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Hoang, T. V., Fusco, V., Fromenteze, T., & Yurduseven, O. (2021). Computational Polarimetric Imaging Using Two-Dimensional Dynamic Metasurface Apertures. *IEEE Open Journal of Antennas and Propagation*, 2, 488-497. Advance online publication. https://doi.org/10.1109/OJAP.2021.3069320

Published in:
IEEE Open Journal of Antennas and Propagation

Document Version:
Publisher's PDF, also known as Version of record

Queen's University Belfast - Research Portal:
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Download date: 05. Jun. 2024
Computational Polarimetric Imaging Using Two-Dimensional Dynamic Metasurface Apertures

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This work was supported by the Leverhulme Trust under Research Leadership Award under Grant RL-2019-019.

ABSTRACT In this paper, we present a two-dimensional dynamic metasurface aperture to perform computational polarimetric microwave imaging for the first time. First, a novel tunable dual-polarized metamaterial radiator element integrated with two PIN diodes is designed to radiate and capture cross- and co-polarized field components. The diodes placed in orthogonal positions are simultaneously switched on or off to configure the transmit and receive polarization states. In diode on state, the metamaterial elements are in off state and the element radiated power is low whereas in diode off state, the metamaterial elements are in on state and the element radiated power is high. By sparsely reconfiguring and random assignment of the developed metamaterial elements across the array aperture, dynamic modulation of the radiated fields is achieved. Using this principle, we synthesize polarimetric, spatio-temporally incoherent wave-chaotic modes that facilitate polarimetric computational imaging. Leveraging the novelty of the dual-polarized dynamic characteristics of the wave-chaotic radiation, polarimetric imaging is computed in the near-field region at K-band frequencies and the polarimetric responses of specific targets are retrieved. The approach is verified by electromagnetic full-wave simulations, and imaging a T-shaped object consisting of two orthogonal metal strips, it is demonstrated that the target characteristics from a set of backscatter measurements compressed by the developed dynamic metasurface antenna

INDEX TERMS Reconfigurable antennas, microwave imaging, polarimetry, singular value decomposition, computational imaging.

I. INTRODUCTION

POLARIMETRIC radar imaging is a promising way to detect and recognize a target of interest by analyzing the polarization properties of the waves scattered from objects [1]–[6]. It is a valuable technique to obtain information about a wide range of sources and objects, and has been used in a wide variety of research fields such as remote sensing [7]–[9], target detection [10] and [11], astronomy [12], and tomographic applications [13]. Most polarimetric radar imaging applications concentrate on the far-field region. With the development of close range imaging modalities operating in the near-field of the synthesized radar aperture, near-field polarimetric imaging has recently gained significant attraction [14], [15].

Active and passive microwave imaging modalities have been widely adopted in various radar systems [15]–[18]. Conventionally, imaging is facilitated by means of raster scanning the scene to be imaged in order to collect backscattered data (active) or to listen to the incoming thermal radiation (passive) on a pixel-by-pixel basis. Recently, it has been shown that this multi-pixel raster scanning requirement can be overcome using alternative aperture modalities through synthesizing random, wave-chaotic bases to reconstruct the scene information from a reduced number of measurements [23]–[26]. Therein, active computational imaging is a technique that allows random radiation patterns from metasurface apertures to be projected onto the scene to encode the backscattered signal into a series of
indirect measurements from which reconstruction of the scene follows by solving an inverse problem [25]. Since computational imaging is facilitated by encoding the scene information onto spatio-temporally incoherent modes and compressing the back-scattered data into a single channel, it can substantially improve the data acquisition speed and reduce the complexity of the hardware layer. This single-pixel approach is in contrast to conventional imaging modalities relying on multi-pixel raster scanning, such as synthetic aperture radar (SAR) [16]–[20] and phased arrays [21], [22].

