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Ghost Image Removal Using Physical Layer Spatial Asymmetry in Frequency-Diverse Computational Imaging

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Abstract—Ghost images are one of the undesired artifacts in an imaging system besides a real image. It also happens in frequency-diverse computational imaging used to reduce the complexity of traditional imaging systems using a mechanical scan or active circuits. We present that by breaking the symmetric structure of frequency-diverse wave-chaotic metasurface antennas, the ghost image artifacts in reconstructions retrieved using frequency-diverse computational imaging can be eliminated.

Index Terms—frequency-diversity, computational imaging, microwave, radar, metasurface, ghost image.

I. INTRODUCTION

Computational imaging is the process through advanced processing algorithms to reconstruct images from a set of indirect measurements [1-8]. In contrast to conventional imaging modalities with a limited data acquisition speed, such as synthetic aperture radar [9-11], and a complex hardware layer, such as phased arrays [12, 13], frequency-diverse computational imaging has recently emerged as a promising alternative [14-21]. In frequency-diverse imaging, the radiation of random complex modes varying as a function of frequency is performed by various structures of metasurfaces, such as a parallel plate waveguide with patterned metamaterial elements [1-3] and mode-mixing cavities [15, 16]. Using the frequency-diverse technique, a simple method is employed to reconstruct the scene information by scanning over a frequency band and encoding the backscattered radar signal using the wave-chaotic transfer function of the frequency-diverse antennas.

Ghost images are one of the undesired artifacts in an imaging system besides a real image. This artifact makes the detection and analysis of the image processing system mishandled. Many reasons cause the ghost image artifact in imaging, such as ghosting due to phase discontinuities in echo-planar imaging [22] or ghosting by capturing multiple images of a scene in high dynamic range images [23]. Furthermore, depending on each type of imaging, the de-ghosting technique is different.

In this paper, we present a method to remove the ghost image artifact in frequency-diverse imaging. First, a symmetric cavity-backed metasurface antenna enabling the radiation of spatially distinct modes as a function of

frequency is selected to implement frequency-diverse imaging because of its advantage in compressing the radar backscattered measurements into a single channel and obtaining video frame-rate images. However, we present that, when the metasurface aperture is constructed symmetrically, the ghost image artifact appears in the reconstructed images. We then demonstrate that breaking the symmetric structure of the frequency-diverse cavity-backed metasurface antenna is necessary to remove the ghost image characteristic of the reconstructed images.

II. RECONSTRUCTION OF FREQUENCY-DIVERSE IMAGING

A. Structure of a frequency-diverse cavity-backed metasurface antenna

Fig. 1 shows two configurations of a cavity-backed metasurface antenna fed by two rectangular waveguide ports. First, to guarantee the modal diversity, the length of the cavity is designed to be several times larger than the operating wavelength. To catalyze the modal diversity, create irregular and convex boundaries, and reduce the coupling between two ports, a metallic ball is inserted into the air-filled cavity [24]. The front side of the cavity is perforated by an array of sub-wavelength holes (or irises) to enable the radiation of spatially distinct modes. The differences between the two configurations are the arrangements of the holes within the front cover and the positions of two ports. While the holes are arranged periodically and symmetrically via the center of the cavity in configuration 1 of Fig. 1 (a), the random and asymmetric holes are placed in configuration 2 of Fig. 1 (b). Similarly, two ports are placed symmetrically in configuration 1 while placed asymmetrically in configuration 2.

3-D demonstration of the frequency-diverse imaging system with the presence of an imaged target is shown in Fig. 2. The cavity was designed to operate over the frequency range of 10–16 GHz. The dimensions of the cavity are 35 cm (x -axis) $\times$ 35 cm (y -axis) $\times$ 30 cm (z -axis), corresponding to an electrical size of approximately $15\lambda \times 15\lambda \times 13\lambda$, where λ is the free-space wavelength at the centre operating frequency of 13 GHz. The radius of the mode-mixing metallic sphere is 7 cm. In both configurations, the

average distance between the two neighboring irises across the metasurface aperture is approximately 20 mm, which is selected to be close to the smallest wavelength across the operating frequency band. This is to ensure that the metasurface can sample all the cavity modes for imaging. The radius of the radiating irises forming the metasurface is chosen to be 7 mm, corresponding to an electrical size of 0.3λ at the centre frequency. The distance between the metasurface aperture and the imaged target is chosen to be $d = 51$ cm, which is in the radiating near-field region of the frequency-diverse antenna.

Fig. 1. Two configurations of a frequency-diverse cavity-backed metasurface antenna with the arrangements of (a) symmetric holes and feeding ports, and (b) asymmetric holes and feeding ports.

