Metamaterial-loaded Huygens' Box Antenna: Highly-Directive Beam Steering with Very Few Phasing Elements

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***Abstract*—In this report, we present a Huygens' metasurface enclosed artificial dielectric medium built from equispaced conductive rods that enhances directive and steerable radiation. The enclosing metasurface is built from sufficiently spaced simplified Huygens' sources arranged around the enclosure's periphery. The simulation results show that the radiation characteristics of this device is similar to what is achievable from a microstrip patch array of similar aperture size. Hence, through the proposed antenna, we have achieved a many-fold reduction in cost especially in the mm-wave regime where component cost for the necessary phase modulating circuit becomes of great consideration.**

***Index Terms*—artificial dielectric, directive radiation, aperture antennas, Huygens' metasurface, phased array antennas**

I. Introduction

High gain antennas are the subject of scientific investigations for very good reasons. They have been applied widely in long range communications [1], [2]. Many antenna configurations have been explored (reflectors, lenses , leaky wave antennas etc), each with one limitation or the other. In cases involving motion, one also desires to change the radiation direction without moving the antenna. For a long time therefore, the true solution has remained microstrip patch arrays wherein changing the relative phases of the excitations to each constitutive radiating element steers the beam to a desired direction. However, antenna arrays have their number of elements proportional to the surface area of the aperture. Consequently, the cost is not friendly for low end commercial usage especially for large arrays at mm-wave frequencies.

Metamaterials and their 2D equivalents called metasurfaces have enabled electromagnetic wave manipulations in unconventional manners with their unusual characteristics [3], [4]. Such materials have been made and applied to a myriad of applications including but not limited to anomalous reflection and transmission and antenna enhancement [5], [6]. The electromagnetic delay lens for instance has been demonstrated to have refractive index less than unity [7]. Negative index materials have also been demonstrated [8] among many other applications. We thus have great control on how our devices interact with electromagnetic fields.

We propose herein a metasurface-based device whose element number is dependent on the perimeter as opposed to surface area. While Refs. [9]–[11] have also demonstrated beam steering by exciting Huygens' sources along a cavity's periphery, however, Refs [9], [10] did not implement the metamaterial and unlike the device explored herein, the enclosed region in Ref. [11] is a dense dielectric that limits the realisable reduction ratio. Also, its beam direction is significantly limited. We demonstrate beam steering capability by leaking out propagating plane waves in an artificial dielectric enclosed in an active metasurface sheet. The artificial dielectric is formed from a 2D array of conductive rods in air, yielding a medium with refractive index less than unity. We show that the device so formed achieves similar radiation characteristics to a conventional patch array and does so with a $m/2$ reduction ratio in the number of radiating elements required for a $m\lambda \times m\lambda$ aperture size. For example, while a $10\lambda \times 10\lambda$ patch array requires 400 elements, our device will need just 80 elements for the same aperture size if the inter-element spacing is $\lambda/2$. This reduction ratio leads to large savings in component cost with increased aperture size, making it attractive in large aperture mm-wave applications.

II. Artificial Dielectric Medium

For our purpose, we adopt a free-space region filled by a 2D array of metallic rods spaced by centre-to-centre distance b. A typical medium is shown in Fig. 1. If the spacings in both x- and y-axes are equal, such an effective medium has its refractive index related to the spacing by

$$n = \frac{\lambda_0}{2\pi b} \cos^{-1}\left[\cos\frac{2\pi b}{\lambda_0} + \frac{\lambda_0 \sin(2\pi b/\lambda_0)}{2b\ln(b/2\pi r)}\right] \tag{1}$$

Hence, one may realise an unnaturally low refractive index $0 \leq n \leq 1$ by arranging conductive rods at appropriate separation if $r \ll \lambda_0$ and $r < b$.