Since the emergence of the metamaterial theory followed by its implementation to synthesize two-dimensional (2D) metasurfaces, metamaterial based structures have gained significant traction in optical and microwave fields [23]–[30]. For instance, a comprehensive study on the concept, theory, and applications of composite right/left-handed transmission lines (CRLH-TLs) used in antenna system designs was provided in [24]. In [25], a comparative review was given on diverse methodologies for suppressing mutual-coupling in antenna arrays for application in MIMO and SAR systems based on metasurface and metamaterial properties. An impedance matching technique based on metasurface was used to overcome the limitations of gain-bandwidth product [26]. A planar antenna-array inspired by the metamaterial concept where the resonant elements have sub-wavelength dimensions for application in microwave medical imaging systems for detecting tumors in biological tissues was shown in [27]. Recently, phase gradient metasurfaces were proposed for manipulating the wavefront of anomalous reflection and refraction waves [28]–[31]. The current trends in the design of Huygens’ metasurfaces (HMSs), which are planar arrays of balanced electric and magnetic polarizable particles (meta-atoms) of subwavelength size were presented in [32]. Various metasurface-based antennas were also proposed for wireless applications [33]–[36].

In microwave imaging systems, metasurface antennas have been demonstrated as useful components for implementing computational imaging schemes. In this context, the two modalities that can be leveraged to generate an ensemble of random, wave-chaotic sensing fields with spatial diversity can be given as (a) frequency-diversity and (b) dynamic metasurface aperture. In the first method, i.e., frequency-diversity, the characteristics of the aperture radiated fields are governed by a frequency sweep, with the aperture radiating a distinct radiation pattern at each frequency, which is ideally, orthogonal to the radiated field patterns at other frequencies. The radiation of random complex modes varying as a function of frequency can be performed by various metasurface structures such as a parallel plate waveguide with patterned metamaterial elements and mode-mixing cavities [37]–[55]. However, this technique exhibits several disadvantages, such as the necessity to sweep a large bandwidth to excite a sufficient number of modes required for reliable image reconstruction, complicated hardware design, and possible interference within the operating bandwidth due to the overly-congested microwave spectrum.

The dynamic aperture technique offers an alternative to the frequency-diversity approach in computational imaging. Using dynamically modulated apertures, the radiation of spatio-temporally varying modes is achieved by dynamically tuning the radiating elements on the aperture over a narrow operating bandwidth or even at a single frequency [56]–[61]. In this technique, each aperture configuration constitutes an individual mask, radiating a distinct radiation pattern, which is ideally orthogonal to the radiated field patterns using different masks. A significant advantage of this technique is that, because the generation of spatio-temporally varying modes is achieved across a narrow frequency band (or at a single frequency), the dynamic modulation approach can have a substantially simplified RF transmit/receive architecture in comparison to the frequency-diversity approach.

Computational imaging facilitated by metasurface-based aperture modalities has conventionally been studied as a scalar problem. In this context, the interaction between the antenna radiated fields and the back-scattered signals is considered without the polarimetric content. This is done either by using apertures radiating single-polarized wave-chaotic radiation patterns [37]–[38] or the polarimetric nature of the imaging problem is ignored by considering the reconstruction problem to be devoid of a specific polarization basis but rather to be a superposition of all polarimetric bases into a single scalar image [54]. Recently, polarimetric computational imaging using frequency-diverse metasurface apertures has received significant attention [62], [63]. In [62], [63], the authors showed that a frequency-diverse, cavity-backed metasurface aperture can be used to retrieve polarimetric images of objects in computational imaging. However, the application of a compressive aperture with dynamically modulated radiation patterns to extract the polarimetric information in computational imaging remains heavily understudied.

In this paper, computational polarimetric imaging using two-port, two-dimensional dynamic metasurface apertures (2D-DMA) is presented for the first time. To demonstrate the validity of this technique, we show a 2D-DMA conceptualized and numerically simulated to facilitate computational polarimetric imaging at K-band frequencies (20–22 GHz). The K-band has been widely adopted in computational imaging, particularly for security-screening applications [41], [46]. The selected 2 GHz frequency band corresponds to a fractional bandwidth of less than 10%. Such a narrow bandwidth makes it necessary to leverage the dynamic aperture technique to facilitate the wave-chaotic modes for computational imaging. First, a tunable dual-polarized metamaterial radiator integrated with two PIN diodes at two orthogonal positions is designed to simultaneously project and capture cross- and co-polarized components. The diodes are simultaneously switched off (reverse bias) or on (forward bias) corresponding to the metamaterial element being on or off, respectively. In on state, the radiated power of the element is high whereas in
off state, the element radiated power is low. By placing an array of the sparse radiator elements in two-dimensions and dynamically tuning the states of diodes, the dynamic manipulation of radiation can be performed to a high diversity. Leveraging the dual-polarized dynamic characteristics of the radiation, polarimetric imaging is computed in the near-field of the synthesized aperture, and the polarimetric response of the K-band image of specific targets, including orthogonal and diagonal shapes, is retrieved with a high reconstruction quality.

