A Novel "Universal" Inkjet-Printed EBG-Backed Flexible RFID for Rugged On-Body and Metal Mounted Applications

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***Abstract* — A novel inkjet-printed electromagnetic bandgap-backed (EBG) RFID tag has been designed and tested for wearable and metal mount applications. An array of split-ring resonators and a dipole antenna matched to an RFID chip at 915 MHz were designed and inkjet printed on paper substrate. Measurements of the tag in free space show that the required reader's minimum transmit power for successful tag reading decreases by 6 dB compared to the case without EBG, while for on-body and on-metal measurements, the read range increases by nearly a factor of 2. It has to be noted that the proposed RFID tag is flexible since it can be easily fabricated by inkjet printing nano-silver particles on paper or platic substrates. It can find numerous applications ranging from wearable antennas and bio-monitoring to transportation and logiitics for mass shipping.**

***Index Terms* — Wearable, antenna, RFID, split ring resonator, EBG, FSS, metamaterial, inkjet printing.**

I. Introduction

One of the biggest challenges for RFIDs real-world applications is to overcome the effect of metal and lossy substrates onto which an RFID tag need to be commonly placed. The degradation of gain due to the antenna proximity to such metal and lossy materials seriously limits the effective read range. To resolve this issue, there have been numerous previous efforts utilizing Electromagnetic Band Gap (EBG) or high impedance surfaces. EBG designs are considered in [1-2], however they require the use of vias which limit the flexibility and ruggedness of the derived wearable RFID tag. Another example of EBG-based design focuses on the improvement of return loss rather than gain being based on a patch antenna on top of an EBG surface [3]. Since the patch antenna already has a ground plane, this EBG surface does not provide improvement in gain. Moreover, no measurements to validate improvement in range are provided. In [4-6], different designs are proposed to mitigate the effect of metal but they lack in flexibility for a truly wearable RFID tag.

Our work considers an ultrathin completely via-less, split-ring-resonator-based EBG design for both on-metal and on-body mounted rugged applications featuring low-cost, low fabrication complexity and flexibility characteristics. In detail, our proposed "rugged" RFID configuration consists of an inkjet-printed dipole antenna laid on top of an inkjet-printed EBG surface, matched to commercially available RFID chips. Its significantly improved performance was verified via measurements performed both inside an anechoic chamber and in real indoor environments by using a commercial tool for Tag performance characterization and a standard RFID reader. Both on-metal and on-body measurements were performed.

It has to be remarked that due to the design of the EBG surface with a ground plane on the bottom, this prototype can theoretically be "universally" mounted on any (e.g. metal, water, body, etc.) surface. Applications can range from wearable antennas for factory works in the industry and patients in the hospital to plastic water bottles and metal containers, to name a few. In the following sections, the EBG design and fabrication is introduced followed by measurement results and conclusion.

II. EBG Design

In this paper, the well-known split ring resonator (SRR) is adopted as a unit cell of the EBG structure. Next, a ground plane is placed below the EBG structure in order to obtain an Artificial Magnetic Conductor (AMC) reflector. It is well known that an RFID tag antenna achieves the maximum increase in directivity when it is placed at a distance of about 80 mm (λ/4 in free space @ 915 MHz) from a conductive ground plane. Such distance can be significantly reduced if an AMC reflector is considered as a ground plane for the RFID tag.

Based on this, we have designed an AMC with a 3 mm gap between the EBG and the ground plane. The distance between the RFID tag and the EBG is kept to 3mm, an optimum value for flexibility and gain improvement. The AMC reflector is designed by means of reflection phase characterization [7]. A plane wave is illuminated onto the infinite EBG surface and the phase of reflection coefficient on the surface of the EBG is observed. The EBG surface can be considered as an AMC reflector if the reflection phase is within range of [-90° — +90°] since the reflected waves will be constructively added to radiated waves. The top of Figure 1 shows the unit cell of the EBG structure. The gap between EBG and ground plane is kept by inserting microwave foam which dielectric constant is close to air. This provides more flexibility, low losses and reduced difference between paper substrate and air dielectric constants. The reflection coefficient at the paper-foam interface is 0.5, a small value because the dielectric constants of paper and foam are 3 and 1, respectively. In other words, 75% of power can be transmitted to EBGs to make in-phase

