High Code Density and Humidity Sensor Chipless RFID Tag

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***Abstract*— This article presents a low cost, miniaturize, flexible, high code density chipless sensor tag. The tag is designed on polyethylene terephthalate (PET) substrate with a compact size of 1cm radius operating in ultra-wideband, ranging from 3.5 to 16GHz. The overall structure and results have been significantly improved in comparison to the latest research. It has high code density of 6.92bits/cm^2, regular geometry, larger sensitivity for the humidity of 60MHz/%RH variation, high magnitude frequency dips, angular stability up to 60^o, high radar cross-section, low cost, and compact size are distinctive outcomes of the suggested sensor tag. It is simulated in computer simulation technology microwave studio (CST-MW). The tag can provide information about biomass locomotion, available weight in storage and combust. It has robustness, grind-bile, and combustible properties during combustion and pyrolysis process. This paper provides a pathway for biomass pellets tracking and humidity monitoring by using a battery-free chipless RFID sensor tag in real-time.**

Index Terms*— Biomass, Chipless RFID Tags, Code density, Humidity monitoring, Tracking.

I. Introduction

Radio-Frequency Identification (RFID) tag is a wireless data capturing device which utilizes its on-board power source or collect power from radio-frequency (RF) signals for recognition of remotely located objects. It has good ability to identify objects remotely due to numerous advantages over barcode technology [1], such as long-distance reading ranges and no requirement for line-of-sight detections. Currently, RFID technology is an emerging technology in commerce, tracking systems, health monitoring systems, security, access control, and industries due to their low cost, simple designing and realization. An Australian company used RFID tag's electronic product code (EPC) in a large scale RFID infrastructure to track goods across the globe[2]. This automation trend includes the Internet of Things (IoT), cyber-physical systems and cognitive computing technologies. Furthermore, manufacturing control, product localization and monitoring of environmental parameter variation can be achieved by integrating RFID tags with/within product during the manufacturing process [3]. For such applications, the existing RFID technology provides two types of Frequency Identification (FID) tags [4]; active and passive. Active RFID tags assisted with on-board battery and can be used for long read rang up to 500 m, high coding capacity and other necessary information [4]. However, it is not a good candidate for tracking of cheap and bulky applications due to the high cost of lithium cell battery [5].

Therefore, an extensive research effort was made to reduce cost by dropping on-board power source which resulted in Passive RFID tags. These battery-free tags provide a good solution in terms of designing, fabrication, cost, size and environmental friendly [6]. Passive tags collect power from RF signals for its operation and response back to the reader [7]. Further Passive technology categorized into chip-based and chipless RFID tags [5]. The chip-based tag consists of an antenna, inlay loop integrated with semiconductor chip (IC), a data storing unit [8]. Where the antenna is used as the transceiver, collecting power from RF signals which coupled to IC and also used for a response back to the reader by using EPC Gen2 standard [7][9]. The passive chip-based tag also provides a good environmental sensing capabilities, where the chip is covered with (or fabricated on sensing) material, such as cardboard and Kapton [10][11].

Generally, the RFID system consists of a large number of deploying tags, a few readers and middleware software that encode and decode tags and transmit data to a computer. Therefore, the total cost of the RFID system depends on unit tag [4]. Significant research efforts has been made to reduce the cost and complexity of the unit tags, by providing the necessary information without a storage unit (IC), which resulted in chipless RFID tags [12]. Chipless RFID tags are simple in design, inexpensive and miniaturized in size, but have smaller coding capacity and less read range as compared to chip-based RFID tags [9] Chipless RFID have a different working mechanism compared to chip-based, as the coding information and sensing capabilities are stored in design and fabrication of geometrical structure [13]. Plain waves were fallen on the geometrical structure of the tag, which was passing through or reflected back (backscatter) in a particular spectral signature pattern, treated as code [5]. In the past decade, an extensive research effort has been made for increasing chipless tags coding capacity, read range and sensing capabilities, which suggesting various alteration in the geometrical structure [7]. For example, *R. Dinesh et al* [13] published a tag with 8 straight slot/resonator for encoding 8 data bits with corresponding frequency signature in radar cross-section (RCS), but this tag has a larger size and low code capacity. In [14][15], the research brings QR optical code integration with 8 bits chipless tag for increasing the combine coding capacity, however this types of tag will increase the cost due to the use of two readers for detection, QR code reader and chipless tag reader, also there is uncertainty in tags code reading. In [6], a 28.5-bit tag is reported with a high code density of 3.56bits/cm^2, however, this work has a lack of advance sensing application. Further research work reported in [16], brings Chipless tag sensors which sense the environmental variation by structural deformation of tag or by variation in the dielectric permittivity of the sensing materials, which encoded as a shift in the spectral signature. A crack sensor was reported in [17], which works on the structural deformation principle. The crack was localized by using a few meter transmission lines integrated with chipless tag, however, it could not encode multiple IDs for use in bulk amount applications.

