



Three-Dimensional Chipless RFID Technology: A New Frontier in Counterfeit Deterrence

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Abstract

A novel methodology for designing Chipless Radio Frequency Identification (RFID) tags is introduced and studied. Leveraging the advantages of Additive Manufacturing (AM) technologies, these tags exhibit a high number of identification states. The designed tags are encoded exploiting the resonances and anti-resonances of its input impedance, specifically utilizing the set of zero-crossing points of its reactance ensuring a robust and unambiguous tag identification, even in the presence of manufacturing tolerances. Furthermore, the inherent flexibility of AM processes, encompassing both 2D and 3D techniques, facilitates the design of highly customized and innovative RFID solutions. This includes the implementation of advanced security features at the physical layer, enhancing the overall security and anti-counterfeiting capabilities of the system.

1. Introduction

Additive Manufacturing (AM) emerges as a compelling alternative to conventional rapid prototyping methods, including injection molding and subtractive techniques. By facilitating the creation of custom-designed and cost-effective solutions [1, 2], AM significantly enhances the speed of manufacturing and provides unprecedented design freedom [3-5]. This transformative potential enables the development of a new generation of devices. Furthermore, AM processes, encompassing fused filament fabrication and stereolithography for three-dimensional objects and material deposition for two-dimensional structures, offer engineers unparalleled design flexibility.

The radiofrequency (RF) domain has significantly benefited from the advent of AM, which has been successfully employed in the fabrication of various RF components, including antennas [6], filters [7], waveguides [8], metamaterials [9], sensors, and even chipless solutions [10]. This exploration has not only expanded the boundaries of existing RF hardware but also facilitated a bridge between the virtual and physical domains. While blockchain-based authentication protocols offer robust security, a critical challenge remains unexplored, viz, securely linking the physical object to its corresponding virtual representation [11].

A key application domain for this research lies in developing advanced anti-counterfeiting measures for

high-value markets such as fashion and pharmaceuticals. While some recent studies have investigated the use of radiofrequency (RF) technology for this purpose [12], the integration of AM processes in this context remains largely unexplored [13]. This work aims to present a selection of anti-counterfeiting solutions currently under development within our research group. These solutions leverage the transformative potential of AM, with a particular emphasis on chipless RFID technology.

A significant technological advancement in recent years has been the development of robust object identification solutions. While conventional technologies such as optical barcodes and Radio Frequency Identification (RFID) tags have demonstrated effectiveness, recent research has explored innovative approaches, including chipless RFID tags. Traditionally, two-dimensional chipless RFID tags have been fabricated using standard Printed Circuit Board (PCB) manufacturing processes. However, a paradigm shift is currently underway towards the development of three-dimensional chipless RFID tags.

Traditional chipless RFID systems typically employ far-field interrogation techniques [15-17]. In contrast, 3D chipless RFID tags operate through proximity reading. The encoded information within these tags is embedded in their unique electromagnetic signatures, which are modulated by strategically positioned inclusions (or voids) within the tag's solid structure, referred to as the Solid Infill (SI). Such chipless tags exhibit exceptional versatility, enabling seamless integration into a wide range of form factors (e.g., cylinders, prisms). This level of integration is achieved without the need for post-processing or the assembly of multiple components, a significant challenge for conventional manufacturing methods.

Information encoding in three-dimensional chipless RFID tags is achieved through their unique radiofrequency (RF) fingerprints, specifically by manipulating the resonances and anti-resonances of the input impedance measured using a simple coaxial probe. The tag's response is precisely tailored by incorporating voids within a dielectric resonator [18], applying metallic coatings to the outer shell, or integrating different materials using dual-nozzle printing techniques. The information capacity of a tag directly correlates with the number of discernible resonances it exhibits.

One recent work [19] explores one such possibility to extract the imaginary impedance parameter and

subsequently encode the information to produce independent tags. Although, such a design and subsequent codification could help in realization of a large set of independent tag signatures, the design suffered from the excitation of only the TM_{11} (to z) modes, hence limiting its capabilities. In addition, the design was characterized at a higher frequency band which necessitated the use of a costly reader setup.