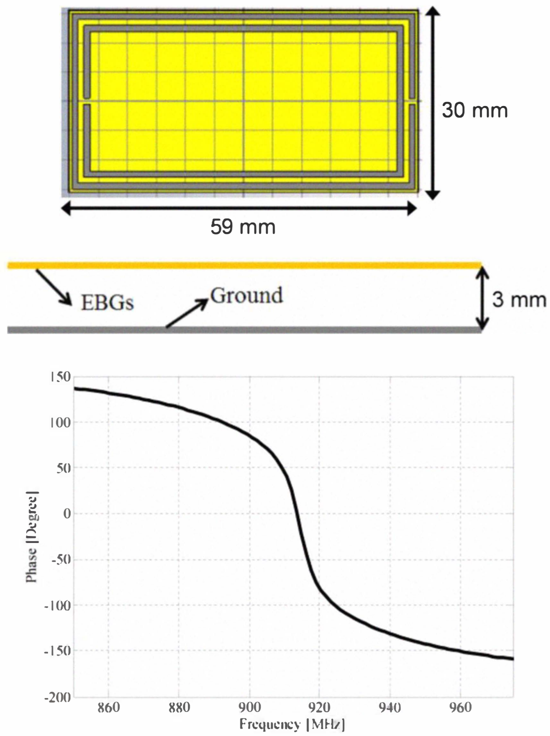

Fig. 1. EBG unit cell (top) and the resulting simulated reflection phase (bottom).

reflection. Different materials can be considered to fill the EBG-ground-plane gap. For example, with high dielectric materials like ceramics the tag loses its benefits in terms of flexibility and weight. With paper substrates, maximum power transfer is achieved but the EBG loses its property due to high loss tangent and the overall flexibility is degraded by the structure thickness. The bottom part of Figure 2 shows the phase of reflection coefficient on the EBG structure. The reflection phase has a value between -90° and +90° in the RFID frequency band.

Based on the single-cell EBG design, we have built a 2D array made up of 3x2 EBG unit cells. This is the minimum dimension required to cover the area of the RFID tag. Figure 2 shows the fabricated EBG structure by means of inkjet printing on commercially available photo paper while the designed

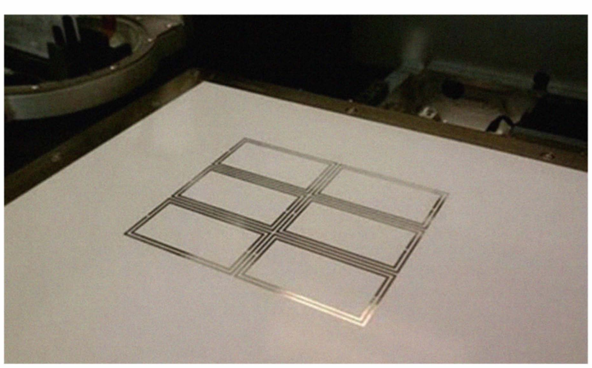

Fig. 2. Fabricated EBG structure by means of inkjet printing.

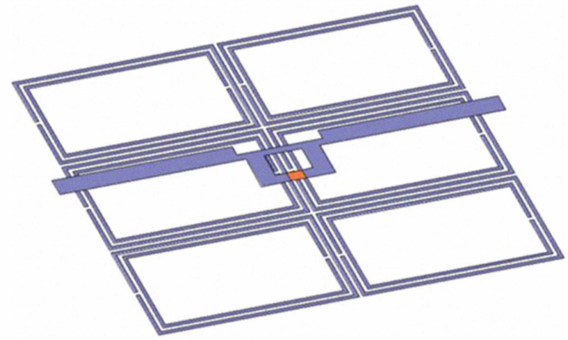

Fig. 3. Dipole antenna matched to the RFID chip on top of the designed SRR-based EBG surface.

EBG-based RFID tag made up of the three-layers structure (ground plane + EBG + dipole) is shown in Figure 3.

III. EXPERIMENTAL RESULTS

The EBG-based RFID Tag was extensively tested in order to assess its capability to work regardless of the surface where it is mounted.

In the first experiment, we performed a sensitivity analysis in anechoic chamber when varying the interrogation frequency. The EBG-based Tag was mounted on a polystyrene sheet and placed 1 meter away from a circularly polarized antenna (8 dBi gain) connected to the Voyantic Tagformance Reader. The minimum power required to communicate with the Tag was recorded at different frequencies in the 840-1000 MHz band with 1 MHz step. Figure 4 shows the comparison between the EBG-based Tag and an inkjet-printed dipole Tag. Both Tags exhibit a broadband behavior with best performance achieved in the U.S. UHF RFID band (902-928 MHz). Here, the EBG-based Tag outperform significantly the dipole which requires about 6 dB more power to communicate with the Reader. Since current RFID systems are forward-link limited [8] and therefore the maximum read range exclusively