Fig. 2. 3-D demonstration of a frequency-diverse imaging system with presence of an imaged target.

B. Frequency-diverse imaging

The frequency-diverse computational imaging process has been outlined in [25]. In this approach, using the first-Born approximation and diffraction-limited imaging, the backscattered radar measurement vector, $\mathbf{g}$, is correlated to

the sensing matrix, $\mathbf{H}$, and the scene reflectivity, $\mathbf{f}$, as follows:

$$\mathbf{g}_{M \times 1} = \mathbf{H}_{M \times N} \mathbf{f}_{N \times 1} + \mathbf{n}_{M \times 1} \quad (1)$$

In (1), $\mathbf{H}$ is proportional to the antenna radiated fields, $\mathbf{H} \propto \mathbf{E}_{Tx} \mathbf{E}_{Rx}$, where $\mathbf{E}_{Tx}$ and $\mathbf{E}_{Rx}$ denote the fields radiated by the transmit and receive apertures propagated to the imaged scene domain [1], and $\mathbf{n}$ is the measurement noise. Here, it should be noted that the bold font in (1) is used to denote the vector-matrix notation only and the fields forming the sensing matrix are scalar. In (1), M denotes the number of total measurement modes radiated by the frequency-diverse antenna to indirectly sample the scene information whereas N is the number of pixels into which the imaged scene is discretized. Because the sensing matrix is not necessarily a square matrix, i.e. $M \neq N$, it does not have a direct inverse. Instead, after $\mathbf{g}$ is measured, several techniques can be adopted to do a phase (or phase and amplitude) compensation of the sensing matrix applied to the backscattered measurements to retrieve an estimate of the scene information by means of several computational reconstruction algorithms, such as pseudo-inverse, matched-filter, least-squares, and TwIST+TV [26]. In this work, the matched-filter technique is used for image reconstruction. Using matched-filtering, an estimate of the imaged scene can be reconstructed as follows:

$$\mathbf{f}_{est} = \mathbf{H}^\dagger \mathbf{g} \quad (2)$$

In (2) the symbol $\dagger$ denotes the Hermitian transpose operator. Here, for a fair comparison between two configurations in Section II-A, we keep the frequency band of operation, 10–16 GHz, the same in both cases. Furthermore, we use 201 frequency points corresponding to $M = 201$ measurements for both cases.

III. GHOST IMAGE AND REMOVAL

A. Frequency-Diverse Computational Imaging Results

In this paper, our goal is to show the ghost image artifact present in the reconstructed images in frequency-diverse imaging when the cavity-backed metasurface antenna is structured symmetrically. Then, we show that by breaking the symmetricity in the mode-mixing mechanism, the ghost image of the reconstructed image can be removed. Therefore, after two configurations of the cavity-backed metasurface antenna are constructed and presented in Section II-A, several offset objects are imaged in this section.

The first imaged target is a square metal that is off the center of the scene in the vertical axis ($x = -5$ cm), as shown in Fig. 3(c). With the arrangements of the symmetric holes and feeding ports of the frequency-diverse cavity-backed metasurface antenna, the reconstructed image in Fig. 3(a) exhibits ghosting artifact with a virtual image appearing symmetrical to the real image in the reconstruction. After

breaking the symmetric configuration, only one square target is present in the reconstruction in Fig. 3(b), which is in agreement with the ground truth shown in Fig. 3(c).

Fig. 3. Reconstructed image of the off-centered square-shaped target with the arrangements of (a) symmetric holes and feeding ports, and (b) asymmetric holes and feeding ports. (c) Ground truth of the off-centered square shape target.

To understand the ghosting artifact present in the image of Fig. 3(a) reconstructed using the symmetric cavity-backed frequency-diverse metasurface antenna, one needs to analyze the distribution of the antenna radiated modes projected to the scene domain. Analyzing the radiated field patterns from the symmetric frequency-diverse metasurface antenna in Fig. 4, the radial symmetric nature of the radiated fields as a function of frequency is evident. To put this statement in the context of the studied imaging scenario in Fig. 3, one can conclude that, using the symmetrically distributed field patterns in Fig. 4 to encode the scene information across the operating frequency band, it is not possible to distinguish whether the imaged object is located at $x = 5$ cm or $x = -5$ cm due to the present symmetry of $\mathbf{H}$ in the forward-model of (1).

Fig. 4. Radiated field patterns from the symmetric frequency-diverse metasurface antenna in the scene (a) 12 GHz of the transmit aperture, (b) 12 GHz of the receive aperture, (c) 14 GHz of the transmit aperture, and (d) 14 GHz of the receive aperture. Radial symmetry in the radiated field patterns as a function of frequency is evident. Colorbar: dB.

