Design of a Printed Metamaterial-Inspired Electrically Small Huygens Source Antenna for Cognitive Radio Applications

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***Abstract* –** Metamaterial-inspired electric- and magnetic-based near-field resonant parasitic (NFRP) elements are electrically coupled to a coaxial-fed printed monopole to realize an electrically small, ka = 0.49 (λ_0/9.41 × λ_0/14.11 × λ_0/104.18) Huygens source antenna that operates at the GSM1800 frequency. The electric NFRP element is a meander patch; the magnetic element is a Capacitively Loaded Loop (CLL). The individual electric- and magnetic-based antennas were studied numerically to ensure they had overlapping frequency behavior near the GSM frequency 1.8 GHz; high radiation efficiency; and very good matching to their 50 Ω sources. They were combined together and retuned to create a three metal – two dielectric layer Huygens source antenna. A 20 nH inductor was inserted between the driven monopole and the SMA connector in order to enhance the input impedance matching. A prototype of this antenna was fabricated and experimentally characterized. The measurements confirmed the Huygens source nature of the prototype antenna.

***Index Terms* –** CLL-NFRP element, electric NFRP element, ESAs, Huygens source, metamaterial-inspired antenna.

I. INTRODUCTION

Electrically small antennas (ESAs) continue generate increasing interest from both academic and industrial communities. Tremendous amount of research has been conducted to enhance and exploit various ESA properties, including high efficiency, stable radiation properties, ease of fabrication and integration, low cost, compactness and low-profile. These performance characteristics are attractive features typically desired in modern wireless communication systems, RFID tags, biomedical monitoring sensors, and other internet of things devices [1-6].

One of proposed approach to meet several these desirable aspects is the design of electrically small, highly efficient, Huygens source antennas [7-11]. Huygens source antennas are attractive for wireless communication and other mobile platforms because a significant amount of power is radiated away from their source into a prescribed hemisphere. For instance, such an antenna in a mobile phone could be designed to radiate away from the head, significantly reducing the specific absorption rate (SAR), leading to fewer health concerns and less power consumption (hence, more battery life). Theoretically, a Huygens source is a particular combination of electric and magnetic dipole antennas. It has been demonstrated that a realizable single Huygens source can achieve a directivity near to its theoretical limit of 4.77 dB [7]. This antenna was constructed as a particular combination of electrically small electric- and magnetic-near-field resonant parasitic (NFRP) elements coupled to a driven dipole antenna. It radiated its maximum directivity in the plane containing the NFRP elements and away from its feed point. Another recent design radiates its maximum directivity in the direction broadside to the plane containing the NFRP and driven elements [12]. In both cases, a single input port was employed, thus avoiding difficulties associated with multiple feeds and matching multiple input impedances.

In this letter, an electrically small Huygens source antenna based on a combination of metamaterial-inspired electric- and magnetic-NFRP elements is reported that radiates its maximum directivity in the plane of those NFRP elements, but orthogonal to the feed direction. Antennas associated with the electrically small electric- and magnetic-NFRP elements and a coax-fed printed monopole antenna were designed and numerically studied individually to be efficient, to be well matched to a 50 Ω source, and to have an overlapping frequency behavior around the GSM1800 frequency. Then, by coupling them to the same driven monopole and adjusting their relative responses to be equal, a three metal – two dielectric layered Huygens source antenna

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having high efficiency, high directivity, and large bandwidth was obtained. A prototype of this Huygens source antenna was fabricated and tested. The measured results were in good agreement with their simulated values.

All of the design simulations were performed with the ANSYS-ANSOFT High Frequency Structure Simulator, HFSS-V15. They all took into account the realistic material properties of the copper and dielectric components. The SMA connector was included in all of the simulations for higher accuracy between the simulated and the measured results.

II. ELECTRICALLY SMALL NRFP DIPOLE ANTENNAS

A printed monopole antenna of length L_M and width W_M is introduced to act as the driven element for both the magnetic and electric NFRP antennas. It is fed by a 50Ω SMA connector. Each antenna, i.e., the monopole and a NFRP element, was printed on a W×L Rogers Duroid^{TM} 5880 substrate of thickness 0.7874 mm, relative permittivity $\varepsilon_r = 2.2$, relative permeability $\mu_r = 1.0$ and loss tangent tan $\phi = 0.0009$. The copper thickness is 0.017 mm.