This work fills up the lacunae and discusses a methodology to increase the number of independent tags feasible from a set of tag geometries, by harnessing the modal orthogonality and usage of two feeders. In addition, the tag geometry has also been scaled down to incorporate a cheap and handy reader, subsequently affecting the overall system cost.

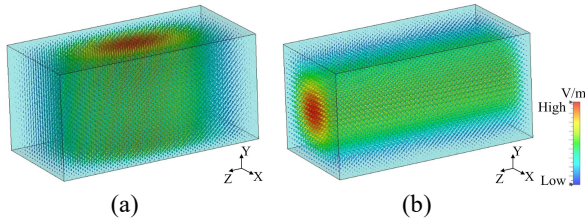


Figure 1. Eigenmodes in a SI resonator (a) TE_{101} , and (b) TM_{110} .

2. Tag Design and Analysis

For the initial analysis, a SI resonator is considered, which is analyzed for its Eigen-Modes. As will be discussed later, two orthogonal feeds would excite the resonator, having orthogonal modes, viz, TE_{10} (to z) and TM_{11} (to z). The first two modes in this series are the TE_{101} and the TE_{110} , having modal fields as shown in Figures 1 (a), and (b), respectively. It is worth noting here that the eigen frequency (f_{mnp}) obtained from the simulations corroborate to that obtained theoretically from the following equation:

$$f_{mnp} = \frac{c}{2\sqrt{\epsilon_r}} \sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2 + \left(\frac{p}{d}\right)^2} \quad (1)$$

where m , n , and p are the mode numbers, and a , b , and d are the physical dimensions along the principal X, Y and Z axes, respectively.

Subsequently, air voids can be strategically introduced within a rectangular cavity to create a functional chipless RFID tag. These air voids effectively function as resonating chambers, enabling the encoding of information. The resonant frequency of each air void exhibits unique characteristics, allowing for the decoding of the encoded information by measuring the resonant frequencies of the tag. One such tag configuration comprising of two cuboidal voids is shown in Figure 2. The tag configuration is fed by two orthogonal coaxial feeds as marked in the figure.

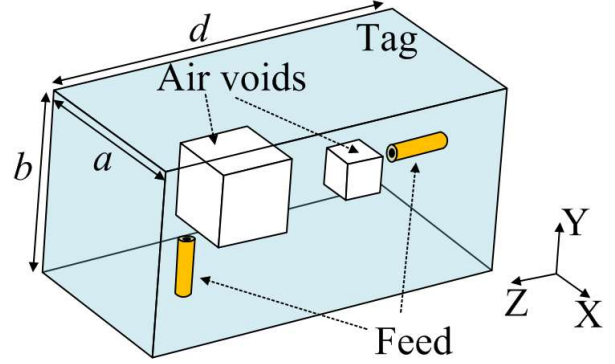


Figure 2. Tag configuration with two cuboidal voids and orthogonal feeding architecture (Tag dimensions: $a=b=50$ mm, $d=100$ mm).

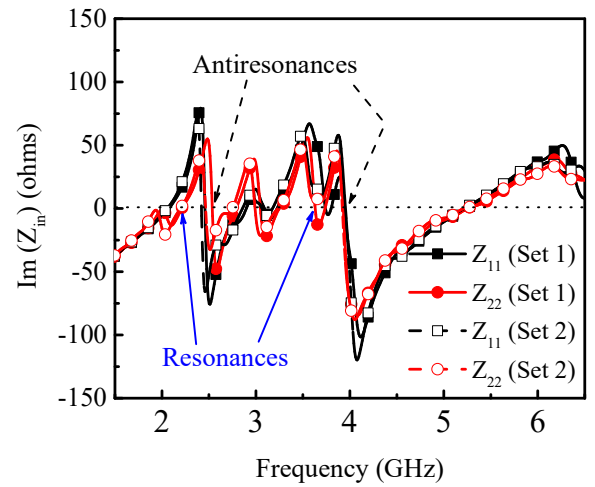


Figure 3. Responses of two test tags, showing the resonances and antiresonances from 1.5 – 6.5 GHz

Data extraction primarily relies on the resonance and anti-resonance characteristics of the tag, as evident in the imaginary impedance plots presented in Figure 3. These resonances and anti-resonances exhibit shifts in their positions upon the inclusion or modification of internal voids. This phenomenon results in a set of independent states, effectively constituting a unique RF fingerprint. This distinct fingerprint facilitates efficient data retrieval and significantly enhances anti-counterfeiting capabilities.

