Active Incoherent Millimeter-Wave Imaging of Dielectric Objects

Stavros Vakalis, Liang Gong, John Papapolymerou, and Jeffrey A. Nanzer
Electrical and Computer Engineering, Michigan State University
{vakaliss, gonglian, jpapapol, nanzer}@msu.edu

***Abstract*—Active incoherent millimeter-wave (AIM) imaging is a recently developed technique that utilizes the transmission of noise waveforms and a sparse receiving array to form imagery. By cross-correlating the received signal pairwise, the receiving array samples the scene in the spatial frequency domain. Thus, the image can be reconstructed using an inverse Fourier transform from a sufficient set of spatial frequency samples. This technique enables the use of incoherent signals that are unlikely to interfere with other systems and a sparse receiving array, minimizing millimeter-wave hardware compared to phased arrays and focal-plane imagers. In this paper we demonstrate the first measurements of dielectric objects using AIM imaging. Using three 37 GHz noise transmitters and a Y-shaped 16-element receiving array, we demonstrate two-dimensional image reconstruction of two dielectric objects in a laboratory environment.**

I. Introduction

Recently, millimeter-wave imaging has become an expanding research area due to the ability of millimeter-wave radiation to easily propagate through materials that are opaque to optical sensors, and due to the increasing availability of low-cost, high-efficiency millimeter-wave components and transceivers. A variety of techniques exist in this active field, including scanning arrays, holography [1], tomographic imaging [2], computational imaging [3] and interferometry [4]. Demonstrated imaging systems have been implemented across a wide range of frequencies, from low microwave frequencies through THz [5], [6]. Among the different techniques of electromagnetic imaging, staring techniques hold significant potential for video-rate imaging because they are not limited by mechanical or electrical scanning speeds. Interferometric imaging in particular can also significantly reduce the hardware components by simultaneously measuring the mutual coherence of a source at sparse antenna locations.

In this work, we present the first measurements of dielectric objects using active incoherent millimeter-wave (AIM) imaging. AIM imaging uses the transmission of incoherent signals to illuminate a scene, the scattered signals from which are captured using a sparse receiving array. Pairwise cross correlations of the signals received at each element provide measurements of the mutual coherence of the source, which is captured in the spatial frequency domain. Through an inverse Fourier transform, a sufficient set of spatial frequencies allows reconstruction of the two-dimensional scene. We present measurements of multiple dielectric objects using a 16-element 37 GHz AIM imaging system along with three 37 GHz noise transmitters.

II. Active Incoherent Millimeter-Wave Imaging

Interferometric imaging systems capture the mutual coherence of electromagnetic radiation by pairwise cross-correlations of the antenna element responses of a sparse distributed antenna array. Different antenna baselines correspond to different numbers of spatial fringes and different orientations, which can be mapped to different points (u, v) in the spatial frequency domain. This represents samples of what in radio astronomy is referred to as the visibility $\mathcal{V}$, the spatial Fourier transform of the scene intensity. If a sufficient number of antenna pairs are cross-correlated, generating a large enough set of spatial frequency samples, an accurate reconstruction of the scene intensity can be obtained through an inverse Fourier transform. A reconstructed scene intensity I_r can then be obtained from the sampled visibility $\mathcal{V}_s$ by

$$I_r(\alpha,\beta) = \sum_{n}^{N}\sum_{m}^{M}\mathcal{V}_s(u_n,v_m)e^{j2\pi(u_n\alpha+v_m\beta)} \qquad (1)$$

where $\alpha = \sin\theta\cos\phi$ and $\beta = \sin\theta\sin\phi$ are the direction cosines along the azimuth and elevation planes, respectively.

