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Metasurface-Enabled Full 360° Azimuth Surface-Level Beam Scanning Antenna System

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***Abstract*—This paper investigates the use of metasurface (MS) to enhance the scan range performance of the phased-array antenna for next-generation sub-6 GHz applications. The proposed system consists of a cylindrical Huygens' MS integrated with the source (phased array), and the MS steers the beam from the source towards the horizon. The metasurface's inherent symmetry also allows for full azimuth surface-level scanning. The proposed system achieves a gain of more than 15.5 dBi across the frequency range of 3.5-3.8 GHz.**

I. Introduction

The scanning range of the conventional phased array antenna (PAA) is practically limited to $\pm 60°$ from the broadside direction due to the significant drop in the directivity, which is proportional to the cosine of the scan angle [1]. This reduction in directivity deteriorates the performance at a near grazing angle, making the PAA inefficient when scanning the beam close to the horizon *i.e.* surface-level scanning. Extending the scan range to near-grazing angles would greatly benefit the operation of wireless base-stations.

A well-designed dielectric radome placed over the PAA offers an intriguing solution for improving scan range [2], [3]. Such radomes, however, are bulky and have large axial [2] and transverse [3] dimensions. In light of recent developments in the area of metamaterials and metasurfaces, several approaches have been reported to extend the scan performance of phased arrays [4]–[6]. In [4] a negative index metamaterial (NIM) radome has been employed to steer the beam towards the horizon. However, the design is extremely complex and the implementation of NIM is highly dispersive and lossy, limiting the system's bandwidth and efficiency. In [5], a phase-gradient MS has been used over a linear PAA to improve the scanning angle from $[-36°,\ 38°]$ to $[-56°,\ 60°]$. Another work [6] used a MS-based diverging lens in the PAA's far-field (40λ) to extend the range from $\pm 15°$ to $\pm 30°$. Due to the large distance between the source and the metasurface, the application realm for such an approach is limited at microwave frequencies.

In this paper, we use a cylindrical Huygens' MS to enable 360° surface-level scanning along the azimuthal direction. As illustrated in Fig. 1, we consider a cylindrical MS (green) integrated with the PAA (blue). The PAA scans the beam (orange) in the direction of (θ, ϕ)=$(45°, \phi_0)$ (where $\phi_0 \in [0°, 360°]$), which hits the cylindrical MS at an oblique angle of 45°. The metasurface, which varies in the z-direction, redirects the beam toward the horizon, resulting in efficient surface-level scanning with a gain of > 15.5 dBi over a bandwidth of 3.5-3.8 GHz (8.22%).

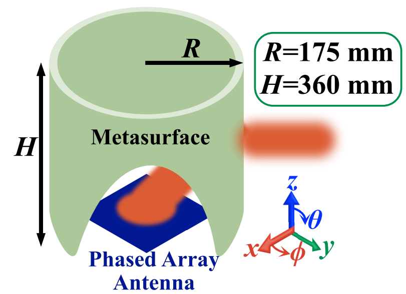

Fig. 1: An artistic view of the metasurface-enabled wide-angle beam scanning system.

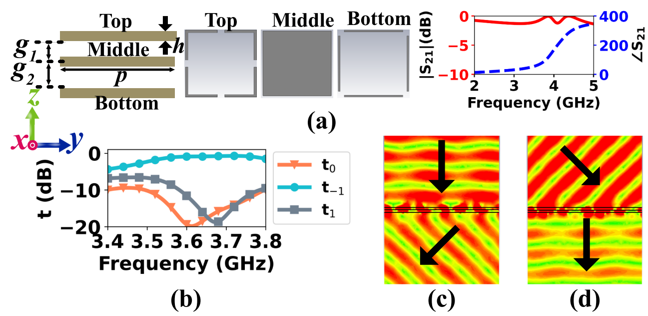

Fig. 2: (a) Geometry of the proposed unit-cell (left panel) and the transmission spectrum of an example meta-atom (right panel). (b) Transmission coefficients corresponding to the three Floquet harmonics. (c,d) E-field distribution in the yz-plane at 3.6 GHz, showing anomalous refraction.

II. Metasurface Design

To design the metasurface, we employ the idea of *coarse discretization* [7], [8], which dramatically simplifies the MS design and is highly efficient compared the conventional phase gradient MS. A coarsely discretized metasurface is composed of a few polarizable particles per period, where the periodicity opens up the higher-order Floquet channels and the meta-atoms are tailored to direct the incident wave towards the intended Floquet channel direction while suppressing the spurious Floquet harmonics.