In comparison, in Fig. 5, we show the radiated field patterns from the asymmetric cavity-backed frequency-diverse metasurface antenna. It is evident that the frequency-diverse modes generated by the antenna do not exhibit any structural symmetry when encoding the scene information. Therefore, the backscattered signal, $\mathbf{g}$, in the forward-model of (1) contains the unique positioning index of the imaged object located at $x = -5$ cm along the vertical axis. As a result, when interacted with the phase compensated sensing matrix, $\mathbf{H}^\dagger$, in (2), which is devoid of spatial symmetry, the reconstructed image in Fig. 3(b) produces a unique outcome with the position of the object correctly reconstructed.

Following the imaging of the square-shaped metal object, we image a more complicated target consisting of a stripe oriented along the vertical axis. The metal stripe is located at $y = -5.5$ cm. The reconstructed images and the ground truth of the imaged object are shown in Fig. 6.

Fig. 5. Radiated field patterns from the asymmetric frequency-diverse metasurface antenna in the scene (a) 12 GHz of the transmit aperture, (b) 12 GHz of the receive aperture, (c) 14 GHz of the transmit aperture, and (d) 14 GHz of the receive aperture. Radiated field patterns do not exhibit symmetry as the frequency is swept. Colorbar: dB.

Fig. 6. Reconstructed image of the off-centered vertical strip target with the arrangements of (a) symmetric holes and feeding ports, and (b) asymmetric holes and feeding ports. (c) Ground truth of the off-centered vertical strip target.

Similar to the reconstructions in Fig. 3, the presence of the ghost image reconstructed using the symmetrical cavity-backed metasurface antenna in Fig. 6(a) is evident. With the presence of the ghost image, the reconstructed image of the off-centered vertical strip target in Fig. 6(c) is not exact, as shown in Fig. 6(a). However, with the arrangements of the random and asymmetric holes and feeding ports of the frequency-diverse cavity-backed metasurface antenna in configuration 2, the ghosting artifact is removed in Fig. 6(b), substantially improving the reconstruction quality and the agreement with the ground truth. It should be noted that the quality of the reconstructed image in Fig. 6 is limited by the selected number of measurement modes, $M = 201$, and the diffraction limited resolution limit of the frequency-diverse aperture. More enhanced reconstructions can be achieved by increasing the number of modes and using a larger aperture at the expense of increased computational complexity.

B. Cavity-Backed Metasurface Antenna Performance

After validating the ghost image elimination, we study several antenna parameters of the asymmetric frequency-diverse cavity-backed metasurface antenna. The simulated S-parameters of the metasurface antenna without a target are shown in Fig. 7. Analyzing Fig. 7, it can be seen that the reflection coefficient at port 1 and port 2 of the cavity remain below -10 dB whereas the cross-coupling between the input ports remains below -20 dB throughout the operating frequency band. The -10 dB magnitudes of S_{11} and S_{22} guarantee that signals from the two ports can transmit and receive efficiently. The -20 dB magnitudes of the S_{21} and S_{12} validate the low coupling between these two ports over the frequency band of 10–16 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 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.

Fig. 7. Simulated S-parameter patterns of the frequency-diverse cavity-backed metasurface antenna.

Finally, in Fig. 8, we present the simulated far-field radiation patterns of the asymmetric frequency-diverse cavity-backed metasurface antenna at the frequencies of 10 GHz, 12 GHz, 14 GHz, and 16 GHz. The gain values at these frequencies are 7.34 dBi, 12.2 dBi, 12.01 dBi, and 12.98 dBi, respectively, with radiation efficiencies 23.9%, 42%, 38.9%, and 43.8%, respectively. In Fig. 8, the diversity of the radiated field patterns as a function of frequency, a key component for the wave-chaotic operation to encode the radar backscattered measurements, can be appreciated.

Fig. 8. Simulated radiation patterns of the frequency-diverse cavity-backed metasurface antenna at (a) 10 GHz, (b) 12 GHz, 14 GHz, and (d) 16 GHz.

IV. CONCLUSIONS

In this paper, ghost image artifact in frequency-diverse computational imaging has been presented when the frequency-diverse metasurface antenna is structured symmetrically. It has been shown that in order to remove the ghost image, the symmetric structure of the frequency-diverse antenna needs to be broken. By randomizing the arrangement of the radiating irises across the metasurface layer and the position of the waveguide ports feeding the cavity-backed architecture, ghost images in the reconstructions have been eliminated successfully, improving the quality of the reconstructed images.

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