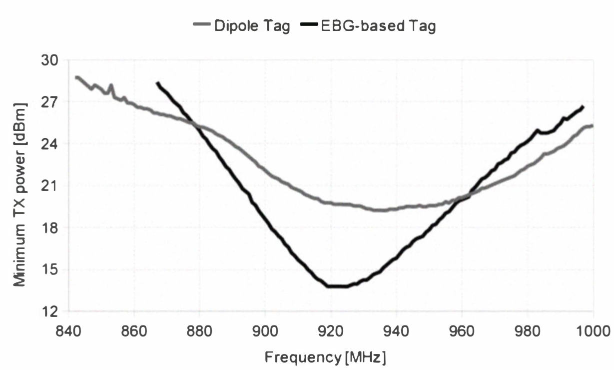

Fig. 4. Sensitivity analysis in anechoic chamber: comparison between EBG-based Tag and dipole Tag.

depends on the Reader EIRP, a sensitivity gain of 6 dB in free space allows to double the read distance of the EBG-based Tag over the dipole.

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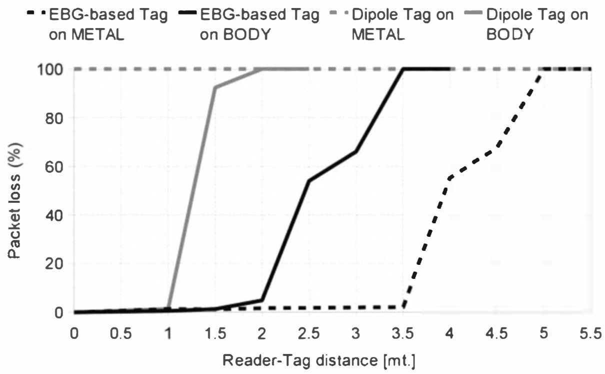

Fig. 5. Indoor read-range analysis: comparison between EBG-based Tag and dipole Tag attached to different surfaces.

In the second experiment, we evaluated the reliability of the Tag-Reader communication in real application scenarios. The EBG-based Tag was attached both to a metal surface and to a human body for future applications like container tagging and bio-monitoring. The Impinj Speedway Reader (operating frequencies 902-928 MHz) was used to interrogate the Tag in a standard office room. Figure 5 shows the measured packet loss, i.e. the ratio between the number of lost Tag replies to the total number of performed interrogations, at the Reader. The EBG-based Tag can be reliably read up to 4.5 meters and 2.5 meters when attached to metal and human body, respectively. The difference in range between metal and body is due to the lossy dielectric properties of the human body close to 0.3 for the loss tangent [9]. There is less constructive reflection off of the body which contributes less to the gain compared to metal. The dipole Tag instead exhibits extremely poor performance on both surfaces: it is never read on metal and can communicate with the Reader up to 1 meter away when attached to human body. The measurement results are in

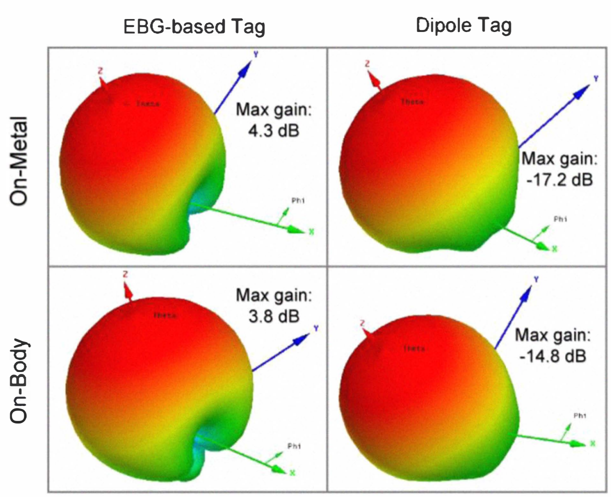

Fig. 6. Simulated 3D radiation patterns of the EBG-based and dipole Tags on both metal and body.

perfect agreement with simulations performed by HFSS: the maximum gain of dipole Tag is extremely poor both on-metal and on-body while the EBG-based Tag exhibits excellent performance on both surfaces (ref. Fig. 6). This clearly demonstrates the inappropriateness of commonly adopted RFID Tags in harsh application environments. In such situations, ad-hoc Tags like the EBG-based one here presented are required in order to ensure a reliable communication with the Reader.

IV. Conclusion

In this paper a via-less, flexible, EBG-based RFID tag has been introduced. Both in chamber and real environment measurements demonstrate the increase in gain and range due to the EBG structure. One of the main applications for this is a wearable RFID tag. However, this can be extended to any surface because any effect of the surface is isolated from the tag due to the ground plane.

Acknowledgements

This research was supported by the IFC-SRC and NSF-ECS-0801798.

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