A Simple Active Huygens Source for Studying Waveform Synthesis with Huygens Metasurfaces and Antenna Arrays

Alex M. H. Wong, *Member, IEEE*, George V. Eleftheriades*, *Fellow, IEEE*
Edward Rogers S. Sr. Department of Electrical and Computer Engineering
University of Toronto
Toronto, Ontario, Canada
*gelefth@ece.utoronto.ca, alex.wong@mail.utoronto.ca

***Abstract*— We have developed a simple active Huygens source consisting of a current strip and a current loop, which is further reduced to two current strips in a 2D environment. We derived the necessary current excitations which would produce a perfect Huygens source, and studied unidirectional plane-wave formation using an infinite array of these sources. The proposed Huygens source forms a simple antenna element for synthesizing an active Huygens metasurface or antenna array. Furthermore, conclusions drawn from studies, made convenient with these elements, can aid the design of active and passive Huygens metasurfaces.**

I. Introduction

Metasurfaces of various kinds have proliferated research literature in recent years [1]-[3]. In particular, Huygens metasurfaces provide magnetic as well as electric response to an incoming radiation, and thereby achieve near-complete control on an electromagnetic wavefront through the use of a single (though sometimes multi-layered) surface. While current developments [2]-[3] have but tapped the surface of what is achievable with Huygens metasurfaces, it is worth to investigate what one can achieve when one combines an arbitrary superposition of co-located electric and magnetic dipoles, as is present in a Huygens source. In this work, we report a study in this direction using a simple active Huygens source. We will first introduce the active Huygens source (AHS) and demonstrate current excitations which will lead to Huygens radiation, then we will use an infinite array of these elements to study plane-wave generation using Huygens sources.

II. An Active Huygens Source

The Huygens source which we would like to consider is shown in Fig. 1a; it consists of a central current strip, and four metal strips to the side which form a square loop. The source as designed is single-layered and of sub-wavelength dimension, which should lend to easy fabrication. Nevertheless, we leave for a later study the topic of practical implementation; instead we concentrate on numerical explorations of a theoretical nature. We can excite an electric dipole by driving a current through the central current strip; similarly we can excite a magnetic dipole by driving currents around the loop formed by

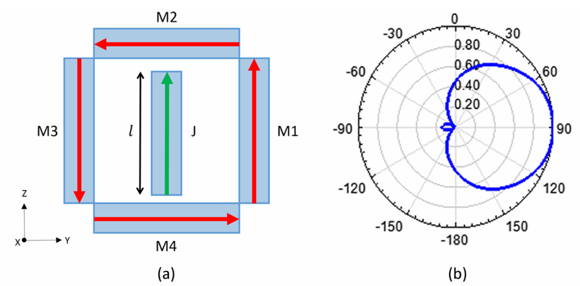

Fig. 1 An active Huygens surface (AHS) in free space. (a) A diagram showing metallic strips from which electric and magnetic dipoles are excited by driving currents through the green and red arrows, respectively. (b) The resultant antenna pattern when the electric and magnetic dipoles are excited with a ratio given in (1). Simulations are performed at a frequency of 3 GHz, with $l = 5$ mm and $S = 36$ mm^2.

the four outer strips. Further, we can simultaneously excite both dipoles in equal power and in phase by choosing

$$\frac{I_e}{I_m} = \frac{2\pi S}{\lambda l} e^{-j\frac{\pi}{2}}. \tag{1}$$

where I_e and I_m are current phasors on the central and outer strips respectively, λ represents the wavelength, S represents the area enclosed by the loop and l represents the length of the central metallic strip. This results in a Huygens source, for which the corresponding antenna pattern is shown in Fig. 1b. We make two observations in regard to this result. Firstly, the currents on the central strip and the outer loop are phase-shifted by $\pi/2$. This is because a loop current excites a magnetic dipole which is $\pi/2$-phase delayed itself. Secondly, one can simplify the Huygens source by removing the central metallic strip, and superimposing the current I_e onto the two vertical metallic strips M1 and M3. We shall make this simplification in the following analysis.

III. Plane-Wave Formation with an Infinite Array of Active Huygens Sources

We adopt the active Huygens source for 2D analysis by placing the source within a parallel-plate waveguide (PPW) environment, as we show in Fig. 2a. Field invariance in the z-direction is guaranteed by the sub-wavelength waveguide height of h=λ/20. In this environment, non-zero field components are (H_x, H_y, E_z), and field propagation is restricted to the xy-plane. We place in the aforementioned AHS without the central metallic strip. Further, we short out the top and bottom strips using the PPW. The structure hence becomes two parallel current strips which should afford even easier implementation. With a single AHS in the PPW, terminated by radiation boundaries, we excite the current strips with $J_a = I_m + 0.5I_e; J_b = -I_m + 0.5I_e$. This reproduces the Huygens source in Fig. 2b and verifies the validity of the proposed AHS in the present 2D environment.

We now turn our attention to the generation of plane waves. We simulate an infinite array of AHSs separated half-wavelength apart. To achieve this we terminate an array of five AHS elements with a master-slave boundary in the +x and –x directions, and with perfect matching layers in the ±y-directions. With the five AHSs excited in uniform phase, a unidirectional plane wave is synthesized as shown in Fig. 2c.