II. 2D-DMA DESIGN

In this section, we start by developing the tunable metamaterial radiator element and 2D dynamic aperture to achieve highly diverse spatial patterns radiated from the aperture. Then, the imaging configuration, including the theory of polarimetric imaging, and the imaging performance of the synthesized system, is presented in the next section.

A. DESIGN OF THE TUNABLE METAMATERIAL ELEMENT

First, a metamaterial element needs to be designed upon which we build the polarimetric DMA. Here we propose the switchable metamaterial element in Fig. 1(a), integrated with two orthogonal PIN diodes. First, the complementary electric-LC radiator with a Jerusalem cross element (cELC-JC) is designed to capture and radiate both cross- and co-polarized components. Therefore, the proposed metamaterial element brings the properties of the complementary electric inductive-capacitive (cELC) resonator in [65], such as only responding to in-plane magnetic fields. Then, to achieve tunability in the cELC-JC elements, two diodes are introduced across the capacitive gaps in orthogonal positions. Here PIN diodes are conductive in the forward bias state and capacitive in the reverse bias state. The diodes are simultaneously switched off (reverse-biased) or on (forward-biased). When the diodes are in on state, they exhibit a low impedance (ideally short-circuit), short-circuiting the cELC-JC elements. Therefore, when the PIN diodes are on, the metamaterial elements are off, weakly radiating. In contrast, when the diodes are in off state, they exhibit a high impedance (ideally open-circuit), preserving the electrical characteristics of the cELC-JC elements. Therefore, when the PIN diodes are off, the metamaterial elements are on, strongly radiating. Although four diodes can be loaded at the four capacitive gaps, it also increases the complexity of the system as well as the loss from a significant number of diodes. Therefore, we only use two diodes for the proposed design. The PIN diodes are modeled in the full-wave simulation as a series inductor-resistor circuit in their conducting state (forward-bias) and as an inductor in series with a parallel capacitor-resistor in their non-conducting state (reverse-bias) as depicted in Fig. 1(a). The values of the inductance, resistance, and capacitance depend on the diode selection. In this work, the MACOM MADP000907-14020W PIN diode is used [60] and [61]. The dimensions of the proposed metamaterial element are shown in Fig. 1(a) as follows: $L_1 = 2.8$ mm, $L_2 = 2.1$ mm, $L_3 = 0.4$ mm, $L_4 = 1.1$ mm, $W_1 = 1.35$ mm, $W_2 = W_3 = W_4 = 0.2$ mm.

Because the metasurface aperture is proposed to operate at K-band frequencies, each of the metamaterial elements must be resonant within the K-band. In addition, the metamaterial element should, when in the on state, guarantee that ample energy is radiated onto the scene. Fig. 1(a) shows the CST Microwave Studio simulation setup used to analyze the metamaterial radiator design. The simulated $S_{11}$ in Fig. 1(b) depicts the resonant frequencies for the element designed to be between 20 GHz and 22 GHz, covering the lower portion of the K band when both diodes are off (black curve).

The radiation patterns of the cELC-JC element as a function of diode configurations are shown in Fig. 2. It is observed that the radiation from the element is strong with low cross-polarization levels for all diode states for the diode states as prescribed in Fig. 2. When both diodes are on, or the horizontal diode is switched off and the vertical
FIGURE 2. Normalized radiation patterns of the cELC-JC element as a function of diode configurations when (a) both diodes are off, (b) both diodes are on, (c) horizontal diode is on and vertical diode is off, and (d) horizontal diode is off and vertical diode is on. Unit: dBi.

state is switched on, the radiation patterns confirm that it radiates weakly into either the co- or cross-pol. The simultaneously switched on or off configuration of the diodes is selected for computational imaging as described in the next section.

