Wearable Antenna Designs Using High Impedance Ground Substrates

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***Abstract*—This paper explores several designs for an efficient wearable antenna for enabling radio-frequency (RF) communication over several frequency bands between wearable sensors and a base station. In order to design efficient wearable antennas, the effects of the human body must be realized and dealt with. Therefore, a combination of full-wave electromagnetic simulations and experimental results of various artificial impedance structures were performed with Ansoft High Frequency Structural Simulator (HFSS) and AWR Microwave Office. Although ultimately three separate antennas will be used (4 GHz, 2.4 GHz, and 400 MHz), this paper focuses primarily on 2.4 GHz.**

***Keywords*—antenna, high impedance substrate, resonator, body sensor**

I. Introduction

BODY sensor networks have seen tremendous improvements over the past few years. The latest in sensor technology utilizes energy harvesting, thus creating ultra low power sensor circuits. Therefore, to build antennas for these ultra low power devices, the antennas must be efficient. The barriers for this project are providing efficient radiation and reception of the RF energy while in close proximity to the body while maintaining a form factor that fits within the specifications of the packaging test bed and the communication circuits. The water content of the body presents a significant RF load to the antenna [1] and in order to operate efficiently, the antenna must be designed to direct the radiated energy towards the base-station and away from the body.

II. Antenna Design

For the purposes of this research, boards were fabricated on FR-4 printed circuit boards with an Antenna Factor ANT-2.45-CHP-x chip antenna. The antenna by itself closely couples with the specifications; however, when a hand is placed below the ground plane of the antenna, the antenna experiences reflections from the large amounts of water in the body. This implies that power is being dissipated and undesired reflections are reducing the efficiency of the antenna. To mitigate this, if the antenna can be directed away from the body in-phase, the efficiency will be maximized. Therefore, I explored various methods of achieving an open-circuited ground plane.

III. High Impedance Designs

A. Quarter-Wave Transformer

One of the simplest methods for achieving an open circuit is using a quarter-wave ($\lambda/4$) transformer. By placing a solid metal plane against the back of the antenna board, there will be a return loss of 0-dB with a phase of 180°, thus short-circuiting the antenna. Therefore, the solution is to separate the antenna board and metal plane by $\lambda/4$. This will cause the backward propagating waves to travel 90°, reflect off of the metal 180° out of phase, and then travel another 90°, ultimately traveling 360°.

The issue with this design is size. First, although the forward propagating wave will be ultimately doubled in power, the initial emission will not experience this added power. Second, for a wearable device at a frequency of 2.4 GHz, the space between the antenna board and metal plane will be too large. At 2.4 GHz, λ is 12.5 cm, which means $\lambda/4$ is 3.125 cm. Therefore, although quarter-wave transformers can be fairly broadband, another more compact design must be implemented.

B. High Impedance Ground Plane

High impedance ground planes are substrates that perfectly reflect waves in phase (0°). The benefit of these substrates is, unlike quarter-wave transformers, which rely on spacing to add phase, these substrates are designed to be placed directly next to the radiating board.

The theory behind high impedance ground planes follows the idea of resonators (Fig. 2). Ideal resonators consist of inductors and capacitors that simultaneously achieve self-resonance. Also, due to a resonator only consisting of capacitors and inductors, there is no power dissipated. Furthermore,

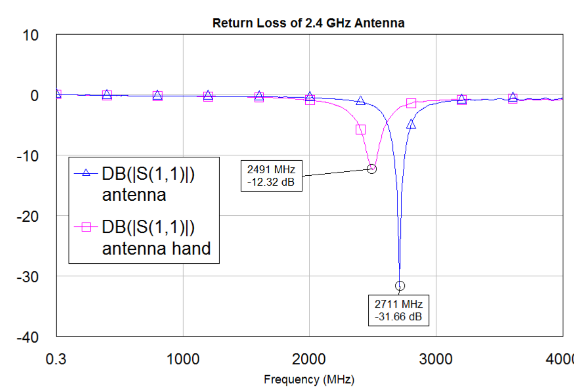

Fig. 1. Measurement of 2.45 GHz ANT-2.45-CHP-x antenna in free-space and with a human arm placed directly underneath the ground plane.

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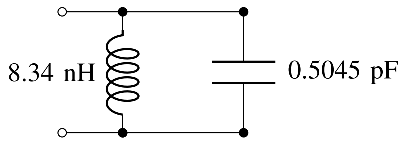

Fig. 2. Circuit representation of ideal resonator specifically designed for 2.4 GHz.

