Active Incoherent Millimeter-Wave Imaging Using a 75-GHz Dynamic Antenna Array

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***Abstract*—We present a 75-GHz dynamic antenna array concept for interferometric Fourier-domain millimeter-wave imaging. By combining active transmission of noise signals to mimic thermal radiation and Fourier-domain sampling with a rotationally dynamic linear array, we show that imagery of reflecting objects can be obtained rapidly with minimal millimeter-wave hardware. A receiving array is rotated around its center, with received signals correlated pair-wise, generating a ring-shaped sampling function in the Fourier spatial frequency domain. With a sparse linear array, multiple such rings can be generated, yielding a dense sampling of the spatial frequency domain, from which an image of the scene can be reconstructed via inverse Fourier transform. We demonstrate the concept at 75 GHz using a two-element transmit array and a two-element receive array. The receiving elements are moved to synthesize a sparse linear array, while the rotational dynamics of the array yields a dense spatial frequency sampling function. We demonstrate the reconstruction of a metallic object in a laboratory setting.**

I. Introduction

Research on millimeter-wave imaging systems has increased in recent years due to their applicability to a broad range of sensing situations. Millimeter-wave signals to propagate through fog, smoke, or clothing material with little attenuation [1] making them ideal for security sensing, automotive imaging, and human-computer interaction, among others. However, rapid formation of millimeter-wave images traditionally necessitates significant millimeter-wave hardware resources, leading to costly or slow imaging systems. Imaging systems generally rely on steered antennas or phased arrays, or passive imaging systems that capture thermal radiation and require long integration time to form images. This has led to various investigations to quickly obtain millimeter-wave imagery with fewer hardware resources. Recent examples include switching a subset of antennas on a metasurface aperture [2] and rotating an ultra-wideband (UWB) imaging system [3]. In this work, we design and implement a 75-GHz two-element dynamic antenna array for imaging, which is based on a correlation interferometric receiver paired with a set of noise transmitters. We recently introduced a new dynamic array concept that combines Fourier-domain imaging with rotational array motion [4]. This concept uses only a sparse linear antenna array that traces a dense Fourier-domain sampling function over the rotation. The array is dynamically rotated over a 180° angle in conjunction with the two receivers adjusting their separation between each successive 180° rotation to synthesize a sparse linear array, producing a circularly dense spatial Fourier sampling function. We demonstrate the ability to reconstruct images of a simple reflecting target.

II. Active Interferometric Imaging and 75-GHz Dynamic Antenna Array

Interferometric imagers capture image information in the spatial frequency (Fourier) domain and reconstruct the image through an inverse Fourier transform. This technique requires the signals emitted or reflected from the scene to be spatially and temporally incoherent [5]. However, most interferometric imaging systems are passive and collect thermal radiation [6] thus requiring high-sensitivity receivers. Recently, we introduced an active incoherent millimeter-wave imaging technique where noise signals are used to illuminate the scene, mimicking thermal radiation but providing significantly higher received power so that standard gain receivers can be used [7].

Interferometric imagers sample the visibility of the scene $V(u,v)$, where u and v are the two dimensions in the spatial frequency domain. The spatial frequency sampling function is given by

$$S(u,v)=\sum_{n=1}^{N}\sum_{m=1}^{M}\delta(u-u_n)\delta(v-v_m), \tag{1}$$

where $N\cdot M$ is the maximum possible number of samples that the sparse imaging array can acquire. Samples are obtained by cross-correlating the received signals pair-wise therefore the antenna layout determines the sampling function. The reconstructed image is obtained by

$$I_r(\alpha,\beta)=\sum_{n=1}^{N}\sum_{m=1}^{M}S(u_n,v_m)V(u_n,v_m)e^{-j2\pi(u_n\alpha+v_m\beta)}, \tag{2}$$

where $\alpha=\sin\theta\cos\phi$, $\beta=\sin\theta\sin\phi$ are direction cosines.

Increasing the number of samples requires either adding more antenna elements or moving their relative locations to obtain a different spatial frequency sample. This motivates the exploration of combining interferometric imaging with a dynamic antenna array. In particular, since the spatial frequency samples are determined by the angle of the antenna pairs, a rotationally dynamic antenna array can obtain a range of spatial frequency samples without changing the antenna baseline. The modified sampling function of (1) for the rotating one-dimensional linear array can be expressed as

$$S_{1D,rot}(u,v)=\sum_{l=1}^{L}\sum_{k=1}^{K}\delta\left(u-u_{lk}\right)\delta\left(v-v_{lk}\right), \tag{3}$$

where u_{lk} and v_{lk} are the resulting uv sampling location that are due to all available baselines L defined by the sparse linear array and the rotation angles K.