B. DESIGN OF THE 2D APERTURE

A depiction of the proposed 2D-DMA is shown schematically in Fig. 3. First, a printed cavity is formed by double-sided copper cladding a dielectric substrate bounded by a metallic via wall. The cavity is excited by two coaxial probes – feeding 1 exciting the cavity at P1 and feeding 2 exciting the cavity at P2 in Fig. 3. The via wall reflects the guided wave, producing reverberating fields inside the cavity. Then, a 2D array of sparse metamaterial elements is patterned randomly across the front surface of the cavity. Here, each cELC-JC in on state acts as a resonant element that couples energy from the waveguide mode to free space. The interaction of the cELC-JC elements with the guided-mode controls the amplitude and phase of the transmitted wave, such that wave-chaotic far-field modes can be generated by modifying the on/off states of the cELC-JCs randomly along the aperture surface. In other words, by controlling the design and distribution of the on/off elements across the metasurface, complex radiation patterns can be created. The complex fields formed within the cavity project into the region to be imaged by superposing the contributions from each of the radiating metamaterial elements. By dynamically switching the states of the diodes, dynamic time sequenced manipulation of the radiation patterns is achieved to high diversity. In this context, each metasurface configuration is called a mask. These masks further allow for multiplexed backscatter measurements of a scene to be post-processed for imaging. The size of the electrically large cavity is $8\lambda_0 \times 8\lambda_0$, where $\lambda_0$ is the free-space wavelength, allowing the DMA to replace a large number of antennas. To put this statement into context, synthesizing the same aperture, $8\lambda_0 \times 8\lambda_0$, at the Nyquist limit ($\lambda_0/2$) would require 17 x 17 individual antennas (also equal to the number of data acquisition channels), whereas the 2D DMA has only two channels, one to transmit and the other to receive.

The simulated reflection coefficient and cross-coupling patterns of the 2D-DMA without a target are shown in Fig. 4. For this proof of concept demonstration, we arbitrarily select four different masks and, without loss of generality, we note that a similar analysis can be made using a larger number masks. Analyzing Fig. 4(a), the reflection coefficients at port 1 and port 2 of the DMA remain below $-10$ dB, whereas the average cross-coupling levels between the input ports remain below $-20$ dB throughout the operating frequency band. The $-10$ dB magnitudes of the reflection coefficient patterns guarantee that signals from the two ports can transmit and receive efficiently. We also observe significant variation in the reflection coefficient patterns as a function of tuning states within the frequency band of 20–22 GHz. This follows as each metasurface mask consists of metamaterial elements with varying on and off states, the interaction of the guided-mode with the metasurface layer undergoes strong variation as a function of generated masks. Further analyzing Fig. 4, a multitude of resonances (represented by the dips in the reflection coefficient patterns) corresponding to the variation of the cavity modes can be observed for all four masks. The $-20$ dB average magnitudes of the cross-coupling levels validate the low coupling between the two ports of the DMA over the
frequency band 20–22 GHz. This low cross-coupling level is important to ensure that the weak backscattered signal from the imaged object is not dominated by the direct coupling between the input ports. This is because the backscattered signal from an imaged object is measured by doing a background subtraction, which is achieved by subtracting the $S_{21}$ without the target (background) from the $S_{21}$ with the target in the imaged scene.

In Fig. 5, we present the simulated far-field radiation patterns of the 2D DMA at midband 21 GHz for four different masks. The peak gain values at these masks are 7.17 dBi, 7.37 dBi, 5.06 dBi, and 7.72 dBi, respectively, with radiation efficiencies 34.74%, 35.90%, 33.86%, and 40.55%, respectively. In Fig. 5, the diversity of the radiated field patterns as a function of varying masks, a key component for the wave-chaotic operation to encode the radar backscattered measurements using DMAs, can be appreciated. To put this statement in context, the average Pearson correlation coefficient for the patterns radiated by the DMA masks shown in Fig. 5 is calculated to be 0.061. This confirms that there is no significant correlation between the DMA radiated field patterns in Fig. 5.