We begin by designing a unit-cell in a 2D periodic formation, using CST Microwave Studio. The geometry of the proposed unit-cell is shown in Fig. 2(a) (left panel). We adopted the stacked layer topology, comprising three metallic layers printed on a dielectric substrate with a thickness of

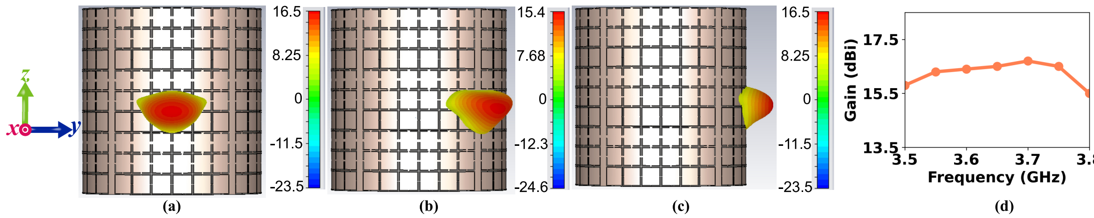

Fig. 3: 3D radiation pattern at 3.6 GHz directed along $\theta = 93°$ (a) $\phi_0 = 0°$. (b) $\phi_0 = 45°$. (c) $\phi_0 = 90°$. (d) Gain versus frequency for $\phi_0 = 0°$.

0.508 mm and a relative permittivity of 4.5. These cascaded metallic layers essentially act as a bianisotropic structure, providing more degrees of freedom for extreme wave manipulation [9]. The air-gaps of height g_1 and g_2 are introduced to achieve the optimal performance and to eliminate the need for bondply to adhere the stacked layers together. The proposed structure is illuminated by a *y*-polarized wave propagating in the negative -*z*-direction. Fig. 2(a) (right panel) depicts the transmission spectrum of the optimized meta-atom, showing high transmission ($|S_{21}| > -1.2$ dB) and a full phase coverage of 360°.

Following that, we design a coarsely discretized metasurface by considering the manipulation of the first three Floquet harmonics, *i.e.* $m = 0$, $m = \pm 1$. According to the theory of coarse discretization [10], to manipulate the aforementioned Floquet harmonics, we only need three elements per period of the metasurface. Consequently, we design the metasurface with three spatially varying meta-atoms per period with near-perfect transmission and equidistant phase, and we termed the resultant MS as *ternary Huygens' metasurface*. The period of the metasurface is $1.44\lambda_0$, where λ_0 is the free-space wavelength calculated at 3.6 GHz. Fig. 2(b) depicts the transmission coefficients for the three propagating harmonics. The plot clearly shows that transmission to the desired Floquet channel is maximized, corresponding to $\theta_{t(-1)} = -\sin^{-1}(\lambda_0/\Lambda_g) = -44°$. The electric field distribution portrayed in Fig. 2(c) illustrates the anomalous refraction performed by the metasurface when incident wave impinges normally. From reciprocity, the proposed metasurface performs similarly when illuminated at an oblique angle of 44°, as shown in Fig. 2(d).

The flat metasurface is transformed into a multi-layer cylindrical metasurface with an outermost radius of 175 mm and a height of 360 mm. Figs. 3(a)-(c) depicts the beam scanning performance of the cylindrical MS integrated with the 6×6 patch array (size of the array is $2.78\lambda_0 \times 2.78\lambda_0$). The cylindrical MS redirects the incident beam from the array towards the horizon ($\theta \approx 93°$), and the MS's circular symmetry allows for full azimuth scanning. When the beam is scanned towards $\phi_0 = 0°$ and $\phi_0 = 90°$, the system achieves a gain of 16.5 dBi. At present, the gain slightly reduces to 15.4 dBi when scanned towards $\phi_0 = 45°$, due to an imperfection in the metasurface wrapping operation, caused by slightly differing radii of the inner and outer layers. The proposed system performs similarly along the rest of the azimuth and is thus not shown here for the sake of brevity. Fig. 3(d) shows the gain variation of 15.5-16.7 dBi for $\phi_0 = 0°$ across the frequency band of 3.5-3.8 GHz.

III. Conclusion

In summary, we have presented a Huygens' metasurface-enabled wide-angle beam scanning antenna system. The cylindrical MS redirects the beam from the PAA toward the horizon, and its circular symmetry allows for complete 360° scanning in the azimuthal plane. The proposed antenna system achieves a gain of > 15.5 dBi over the frequency range of 3.5-3.8 GHz. This level of gain represents a clear improvement over surface scanning antennas of similar electrical sizes, and should provide a practical solution to surface-level beamforming with a single antenna array.

Acknowledgement

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