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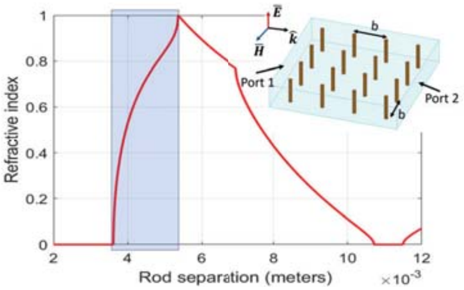

Fig. 1: Forming an effective artificial dielectric medium by arranging equispaced conductive rods. The plot relates n to spacing b at $f = 28GHz$ and $r = 0.25mm$. The shaded portion has real $n < 1$ at $b < \lambda_0/2$. $\vec{E}$, $\vec{H}$ and $\hat{k}$ are the E-field, H-field and wave propagation direction respectively. The E-field is polarized along the direction of the rods. ε_r, μ_r and n can be extracted using the S-parameters.

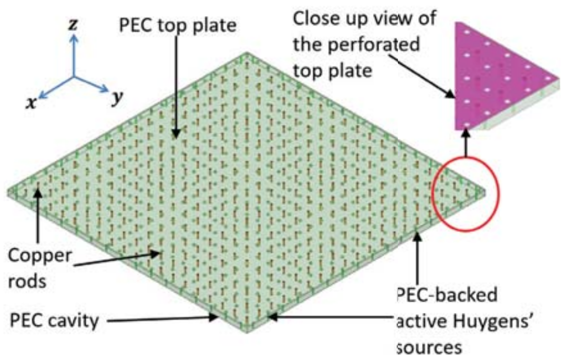

Fig. 2: The $8\lambda\times 8\lambda$ simulation model at 28GHz with Huygens' sources arranged around the box perimeter at half wavelength apart. The equispaced brown copper rods constitute the artificial dielectric medium.

III. Forming an Enclosed Region with Active Huygens' Elements

In our previous works [9], [12], [13], we have explored the promise of discretizing surfaces with active Huygens' sources. We herein give a very brief overview. The active Huygens source favoured is the PEC-backed current-carrying strip that constitute both electric and magnetic dipoles depending on the current propagation direction. Arranging these active sources at appropriate separations (usually less than $\lambda/2$) forms an electromagnetically penetrable boundary separating the enclosed region from the outer free space. Upon setting the outer field to zero, cavity wave $\{\vec{E}_{cav}, \vec{H}_{cav}\}$ is related to the electric and magnetic surface currents on the boundary by $\vec{J}_s = -\hat{n}\times\vec{H}_{cav}$ and $\vec{M}_s = \hat{n}\times\vec{E}_{cav}$. Thereafter, we impress necessary complex excitation currents on the peripheral current strips to synthesize a plane wave $\{\vec{E}_{cav}, \vec{H}_{cav}\}$ according to

$$I = j\frac{sM_s}{\omega\mu_0 w} \tag{2}$$

where $\{\vec{E}_{cav}, \vec{H}_{cav}\}$ is defined by the plane wave equation, $k = 2\pi n/\lambda_0$ is the wavenumber and $r(x,y) = \sqrt{x^2+y^2}$ denotes the source locations on the x-y plane. Also, s is the separation between Huygens' sources, w is the width of the current filament and ω is the angular frequency. The wave propagation direction inside the cavity can be set by the component of $\vec{k}$ in x and y axes according to

$$\vec{k} = k_0 n\cos\phi\hat{\mathbf{x}} + k_0 n\sin\phi\hat{\mathbf{y}} \tag{3}$$

where ϕ is taken with respect to the x axis.

Next, We couple the synthesized plane wave to directive radiation. This requires matching the propagating cavity wave's wavenumber to the radiated wave's horizontal spatial frequency. Hence the refractive index of the enclosed region is $n = \cos\theta$ where θ is the elevation angle of the radiated wave. Hence the enclosed medium may have an index $0 \le n \le 1$ for $0^\circ \le \theta \le 90^\circ$. We radiate to the upper half plane by perforating the upper metallic plate. Using (1), we formulate such a medium of desired refractive index.