Recently, further innovation in chipless tags brings sensing capabilities added with ID encoding bits to make tags more diverse and smart for academic and industrial field [1], such as humidity, temperature, and CO_2 sensors. Humidity control is of great concern to various industries such as pharmaceutical, climate control, and foods storage. Numerous humidity sensors have been developed, as reported in [7] [12] [18] [19]. In [7], a humidity sensor was designed on a moisture-sensitive paper substrate and ID encoding slots were designed on polyethylene terephthalate (PET). This work suggests two tags, one for sensing and another for ID encoding, which is expensive for low-cost applications and decrease the coding density.

In [12], four planners stepped impedance resonators based structure were designed on a single tag. One resonator was covered with Kapton humidity sensitive material which results in spectral signature shift with humidity variation, while the rest of three resonators was used for ID encoding. However, this tag has a larger size due to separately designing each resonator. In [18], an inductive capacitive (LC) resonator added with three nested 'U' shape slot. Later on, LC resonator was covered with humidity sensitive Polyvinyl Alcohol (PVA) solution, thus it incorporates ambient humidity variation. While three nested 'U' shape slots were used for data encoding. The LC and 'U' shape slots were designed separately on same substrate, which resulted in large size and low code density. Another research work proposed data encoding slots on humidity sensitive material Kapton, but it's all spectral signatures were disturbed with humidity variation [19]. Moreover, the spectral signature was also very small in magnitudes, which result in difficulties for the reader to differentiate between the bit and electrical noise. In [5], A 12 nested 'U' shaped slots were designed in a compact dimension of 17x20mm. The interior slot was covered with Kapton for monitoring humidity variation and outer 11 slots were used for ID encoding. This structure topology increased code density along-with ID encoding and humidity sensing.

This research presents a high code density, maximum average humidity sensing, inexpensive, miniaturize and easily fabricate-able sensor tag. In this research, a unique geometrical structure is adopted with a PVA solution for humidity monitoring. Due to the unique geometrical structure, the following features have been significantly improved to the performance of the suggested tag:

- Code density were significantly improved as compared to [1][6][7][19][20][21] [22][23][24][25][26][27].
- Spectral signatures of 5 to 22 dB Magnitude has been achieved as compared to [19][28][29].
- Highest and clear humidity sensing have been achieved as compared to [1][7][20][30][31][24][32].
- Moreover, miniaturization, item identification of 2^{17} and humidity sensing are the most important aspects of this work.

This paper consists of section II describing tag designing and operations, section III explains results and discussion, section IV humidity monitoring, section V application of the tag, and concluded in section VI.

II. Design And Operation Of Passive RFID Tag

A. Tag Designing

The proposed tag consists of nested concentric hexagonal and spiral shapes resonators, which is simulated in computer simulation technology (CST). A polyethylene terephthalate (PET) substrate was used with a thickness of 75μm having dielectric permittivity ε_r=2.94 and tangent loss is 0.0012. The hexagonal shape was selected for geometrical structure due to its maximum angular stability and minimum mutual coupling which result in highest code density with minimum noise [3]. The plane waves were incident for exciting the tag. Spectral signature at a particular frequency is achieved by etching resonator in copper cladding of thickness 0.012mm.