A. Magnetic NFRP antenna

The metamaterial-inspired capacitively loaded loop (CLL)- based NFRP antenna introduced previously [13-16] was used as the core design to achieve the requisite magnetic dipole antenna. The CLL NFRP element and the ground strip line were printed in the top side of the Duroid substrate. The driven monopole and the extra-strip line of dimensions L_S and W_S (to achieve the maximum directivity in the horizontal direction [13]) were printed on its back side as exhibited in Fig. 1. The optimized design parameters of this antenna are summarized in Table 1. This CLL based NFRP antenna is electrically small with ka=0.49 (where "k=2π/λ" is the free space wavenumber, and "a" is the radius of the smallest sphere circumscribing the maximum dimensions of the antenna).

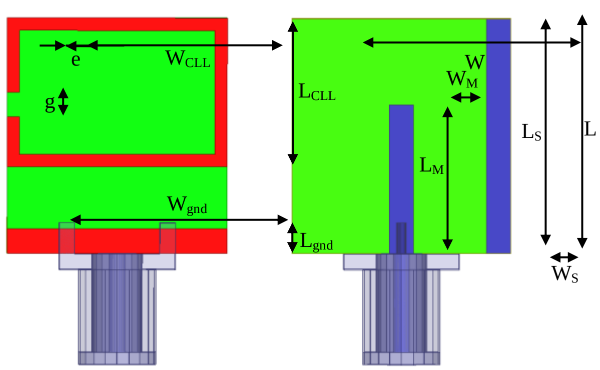


Fig. 1. The magnetic NFRP antenna geometry: (a) front side and (b) back views.

Table 1: Magnetic NFRP antenna parameters

Parameter	Value (mm)	Parameter	Value (mm)
W	18	**W_{CLL}**	18
L	19	**L_{CLL}**	12
W_M	2	**W_{gnd}**	18
L_M	12	**L_{gnd}**	2
W_S	2	**e**	1
L_S	19	**g**	2

The proposed structure dimensions were rescaled from those in [13, 14] so that the antenna would radiate at the GSM1800 frequency. As illustrated in Fig. 2, nearly complete input impedance matching $|S_{11}|_{min}$ = -21.35 dB was achieved at 1.815 GHz. The simulated total directivity pattern at this resonance frequency is shown in Fig. 3 and verifies that the antenna radiates as a magnetic dipole oriented, along the y-axis with its maximum directivity orthogonal to the feed structure. The simulated performance characteristics are: front-to-back ratio: FTBR=1.0 (0dB); accepted power: AP=0.992W; total radiated power: RP=0.754W, giving the radiation efficiency RE=76%; the maximum directivity: D_{max} = 2.22dB; and the peak realized gain RG_{max}=1dB. The 3dB bandwidth is 27 MHz.

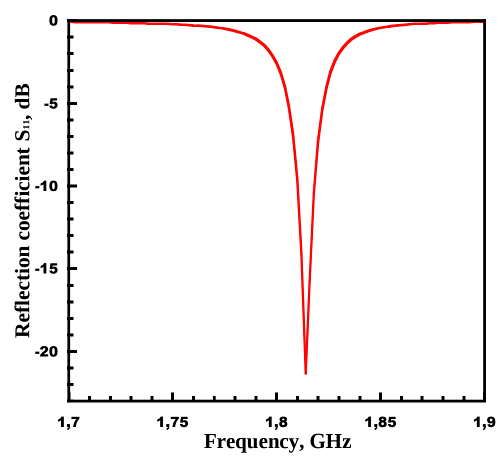


Fig. 2. Simulated $|S_{11}|$ values of the magnetic antenna versus the source frequency.

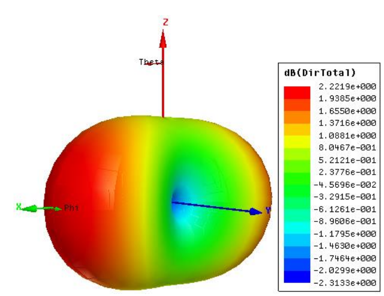


Fig. 3. Simulated 3D total directivity pattern at the resonance frequency of the magnetic NFRP antenna, 1.815 GHz.

B. Electric NFRP antenna

The other component of the Huygens source antenna is a metamaterial-inspired electric NFRP dipole antenna. With the driven printed monopole, it is an adaptation of the 2D electric EZ antenna [17]. The electric NFRP element is a meandered strip; it was printed on the same Rogers Duroid™ 5880 substrate and with the same overall dimensions as the magnetic dipole. The electric NFRP dipole antenna geometry and its optimized design parameters are shown in Fig. 4 and given in Table 2, respectively.

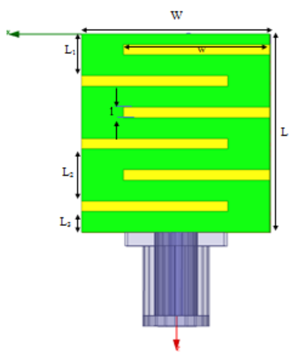


Fig. 4. Front side view of the electric NFRP antenna.