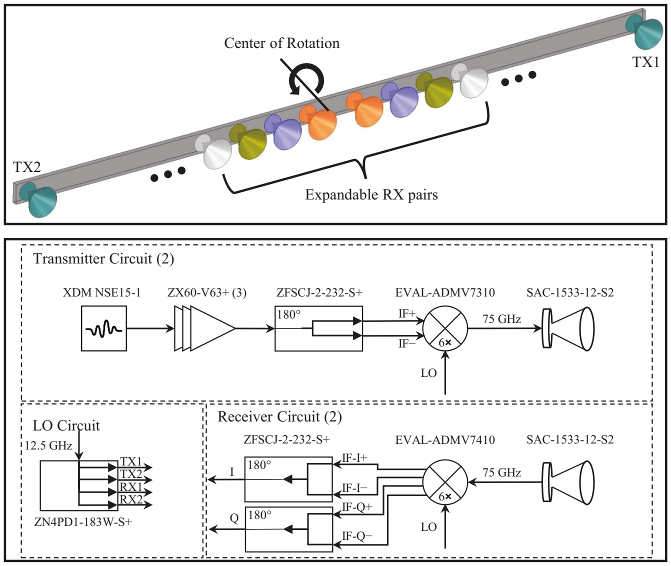

Fig. 1. Top: Concept diagram of the proposed sparse linear array with rotational dynamics. Bottom: Schematics of the 75-GHz dynamic antenna array. The noise sources were selected to achieve spatio-temporally incoherent illumination of the scene. Upconverters and downconverters were selected for their 6× LO multiplier to allow a compact design. I: In-phase. Q: Quadrature. IF: Intermediate frequency. LO: Local oscillator. TX: Transmitter. RX: Receiver.

III. Experimental Evaluation

We implemented the dynamic millimeter-wave imaging concept in a 75-GHz system. The schematic of the dynamic antenna array is shown in Fig. 1 with corresponding part numbers and quantities listed. The system is a one-dimensional array with two noise transmitters and two receivers that are installed on the dynamically rotating arm with its center of rotation being the centroid of both the transmitter and receiver pairs. The relative baseline between the receivers could be adjusted accurately at 1 mm increments, allowing us to synthesize a sparse linear array. A 400 pulses per revolution motor encoder was coupled to the rotating arm yielding an angle resolution of 0.9°. For a given interferometric array, the spatial resolution is dependent on the maximum receiver baseline of the given dimension and is defined by

$$\Delta\theta_{x,y} \approx \frac{\Theta_{typ}}{\max\{D_{\lambda_{x,y}}\}} \text{ (rad)}, \tag{4}$$

where $D_{\lambda_{x,y}}$ denotes the receiver baseline in wavelengths among the x and y dimension and the term Θ_{typ} is the beamdwidth-type factor where $\Theta_{NN} = 2$ or $\Theta_{HP} = 0.88$ when considering the null-to-null beamwidth (NNBW) or half-power beamwidth, respectively [8]. The receivers baseline can change dynamically such that at 75 GHz, a range of 47–127 D_λ at all sampled angles can be achieved, yielding a theoretical spatial resolution of approximately 0.0125 rad.

As shown in Fig. 2(a), the experiment was conducted in an indoor laboratory environment where the target was placed 1.83 m from the 75-GHz dynamic antenna array. The target is made out of two copper tape stripes intersecting at a 45° angle, forming a χ shape, on top of a Styrofoam board. Each copper stripe had a dimension of 5 cm×61 cm. The two receivers of the dynamic antenna array were adjusted between each successive dynamic rotations of 180° to form a sparse linear array with 45 unique baselines ranging from 47λ to 69λ in 0.5λ increments yielding a total of 9000 unique spatial Fourier samples. The integration time at each 200 discretely sampled angle is approximately 1 ms yielding a total of measuring time of 0.2 s which corresponds to a rotational rate of approximately 150 revolution per minute. The measured result is shown in Fig. 2(b) where the pink dashed lines indicate the location of the target. The ends of the stripes and the 45° feature of the target are apparent.

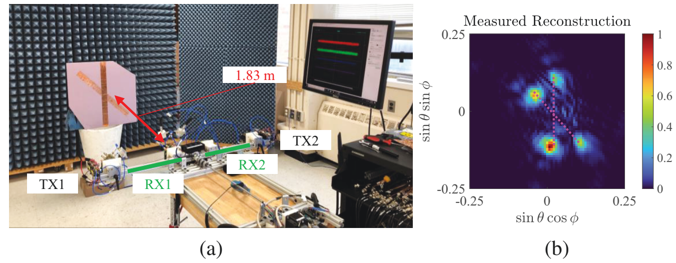

Fig. 2. (a) Measurement setup of the two-stripe target forming 45° angle that is 1.83 m away from the broadside of the 75-GHz dynamic antenna array. Each stripe has a dimension of 5 cm×61 cm. The green bars indicate the available range where the receiver can be adjusted to synthesize a sparse linear array. (b) Measured reconstruction using the 75-GHz dynamic antenna array with the pink dashed annotation noting the expected two stripes. TX: Transmitter. RX: Receiver. N.U.: Normalized Units.

Acknowledgment

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