The utilization of air voids for information encoding within chipless RFID tags presents several key advantages compared to conventional approaches. Firstly, additive manufacturing techniques facilitate the rapid prototyping and customization of these structures by enabling the creation of air voids with ease. Secondly, the flexibility of additive manufacturing allows for the incorporation of air voids in diverse shapes and sizes, thereby enabling the integration of these tags into a wide array of objects. Thirdly, this encoding method exhibits a relatively high degree of immunity to environmental factors such as temperature and humidity, resulting in enhanced tag

reliability. Lastly, the use of modal orthogonality is helpful in providing a larger number of independent datasets.

3. Conclusion

Chipless 3D RFID tags incorporating air voids and orthogonal feeding architecture present a promising paradigm for unique object identification, offering several key advantages over conventional chipless RFID technologies, requiring the need of a cheap reader architecture. The inherent flexibility of additive manufacturing processes facilitates rapid prototyping and customization, enabling seamless integration into a diverse array of objects and applications. Moreover, the encoding methodology, predicated upon the distinctive RF fingerprint generated by the strategic arrangement of air voids, exhibits a high degree of resilience to environmental influences, ensuring reliable operational performance.

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References

- [1] K. S. Prakash, T. Nancharaih, and V. V. S. Rao, 'Additive Manufacturing Techniques in Manufacturing - An Overview', *Mater. Today Proc.*, vol. 5, no. 2, Part 1, pp. 3873–3882, Jan. 2018, doi: 10.1016/j.matpr.2017.11.642.
- [2] T. D. Ngo, A. Kashani, G. Imbalzano, K. T. Q. Nguyen, and D. Hui, 'Additive manufacturing (3D printing): A review of materials, methods, applications and challenges', *Compos. Part B Eng.*, vol. 143, pp. 172–196, Jun. 2018, doi: 10.1016/j.compositesb.2018.02.012.
- [3] T. J. Horn and O. L. A. Harrysson, 'Overview of Current Additive Manufacturing Technologies and Selected Applications', *Sci. Prog.*, vol. 95, no. 3, pp. 255–282, Sep. 2012, doi: 10.3184/003685012X13420984463047.
- [4] S. Salifu, D. Desai, O. Ogunbiyi, and K. Mwale, 'Recent development in the additive manufacturing of polymer-based composites for automotive structures—a review', *Int. J. Adv. Manuf. Technol.*, Jan. 2022, doi: 10.1007/s00170-021-08569-z.
- [5] C. Sun, Y. Wang, M. D. McMurtrey, N. D. Jerred, F. Liou, and J. Li, 'Additive manufacturing for energy: A review', *Appl. Energy*, vol. 282, p. 116041, Jan. 2021, doi: 10.1016/j.apenergy.2020.116041.
- [6] D. Helena, A. Ramos, T. Varum, and J. N. Matos, 'Antenna Design Using Modern Additive Manufacturing Technology: A Review', *IEEE Access*, vol. 8, pp. 177064–177083, 2020, doi: 10.1109/ACCESS.2020.3027383.