Table 2: Electric NFRP antenna parameters

Parameter	Value (mm)
L_1	4
L_2	5
L_3	2
l	1
w	14
L	19
W	18

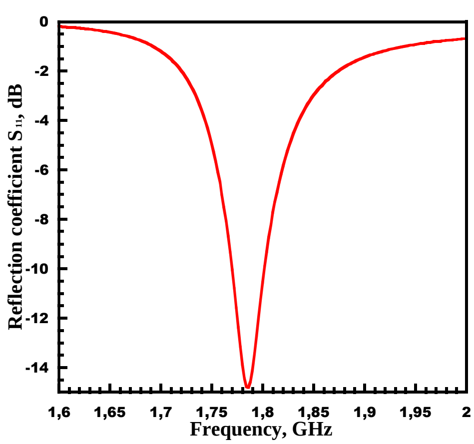


Fig. 5. Simulated $|S_{11}|$ values of the electric NFRP antenna versus the source frequency.

The electric dipole was designed to have a resonance behavior that overlaps with that of the CLL-based NFRP element. It radiates at 1.78GHz as presented in Fig. 5. The proposed NFRP element remains electrically small with ka = 0.49. Figure 6 show that the antenna behaves as an electric dipole oriented along the z-axis. The antenna performance characteristics are: FTBR = 1.0 (0dB), AP = 0.967W, RP = 0.862W (giving RE = 89.14%), D_{max} = 2.23dB, and RG_{max} = 1.58dB. The 3dB bandwidth is 120 MHz (FBW = 6.74%).

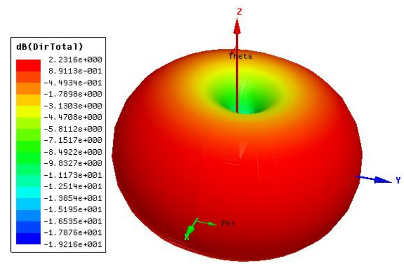
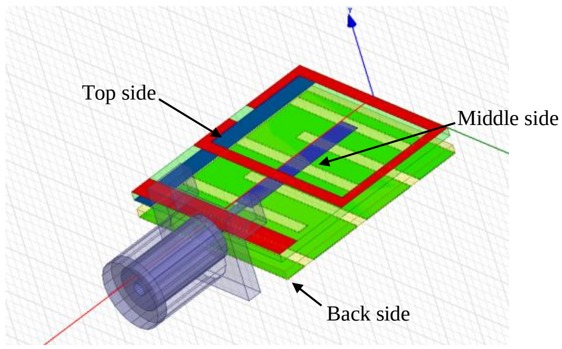


Fig. 6. Simulated 3D total directivity pattern at the resonance frequency of the electric antenna, 1.78 GHz.

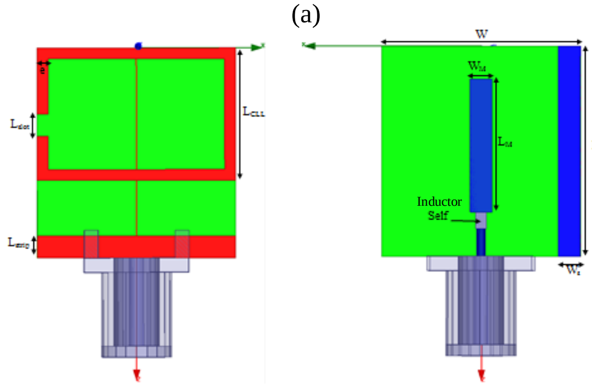
III. HYUGENS SOURCE ANTENNA

The Huygens source antenna was obtained by combining the meandered NFRP and CLL based NFRP designs as shown in Fig. 7. Two Rogers Duroid™ 5880 substrates were used. The CLL NFRP element and the ground strip line were printed in the top side of the first substrate; the driven monopole and the extra-strip line were printed on its back side. The electric NFRP element was printed on the back side (outside face) of the second substrate. The two substrates were combined so that the electric and magnetic NFRP elements were on the external sides and the driven monopole was in the middle. The gap between the two substrates was G=0.9mm, it was filled with foam in order to easily maintain the structural integrity of the whole structure.

