Design and Feasibility Analysis of Conventional Planar Antennas as Chipless RFID Strain Sensors

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***Abstract*—This paper focuses on the design and feasibility analysis of conventional planar antennas as chipless RFID strain sensors. A number of printed monopole and dipole antennas are designed and their structural deformation due to different types of applied strain is theoretically analyzed. This theoretical deformation results are used to calculate the corresponding resonance frequency and quality factor deviation to determine the maximum amount of strain the antennas can handle. Thus a novel analysis is presented to determine the acceptability of the designed antennas as strain sensors.**

Keywords— Structural Health Monitoring; Chipless RFID; Strain; Planar antenna; Monopole; Opposite Bent Dipole.

I. INTRODUCTION

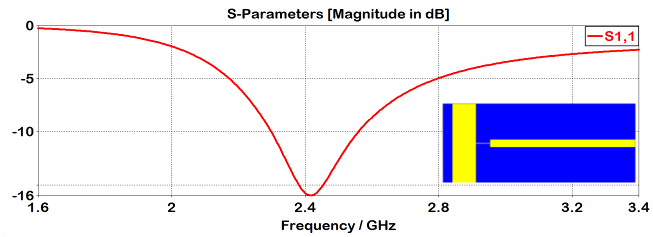
Radio Frequency Identification (RFID) is a wireless data capturing technology that utilizes radio frequency waves for automatically extracting the identity of remotely placed objects. The recent development of chipless RFID technology gives a new direction in the field of RF identification to address new markets such as item tracking. This technology does not embed any silicon ICs for the ID extraction; instead it uses the EM signature for data encoding which reduces the cost of the RFID tag to a level as low as the barcode [1]. Recent advancement in wireless sensor networks has paved the way to combine sensor and sensing technologies with RFID system. The development of sensors and associated measurement circuits pose a challenge towards the deployment of a low cost intelligent sensing system for which chipless RFID technology could offer an appropriate solution [2]. Such sensors are more adaptable to energy harvesting, have a simpler structure and are more compatible with harsh environments. Chipless RFID sensors have huge potential in retail, structural health monitoring, transportation, biotech, pharmaceuticals, security and surveillance as well as precision agriculture (PA) [3].

Strain is a parameter that indicates a physical deformation due to some mechanical loading. Strain is a critical parameter in structural health monitoring essential to many industries ranging from civil infrastructure, mechanical equipment to aerospace as well as agricultural applications. In civil structures, strain sensing is needed for safety assurance of roads, bridges, and building supports to avoid unexpected collapses [4]. In manufacturing processes and constructions, strain sensing allows the monitoring of vibration, excessive loading, and crack developments to be detected early [5]. In modern agriculture, the soil shrink-swell phenomenon is a major threat to a sustainable soil quality and it has become a real concern to many agricultural soil scientists and farmers. Agricultural soils are exposed to great mechanical stress due to heavy farm machinery traffic, which can lead to a reduction of porosity and hence introduce soil shrinkage or compaction. The determination of soil strain/stress enables the scientists to verify the prediction models of soil compaction or swelling, resulting from applied loads [6]. The strain detection has a tremendous requirement of wireless, low-cost, compact, fully autonomous and highly reliable devices that are able to continuously monitor possible anomalies in materials and/or in the geometric properties of a structural system [7]. There have been several different approaches to strain detection through chipless RFID technology. An RF strain transducer equipped with a microstrip patch antenna loaded with an open loop is proposed in [5]. Occhiuzzi et al. proposed a passive RFID strain sensor based on meander line antennas [7]. The feasibility of using antennas in general as radio sensors for strain and crack monitoring has been investigated in [8, 9]

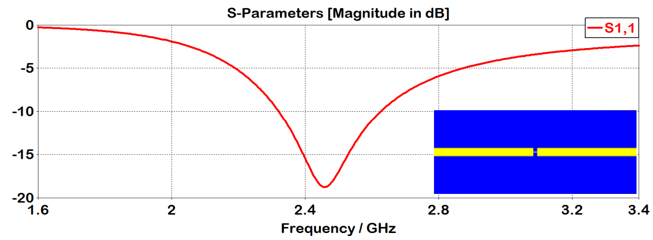
This paper focuses on the design and feasibility analysis of a number of planar antennas as chipless RFID strain sensors. Conventional and printed monopole and different types of dipole antennas are investigated here. The article provides a theoretical comparison of performance of the designed antennas under different types or orientations of applied strain and thus detects their acceptability of being used as strain sensors.

