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Near-Field Electro-Optic Measurement for Multiphysics Analysis of THz Antennas

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Abstract

In this paper, we propose a novel approach using near-field electro-optic measurements to evaluate the impact of mechanical deformations that must be considered in the multiphysics design of THz systems. Unlike conventional microwave systems, THz systems feature much shorter wavelengths, making them highly sensitive to even minute mechanical displacements. By measuring the near-field phase distribution of the antenna, our method enables accurate quantification of the effects that structural deformations—such as twisting or shifting of the antenna aperture—have on the radiation pattern. Focusing on a 40 dBi, 300 GHz high-gain antenna (FWHM: 1.4 degrees), we demonstrated that a beam tilt of 0.17° can be detected using this technique.

1. Introduction

Research on terahertz (THz) wireless communications is actively underway worldwide [1]. In addition to laboratory demonstrations of high-capacity and high-speed wireless transmission, recent reports have showcased point-to-point THz wireless communication over long distances under outdoor operating conditions [2]. Unlike indoor laboratories, outdoor environments are subject to weather effects, and thus studies on rain-induced attenuation and scattering and their impact on communication quality have also been progressing [3].

In the microwave band traditionally used for wireless communications, antennas have generally been treated as rigidly installed and stationary, and evaluations focusing solely on electromagnetic characteristics have proven sufficient. However, in the THz band, where the wavelength is more than an order of magnitude shorter than in the microwave range, higher directivity naturally arises, and the narrower beamwidth makes even minor mechanical displacements of the antenna non-negligible. Hence, a comprehensive multiphysics perspective, encompassing mechanical displacements (e.g., vibrations, wind- or heat-induced shifts, or torsion in the antenna aperture), becomes crucial. For instance, in a purely static installation, enhancing antenna directivity (equivalent to narrowing the beamwidth) straightforwardly improves link gain. However, in the THz band—where dynamic changes in the antenna's structural environment must be considered—even slight mechanical deviations can misalign the beam and potentially decrease the time-averaged link gain. Therefore, from a link-design perspective, establishing an integrated evaluation method that considers both electromagnetic characteristics and mechanical/thermal disturbances as a multiphysics problem is essential.

We have developed a near-field electro-optic (EO) measurement technique for high-gain antennas [4, 5]. For antennas with gains above 40 dBi in the 300 GHz band, the far-field distance can be on the order of tens of meters, making far-field measurement of the radiation pattern challenging. In contrast, near-field measurements enable highly accurate evaluation of the radiation pattern in a controlled environment. In this paper, we propose a method to estimate the twisting and displacement of the antenna aperture plane caused by structural mechanical deformations by measuring the phase distribution in the antenna's near field. By employing this technique, one can precisely quantify how vibrations or other external mechanical disturbances applied to the antenna head affect the radiation pattern under controlled conditions.

2. Electrooptic Near-Field Measurement System

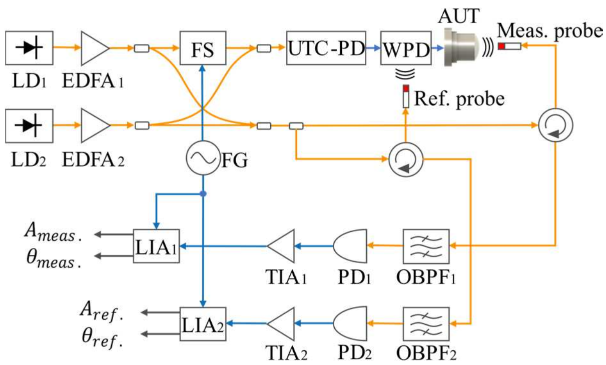

Figure 1. Electrooptic near-field measurement system. LD: laser diode; FS: frequency shifter; UTC-PD: unitraveling-carrier photodiode; WPD: waveguide power divider; AUT: antenna under test; EDFA: erbium-doped optical amplifier; OBPF: optical band pass filter; PD: photodiode; TIA: transimpedance amplifier; and LIA: lock-in amplifier.