III. POLARIMETRIC IMAGING

A. THEORY OF POLARIMETRIC IMAGING

The computational polarimetric imaging process was outlined in [62] using the frequency-diverse technique. Using the first-Born approximation and under diffraction-limited imaging, the backscattered radar measurement vector, $g$, is correlated to the sensing matrix, $H$, and the scene reflectivity, $f$, as follows:

$$g = \sum_{i=x,y,z} \sum_{j=x,y,z} H_{ij} f_{ij} + n = Hf + n$$

In Eq. (1), bold font is used to denote the vector notation and $n$ denotes system error, a metric we can use to control the imaging signal-to-noise ratio (SNR) level [55]. Here, the sensing matrix is given by the dot product of the transmit and receive fields, $E_{t,i}(m; r)$ and $E_{r,j}(m; r)$ respectively, as $H_{ij} = [E_{t,i}(m; r)E_{r,j}(m; r)]$, for $i, j = x, y, z$. In this definition, $m$ refers to the $m^{th}$ measurement at the scene location $r$, and the imaged scene is discretized into $p$ pixels. $H_{ij}$ is a $m \times p$ sub-block of sensing matrix formed by the product of $i^{th}$ polarization component of the transmitted fields and $j^{th}$ polarization component of the received fields. Because $i, j = x, y, z$, the total number of possible $H_{ij}$ combinations can be given as $3 \times 3$, although, in this paper, the polarimetric imaging concept is studied to leverage the cross-range ($xy$-plane) components only, $i, j = x, y$. Rows and columns of $H_{ij}$ correspond to the measurements and discrete voxels, respectively. Therefore, for the investigated scenarios, $H$ is the $m \times (p \times 4)$ complete sensing matrix formed by concatenating the sub-block sensing matrices as $[H_{xx}, H_{xy}, H_{yx}, H_{yy}]$. Here, $f_{ij}$ is the $p \times 1$ vectorized $f_{ij}$ of all...
FIGURE 6. Singular values of $H_{xx}$ with different configuration.

FIGURE 7. Spatial correlation of the NFS represented for varying port and polarization states.

voxels in the scene and $f$ is the combined $(4 \times p) \times 1$ vector of $f_{ij}$ with $[f^T_{xy}, f^T_{yx}, f^T_{yy}]$. From Eq. (1), the sub-block sensing matrices $H_{ij}$ interrogate the corresponding polarimetric scattering terms $f_{ij}$ and coherently sum to the complex measurement. The polarimetric responses are reconstructed by solving a least squares problem posed as

$$\hat{f}(r) = \arg \min_f \| g - Hf \|_2 .$$

B. IMAGING PERFORMANCE

Our final goal is to perform computational polarimetric imaging through a set of quasi-random bases radiated by the developed 2D polarimetric DMA. To this end, we first evaluate the orthogonality of the DMA radiated fields and correlation between them as a number of varying number of masks. For this purpose, a powerful technique is the singular value decomposition (SVD) of $H$. A rapid decay rate of the singular value spectrum (SVS) indicates a large level of correlation among measurements described by $H$ [64]. By plotting these singular values, the slope of an SVD plot can be used to compare different imaging configurations and the role of different features in the imaging process [64].

In Fig. 6, various imaging configurations are shown with the different slopes of the singular values when the SVS of $H_{xx}$ is computed, which helps us assess the level of correlation between these cases. We note that a similar analysis can be made for $H_{xy}, H_{yx}, H_{yy}$ without loss of generality. For fair comparison, the bandwidth of 2 GHz from 20 GHz to 22 GHz is held fixed. When the number of masks ($N_m$) is set at 12, the frequency sampling ($N_f$) is changed in order to evaluate the performance. The comparison between $N_f = 201$ (red curve) and $N_f = 101$ (green curve) shows that the denser frequency sampling does not help improve diversity. This implies that as the number of frequency points increases, the encoded information from the imaged scene becomes highly redundant. In contrast, when the number of frequency points is fixed, if more masks are used, as seen in black, blue, and green curves, the slope of the SVS becomes flatter. This indicates that the correlation between the imaging modes radiated by the DMA is reduced, and hence the redundancy of the scene information encoded by these modes is decreased. Another interesting outcome in Fig. 6 can be observed by comparing the SVD patterns in green and orange colors. Albeit producing a similar number of total modes, the SVD pattern of the case with $N_f = 101$ and $N_m = 18$ (orange curve) is substantially better than the case with $N_f = 201$ and $N_m = 12$ (green curve). This suggests that the diversity of the DMA radiated field patterns is dominated by the number of masks in comparison to the number of frequencies. Hence, for our final configuration, $N_f = 101$ and $N_m = 18$ are chosen.