The structure dimensions were readjusted to construct the Huygens source while operating at the GSM frequency. However, the input impedance matching was poor. In order to fix this problem, a 20 nH inductor was introduced between the driven monopole and the source feed line. The driven monopole was offset upwards of 4mm from the bottom side as presented in Fig. 7 (c) to accommodate this lumped element. The resulting simulated minimum values of $|S_{11}|$ were significantly improved at the GSM frequency. Figure 8 exhibits the prototyped metamaterial-inspired Huygens source antenna. The simulated and measured values of $|S_{11}|$ as functions of the source frequency are compared in Fig. 9. The prototype antenna radiated at 1.77GHz with nearly complete input impedance matching $|S_{11}|_{min}$=-22.91dB. The difference between the measured and simulated values is attributed to small variations in the design parameters that resulted from fabrication errors and the measurement setup, which did not include any ferrite beads nor matching balun to isolate the antenna from the VNA cables.

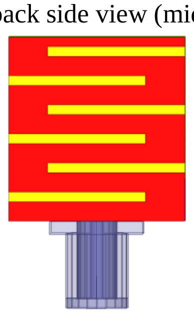


(a)



(i) (ii)

(b) Duroid sheet 1: (i) front side view (outside face), and (ii) back side view (middle face)



(c) Duroid sheet 2: back side (outside face)

Fig. 7. The Huygens source antenna geometry: (a) perspective view, (b) Duroid sheet 1, and (c) Duroid sheet 2.

Fig. 8. Photos of the fabricated prototype Huygens source antenna.

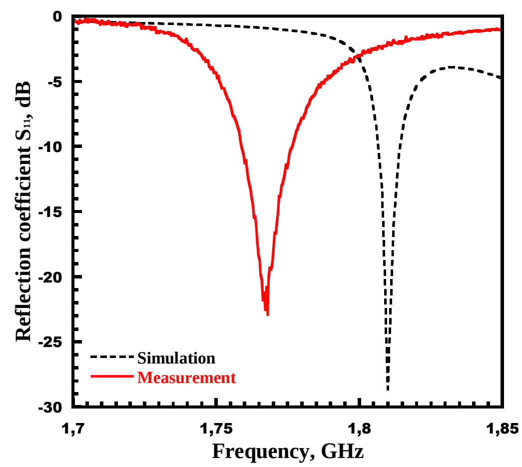
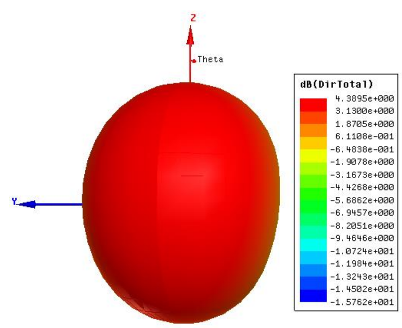


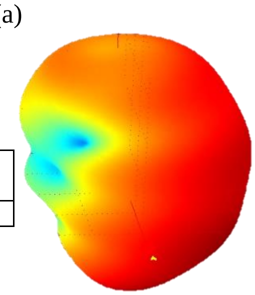
Fig. 9. Simulated and measured $|S_{11}|$ values of the Huygens source antenna versus the source frequency.

The simulated performance characteristics of the prototype Huygens source antenna were: AP = 0.99W; RP = 0.6W; giving RE = 60.19%; D_{max} = 4.38dB and RG_{max} = 2.17dB. The measured values were: RE = 31.05%; D_{max} = 3.39dB; and RG_{max}=1.67dB. The 3dB bandwidth is 60MHz.



(a)

Maximum Value (dB)	Minimum Value (dB)
3.399	-95.18



(b)

Fig. 10. (a) Simulated and (b) measured 3D total directivity pattern.

One can note that the overall measured antenna performance characteristics were lower than predicted. The differences between the simulated and measured results are due to inaccuracies in the measurements and in the manufacturing of the prototype antenna:

- The gap between the two substrates was filled using with a 1.0 mm thick foam rather than the simulated 0.9 mm value.
- The inductor model used in the simulations was ideal; losses were not taken into consideration.

Despite the fact that the realized antenna is not as efficient as predicted, the Huygens source behavior is well obtained along the x-axis as illustrated in Fig. 10.

IV. CONCLUSION

A metamaterial-inspired electrically small Huygens source antenna was numerically studied, manufactured and tested. It was fed with a single 50 Ω coaxial cable. The electric- and magnetic-based NFRP designs were designed first to have overlapping frequency behaviors at the GSM 1.8 GHz frequency. The two designs were then combined to achieve the desired electrically small Huygens source antenna. The input impedance matching was significantly improved by inserting a 20 nH inductor between the driven monopole and the SMA connector. The measured antenna efficiency, the maximum directivity and realized gain were much lower than predicted. This degradation of the antenna performance could be corrected to obtain the predicted values by taking into consideration the actual antenna design specifications.

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