Figure 1 illustrates a photonics-based near-field measurement (NFM) system [4] that employs self-heterodyne [6] and nonpolarimetric frequency down-conversion [7] techniques. In the diagram, the orange lines indicate optical fibers, while the blue lines denote electrical cables. Two free-running 1550 nm laser diodes (LDs) are used to generate the RF and LO signals. The probe consists of a 0.5 mm square electro-optic crystal mounted at the tip of an optical fiber. Thanks to its extremely compact size and absence of any metal components, it introduces minimal disturbance to the measured electric field. This feature is crucial for accurately measuring the electric field distribution, both in terms of amplitude and phase. For details on the detection principle and system configuration, please refer to other publication [4]. Figure 2 provides a photograph of the near-field measurement setup for the high-gain antenna. The setup is based on a cylindrical scanning system. The antenna under test (AUT) is a J-band lens horn antenna with a physical diameter of 56.6 mm. Its gain at 300 GHz is approximately 40 dBi.

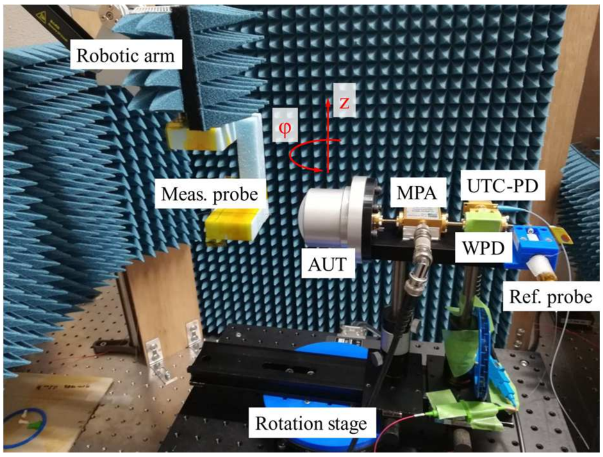

Figure 2. Photograph of the near-field measurement setup. MPA: Medium power amplifier, UTC-PD: unitraveling-carrier photodiode; WPD: waveguide power divider; AUT: antenna under test

3. Estimation of Dynamic Far-Field Variations from Near-Field Measurements

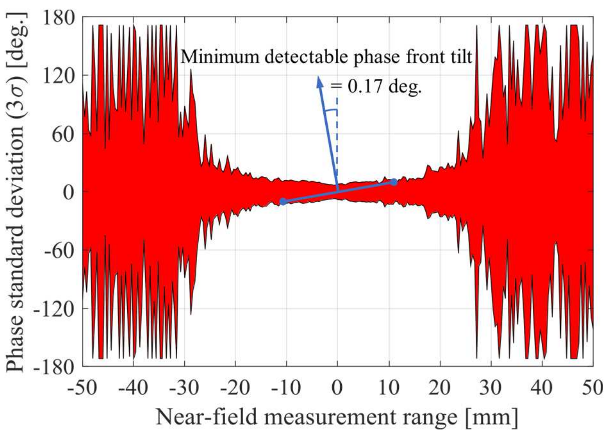

Figure 3. Standard deviation of the phase measurements along the Z-axis.

Figure 3 shows the standard deviation (σ) of the near-field phase measurement of the AUT. The horizontal axis corresponds to the Z-axis in Figure 2. The standard deviation is calculated using the Z-axis dependence of the amplitude-measurement signal-to-noise ratio (SNR) based on the following equation.

$$\sigma[deg.] = 10^{-\frac{SNR}{20}} \cdot \frac{180}{\pi} \quad (1) \;.$$

The red hatched region enclosed by the black outline represents ±3σ. Note that at 0 mm on the horizontal axis—the center of the antenna—the SNR is highest, resulting in the smallest standard deviation in the phase measurement. At ±11 mm, the 3σ value was approximately 12.0 degrees.

Phase fluctuations resulting from twisting or lateral shifts of the antenna aperture—induced by vibrations or other factors—are simultaneously monitored by fixing two EO probes at ±11 mm. Once the measured phase fluctuation exceeds the 3σ threshold (12.0 degrees) at ±11 mm, vibration-induced beam steering becomes clearly discernible. For a simple antenna tilt, the minimum detectable main-lobe shift is calculated to be 0.17 degrees, which is considerably smaller than the 1.4 degrees beamwidth of the AUT. Consequently, real-time monitoring of the near-field phase distribution enables high-resolution detection of antenna orientation changes due to vibration.

4. Summary

In this paper, we propose a novel method for quantitatively evaluating the impact of external factors—such as antenna vibration and thermal expansion—on far-field characteristics in THz antennas by using near-field EO measurement. This approach is crucial for gathering the information needed in multiphysics design of THz systems. By conducting measurement campaigns in a controlled environment based on the proposed method, it becomes possible to model how various disturbances anticipated under outdoor conditions affect link gain.

5. Acknowledgements

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