The Huygens' Box Antenna: Metasurface-Based Directive Antenna Beam-Steering with Dramatically Reduced Elements

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***Abstract*—In this paper, we demonstrate the Huygens' box antenna. We show that we can synthesize waves in a region enclosed by an active metasurface, and that by allowing the wave synthesized in such a cavity to leak out through an aperture a highly directive antenna can be formed. We present simulation results and compare these results to those obtainable from a microstrip patch array of the same aperture size as our Huygens' box antenna. We show that similar radiation patterns can be achieved in both cases, but with the Huygens' box antenna we are able to significantly reduce the number of sources required, which also dramatically reduce the complexity and component cost for the antenna array. We envision the Huygens' box antenna will be a great cost-saving alternative to microstrip patch arrays for mm-wave regime.**

Keywords—Huygens' sources, active metasurface, metamaterial, leaky wave antennas, directive antennas, phased arrays

I. INTRODUCTION

Microstrip patch arrays have been shown to have a good number of desirable traits despite bandwidth limitation. The deployment of these arrays at mm-wave frequencies enables small-volume antenna arrays to be highly directive [1]. Despite the aforementioned advantages, a major drawback has been the very high cost associated with these arrays in the mm-wave regime as the number of patch elements, and by extension the size and complexity of power dividers and phase shifters required for excitation, increase dramatically with increase in overall array dimension. We propose in this paper a metamaterial-based cost-effective alternative. We call our innovation the Huygens' box antenna.

Refs. [2] and [3] has reported Huygens' box: through simulation and experiment, the authors demonstrated the generation of electromagnetic plane waves that travel in arbitrary directions inside a closed metallic cavity, by using an active metasurface to explicitly satisfy the electromagnetic equivalence principle. We present in this paper the application of the Huygens' box concept to developing a directional antenna. We first generate some electromagnetic waves in a region surrounded by an active metasurface. We then allow the waves to leak out in a defined manner. We develop and simulate the Huygens' box antenna model using the commercial software HFSS. Thereafter, we compare the radiation pattern of the Huygens' box antenna to that obtainable from a microstrip patch array of the same aperture size. This comparison shows that the Huygens' box antenna achieves similar radiation characteristics as the patch array, but with a dramatically reduced number of source elements. Finally, we conclude with a summary and short discussion on applications.

II. HUYGENS' BOX ANTENNA

This work advances the Huygens' box concept by allowing some of the waves in the box to radiate through a pattern of holes on the box's top plate. One can control the radiation pattern by engineering the direction and wavenumber of the cavity wave travelling within the Huygens' box. Specifically, the direction of cavity wave dictates the radiated wave's azimuthal direction (ϕ), and the wavenumber of the cavity wave determines the elevation (θ) of the emitted radiation. To achieve radiation at elevation angle θ, one can fill the Huygens' box with a metamaterial of refractive index $n = \cos\theta$, which would match the cavity wave's wavenumber to the radiated waves horizontal spatial frequency: $k_x = k_0 \cos\theta = k_0 n$. As an example, we design a Huygens' box antenna with its main beam directed at $(\theta, \phi) = (45°, 0°)$. We discuss the design in the next section.

III. DESIGN EXAMPLE

We design a Huygens' box of dimension $4\lambda \times 4\lambda$ using HFSS. We use eight active sources on each side of the box. We then calculate the necessary complex excitation weightings required to synthesize a plane wave travelling at $\phi = 0°$ inside the cavity. We also create an array of 21 by 21 holes with dimension $\lambda/40$ by $\lambda/40$ on the top plate with an inter-element separation of 0.095λ between the holes. Fig. 1 shows a diagram of the Huygens' box antenna. We attempt to couple the cavity wave through the top plate to a radiated wave at $\theta = 45°$. We achieve this using a material with refractive index $n = \cos\ 45° = 1/\sqrt{2}$ in the region enclosed by the Huygens' box. While non-trivial, refractive indices of this type can be constructed with a plethora of demonstrated metamaterial technologies [4]. We see that $k_x = k_0 \cos 45° = k_0 n$. Thus the wave travelling within the

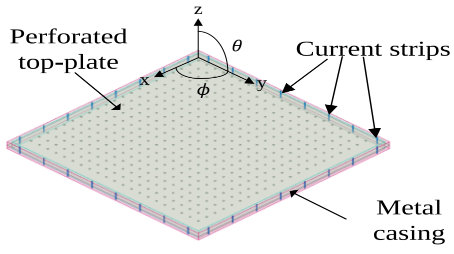


Fig. 1. The Huygens' box antenna with 32 active sources

Huygens' box cavity achieves phase matching, and hence couples to the plane wave travelling at $(\phi, \theta) = (0°, 45°)$, forming the radiation. We also consider a second possible scenario. We attempt to further reduce the number of sources by calculating the wavelength in the box according to the relation $\lambda = \lambda_0/n$ where λ_0 and λ are the wavelengths in free space and the cavity respectively and n is the refractive index of the medium. We deduce that the Nyquist sampling criterion is also satisfied using six active sources per side of the box. We perform HFSS simulations at a frequency of 1GHz. We terminate the simulation region in a perfectly matched layer absorbing boundary. Fig. 2b-c show the Huygens' boxes with the plane wave generated. We also show polar plots of the radiation pattern for the two cases in Fig. 2e-f.