Equation 1 is used for calculating the radius R_s of hexagonal shape resonator for particular frequency f_{res}. Here C is the speed of light and ε_r is the relative permittivity of the substrate used.

$$R_s = \frac{C}{2\pi f_{res}}\sqrt{\frac{2}{\varepsilon_r+1}} \quad (1)$$

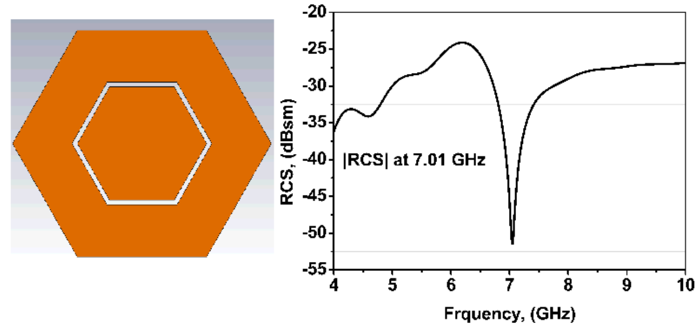

Fig. 1. (a) RCS response of a resonator (radius 5.4mm) having a spectral signature at 7.01 GHz.

Initially, a single hexagonal resonator of radius 5.4 mm was calculated for a frequency of 7.01 GHz. Its Radar Cross Section (RCS) response of 27dBsm magnitude dip was achieved after illuminating the tag with a plane wave, as shown in Fig. 1. Thus, it can be used as a 1-bit data encoding chipless tag. For further increasing data capacity, the same design approach was followed and extended to 17 hexagons and a spiral shape slot at the interior space. During the design, it was observed that addition of new slot affected the earlier slot spectral signatures in terms of resonating frequencies, magnitude dips and guard band of consecutive bits. Therefore, each hexagonal slot has a 0.2mm width and space with consecutive slot. The optimized tag substrate has radius Rs=10mm, the innermost slot has a radius of R1=2.6mm. Each slot separated from the consecutive slot by a gap of 0.2 mm except R17 having a gap of 0.4 mm. The outermost slot has radius R17 =9.2mm. Subsequently, a spiral slot of minimum length 11.5, width and spacing 0.2mm was added inside concentric hexagonal for sensing purpose. The mutual coupling is more reduced by a change of geometry pattern from hexagonal to spiral (Fig. 2). The detail tag dimensions were summarized in Table I.

III. Results and Discussion

The simulation was performed in commercially available electromagnetic simulation software Microwave Studio (CST-MWS) [5]. Where the tag was excited by a horizontal plane waves. RCS probe is placed in a far-field at 70cm distance and observed the backscattered signals. This distance can be calculated by using equation 2. Where 'D' is the maximum dimension of tag and 'λ' is a central wavelength of the used operating frequency band.

$$d = \frac{2D^2}{\lambda} \quad (2)$$

The simulated results of the 18-bit tag are presented in Fig. 3. It has been observed that the addition of resonator effect nearby frequency signature magnitude and guard band in terms of overall band compression, which is due to strong mutual electromagnetic capacitive and inductive coupling. The simulated results show that each bit has 1:1 correspondence with hexagonal resonator such as B1-to-B17 has correspondence with R1-to-R17. B17 was treated as the most significant bit (MSB). Where the least significant (LSB) bit is a spectral signature of the spiral resonator which was used for sensing purpose. The mutual coupling was stronger after removal of a resonator for producing a different combination, which causes a slight shift in nearby spectral signature dips. Therefore, a minimum guard band of 0.2 GHz is achieved between two closely resonating data bits to avoid spectral dips interference.

