Metamaterial-inspired Near-Field Resonant Parasitic Dipole Antennas on High Permittivity Dielectrics

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***Abstract*— It is well-known that if a (horizontal) electric dipole antenna is placed on the interface between a high permittivity dielectric and air, it will radiate a majority of its power into the dielectric rather than into the air region. This basic physics effect is a significant roadblock to achieving efficient on-body and on-chip antennas. The future 5G outlook includes numerous Internet-of-Things (IoT) devices that involve both types of antenna systems. It will be described herein and in my presentation how one can use metamaterial-inspired Huygens dipole antennas to achieve systems that radiate primarily into the air region rather than into the dielectric.**

***Index Terms*—Antenna theory, electrically small antennas, high permittivity dielectrics, on-body antennas, on-chip antennas.**

I. INTRODUCTION

A dipole antenna radiating in the presence of a material half-space has been the subject of extensive theoretical investigations for over a century, beginning with the famous results of Sommerfeld in 1909 [1]. It was demonstrated in [2] that the field radiated by a horizontal infinitesimal electric dipole located on the interface between air and a dielectric half-space would be directed primarily into the dielectric region. Related results for an infinitesimal magnetic dipole radiator were considered in [3].

Fifth generation (5G) wireless systems promise ubiquitous interconnectivity between devices. The associated Internet-of-Things (IoT) applications include multitudes of on-body sensors and communication devices. Moreover, the desire for them to be very compact and lightweight is driving their enabling technologies to be wirelessly powered. However, batteryless devices require efficient wireless power transfer (WPT) systems, i.e., rectennas. Because the human body is basically a very high permittivity region, this electromagnetic ecosystem further underscores the need for antenna systems that reside on the body but communicate efficiently off of it through the air. Similarly, on-chip antennas (OCAs) are expected to facilitate many of those IoT applications as well as many others including the systems associated with autonomous vehicles. The latter will require massive networks facilitating wireless device-to-device (D2D) communications. Typical OCAs are basically radiators residing on high permittivity silicon. Since they facilitate the communications to other off-chip systems, they need to radiate very efficiently into the air.

Unfortunately, as demonstrated in [2], an efficient dipole antenna radiating in free space is transformed into an inefficient radiator when placed on a high permittivity substrate because it will radiate primarily into it. This issue has become an intrinsic bottleneck for system-on-chip (SoC) applications [4]−[6]. The need for improved radiation efficiencies has led to a variety of attempts to overcome this problem for those systems. These include, for instance, impedance matched silicon lenses and even artificial magnetic conductors (AMCs) in the multilayered stack delineating the OCA [7].

It will be described herein and in my presentation how Huygens dipole antennas (HDAs) offer a solution to this fundamental interface problem. A Huygens source is a balanced pair of orthogonal electric and magnetic radiators that produce a broadside cardioid directivity pattern. A variety of HDAs have been successfully realized recently [8-10]. They are based on balanced combinations of the metamaterial-inspired electric (Egyptian axe dipole - EAD) and magnetic (capacitively loaded loop – CLL) near field resonant parasitic (NFRP) elements. These NFRP HDAs provide a potential practical resolution to realizing efficient radiators residing on high permittivity dielectrics.

II. 1D HUYGENS SOURCE

Consider first the one-dimensional (1D) configuration shown in Fig. 1. Orthogonal infinite electric $\left(\vec{J}_s = J_0\,\delta(z)\,\hat{x}\right)$ and magnetic ($\vec{K}_s = K_0\,\delta(z)\,\hat{y}$) time harmonic current sheets are sandwiched between two semi-infinite media. The total fields in both regions follow immediately from the superposition of the two independent 1D solutions associated with each source.

