Novel “Smart Cube” Wireless Sensors with Embedded Processing/Communication/Power Core for “Smart Skins” Applications

James R. Cooper
School of Electrical and Computer Engineering
Georgia Institute of Technology
Atlanta, GA, USA
JCooper45@Gatech.Edu

Manos M. Tentzeris
School of Electrical and Computer Engineering
Georgia Institute of Technology
Atlanta, GA, USA
etentze@ece.gatech.edu

Abstract—**This paper presents a novel topology of isotropically radiating “smart cubes” for use in wireless sensors. The novelty of this antenna is the use of 3D frequency selective surfaces which are used both for creating the desired radiation pattern and for creating a core which is electrically isolated from the antenna at the frequency of operation. The core allows for an embedded power source, processor, amplifier, and/or secondary antenna without interfering with the operation of the radiator. As demand for wireless sensors continues to grow, this device will allow for the implementation of sensors in a wider range of applications including autonomous “smart skins”, biosensing, and RFID-enabled sensors. The prototype is printed on glossy paper using a conductive ink, which gives it the potential for low cost production, allowing it to be used in a variety of applications requiring large numbers of sensing nodes, while meeting enhanced data processing, security or autonomy requirements.**

I. INTRODUCTION

Wireless sensors allow for variety of different applications including the sensing of moisture [1], temperature [2], or gases such as ethanol, acetone, nitrogen, etc [3] [4]. This makes it invaluable in many fields including industrial, medical and military. However, large disbursements of wireless sensors are held back by three major concerns. First is the orientation of the sensor transponder with respect to a reader. If the reader is facing a null in the transponder’s field of radiation then the two will be unable to communicate. The second concern is the maximum read range between interrogator and transponder. In order to guarantee that the two can communicate at a large distance, it is necessary to use an active tag. This includes the use of either a battery or energy scavenging device [5]; both of which have a large size and potential to interfere with the radiator. The third concern is cost, since it may be desired to deploy large numbers of these sensors.

Therefore, in the pursuit of expanding the usage of wireless sensors, presented herein is a near-isotropic radiating RFID based transponder, constructed in a low cost manner, with an isolated core for embedding sensors and/or power source. Within this paper will be presented the background research, which led the proposed design. Next will be presented the design and simulation data of said proposed design. This will be followed by the fabrication and verification through measurement. Finally, conclusions will be presented based upon the design process and measurement data.

II. BACKGROUND DATA

A. RFID Sensors

The two responsibilities of wireless sensors are that they are able to detect some aspect of their environment and that they be able to communicate back to an observer or interrogator what is being detected. It is the latter which makes RFID a great solution. Since the root function of RFID is to transmit encoded data back to an interrogator, it should have the ability to transmit encoded data taken from a sensor.

Measurement data can be collected and encoded using a discrete sensor and processor. It can also be encoded though the parameters of communication with the tag itself. This can be done by allowing the sensor to shift the operating parameters of the tag [1] [6], or the sensor can be embedded in the antenna and shift the operation of the radiator [4] [7]. The latter of the two is often referred to as Smart Skin sensing. The encoding can also be done by using the sensor as a load on the tag, where a shift in the load translates to a shift in the retransmitted signal [8, 9]. When these sensing methods are combined with an RFID tag, the sensed data can be transmitted to and processed by an interrogator.

Through these ends, RFID based sensors have been used in a wide range of applications as mentioned earlier. Because RFID based sensors are capable of versatile sensing, there is

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great demand to continue to investigate new designs and applications.

B. Isotropic Radiators

Perfect isotropic radiating antennas are a theoretical reference for how an antenna radiates energy. They are characterized by their ability to radiate an equal amount of energy in all directions. By the basic operation of an antenna, this means that they receive power equally from any direction. This makes them ideal candidates for use in RFID systems, where the orientation of a tag is random.