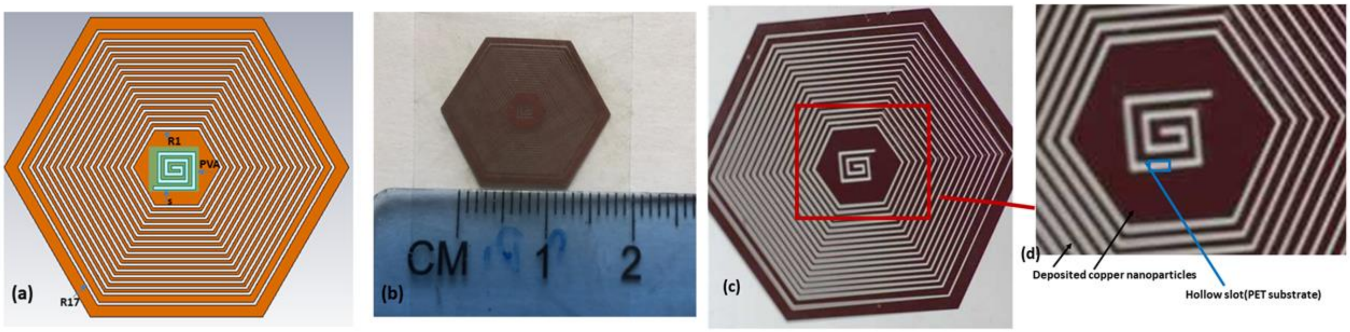

Fig. 2. a) 18-bit chipless RFID sensor tag having 0.2mm slots width and gapes (Radius R17=9.2mm, R1 =2.6mm), Along with spiral resonator (S=11.5m) covered with PVA solution, b) Laser printed tag, c) Microscopic picture of laser printed tag, d) Zoomed view of microscopic picture.

TABLE I: Dimension of proposed Tag, all resonators have a 0.2mm gap and width.

Resonator R_X	Radius (mm)	Frequency (GHz)	Guard Band (GHz)
R_1	2.6	14.57	0.79
R_2	3.0	12.37	2.2
R_3	3.4	10.88	1.49
R_4	3.8	9.73	1.15
R_5	4.2	8.81	0.92
R_6	4.6	8.0	0.81
R_7	5.0	7.38	0.62
R_8	5.4	6.7	0.68
R_9	5.8	6.28	0.39
R_{10}	6.2	5.89	0.33
R_{11}	6.6	5.56	0.35
R_{12}	7	5.21	0.29
R_{13}	7.4	4.92	0.28
R_{14}	7.8	4.92	0.23
R_{15}	8.2	4.64	0.22
R_{16}	8.6	4.41	0.21
R_{17}	9.2	4.21	0.2
S	Length 11.5	14.2 TO 25	--

A. Highest Code Density

After achieving the larger magnitude bits, miniaturize size with maximum encoding data bits of the proposed tag, the next goal was achieving the highest code density in a compact size. The code density of a tag was reported by *Munawar et al* in [6], which is a key for the performance of tags, instead of analyzing various parameters such as dimension, code capacity, and operating frequency. Using equation 3, they claimed the highest code density of 3.56-bits/cm^2. But it did not address humidity sensing and angular stability, which were the main concern of today industrial applications.

$$code\ density = \frac{Code\ capacity}{Tag\ surface} = \frac{Bits\ encoded\ per\ tag}{surface\ Area} \qquad (3)$$

Table II compares code density, and humidity monitoring achieved by various published literature to-date. Among the reported research work, although [12] has humidity monitoring capability, but in a large size with zero ID encoding bit. Later-on, [1][7][33][34] addressed humidity monitoring,

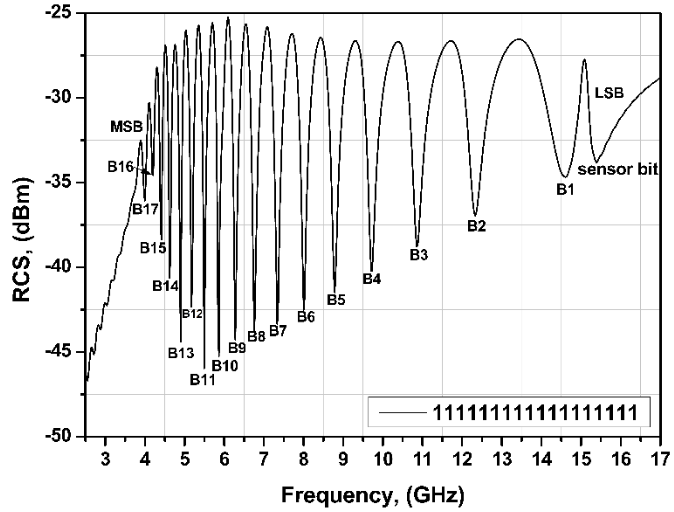

Fig. 3. The simulated RCS response of 18-bit tag, bit (B1) corresponds to the resonator (R1) and vice versa, MSB represent most significant bit and a least significant bit (LSB) or sensor bit is the response of spiral resonator.