A significant benefit of interferometric imaging is that the receiving array can be sparse, allowing for a wide variety of spatial configurations that, while spatially sparse, represent a dense sampling function in the spatial frequency domain [7]. However, the Fourier reconstruction requires the scene intensity to be spatially and temporally incoherent, a requirement that is met for natural objects such as celestial objects [8] and thermal radiation detected by passive mm-wave imagers [9], but that is not satisfied with coherent active systems. AIM imaging overcomes this by transmitting from a number of noise sources, mimicking random thermal radiation [4]. This mitigates the high sensitivity and wide bandwidth requirements of passive systems and retains all the benefits of interferometric processing including sparse arrays [10] and tolerance to element failures [11]. Due to the incoherent illumination the possibility of non-cooperative imaging using third party radiation has also been experimentally demonstrated [12]. However, prior work has only shown imaging of metal objects.

III. Experimental Imaging of Dielectric Objects

The AIM imaging system, shown in Fig. 1, consists of three noise transmitters and a 16-element Y-shaped interferometric receiving array. The noise signals were generated at baseband and upconverted to the carrier using heterodyne upconversion;

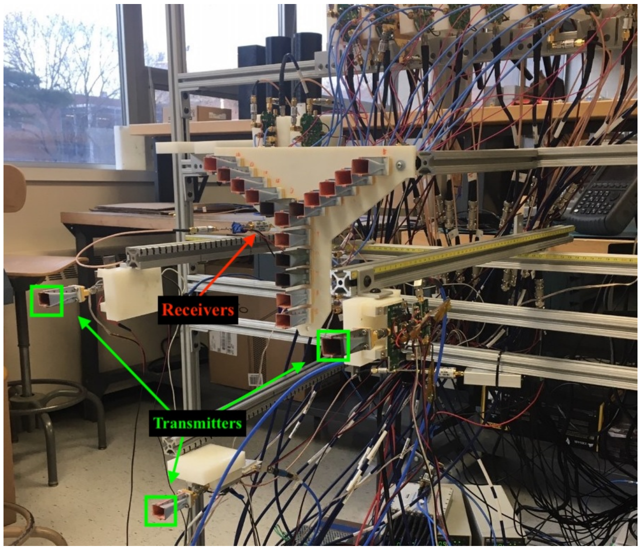

Fig. 1. Photograph of the 16-element active incoherent imager with three noise transmitters.

the received signals were downconverted using a quadrature heterodyne downconversion. The antennas are standard-gain horns manufactured with 3D printing. The spacing between receive antennas was 24 mm and the integration time at baseband was 50 μs. The received baseband signals were sampled using a bank of parallel digitizers and processed in MATLAB. Since the antenna elements are placed in a uniform grid with spacings larger than $\frac{\lambda}{2}$, spatial ambiguities arise; however, as shown in the measurement results these fall outside the field-of-view for the present application.

Two dielectric cylinders ($\epsilon_r = 3.8$) were placed in front of the array in a semi-enclosed range at a distance of 2.2 m while the horizontal separation between them was 20 cm and the vertical displacement was 15 cm. The scene can be seen in Fig. 2(a) and the reconstructed image of them in Fig. 2(b). The imaging system clearly reconstructs the relative locations of the cylinders. The point-like responses of the cylinders are due to the large specular response of the shapes, matching the expected scattering response of a cylinder.

IV. Conclusion

The ability of active incoherent millimeter-wave systems to create millimeter-wave images of dielectric targets is shown in this paper. Despite the fact that there is no coherent beamforming gain compared to a phased array or processing gain compared to coherent computational techniques, these results demonstrate the capability of achieving sufficient SNR from the noise illumination to detect non-conducting targets, thus supporting applications including non-destructive evaluation and medical imaging.