Perfect isotropic antennas, which have a 0dB variance in relative power between any two directions, are mathematically impossible without the use of magnetic monopoles. However, several semi-isotropic antennas have been created. These have included a dipole coupled with a resonator printed on kapton yielding < 9dB variances [10], two crossed dipoles yielding < 4dB variance [11] and four phased monopoles in a circle yielding < 8dB variance [12].

C. Frequency Selective Surfaces

Electronic Bandgap, or EBG, materials and Frequency Selective Surfaces, or FSS, are types of meta-materials which appear as infinite impedance or perfect magnetically conducting surfaces in the range of their operating frequency. They can also appear as transparent (FSS) or as perfect electric conductors (EBG) away from the operating frequencies [13]. This makes them very useful reflectors for dipoles and other compact antennas for increasing the directivity. They can also act as parasitic elements and be used to decrease directivity [10].

FSS are normally composed of some type of periodic, resonating structure. This could be a 2-D array of dipoles[14], an array of loops linked together with lumped elements[15], stacked arrays of dielectric rods[16], etc. The EBG is different from the FSS in that it contains a ground plane underneath the structure and may contain vias [17].

In order to achieve both an isotropic radiating pattern and an electromagnetically isolated core which will not interfere with said radiation pattern (criteria one and two to be discussed in section III), FSS/EBG structures are implemented.

D. Inkjet Printed Circuits

Since wireless sensors contain a wide variety of applications, and the use of wireless sensors can include wide disbursements of a large number, it is necessary to consider cost, environmental impact, and difficulty of fabrication. The printing of conductive ink on organic substrates, such as paper, allows for a reduction in all three of these areas [18]. Therefore, this design utilizes the inkjet printing of silver nano-particles onto a glossy paper substrate.

III. DESIGN AND SIMULATION

A. Specifications

The design of the cube includes the meeting of two major criteria and one minor criterion. The first is that the cube be an isotropic radiator. The second is that the cube contains a portion, preferably in the middle, which can contain a wide range of materials without interfering with the first criterion. The third criterion is that the input impedance on the port of the cube be close to the input impedance of an RFID tag.

B. Design

For the second criterion, a cube with PEC boundaries was chosen. This PEC could be a solid sheet of copper, or another good conductor, or it could be an FSS babinet compliment structure with an operating frequency away from that of the cube. The use of PEC boundaries allows for complete isolation at the cube's frequency of operation. The use of an FSS babinet compliment would allow for wireless transmission with a secondary radiator contained within while still acting as a PEC. For the purpose of simplicity in the proof of concept, a copper plated core was used.

For the radiator, a simple dipole was used. Since the core is a good conductor, when a dipole is placed near it, the dipole would be severely detuned and non-functional as a radiator. Therefore, an FSS was placed on three sides of the core with a separation of 5mm. The Antenna was then placed 5mm above the FSS (which now acts as an EBG with the core acting as a ground plane). The FSS/EBG now acts as a perfect magnetic conductor, PMC, constructively interfering with the antenna, as well as acting as parasitic resonators, giving the antenna a less directional radiation pattern.

The FSS unit cell chosen is a second generation convoluted square. This was chosen because it's not polarized, unlike a split ring resonator. Polarization can sometimes create unwanted affects with surface waves and waves of different incidence. It was also chosen since it is easily miniaturized. A second generation convoluted square was chosen due to being significantly smaller than a first generation while still being less susceptible to detuning than a third generation.

At the operational frequency of 900 MHz, the square has a size of 56mm x 56mm. As such, the cube has dimensions of 56mm x 56mm x 56mm. The antenna length was chosen to be that of a free-space dipole, 167mm. The complete design of the cube, including core, FSS/EBG and antenna can be seen in