However, their humidity sensing profile was low, and low code density. The code density was highly improved to 6-bits/cm^2 by [19], at the cost of low magnitude bits which can easily demolish with noise. This work integrate spiral resonator (sensor) with hexagonal shape tag provides high humidity sensing (60 MHz/%RH variation) and high code density (6.92-bits/cm^2) in a compact size of 2.6 cm^2.

B. Tag Manufacturing

Laser manufacturing processes at the University of Nottingham were used for this high bit density (18 bit) tag's manufacturing. manufacturing process were consist of sequential deposition of multilayer copper nano particles (Cu-NP), bar coating, and laser sintering [35]. The Cu-NP ink were deposited through glass pipet nozzle onto PET substrate. A metal bar with a wire wrapped around it was moved across each layer to build each layer, spreads the deposited ink and create even layers. The laser beam is focused onto the surface through an f-theta lens moves across the surface to selective sinter the Cu-NP layer into the previous layer. Polyethylene terephthalate (PET) was used as substrate. Fig. 2 shows that the laser printed tag normal picture, microscopic and zoomed view of microscopic picture. In zoomed view, the hollow slots are in white color which do not have any Cu-NP having PET substrate only, while the redish areas are the deposited Cu-NP layer on PET substrate. The future work consists of achieving its real time response.

TABLE II: Comparison of chipless RFID tag code density, and sensing performance with the reported in the literature.

Reference #	Dimension	Capacity	Code density	Item Encoding	Humidity Sensing (MHz/% RH)
[12]	10 cm^2	1 bit	0.1-bits/cm^2	×	√ (0.17)
[34]	2 cm^2	5 bits	0.2-bits/cm^2	√	√ (0.5)
[7]	16 cm^2	4 bits	0.25-bits/cm^2	√	√ (0.5)
[34]	2 cm^2	5 bits	2.5-bits/cm^2	√	√ (2)
[36]	3.65 cm^2	10 bits	2.74	√	×
[1]	1.05 cm^2	3 bits	2.84-bits/cm^2	√	√ (5)
[24]	1.02 cm^2	3 bits	2.94-bits/cm^2	√	√ (6)
[6]	8 cm^2	28 bits	3.56-bits/cm^2	√	×
[19]	4 cm^2	24 bits	6-bits/cm^2	√	×
[28]	4.52 cm^2	30 bits	6.63-bits/cm^2	√	×
This work	2.6 cm^2	18 bits	6.92-bits/cm^2	√	√ (50)

IV. Humidity Monitoring

Chipless RFID sensors can have a variety of sensor applications, such as crack sensor, gas sensor, strain sensor, and temperature sensor [16][21]. These sensors incorporate environmental variations by permanent structural deformations of tags such as crack sensor and pressure sensor [16], or by variation in the dielectric permittivity of sensing material used in the tag designing [12]. PEDOT, Graphene, metallic oxide, Kapton, Gelatin and single-walled carbon nano-tube (SWNCT) are reported in [1][5][16]. In [5], Adhesive Kapton tape was superstrated on interior slot for humidity incorporation. A thick layer of PVA was glued over resonator and observed its spectral signature response with variation in humidity [1][32]. Another humidity sensor was designed by using Kapton as a humidity sensing material [5]. Cardboard also has a strong affinity toward humidity absorption and has been used as a substrate in sensor designing [37].

In this work, a square shape PVA layer was model in CST simulation and used as superstrate on the spiral resonator [1]. It has a strong affinity toward humidity absorption which resulted in variation of its dielectric permittivity from 1.6 to 10 [33]. The spectral signature of the spiral resonator was strongly dependent on dielectric permittivity of the substrate (or covered material (PVA)). The change in humidity causes PVA dielectric permittivity variation, which is seen by spiral resonator by producing a spectral signature shift. Fig. 4 shows, that spectral signature of spiral resonator produce a negative frequency drift from 20GHz-to-18.8, 17.82, 17.3, 16.52, 15.85, and 15.24GHz with a relative humidity variation respectively, reported in [38]. Fig. 5 shows the general block diagram setup for measuring the humidity of the proposed Chipless RFID tag.

