change in its refractive index, which then leads to a change in the polarization of an optical beam that passes through the EO crystal (linear birefringence) as shown in Figure 1. This in turn produces a measurable change in the optical intensity of the beam at a polarization analyzer. The EO field probes are constructed from extremely small EO crystals mounted at the tip of an optical fiber. Figure 2 shows the photo of a fiber-coupled EO field probe with an optical FC/APC connector. It also shows the probe placed at a very low height above the surface of a microstrip patch antenna array while scanning.

Figure 1: An optical beam propagation through an EO crystal and experiencing polarization change due to the Pockels’ effect.

Figure 2: (Left) A fiber-coupled EO crystal probe, and (Right) the EO probe measuring the near fields of a printed patch antenna array (note how close the probe is placed above the antenna surface).
Figure 3 shows the optical mainframe of the EO near-field scanning system and its RF back end. This system can measure the amplitude and phase of the electric field simultaneously. As can be seen from Figure 3, the detected RF signal is down-converted to 100MHz and processed through a lock-in amplifier that is synchronized (phase-locked) with the signal generator or frequency synthesizer that feeds the AUT.

The EO field probes provide accurate multi-dimensional signal flow maps of RF, microwave and millimeter wave devices and circuits. The combination of the small probe size and absolutely non-metallic parts leads to the ultimate RF non-invasiveness. Some of the key features of our field probe systems include:

- Broad measurement bandwidth (>20GHz) using the same optical probes
- High spatial resolution driven by the laser beam spot size (finer than 100 μm sq)
- Simultaneous amplitude and phase measurement
- Vectorial field measurement with very high cross-polarization suppression

III. THEORETICAL FOUNDATION FOR FAR FIELD MEASUREMENT

According to the equivalence principle in electromagnetics, if the tangential electric and magnetic field components are known on the surface of a closed surface like a box enclosing a radiating system, then one can determine the electric and magnetic fields everywhere outside that surface [7]. This applies equally well to the far-zone radiated fields of the structure under test. Such a closed surface is typically known as a Huygens surface. According to the equivalence theorem, one can define equivalent electric and magnetic surface current on the Huygens surface in the following manner:

\[
J_s(r) = \hat{n} \times H(r) \\
M_s(r) = -\hat{n} \times E(r)
\]  

(2)

where \(\hat{n}\) is the unit outward normal vector on the Huygens surface. Then, the radiated electric and magnetic fields by these equivalent sources in the free space are given by:

\[
E(r) = E^{inc}(r) - jk_0Z_0 \int \int_{S_2} \left[ \frac{1 - j}{k_0 R} - \frac{1}{(k_0 R)^2} \right] J(r') - \frac{3}{(k_0 R)^2} (\hat{R} \cdot J(r')) \hat{R} \frac{e^{-jk_0 R}}{4\pi R} ds' \\
+ jk_0 \int \int_{S_2} \left[ 1 - \frac{j}{k_0 R} \right] (\hat{R} \times M(r')) \frac{e^{-jk_0 R}}{4\pi R} ds'
\]  

(3)
\[
H(r) = H^{inc}(r) - jk_0 Y_0 \oint_{S_M} \left\{ \left[ 1 - \frac{j}{k_0 R} - \frac{1}{(k_0 R)^2} \right] M(r') - \frac{3 j}{k_0 R} - \frac{3}{(k_0 R)^2} \right\} \left( \hat{R} \cdot M(r') \right) R \frac{e^{-j k_0 R}}{4 \pi R} ds'
\]
\[
- jk_0 \oint_{S_M} \left[ 1 - \frac{j}{k_0 R} \right] \left( \hat{R} \times J(r') \right) e^{-j k_0 R} \frac{ds'}{4 \pi R}
\]

where \( r \) and \( r' \) are the position vectors at the observation and source points, respectively, and \( R = |r-r'| \). In the above equations, \( E^{inc} \) and \( H^{inc} \) account for any impressed or incident electric and magnetic fields besides the fields radiated by the equivalent surface electric and magnetic currents \( J \) and \( M \). In the Fraunhofer region around the radiating structure, the far-zone fields can be approximated by:

\[
E^F (r) = \frac{jk_0}{4\pi r} e^{-jk_0 r} \left\{ Z_0 \hat{r} \times \oint_{S_M} J(r') e^{-jk_0 r'} dr' + \hat{r} \times \oint_{S_M} M(r') e^{-jk_0 r'} ds' \right\}
\]

\[
H^F (r) = \frac{1}{Z_0} \hat{r} \times E^F (r)
\]

In the limiting case, a closed Huygens surface may consist of a plane placed slightly above the surface of an antenna and laterally extending to the infinity. This unbounded plane together with a hemisphere of infinite radius in the lower half-space constitutes a closed Huygens surface, completely encircling the radiating structure under test. Most practical antennas and array systems have highly evanescent near-zone fields at the surface of the radiator, which fade away very quickly in the lateral directions. This amounts to vanishing tangential E- and H-field components everywhere on the infinite Huygens plane except in the area directly above the antenna. This area will constitute the scanning plane where the EO field probe measures the tangential field components.