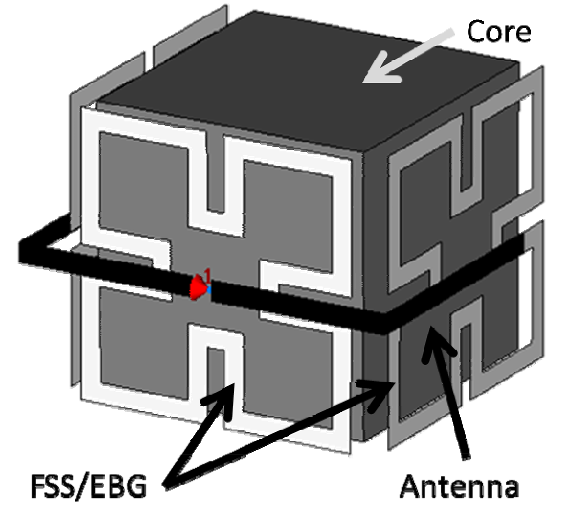

Figure 1. RFID Tag Cube

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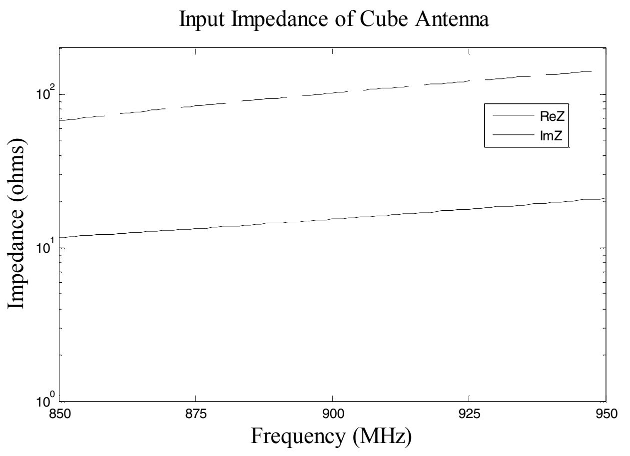

Figure 2. Input Impedance of the Cube Antenna

Figure 1.

C. Simulation

Simulation and optimization were done using CST Microwave Studio. Frequency domain analysis was done for optimizing the dimensions of the FSS/EBG. Transient Analysis was done for calculating the input impedance and radiation pattern of the cube. A plot of the input impedance can be seen in Figure . The radiation pattern will be covered in the results.

From the impedance plots, it can be seen that the effects of the cube have shifted the input impedance of the dipole antenna to a low real part and a large, positive imaginary part.

In order to calculate the reflection coefficient between the complex impedance of the antenna and the complex impedance of the RFID chip, Kurakowa's definition for reflection coeffiecent, given by

$$\Gamma = \frac{Z_{cube} - Z_{chip}^{*}}{Z_{cube} + Z_{chip}} \qquad (1)$$

where Z_{cube} and Z_{chip} are the impedances of the cube antenna and RFID respectively, was used. The reflected power was calculated using a chip impedance of 16 - j122 at 900 MHz, and a cube input impedance of 17.76 + j121.76. The power reflection coefficient came out to be ~ -12dB. This means that the cube has a good matching to an RFID chip without the need for a matching network. Thus, the third criterion was met without the need for a modification to the antenna.

IV. FABRICATION AND MEASUREMENTS

A. Fabrication

In figure 3, the fully fabricated cube can be seen. The cube was fabricated using an inkjet methodology as described above. Foam pads with a dielectric constant close to 1, were used as spacers between the antenna and FSS/EBG, and in between the FSS/EBG and the central core. The core was constructing using several layers of copper tape wrapped around a paper box.

B. Measurement

No external connector was used on the cube. This was because the cube is meant to be used as an RFID tag, and therefore does not have a connector designed into it; and also any connector brought to the tag would interfere with the overall performance of the tag due to its dependence on parasitic resonators.

Therefore, the measurements were made using Voyantic's Tagformance interrogator system and an off the shelf Gen2 RFID chip. The radiation pattern was calculated by determining the minimum output power required to activate the chip on the cube. These values were then negated and normalized to a maximum point (minimum before negation).