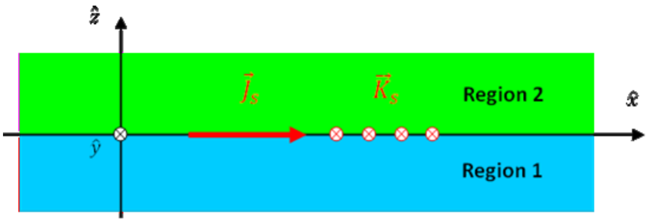


Fig. 1 1D canonical problem: Orthogonal infinite electric and magnetic current sheets lie on the interface between two semi-infinite homogeneous regions.

Let the wave number and wave impedances in each region be, respectively, $k_n = \omega\sqrt{\varepsilon_n \mu_n}$ and $\eta_n = \sqrt{\mu_n / \varepsilon_n}$, for $n = 1{,}2$. One finds that if the electric and magnetic currents are selected to be balanced as: $K_0 = \eta_2 J_0$, then the total fields become Huygens fields pointing strictly into Region 2, i.e.,

$$\begin{aligned} \vec{E}_{\omega,total\,2} &= -\eta_2 J_0\, e^{-jk_2 z}\ \hat{x} \qquad & \vec{E}_{\omega,total\,1} &= 0 \\ \vec{\boldsymbol{H}}_{\omega,total\,2} &= -J_0\, e^{-jk_2 z}\ \hat{y} \qquad & \vec{H}_{\omega,total\,1} &= 0 \end{aligned} \qquad \textbf{(1)}$$

Consequently, the total average radiated power density in both regions is:

$$< \vec{S}_{\omega,e2} > = +\frac{1}{2}\ \eta_2\ |J_0|^2\ \hat{z} \qquad < \vec{S}_{\omega,e1} > = 0 \qquad (2)$$

Therefore, with the electric and magnetic current sources balanced with respect to the impedance of Region 2, one recovers the plane wave fields that would exist if both regions were free space, i.e., the power density associated with a plane wave propagating in the +z-direction. On the other hand, the balanced condition choice: $K_0 = -\eta_1 J_0$ leads to the opposite effect, i.e., zero fields are found in Region 2 and the emitted plane wave is propagating solely into Region1.

III. 3D IDEAL HUYGENS DIPOLE

To confirm that the 1D result would hold true in three dimensions (3D), the configuration shown in Fig. 2 was considered and evaluated numerically. All of the simulated results reported herein were obtained with the ANSYS Electromagnetics Suite v17.0 using realistic material properties.

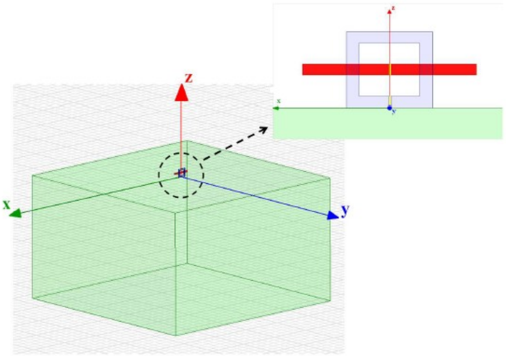


Fig. 2 Numerically treated 3D problem: An electrically small Huygens dipole array is centered on the high permittivity block.

Electrically small electric dipole and magnetic dipole antennas are located on the interface between a high permittivity, finite-sized dielectric block and air. This dielectric block is selected to have bulk parameters the same as the Rogers RT/Duroid 6010 laminate material with ε_r = 10.2, μ_r = 1.0, and tan δ = 0.0023. The size of the block is large, 0.5 λ_0 × 0.5 λ_0 × 0.3 λ_0. The electrical dipole is center-fed with a lumped source and is electrically small; its length is λ_0 / 25. The magnetic dipole is a square loop with side length λ_0 / 50 and is fed with a lumped source centered on the interface side of the loop. The relative positions of these dipoles are depicted in the inset of Fig. 2. The impedance of the lumped sources for both elements was specified for nearly complete matching at λ_0. This electric and magnetic dipole pair radiates as Huygens source.