IV. Simulation Results

Here we present our simulation results. We consider a sizeable $8\lambda\times 8\lambda$ size aperture targeted at a mm-wave frequency of 28GHz. We arrange the simplified PEC-backed active Huygens' sources at $\lambda/2$ separation on the four sides, resulting in 64 active Huygens' sources along the box periphery. For the same aperture size, a patch array would require 256 radiating elements and a corresponding number of phase shifters. The conducting filament of the Huygens' source is placed at $\lambda/40$ from the PEC backing. The top and bottom of this enclosure is shorted by PEC plates to a height of $\lambda/6$. We then make subwavelength perforations (0.5mm radius arranged in a regular pattern with 3.7mm center-to-center separation) on the top plate. We couple the cavity wave propagating at an angle $\phi = 0^\circ$ to radiation at an elevation angle $\theta = 45^\circ$. From Section III, we will have to fill the region by an artificial dielectric of index $n = \cos\theta$. To achieve this, we adopt the rodded dielectric medium of Section II. For the conducting rods, we use thin copper wires with radius $r = 0.25mm$ aligned along the z-axis. Using (1), we calculate the required spacing between these copper wire strands as $b \approx 4.4mm$. We achieve azimuth beam steering by varying the cavity wave propagation direction. This we do by impressing necessary excitation currents for each constitutive active Huygens' element as calculated from (2) into which the desired propagation direction has been incorporated.

The simulation model is shown in Fig. 2. We perform full wave simulation using Ansys HFSS at 28GHz. Fig. 3 (a-d) shows simulated 3D radiation patterns for some azimuth directions ϕ. The results show that the device radiates at expected directions.

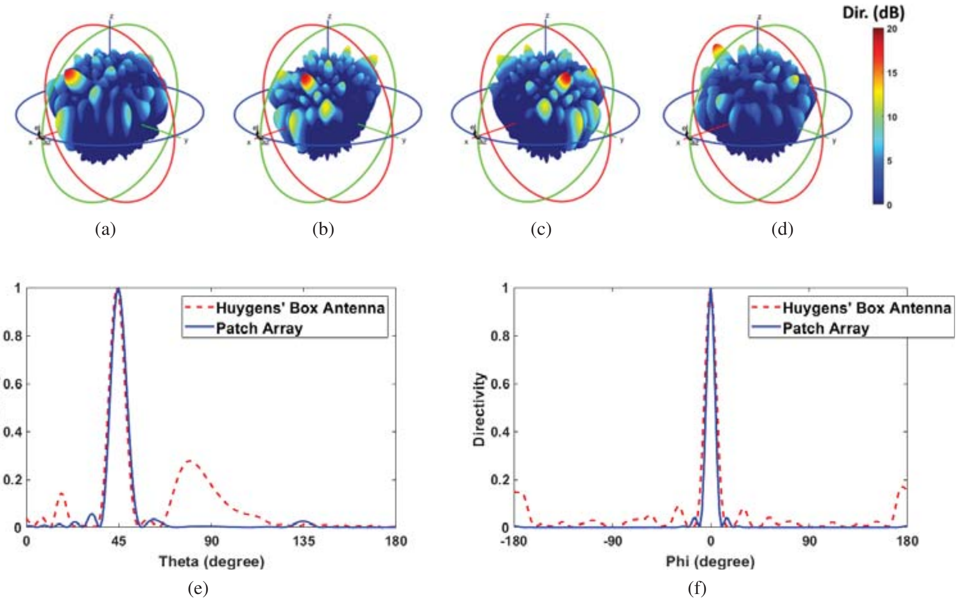

Fig. 3: Simulated radiation patterns. (a) - (d) shows radiated beams for elevation $\theta = 45°$ at $\phi = 0°$, $\phi = 22.5°$, $\phi = 67.5°$ and $\phi = 275°$ respectively. (e) 2D radiation patterns at $\phi = 0°$ plane (f) 2D radiation patterns at $\theta = 45°$ plane.