C. Results

The normalized radiation pattern, across the E-field and H-field planes, can be seen in figure 4. From the plot, it can be seen that the cube is an isotropic radiator with less than 3 dB

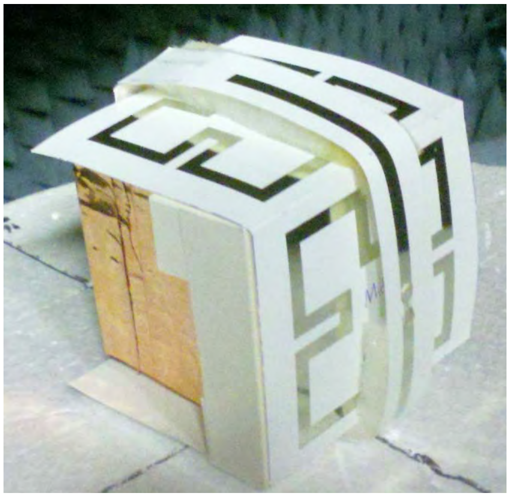

Figure 3. Fully Fabricated Cube

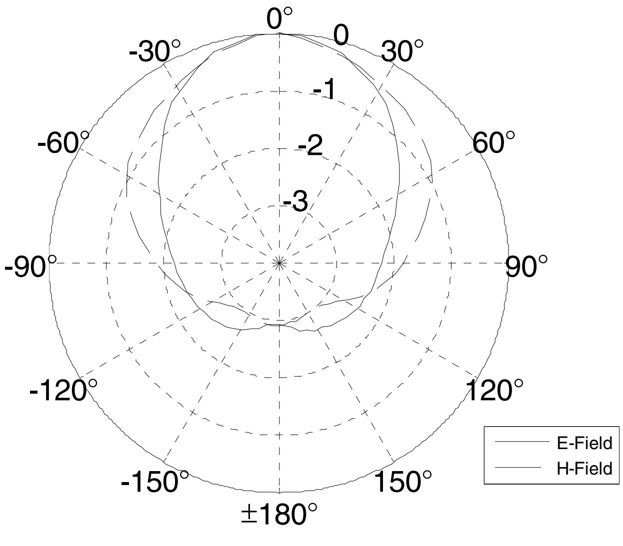

Figure 2. Measured Radiation Pattern of Cube for Both E-Field and H-Field

variance between the direction of maximum power transmission and any other direction. Thus, the first criterion is met. At the same time, the core is made out a solid metal housing, which isolates the inside from the outside electromagnetically.

V. CONCLUSIONS

Presented thus far have been the design, simulation, fabrication and measurement of a isotropic radiating cube antenna, with an electromagnetically isolated core, for the purpose of RFID based wireless sensing. Through measurement, it was shown that the cube acts as good isotropic radiator with less than 3dB of variance in directivity in all directions. It was explained that the core is isolated by the use of a near PEC material around the core. And, it was shown through simulation that the cube matches an RFID chip with >90% efficiency.

Through this, it has been shown that the cube is a versatile, low cost option in the design and implementation of RFID wireless sensors and smart skin applications.

REFERENCES

[1] J. Gao, J. Siden, and H.-E. Nilsson, "Printed Electromagnetic Coupler With an Embedded Moisture Sensor for Ordinary Passive RFID Tags," *Electron Device Letters, IEEE* vol. 32, pp. 1767-1769, 2011.

[2] L. M. Reindl and I. M. Shrena, "Wireless measurement of temperature using surface acoustic waves sensors," *Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transactions on,* vol. 51, pp. 1457-1463, 2004.

[3] S. Shrestha, M. Balachandran, M. Agarwal, V. V. Phoha, and K. Varahramyan, "A Chipless RFID Sensor System for Cyber Centric Monitoring Applications," *Microwave Theory and Techniques, IEEE Transactions on* vol. 57, pp. 1303-1309, 2009.

[4] L. Yang, G. Orecchini, G. Shaker, H.-S. Lee, and M. M. Tentzeris, "Battery-free RFID-enabled wireless sensors," in *Microwave Symposium Digest (MTT), 2010 IEEE MTT-S International*, 2010, pp. 1528-1531.