The numerically predicted two-dimensional (2D) directivity patterns in the two principle planes for this two-element, Huygens dipole array in free space and its optimized version on the dielectric block are shown in Fig. 3. Their maxima are pointed in the broadside direction along the +z-axis, normal to the interface of the block. There is little back-radiated field in either case. The maximum directivity in the free space case is D_{max} = 4.38 dBi (2.74). This value is near to the maximum directivity, 4.77 dBi (3.0), for an infinitesimal HDA in free space. The directivity in the back direction is −13.62 dBi (0.043). The cardioid pattern characteristic of a Huygens source is clear. The front-to-back-ratio is FTBR = 63.1 (18.0 dB).

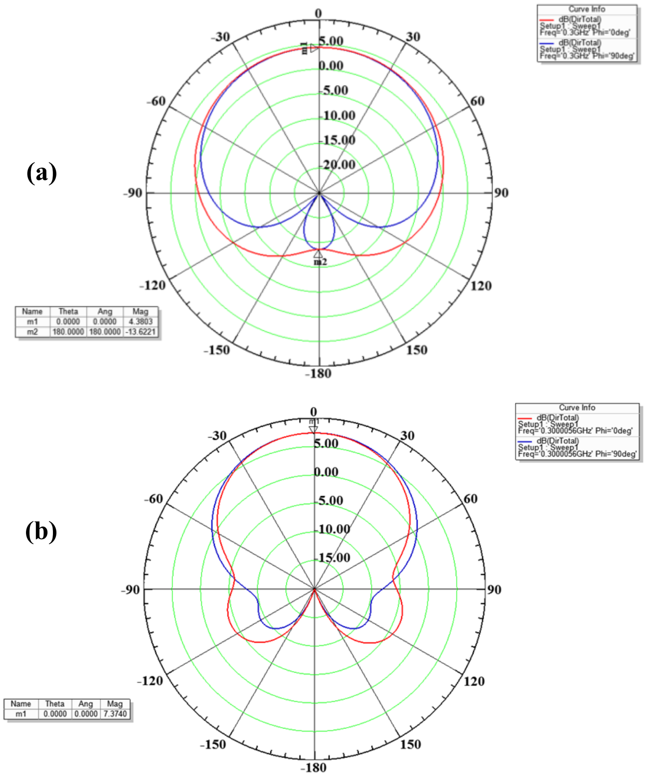


Fig. 3 Simulated 2D directivity patterns for the electrically small Huygens dipole array. (a) Free space. (b) Centered on the high permittivity block

On the other hand, the maximum directivity in the block case is D_{max} = 7.37 dBi (4.92) along the +z-axis. The directivity along the –z-axis is -31.77 dBi (6.65×10^{-4}). This gives the FTBR = 39.14 dB (8210.3). The maximum directivity is notably larger than that of the Huygens dipole array in free space. The Huygens array induces electric and magnetic polarization currents in the dielectric that reinforce the fields radiated into the air region. These 3D results for the electrically small, ideal Huygens dipole array confirm the hypothesis that such a system could overcome the issues typically faced by antennas residing on high permittivity dielectrics.

IV. REALISTIC HUYGENS DIPOLE SYSTEM

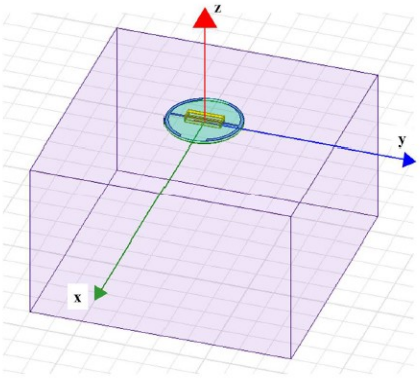
To investigate further if a realistic antenna could be developed with nearly complete impedance matching to its source, the coax-fed HDA developed in [8] was modified for the configuration shown in Fig. 4(a). The dielectric block has the same size as in the ideal case. The coax is embedded into the dielectric; it has a 50 Ω impedance. The bottom of the HDA rests on the interface. The overall size of the HDA is $ka = 0.46$; it is electrically small and small in comparison to the top face of the block. Aside from small adjustments to the length of the driven dipole element and the values of the capacitors embedded in the CLL elements and the value of the inductor embedded in the EAD element, the main adjustment in the original design was the need to have the EAD element be significantly closer to the driven dipole element. Thus, the EAD phase center is offset below the CLL's phase center to compensate for the presence of the electric polarization currents induced in the dielectric.