Moreover, theoretical results show that the frequency resonance of only sensing bit was changed with a variation in humidity while remaining frequency resonance (ID encoding bits) remained unchanged. Emran et al reported in [34], a 3.2 MHz/% RH variation, which was further improved by Dongh et al [32], which claimed the highest humidity sensing of 42.7 MHz/ %RH. Based on theoretical simulation and results of suggested sensor tag provides higher sensing capabilities of 60 MHz/ %RH shift.

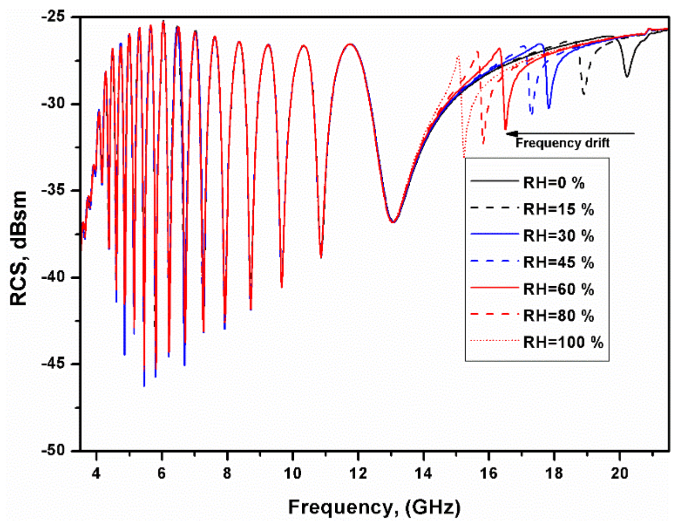

Fig. 4. Simulated RCS response of Humidity sensor at a different relative permittivity of PVA solution.

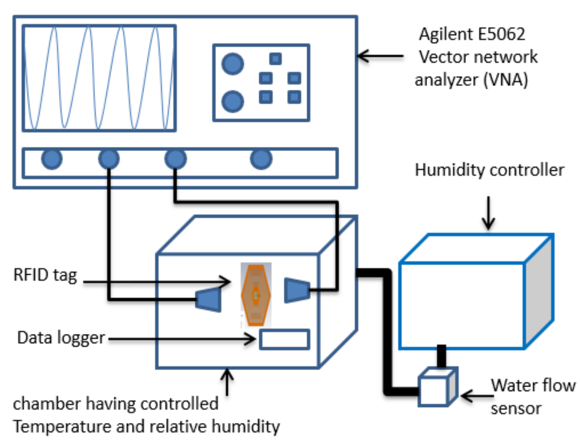

Fig. 5. 3D block diagram of the experimental setup.

V. APPLICATION SPECIFIC TAG

Biomass pallets are worldwide used as 4th largest and primary power generation source after oil, gas, and coal in industries [39]. The main objective of replacing biomass fuel as an energy source is to reduce greenhouse gas (GHG) emission, sustain depleting fuel sources and deliver competitive lower price fuel to end-user/ industries [40]. In [41], It is estimated that United Kingdom will be using at least 15% biomass fuel of its total energy consumption by 2020. Therefore, efficient use of biomass fuels needs online information with automatically updating of its receiving from the provider, available in-store and combusted. A number of research approaches [39][40][42], is suggested and supposed to fulfill these needs. However, none of these research efforts could cope several requirements such as tracking/ localization, managing whole supply chain along-with humidity, temperature monitoring, and gas sensing. In contrast, radio frequency identification (RFID) technology has that much flexibility to track biomass supply chain, automatically updating along with monitoring of different effective environmental parameter variation [1]. This tag is designed for biomass tracking from supplier to end-users and in storage units and providing information about humidity level variation.

VI. CONCLUSION

This tag is designed on low-cost PET substrate for biomass tracking and monitoring its humidity level. A unique feature of high code density in a small geometry were added due to application requirements. This battery free sensor is environmentally friendly along-with enough robust to provide data in harsh conditions. Additionally, it has grindable and combustible properties during combustion and biomass pyrolysis process.

The future work is to measure the manufactured tag RCS response. Additionally, the proposed block diagram setup will be realized for humidity monitoring.

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