- [7] C. Tomassoni, O. A. Peverini, G. Venanzoni, G. Addamo, F. Paonessa, and G. Virone, '3D Printing of Microwave and Millimeter-Wave Filters: Additive Manufacturing Technologies Applied in the Development of High-Performance Filters with Novel Topologies', *IEEE Microw. Mag.*, vol. 21, no. 6, pp. 24–45, Jun. 2020, doi: 10.1109/MMM.2020.2979153.
- [8] E. Massoni *et al.*, '3-D Printed Substrate Integrated Slab Waveguide for Single-Mode Bandwidth Enhancement', *IEEE Microw. Wirel. Compon. Lett.*, vol. 27, no. 6, pp. 536–538, Jun. 2017, doi: 10.1109/LMWC.2017.2701323.
- [9] T. Whittaker, S. Zhang, A. Powell, C. J. Stevens, J. Y. C. Vardaxoglou, and W. Whittow, '3D Printing Materials and Techniques for Antennas and Metamaterials: A survey of the latest advances', *IEEE Antennas Propag. Mag.*, pp. 2–12, 2022, doi: 10.1109/MAP.2022.3229298.
- [10] M. Elgeziry, F. Costa, A. Tognetti, and S. Genovesi, 'Wearable Textile-Based Sensor Tag for Breath Rate Measurement', *IEEE Sens. J.*, vol. 22, no. 23, pp. 22610–22619, Dec. 2022, doi: 10.1109/JSEN.2022.3217325.
- [11] Anthony, M. C. Lee, R. R. Pearl, I. S. Edbert, and D. Suhartono, 'Developing an anti-counterfeit system using blockchain technology', *Procedia Comput. Sci.*, vol. 216, pp. 86–95, Jan. 2023, doi: 10.1016/j.procs.2022.12.114.
- [12] V. Lakafosis, *et. al.*, 'RF Fingerprinting Physical Objects for Anticounterfeiting Applications', *IEEE Trans. Microw. Theory Tech.*, vol. 59, no. 2, pp. 504–514, Feb. 2011, doi: 10.1109/TMTT.2010.2095030.
- [13] A. Sola, Y. Sai, A. Trinchi, C. Chu, S. Shen, and S. Chen, 'How Can We Provide Additively Manufactured Parts with a Fingerprint? A Review of Tagging Strategies in Additive Manufacturing', *Materials*, vol. 15, no. 1, Art. no. 1, Jan. 2022, doi: 10.3390/ma15010085.
- [14] F. Costa, S. Genovesi, and A. Monorchio, 'A Chipless RFID Based on Multiresonant High-Impedance Surfaces', *IEEE Trans. Microw. Theory Tech.*, vol. 61, no. 1, pp. 146–153, Jan. 2013, doi: 10.1109/TMTT.2012.2227777.
- [15] A. Vena, E. Perret, and S. Tedjini, 'Chipless RFID Tag Using Hybrid Coding Technique', *IEEE Trans. Microw. Theory Tech.*, vol. 59, no. 12, pp. 3356–3364, Dec. 2011, doi: 10.1109/TMTT.2011.2171001.
- [16] S. Genovesi, F. Costa, F. A. Dicandia, M. Borgese, and G. Manara, 'Orientation-Insensitive and Normalization-Free Reading Chipless RFID System Based on Circular Polarization Interrogation', *IEEE Trans. Antennas Propag.*, vol. 68, no. 3, pp. 2370–2378, Mar. 2020, doi: 10.1109/TAP.2019.2949417.
- [17] S. Preradovic, I. Balbin, N. C. Karmakar, and G. F. Swiegers, 'Multiresonator-Based Chipless RFID System for Low-Cost Item Tracking', *IEEE Trans. Microw. Theory Tech.*, vol. 57, no. 5, pp. 1411–1419, May 2009, doi: 10.1109/TMTT.2009.2017323.
- [18] S. Terranova, F. Costa, G. Manara, and S. Genovesi, 'Three-Dimensional Chipless RFID Tags: Fabrication through Additive Manufacturing', *Sensors*, vol. 20, no. 17, Art. no. 17, Jan. 2020, doi: 10.3390/s20174740.
- [19] S. Choudhury, F. Costa, G. Manara and S. Genovesi, "3-D Chipless RFID Tag for Anti-Counterfeiting Applications," in *IEEE Open Journal of Antennas and Propagation*, vol. 5, no. 6, pp. 1681–1690, Dec. 2024, doi: 10.1109/OJAP.2024.3437687.