As shown in Fig. 4(b), the $|S_{11}|$ value at the resonance frequency was -21.10 dB, which signifies a very good impedance match to the 50 Ω source. Moreover, the radiation efficiency at the resonance frequency is 81.75%. The simulated 2D directivity patterns for the block case are shown in Fig. 4(c). The maximum value, 6.22 dBi, is along the +z-axis; the value in the opposite direction is −15.87 dBi, giving the FTBR = 22.09 dB (162.16).

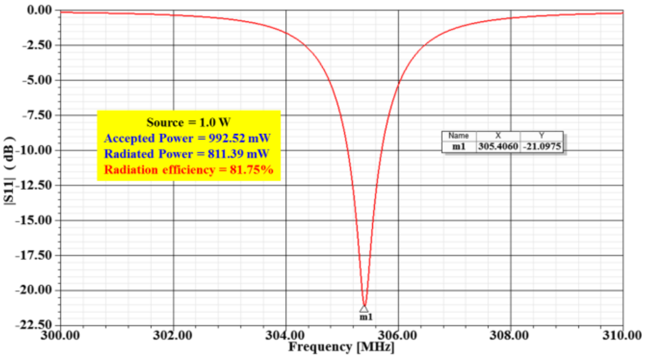
V. CONCLUSIONS

It was conclusively demonstrated that Huygens dipole antennas provide an approach to dealing with the critical physics issues associated with antennas residing on high permittivity dielectrics. A 1D solution in which the amplitudes of the electric and magnetic current sheets were properly balanced illustrated that such a Huygens source would radiate all of its power into the air region rather than into the dielectric. An ideal two-element dipole array was then simulated numerically to confirm that the positive 1D Huygens results were not impacted negatively by going from 1D to 3D. Finally, a custom-designed coax-fed HDA that was matched to its source and that radiated efficiently into the air region was briefly described. Its performance characteristics demonstrate that Huygens-based antenna systems would be very effective candidates for on-body and on-chip antenna systems associated with 5G wireless applications and related IoT devices. Additional ideal and practical antenna results will be discussed in my presentation to further support the outcomes reported herein.

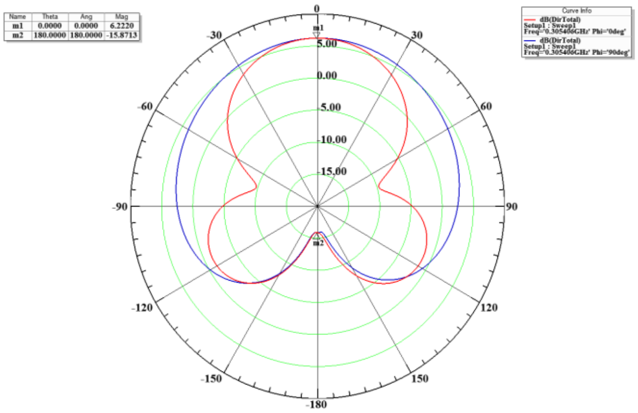
Further and much more expansive details of this work can be found in [11] which was submitted, accepted and published during the EuCAP paper review process.



(a)



(b)



(c)

Fig. 4 Numerically treated 3D problem: An electrically small coax-fed HDA is centered on the high permittivity block. (a) Configuration. (b) $|S_{11}|$ values as a function of the source frequency. (c) Simulated 2D directivity patterns at the resonance frequency 305.406 MHz.

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