IV. VALIDATION WITH MICROSTRIP PATCH ARRAY

We compare our Huygens' box antennas against a patch antenna phased array of the same aperture dimension. To avoid grating lobes the inter-element spacing between the elements should not exceed half wavelength. We hence design an array of 8 x 8 microstrip patches on a Duroid RF-60 substrate ($\varepsilon_r = 6.15$) backed by a ground plane. The center-to-center inter-element spacing is 0.4λ. We present a diagram of this in Fig. 2a. We calculate, then apply, the phase shift required for each patch element to steer the main beam to the direction of $\theta = 45°$, through the beam steering relation $\alpha = -k_0 d \cos\theta$. The patch array is thus linearly phased to achieve radiation at $(\phi, \theta) = (0°, 45°)$. We perform simulation at 1GHz using Ansys HFSS. Fig. 2d shows a polar plot of its radiation pattern.

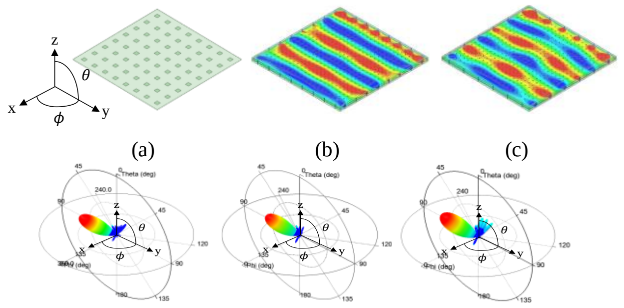
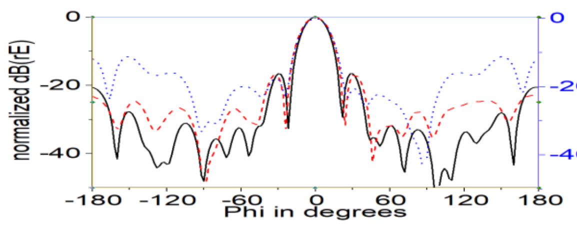
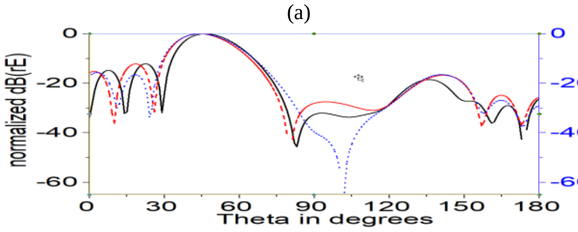

(a) (b) (c) (d) (e) (f)

Fig. 2. (a) 8 x 8 microstrip patch array (b-c) Huygens' Box Antenna with 32 sources and 24 sources respectively showing generated waves (d-f) radiation pattern of the microstrip patch array, Huygens' Box



(a)



(b)

Fig. 3. Radiation Patterns: (a) $\phi = 0°$ plane (b) $\theta = 45°$ plane. Solid black line represents the patch array, red dashed line represents the Huygens' box antenna with 32 sources, blue dotted lines dashed line represents the Huygens' box antenna with 24 sources.

Fig. 2d-f compares the radiation patterns of the Huygens' box antennas to that of a microstrip patch array antenna of the same aperture size. We notice some distortions in the waveform as we attempt to further reduce the number of sources from 32 to 24. We show this more clearly with the 2D graphs of Fig. 3. We also observe that there is appreciable backside radiation when we reduce the number of sources to 24, even though we expect that the Nyquist criterion is satisfied based on the provisions of our design. One focus of our subsequent work will be to mitigate this anomaly. In Table 1, we summarize some key features of the radiated waves. In both cases, the Huygens' box antennas we simulated show slightly wider beamwidths and lower first sidelobe levels, both of which are very comparable to the patch array. We can submit therefore the Huygens' box antenna as a cost-saving alternative to patch arrays in the millimeter wave regime that requires large array sizes.

TABLE I. SUMMARY OF RESULTS

	Patch Array	HBA (32 sources)	HBA (24 sources)
3dB Beamwidth (ϕ-dir.)	17.89°	20.03°	20.40°
3dB Beamwidth (θ-dir.)	18.33°	19.40°	20.27°
Main / First sidelobe level (ϕ)	16.7dB	16.8dB	17.2dB
Main / First sidelobe level (θ)	12.1dB	12.2dB	16.5dB

V. CONCLUSION

In this paper, we have demonstrated Huygens' box antennas that produce highly directive radiation, comparable to microstrip patch arrays of similar aperture sizes. An obvious advantage of this new device is a large reduction in the number of sources required. We confirmed that for a box having a dimension of $4\lambda \times 4\lambda$ at 1GHz, we could reduce the number of active sources from 64 to 24 to get a directional pattern of similar beamwidth. A much more dramatic reduction ratio will result for larger antenna arrays, which shall find important applications at mm-wave frequencies. It is pertinent to state now that the Huygens' box is not limited to radiation at $(\phi, \theta) = (0°, 45°)$. One can steer the emitted radiation to a direction (ϕ, θ) of choice by changing the direction of cavity wave travel and the wavenumber of the cavity wave respectively. Hence the Huygens' box antenna shows great promise as a cost-effective alternative to phased arrays in a wide range of mm-wave applications in communication, imaging, autonomous vehicular technology and the internet of things.

REFERENCES

[1] A. H. Naqvi and S. Lim, "Review of Recent Phased Arrays for Millimeter-Wave Wireless Communication", Sensors, Sept 2018 .

[2] A. M. H. Wong and G. V. Eleftheriades, "Active Huygens' metasurfaces for RF waveform synthesis in a cavity", IEEE Mediterranean Electrotechnical Conf. (MELECON), Apr. 2016.

[3] A. M. H. Wong and G. V. Eleftheriades, "Active Huygens' Box: Metasurface-Enabled Arbitrary Electromagnetic Wave Generation Inside a Cavity" IEEE International Symposium on Antennas and Propagation (AP-S), Boston, USA, Jul. 2018.

[4] T. J. Cui, D. R. Smith, and R. Liu, Metamaterials: Theory, Design, and Applications, Boston, MA: Springer US, 2010, pp.1-17.