We compare the radiation pattern to that obtainable from a microstrip patch array of similar aperture size for $(\phi, \theta = 0°, 45°)$. We show in Fig. 3 (e)-(f) the 2D patterns at respective phi and theta planes. While the beamwidth is very similar, we observed higher sidelobes for the Huygens' box antenna, and the presence of spurious radiation lobes when azimuthal angle points to $\phi = 45°$. We are working on improving the mode purity in the cavity through fine-tuning the metamaterial parameters and its interaction with the cavity boundary.

V. Conclusion

In this report, we have demonstrated in simulation a metasurface-enclosed artificial dielectric medium formed from periodically arranged conducting rods in free space. The conducting rods are aligned in a direction perpendicular to the wave propagation direction, hence assuming an effective refractive index less than unity. This aids our cause to couple the cavity wave to directive radiation; we simply match the cavity wave's wavenumber to the radiated wave's horizontal spatial frequency by setting the rods separation such that $n = \cos\theta$ where θ is the desired radiation elevation. In addition, azimuth direction is exactly same as the wave's propagation direction. The device so formed radiates similarly to a conventional microstrip patch array, but very importantly with much reduced number of elements.

References

[1] R. J. Mailloux, *Phased array antenna handbook*, third edition. ed., ser. Artech House antennas and electromagnetics analysis library. Norwoood, MA: Artech House, 2018.

[2] A. H. Naqvi and S. Lim, "Review of recent phased arrays for millimeter-wave wireless communication," *Sensors*, vol. 18, no. 10, p. 3194, 2018.

[3] C. L. Holloway, E. F. Kuester, J. A. Gordon, J. O'Hara, J. Booth, and D. R. Smith, "An overview of the theory and applications of metasurfaces: The two-dimensional equivalents of metamaterials," *IEEE Antennas and Propagation Magazine*, vol. 54, no. 2, pp. 10–35, 2012.

[4] A. Li, S. Singh, and D. Sievenpiper, "Metasurfaces and their applications," *Nanophotonics*, vol. 7, no. 6, pp. 989 – 1011, 2018.

[5] M. Chen, M. Kim, A. M. Wong, and G. V. Eleftheriades, "Huygens' metasurfaces from microwaves to optics: a review," *Nanophotonics*, vol. 7, no. 6, pp. 1207–1231, 2018.

[6] M. Faenzi, G. Minatti, D. González-Ovejero, F. Caminita, E. Martini, C. Della Giovampaola, and S. Maci, "Metasurface antennas: New models, applications and realizations," *Sci. Rep.*, vol. 9, no. 1, p. 10178, Jul 2019.

[7] J. Brown, "Artificial dielectrics having refractive indices less than unity," *Proceedings of the IEE - Part IV: Institution Monographs*, vol. 100, no. 5, pp. 51–62, 1953.

[8] V. G. Veselago, "The electrodynamics of substances with simultaneously negative values of ε and μ," *Soviet Physics Uspekhi*, vol. 10, no. 4, pp. 509–514, apr 1968.

[9] K. A. Oyesina and A. M. H. Wong, "The Huygens' box antenna: Metasurface-based directive antenna beam-steering with dramatically reduced elements," in *2019 IEEE Int. Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting*, 2019, pp. 443–444.

[10] ——, "Metasurface-enabled cavity antenna: Beam steering with dramatically reduced fed elements," *IEEE Antennas and Wireless Propagation Letters*, vol. 19, no. 4, pp. 616–620, 2020.

[11] A. H. Dorrah and G. V. Eleftheriades, "Peripherally excited phased array architecture for beam steering with reduced number of active elements," *IEEE Trans. Antennas Propag.*, vol. 68, no. 3, pp. 1249–1260, 2020.

[12] A. M. H. Wong and G. V. Eleftheriades, "Active Huygens' box: Arbitrary electromagnetic wave generation with an electronically controlled metasurface," *IEEE Trans. Antennas Propag.*, pp. 1–1, 2020.

[13] K. A. Oyesina, O. Z. Aly, G. G. L. Zhou, and A. M. H. Wong, "Active Huygens' box: Arbitrary synthesis of em waves in metallic cavities," in *2019 International Applied Computational Electromagnetics Society Symposium (ACES)*, 2019, pp. 1–2.