**IV. SIMULATION AND MEASUREMENT RESULTS**

A microstrip patch antenna was designed to resonate at the frequency 2.4GHz. The antenna was fabricated on a Rogers 4003 substrate and connectorized using an SMA connector as shown in Figure 4. The frequency response of the fabricated antenna was measured using a network analyzer and showed that the antenna was indeed tuned and matched at 2.349GHz rather than the original design frequency of 2.4GHz. This antenna with its finite substrate was simulated using EM.Cube’s FDTD Module [8] and its near field distributions and far field radiation patterns were calculated at \( f = 2.35GHz \). Figure 5 shows the amplitude and phase of the X and Y components of the electric field right above the surface of the antennas. Figure 6 shows the polar far field radiation pattern of the simulated patch antenna in the two principal E and h planes.
Figure 5: (Top) Magnitude and phase of the X-component, and (bottom) magnitude and phase of the Y-component of electric field distribution on a horizontal plane 1mm above the surface of the patch antenna of Figure 4 computed by EM.Cube’s FDTD Module. The white frame marks the boundary of the finite substrate.

Figure 6: 2D polar radiation patterns of the patch antenna of Figure 4 computed at $f = 2.35\text{GHz}$ by EM.Cube’s FDTD Module in the YZ plane (left) and ZX plane (right).
The radiation patterns of the fabricated antenna were also measured at EMAG Technologies Inc.’s in-house anechoic chamber. The chamber measurements were done at the frequency $f = 2.349$GHz, where the actual patch antenna resonates. Figure 7 shows the measured radiation patterns in the chamber.

![Figure 7: Measured 2D polar radiation patterns of the fabricated patch antenna at EMAG’s in-house anechoic chamber at $f = 2.349$GHz in the YZ plane (left) and ZX plane (right). Note that these figures are flipped vertically in relation to those of Figure 6.](image)

Next, a tangential EO probe was used to scan the near field of the fabricated antenna. The probe is first oriented along the X-axis to scan the X-component of the electric field. It is then realigned along the Y-axis to measure the Y-component. During each scan, both the magnitude and phase of the particular electric field component are measured. Figure 8 shows the magnitude and phase of the X- and Y-components of the electric field at a plane about 1mm above the surface of the patch antenna. Note that the X-axis is oriented along the feeding microstrip line. One can clearly see the radiating edges of the patch antenna.

![Figure 8: Magnitude and phase of the X-component (left half) and Y-component (right half) of electric field distribution on a horizontal plane 1mm above the surface of the fabricated patch antenna measured using the EO field probe system. Comparing this figure to Figure 5, note the $90^\circ$ rotation and reverse color scale.](image)

Figure 8 shows very good agreement with the simulated $E_x$ and $E_y$ magnitude and phase data computed by the FDTD method. Note that the red regions of Figure 8 correspond to the purple/blue regions of Figure 5. The contour of the feeding microstrip line is clearly visible in the
figure, where the field exhibits singularity. This observation is feasible due to the very resolution of the EO field probes.

The near field maps of the patch antenna measured by the EO scan system were effectively used to estimate its radiation patterns using the near-to-far-field transformation. It is evident from Figure 8 that the near fields decay very rapidly when one moves away from the boundary of the antenna. As a result, a knowledge of tangential fields is required only at a finite portion of the horizontal plane immediately above the radiating aperture and its vicinity. Figure 9 shows the 3D far field radiation pattern as well as 2D polar graphs of the radiation pattern of the fabricated patch antenna using the near-field maps in the two principal YZ and ZX planes, respectively. Note that the near-to-far-field transformation used for these results are valid only in the upper half-space due to the 2D surface scanning. That’s why the polar graphs have been cut from the bottom and do not show any back-radiation of the finite-sized antenna structure.

![Figure 9: (Left) 3D far field radiation pattern, and (Right) 2D polar radiation patterns of the fabricated patch antenna estimated from near field scan maps in the YZ (blue) and ZX (red) planes.](image)

Finally, to draw a fair conclusion, the results of the FDTD simulation, anechoic chamber measurement and compact near-field range measurement were all put together. Additional results from EM.Cube’s Planar Method of Moments (MoM) simulator [8] were also added for comparison. Note that the Planar MoM method assumes a conductor-backed dielectric substrate of infinite extents in contrast to the FDTD method’s finite-sized substrate.

![Figure 10: A comparison of 2D Cartesian radiation patterns of the fabricated patch antenna estimated from near field scan maps, simulated radiation patterns of the patch with an infinite substrate using Planar MoM method, simulated radiation patterns of the patch with a finite-sized substrate using FDTD method, and measured radiation patterns of the fabricated antenna in the anechoic chamber, in the YZ (left) and ZX (right) planes.](image)
Figure 10 shows a comparison of 2D Cartesian radiation patterns of the fabricated patch antenna estimated from near field scan maps, simulated radiation patterns of the patch with an infinite substrate using EM.Picasso (EM.Cube’s Planar Module), simulated radiation patterns of the patch with a finite-sized substrate using EM.Tempo (EM.Cube’s FDTD Module), and measured radiation patterns of the fabricated antenna at EMAG’s in-house anechoic chamber. The two graphs in the left and right parts of Figure 10 correspond to the YZ and ZX plane patterns, respectively.

V. CONCLUSION

The near field maps of antennas and arrays measured by the electro-optic (EO) probes can effectively be used to estimate their radiation patterns using a near-to-far-field transformation. This transformation is indeed identical to the one used by most computational electromagnetic (CEM) solvers including EM.Cube. The non-invasive of the EO probes makes it possible to scan the antenna very close to its surface thus reducing the scan area size significantly.

VI. REFERENCES


