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Design and Analysis of a W-Band Meta surface Based Computational Imaging Processing System

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Abstract

We design and numerically analyze a coherent computational imaging system that utilizes a sparse detector array of planar, frequency-diverse, metasurface antennas designed to operate over the W -band frequency range (75–110 GHz). Each of the metasurface antennas consists of a parallel plate waveguide, into which a center coaxial feed is inserted into the lower plate, launching a cylindrical guided wave. A dense array of metamaterial resonators patterned into the upper plate couples energy from the waveguide to free space radiative modes. The resonance frequency of each element, determined by its specific geometry, can be positioned anywhere within the W -band. The geometry of each element is chosen to produce a resonance frequency selected randomly from the W -band. Since a random subset of elements is resonant at any given frequency, the metasurface antenna forms a sequence of spatially diverse radiation patterns as a function of the excitation frequency. We analyze the metasurface aperture as an imaging system, optimizing key parameters relevant to image quality and resolution, including: aperture size; density and quality factor of the metamaterial resonators; number of detectors and their spatial distribution; bandwidth; and the number of frequency samples. A point-spread function analysis is used to compare the metasurface imager with traditional synthetic aperture radar. The singular value spectrum corresponding to the system transfer function and the mean-square-error associated with reconstructed images are both metrics used to characterize the system performance.

Keywords: *Computational imaging, metamaterials, metasurface, millimeter-waves, sparse antenna array.*

Introduction

Microwave and millimeter waves have been routinely used for imaging in the medical, security, and aerospace fields [1]– [8], and have unique capabilities for certain applications such as composite material investigation or through-wall imaging. Specific imaging approaches such as synthetic aperture radar (SAR) [9] and phased arrays [10] are well- established but require long acquisition time, or costly feeding networks, respectively. Hybrid mechanical and electronic approaches, such as cylindrical scanners [11] and focal plane arrays [12] use SAR principles and achieve moderate acquisition times but do not provide an obvious roadmap to real- time imaging rates and compact system form factors. Principles of holographic imaging scheme used in this manuscript are described in detail in [13].

In recent work [13]–[15], an alternative imaging modality has been developed that combines computational imaging concepts with emerging metasurface architectures. The coherent, sparse imager analyzed in this paper leverages fre- quency diversity to achieve a large number of measurements, avoiding both mechanical scanning components as well as potentially expensive active components. The frequency-diverse metasurface imager thus trades expensive and elaborate hardware for increased data processing, relying on a fully determined model of the antenna radiation patterns and their scattering from targets in the scene, or the forward model.

There has been a steady stream of developments relating to the metasurface imager, culminating in compelling imaging demonstrations performed at frequencies in the K-band (18–26.5 GHz) [16], [17] using the planar waveguide approach. These experiments have proven the meta- surface imager concept, and allowed key system parameters and features to be identified and optimized. In addition, a suite of computational tools has been created that enables end-to-end modeling of the metasurface imager [18], which has been shown to predict imaging performance with excel- lent accuracy.

In this paper, we examine the possibility of scaling the metasurface imager to W-band frequencies (75-110 GHz), where potential capabilities such as increased resolution [19]–21] and spectrum-based identification of dielectrics can be attractive advantages. While the underlying metasurface aperture concept scales trivially to shorter wave- lengths in terms of the electromagnetics, a W-band imaging system presents particular challenges for image processing and reconstruction.

Consider a metasurface aperture designed for full- resolution imaging of human-sized targets. Such a system operating at K-band frequencies (18 – 26.5 GHz) was ana- lyzed in [22]. For a 2 m × 2 m sized aperture, with resolution of 1.5 cm in range and 5 mm in cross-range, approximately 200,000 measurement modes, and 0.26 × 1 × 1.9 m region of interest dimensions, roughly 90 gigabytes of data is required for diffraction-limited resolution of the full scene (multi- plying the number of modes, and voxels, assuming single precision).This is for the case of constrained region of inter- est (ROI) enveloping the target body decreasing the number of voxels from 872,336 to 122,000 [22].

A W-band system of the same size has diffraction-limited resolution on the order of 1 mm in cross-range at a center frequency of 92.5 GHz, and 4.3 mm resolution in range. The resulting number of diffraction limited scene voxels is proportionally larger at nearly 13 terabytes of data. Based on typical reconstruction approaches demonstrated to date and reasonably available computational power, full resolution images at W-band are thus not a practical goal certainly not for fast, near real-time imaging.

A more realistic scenario for a W-band metasurface imager is one in which the target reconstruction volume is con- strained, so that a vastly reduced number of measurements is required for diffraction-limited imaging. That is, rather than a human-scale target, just a small portion of the overall region would be imaged using the W-band aperture. To achieve high resolution over the constrained volume, a large aperture is still necessary, but the reduced number of measurements suggests that transmitting and receiving sub-apertures can sparsely populate the overall aperture. Such a W-band system could be, for example, co-integrated into a composite aperture for multiband operation, with a lower frequency aperture providing complete coverage of a target with lower resolution, while the W-band aperture can be used to provide high-resolution detail on certain smaller ROI.