In order to assess the performance of the synthesized DMA modes for polarimetric computational imaging, the global representation of the spatial correlation of the near fields, as shown in [62], for each couple of ports and polarizations of one aperture is presented in Fig. 7. This depicts the properties expected for interrogating the target space: the four autocorrelations are close to diagonal matrices, while all the other cross correlations are low. In this manner, the polarization information is encoded by the radiation of the metasurface in transmission and reception, and can be retrieved from the inverse formulation by exploiting the dynamically modulated diversity.

To demonstrate polarimetric imaging using the proposed 2D DMA, we utilize the configuration shown in Fig. 8(a), where two DMA apertures are used. We demonstrate the extraction of polarimetric target characteristics $f$ in Eq. (2) using the numerical, full-wave simulated backscatter measurements of the imaged object in CST Microwave Studio consisting of two orthogonal metal strips, forming a T-shaped object. This conductive target is placed at $z = 100$ mm from the aperture surface in the near-field region. For the studied polarimetric imaging scenario in
Fig. 8, the system signal-to-noise (SNR) level is selected to be 20 dB. For the scenario studied in Fig. 8(a), the orientation of the metal strips forming the T-shaped object is horizontal (y-axis) and vertical (x-axis) respectively. Therefore, for the imaged object in Fig. 8(a), we focus on reconstructing the co-polarized components of the scene information, $f_{xx}$ and $f_{yy}$. The reconstructed polarimetric reflectivity distribution $f$ of the target is illustrated in Figs. 8(b) and 8(c) as two different polarimetric channels. It demonstrates that our system can resolve targets in both polarimetric channels. The two transverse “xx” and “yy” reconstructions exhibit distinct polarimetric signatures in line with the geometrical orientation of the strips forming the imaged T-shaped object. For example, analyzing the reconstructed image in the ypolarization basis, $f_{yy}$, in Fig. 8(b), the horizontal strip is dominant, suggesting that the polarimetric DMA computational imaging system can recover the response of the imaged object to y-polarized incident fields and y-polarized scattered fields. Similarly, in Fig. 8(c), the reconstructed image in the xx-polarization basis, $f_{xx}$, reveals that the vertical strip of the T-shaped object is dominant.

In order to demonstrate the capability of the developed polarimetric DMA aperture to leverage cross-polarized reconstruction bases for computational imaging, we image a rotated T-shaped object consisting of diagonal strips as depicted in Fig. 9(a). The cross-polarized reconstructed image, $f_{xy}$, of the rotated T-shaped object is depicted in Fig. 9(b). Analyzing the reconstructed image in Fig. 9(b), it can be seen that both diagonal strips exhibit a similar cross-polarized signature with equal amplitudes. We note that, although not shown here, $f_{yx}$ has a reciprocal behavior.

We also note that more enhanced reconstructions can be achieved by increasing the number of masks and using a larger aperture at the expense of increased computational complexity.

A comparison between the proposed design and several published metasurface aperture designs for computational imaging is shown in Table 1.
TABLE 1. Comparisons between the proposed design and the previous metasurface aperture designs for computational imaging.

| Reference | Diversity Mechanism | Required Bandwidth | Layout | Polarimetry |
|-----------|---------------------|--------------------|--------|-------------|
| [58], [59] | Dynamic reconfiguration with/without frequency-diversity | From 0 to 4.3 GHz | 1D | No |
| [60], [61] | Dynamic reconfiguration with/without frequency-diversity | From 0 to 9 GHz | 2D | No |
| [62], [63] | Frequency-diverse only | 9 GHz | 2D | Yes |
| This work | Hybrid dynamic reconfiguration with frequency-diversity | 2 GHz | 2D | Yes |

Leveraging the developed 2D polarimetric DMA, we synthesized a computational imaging radar system consisting of two DMA apertures. Using a full-wave numerical analysis, we validated the computational polarimetric imaging capability of the synthesized aperture.

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