[5] R. Vyas, V. Lakafosis, and M. Tentzeris, "Wireless remote localization system utilizing ambient RF/solar power scavenging RFID tags," in *Microwave Symposium Digest (MTT), 2010 IEEE MTT-S International*, 2010, pp. 1764-1767.

[6] S. M. Presas, T. M. Weller, S. Silverman, and M. Rakijas, "High efficiency diode doubler with conjugate-matched antennas," in *Microwave Conference, 2007. European*, 2007, pp. 250-253.

[7] X. Yi, J. Cooper, Y. Wang, M. M. Tentzeriz, and R. T. Leon, "Wireless Crack Sensing Using an RFID-based Folded Patch Antenna," in *Proceedings of the 6th International Conference on Bridge Maintanance, Safety and Management*, Villa Erba, Lake Como, Italy, 2012.

[8] S. Shrestha, M. Balachandran, M. Agarwal, V. V. Phoha, and K. Varahramyan, "A Chipless RFID Sensor System for Cyber Centric Monitoring Applications," *Microwave Theory and Techniques, IEEE Transactions on,* vol. 57, pp. 1303-1309, 2009.

[9] T. Trang, J. Ratner, C. Wenhua, G. DeJean, and M. M. Tentzeris, "Characterization and testing of novel polarized nanomaterial textiles for ultrasensitive wireless gas sensors," in *Electronic Components and Technology Conference, 2009. ECTC 2009. 59th*, 2009, pp. 1049-1052.

[10] K. In Kwang and V. V. Varadan, "Flexible isotropic antenna using a split ring resonator on a thin film substrate," in *Antennas and Propagation (APSURSI), 2011 IEEE International Symposium on*, 2011, pp. 3333-3335.

[11] P. Guoping, L. Yue, Z. Zhijun, and F. Zhenghe, "An isotropic-radiated planar antenna using two crossed dipoles," in *Microwave and Millimeter Wave Technology (ICMMT), 2012 International Conference on*, 2012, pp. 1-4.

[12] M. Huchard, C. Delaveaud, and S. Tedjini, "Miniature Antenna for Circularly Polarized Quasi Isotropic Coverage," in *Antennas and Propagation, 2007. EuCAP 2007. The Second European Conference on*, 2007, pp. 1-5.

[13] R. C. Hansen, "Effects of a High-Impedance Screen on a Dipole Antenna," *IEEE Antennas and Wireless Propogation Letters,* vol. 1, pp. 46-49, 2002.

[14] E. A. Parker and A. N. A. El Sheikh, "Convoluted Array Elements and Reduced Size Unit Cells for Frequency-Selective Surfaces," *Proc. Inst. Elect. Eng. Part H: Microwaves, Antennas, and Propogation,* vol. 138, pp. 19-22, 1991.

[15] F. Bayatpur and K. Sarabandi, "Single-Layer High-Order Miniaturized-Element Frequency-Selective Surfaces," *Microwave Theory and Techniques, IEEE Transactions on* vol. 56, pp. 774-781, 2008.

[16] C. Biancotto and P. Record, "Triangular Lattice Dielectric EBG Antenna," *Antennas and Wireless Propagation Letters, IEEE,* vol. 9, pp. 95-98, 2010.

[17] D. Sievenpiper, L. Zhang, and E. Yablonovitch, "High-impedance electromagnetic ground planes," in *Microwave Symposium Digest, 1999 IEEE MTT-S International*, 1999, pp. 1529-1532 vol.4.

[18] A. Rida, L. Yang, R. Vyas, S. Basat, S. K. Bhattacharya, and M. M. Tentzeris, "Novel Manufacturing Processes for Ultra-Low-Cost Paper-Based RFID Tags with Enhanced "Wireless Intelligence"," in *Rida, A.; Li Yang; Vyas, R.; Basat, S.; Bhattacharya, S.K.; Tentzeris, M.M.*, 2007, pp. 773-776.