Our goal here is to investigate the potential design of a sparse, metasurface aperture for W-band operation. We do not delve further into the system aspects, but note that to achieve a sparse imager implies that there is no reflection from any other objects in the scene outside of the particular ROI. In the envisaged operation, these objects would certainly reflect W-band radiation, and therefore some provision would be necessary to ensure the modes of the transmitting or receiving aperture would have high gain. Such designs are possible, and represent a topic of future investigation [23]. Here, we concern ourselves with the image fidelity available from a sparse, W-band aperture, in which a small target is considered and no other objects are in the field-of-view. The reconstructed images thus represent a best-case scenario of what might be possible in an actual system.

We present the basic W-band metasurface imager design and assess the expected resolution, considering such system parameters as: the number of transmitters; number of receivers; available SNR; spatial distribution of the antennas; antenna size; number of radiating elements and their quality factors; and Fourier (k-) space coverage.

We outline those elements of the general computational imaging theory pertinent to our system. In Section IV, the imager parameters are determined through the PSF and trade-off studies based on EM simulation and Fourier coverage analysis [24].

II. Metasurface Imager

The metasurface aperture consists of several frequency- diverse aperture antennas that each produce a sequence of complex radiation patterns whose spatial fields vary as a function of the excitation frequency. Each antenna consists of a parallel plate waveguide, the top conductor of which is patterned with an array of resonant metamaterial elements [25] (Fig. 1a). The resonance frequencies of the resonators are randomly selected across the W-band spectrum. While we do not detail the design of the metamaterial elements here, we note that we are assuming complementary electric resonators (cELCs), which scatter and radiate approximately as polarizable magnetic dipoles. The guided mode is mod- eled as a cylindrical wave excited at a known location on the antenna (in our case the geometrical center) to correctly calculate the phase of the exciting wave at each cELC. In the present context, we thus model the resonators as polarizable dipoles, simulating both the antennas and scattering from the scene using procedures previously reported [18].

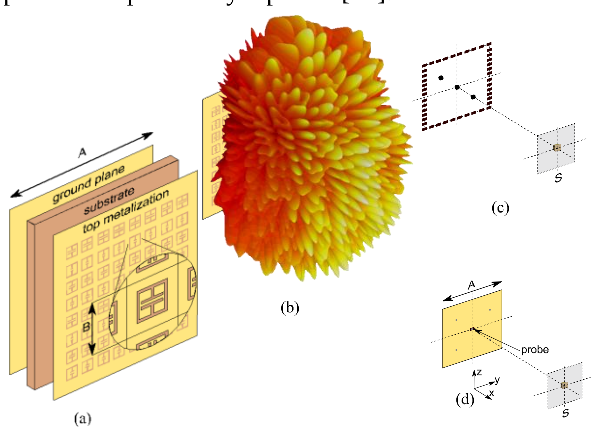

FIGURE 1(a) An illustration of the metamaterial parallel plate antenna with characteristic cELC resonators etched into the top layer. (b) A plot of the radiation pattern of the metamaterial panels at a fixed frequency is shown. (c) The SAR imaging configuration used in the PSF analysis is shown, with a single voxel as a target in the region of interest S; (d) The modeled one panel and one probe frequency diverse imaging system is illustrated.

At any given excitation frequency, a subset of the metamaterial elements is excited; the elements off-resonance can be considered as ''off,'' or non-transmissive. The corresponding field patterns feature a random pattern of lobes and nodes spread over a large angular region, as shown in Fig. 1b). Energy scattered by the target is detected by an array of low- gain, open-ended waveguide (OEWG) probes. By positioning the OEWG probes over a larger area, a sparse detector is formed, with the received power at each probe constituting a set of measurements (many frequency samples at each location).

Each measurement can be related to the scene reflectivity by the forward model. Since the smallest detectable volume is set by aperture and bandwidth limits, the scene can be discretized into a set of voxels, so that the finite set of measurements is related to the finite set of reflectivity values by

$$\bar{g} = \bar{H}\bar{f} + \bar{n}. \qquad (1)$$

Conclusions

A W-band compressed imaging system leveraging the computational imaging techniques was designed. A point spread function analysis proved the advantage of the frequency diverse imager over traditional SAR, significantly decreasing the acquisition time while the image quality remained com- parable when using iterative reconstruction methods.

Minimum viable system requirements were determined for a full sized 1 m × 1 m aperture using the singular value spectrum of the measurement modes; the MSE – a comparison of reference and resolved image; and, k-space coverage. The optimized parameters were found as follows: 16 transceiver antennas, 12 receiving probes with random distribution, Qelem ≤ 100, A = 10 cm, B ≤ 5 mm, D = 1 m, SNR = 10 dB, N_f = 100. Although the achievable quality factor of the metamaterial elements in the W-band frequency regime is low (resulting in unavoidable correlation of the measurement modes), through optimization of the full system parameters, a viable imaging system was designed. At W-band frequencies the motivation for harnessing computational methods becomes extremely compelling compared to the K-band systems, where moderate quality factor values are still technologically feasible.

Demonstrations of random mode imaging of human size targets at lower frequencies (K-band) rely heavily on the computational power. Scaling the discretization mesh to W-band frequencies renders this imaging scheme computationally prohibitive. Substantially higher path loss (resulting into lower SNR of the measured data) adds further challenges in using broadly radiating random mode panels. A ‘‘spotlight’’ imaging scheme, however, can elegantly address both issues, collimating power only on the ‘zoom-in’ high-resolution area of the target (e.g. threat detection on the human body). The spotlight approach will ultimately require rough beam forming capabilities. Approaches such as [23], [35] have proven that low cost systems at K-band are viable, and suggest that similar systems could be feasible at W-band.

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