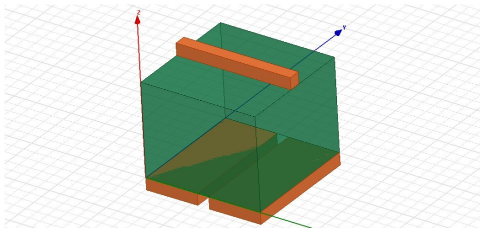

Fig. 3. Model of Resonator in HFSS; orange - copper layers, green - FR4 substrate. The top strip of copper acts inductive, while the bottom two copper strips act capacitive. The wave propagates in the z-direction toward the top layer of copper.

at resonance the phase is $0°$. Given that resonators follow

$$\omega_c = \frac{1}{\sqrt{LC}}, \tag{1}$$

at 2.4 GHz, a solution to this equation is $L = 8.34$ nH and $C = 0.5045$ pF. There are two main designs for achieving a high impedance substrate: a perpendicular resonator and an artificial impedance surface.

1) Resonator Plane: Taking the idea of the ideal resonator, a 3D model of a resonator can be realized by placing an inductive strip of copper on top of a substrate and two capacitive strips on the bottom of the substrate, orthogonal to the top (Fig. 3). Simulated in HFSS, this design had 10-dB return loss at the design frequency (2.4 GHz), which does not maximize the efficiency of this antenna.

2) Artificial Impedance Surface: High impedance substrates have been researched in-depth for the past ten years. The idea of these artificial substrates follows the idea of a resonator – i.e. using multiple disconnected patches (capacitance) of via-holes to a ground plane (inductance) [2]. These designs have been shown to work at higher frequencies [3], so the challenge is to bring them down to 2.45 GHz. To lower the design frequency, the inductance must be increased. There are two ways to increase the inductance: extend the length of the via or add inductors connected to the via. The former requires a sacrifice of thickness, which is a constraint. Therefore, adding chip inductors should reduce the resonance frequency, thus allowing for further fine-tuning.

IV. Conclusion

Various designs for achieving an open-circuited ground plane have been discussed, with the artificial impedance surface showing the most promise. The board shown in Fig. 5 was fabricated, but not yet measured. The next steps for this research involve measuring the fabricated high impedance substrate, and then converting the prototypes from FR-4 to a thinner, more flexible substrate that can be placed on the human body.

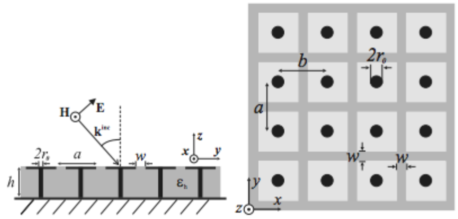

Fig. 4. Artificial high impedance substrate presented in [2]. The values calculated for this project were $a = b = 3.6$ mm, $w = 0.6$ mm, $h = 100$ μm, ϵ_r = 2.9, $r_0 = 1.4$ mm.

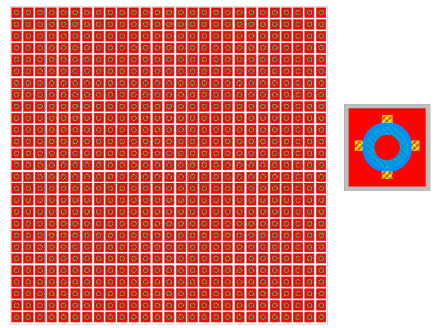

Fig. 5. 28 x 28 Cell Array (left) and Single Cell (right) of High Impedance Ground Plane. Layout from AWR Microwave Office. Red is the top copper layer, blue is the bottom copper layer, and yellow is the soldermask. The middle red circle is a via-hole to the bottom copper.

V. Acknowledgments & Future Career Plans

I would like to thank MTT-S for the opportunity to engage in microwave research and attend the International Microwave Symposium 2014. I would also like to thank Dr. Scott Barker and Chenqian Gan for their supervision and guidance.

Having graduated from the University of Virginia in May 2014 with a B.S. in Electrical Engineering, I will begin working towards an M.S. in Electrical Engineering in Fall 2014. Afterward, I intend to pursue a Ph.D. The MTT-S scholarship and experience at IMS further increased my desire to do research in the area of microwave/RF engineering.

References

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