We then synthesize unidirectional tilted plane waves in our PPW environment, which is easily done by applying a linear phase progression to adjacent elements of the AHS array. Fig. 2d, for example, shows a plane wave propagating at an angle of 23.6° from broadside (y-axis). However, Fig. 2e shows that at a larger angle (53.1°) with respect to normal, the Huygens antenna array generates appreciable back radiation. This artefact can be understood by reconsidering plane-wave synthesis as a boundary-value problem, through which we conclude that, to properly synthesize the tangential electromagnetic waves at the source plane, the electric dipole of the AHS needs to be reduced by a multiplicative factor $\cos\theta$. When we adjust the currents J_a and J_b to account for this factor, the synthesized waveform is shown in Fig. 2f. Clearly, unidirectional propagation is restored notwithstanding the large propagation angle with respect to broadside.

We note that since perfect Huygens sources were used for this study, the emergence of radiation in the undesired direction is not due to any insufficiency of the Huygens source itself. Rather, this study shows that a total control of wavefront transmission, reflection and/or radiation requires not only that each array element behaves like a Huygens source (and hence has the most unidirectional behavior); instead, one must individually control the excitation strength for both the electric and magnetic dipoles. Our proposed AHS provides this needed degree of control. Nonetheless, a traditional Huygens antenna array is sufficient for producing unidirectional beams at small propagation angles from Broadside.

IV. Conclusion

In this work we have introduced a simple active Huygens source, potentially amenable for use in Huygens antenna arrays and metasurfaces, in 3D and 2D environments. We have numerically demonstrated Huygens source operation with the proposed AHS, and used it to study the synthesis of unidirectional plane waves by an infinite AHS array. From our study we conclude that unique control on the electric and magnetic dipole strengths proves useful to eliminate back radiation when synthesizing plane waves propagating at large angles off broadside. We envision further study with AHS arrays will provide much insight and help for designing and implementing passive and/or active Huygens metasurface and antenna arrays for a multitude of applications including super-resolution imaging [4] and active cloaking [5].

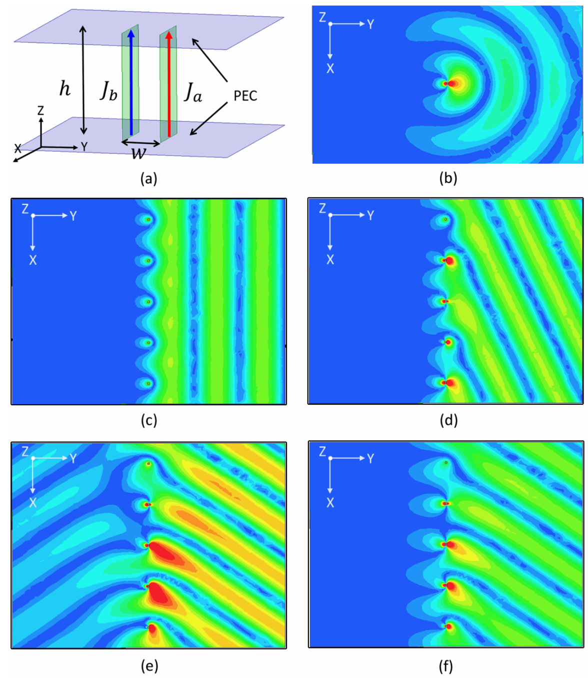

Fig. 2. An infinite AHS array in a 2D environment. (a) A diagram of the AHS within the parallel plate waveguide. $h = 5$ mm, $w = 1$ mm and simulations are performed at 3 GHz. (b) $|\boldsymbol{E}|$ (at a reference phase) for a single AHS. (c) $|\boldsymbol{E}|$ for an AHS array radiating at broadside. (d) $|\boldsymbol{E}|$ for an AHS array radiating at 23.6° from broadside. (e) $|\boldsymbol{E}|$ for an AHS array radiating at 53.1° from broadside. An appreciable backward-propagating component is also excited. (f) The backward radiating component is eliminated by reducing the weight of the electric dipole by a multiplicative factor $\cos\theta = 0.6$.

References

[1] C. L. Holloway, M. A. Mohamed, E. F. Kuester, and A. Dienstfrey, "Reflection and transmission properties of a metafilm: with an application to a controllable surface composed of resonante particles," IEEE Trans. Electromagn. Compat., vol. 47, no. 4, pp. 853–865, Nov 2005.

[2] C. Pfeiffer, and A. Grbic, "Metamaterial Huygens' surfaces: tailoring wave fronts with reflectionless sheets," Phys. Rev. Lett., vol. 110, 197401, May 2013.

[3] M. Kim, A. M. H. Wong, and G. V. Elefteriades, "Optical Huygens' metasurfaces with independent control of the magnitude and phase of the local reflection coefficients," Phys. Rev. X, vol. 4, 041042, Dec. 2014.

[4] A. M. H. Wong, and G. V. Elefteriades, "Sub-wavelength focusing at the multi-wavelength range using superoscillations: an experimental demonstration," IEEE Trans. Antennas Propag., vol. 59, no. 12, pp. 4766–4776, Dec. 2011.

[5] M. Selvanayagam, and G. V. Eleftheriades, "Experimental demonstration of active electromagnetic cloaking," Phys. Rev. X., vol. 3, 041011, Nov. 2013.