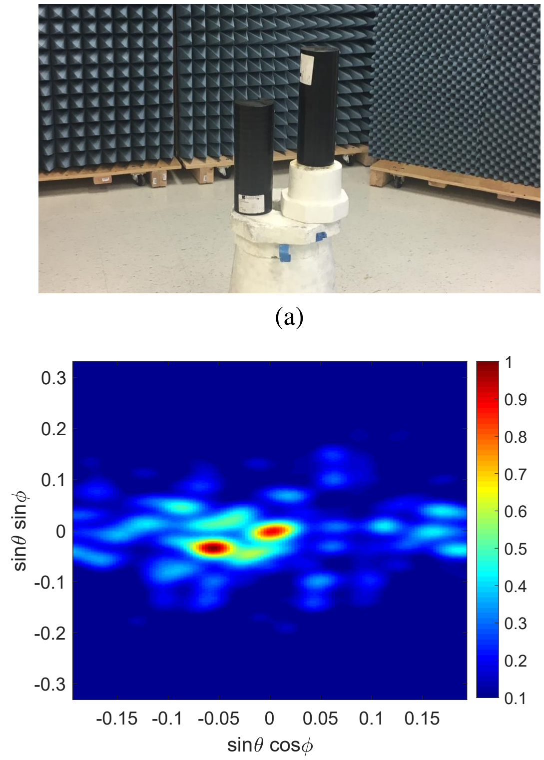

Fig. 2. (a) Two dielectric cylinders (ϵ_r = 3.8) placed inside a semi-anechoic range (b) 2-D image reconstruction I_r of the two dielectric cylinders. The colorbar is normalized, and hence, the vertical axis is in normalized units (N.U.).

References

[1] D. M. Sheen, D. L. McMakin, and T. E. Hall, "Three-dimensional millimeter-wave imaging for concealed weapon detection," *IEEE Trans. Microw. Theory Techn.*, vol. 49, no. 9, pp. 1581–1592, Sep 2001.

[2] J. Doroshewitz, S. Mukherjee, E. J. Rothwell, L. Udpa, and J. A. Nanzer, "Time-reversal microwave tomography using frequency domain sampling," in *2019 IEEE MTT-S International Microwave Symposium (IMS)*, June 2019, pp. 1519–1521.

[3] T. Sleasman, M. Boyarsky, M. F. Imani, T. Fromenteze, J. N. Gollub, and D. R. Smith, "Single-frequency microwave imaging with dynamic metasurface apertures," *J. Opt. Soc. Am. B*, vol. 34, no. 8, pp. 1713–1726, Aug 2017.

[4] S. Vakalis and J. A. Nanzer, "Microwave imaging using noise signals," *IEEE Trans. Microw. Theory Techn.*, vol. 66, no. 12, pp. 5842–5851, Dec 2018.

[5] R. Han, Y. Zhang, Y. Kim, D. Y. Kim, H. Shichijo, E. Afshari, and K. K. O, "Active terahertz imaging using schottky diodes in cmos: Array and 860-ghz pixel," *IEEE J. Solid-State Circuits*, vol. 48, no. 10, pp. 2296–2308, Oct 2013.

[6] P. C. Theofanopoulos, M. Sakr, and G. C. Trichopoulos, "Multistatic terahertz imaging using the radon transform," *IEEE Trans. Antennas Propag.*, vol. 67, no. 4, pp. 2700–2709, April 2019.

[7] J. A. Nanzer, *Microwave and Millimeter-Wave Remote Sensing for Security Applications*. Artech House, 2012.

[8] A. R. Thompson, J. M. Moran, and G. W. Swenson, *Interferometry and Synthesis in Radio Astronomy*. John Wiley and Sons, 2001.

[9] L. Yujiri, M. Schoucri, and P. Moffa, "Passive millimeter-wave imaging," *IEEE Microw. Mag.*, vol. 4, pp. 39–50, 2003.

[10] S. Vakalis and J. A. Nanzer, "Analysis of array sparsity in active incoherent microwave imaging," *IEEE Geosci. Remote Sens. Lett.*, vol. 17, no. 1, pp. 57–61, 2020.

[11] ——, "Analysis of element failures in active incoherent microwave imaging arrays using noise signals," *IEEE Microw. Wireless Compon. Lett.*, vol. 29, no. 2, pp. 161–163, Feb 2019.

[12] S. Vakalis, L. Gong, and J. A. Nanzer, "Imaging with wifi," *IEEE Access*, vol. 7, pp. 28 616–28 624, 2019.