II. DESIGN AND WORKING PRINCIPLE

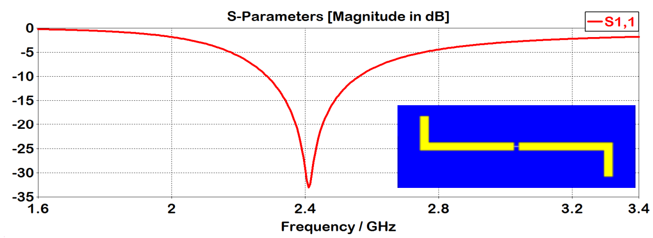
Antennas play one of the most significant roles in Auto-ID and sensing procedure which comprises both the RFID tag-sensors and readers. If properly optimized, antennas increase the efficiency and overall performance of the system. In this paper, four conventional printed antennas - monopole, dipole, opposite-bent dipole and a flying bird dipole are designed. The proposed sensing antennas are designed on Taconic TLX-8 susbtrate material with relative permittivity, ε_r= 2.55 and dissipation factor, tan δ = 0.0019. The thickness of the substrate is 0.127 mm with a 17 um thick copper cladding which indicates the flexibility of the sensors. The Fig. 1 shows the designed antennas with different configurations and their return losses. It can be observed that all the designed antennas operate at Industrial, Scientific and Medical (ISM) band 2.45 GHz.



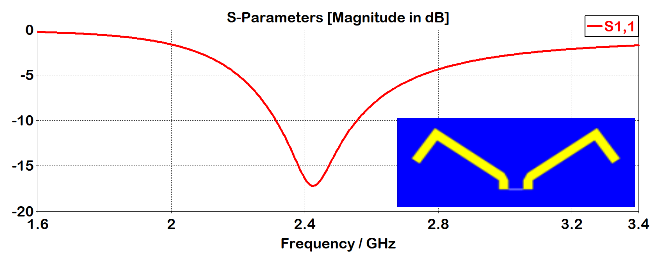
(a) Monopole antenna and its return loss



(b) Dipole antenna and its return loss



(c) Opposite Bent Dipole antenna and its return loss



(d) Flying Bird Dipole antenna and its return loss

Fig. 1. Designed conventional printed antennas with return loss

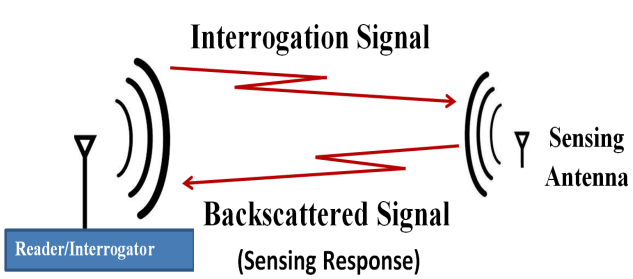


Fig. 2. Chipless RFID strain sensor interrogation system

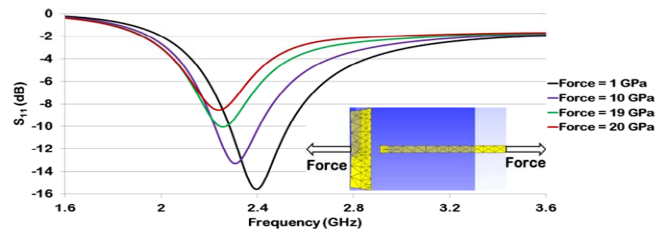
An applied strain changes the size of the resonating metallic arms or patch, which produces a shift or deviation in the antenna's resonant frequency or quality factor. However, the proposed platforms require specific interrogation system and dedicated receivers in order to detect such deformations. Fig. 2 shows the sensing system consisting of a reader or interrogator along with the chipless RFID based strain sensing antenna. The RF interrogating pulse from the reader illuminates the antenna which is then reflected back to the reader with the encoded strain information due to deformation.

Strain is measured by the deformation of the material volume along the direction of strain. It is denoted by $\varepsilon_L = \Delta L/L_0$ where the initial length L_0 in the stretched direction is deformed into L as depicted in Eq.1 [5].

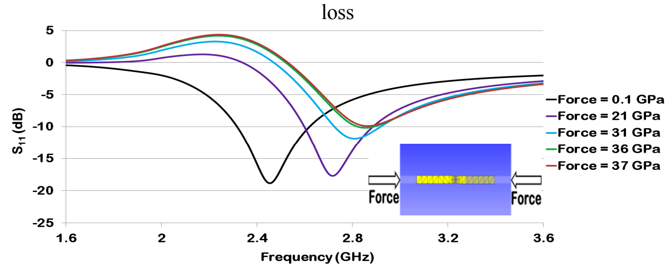
$$L = (1 + \varepsilon_L)\, L_0 \qquad (1)\ [5]$$

III. RESULTS AND DISCUSSION

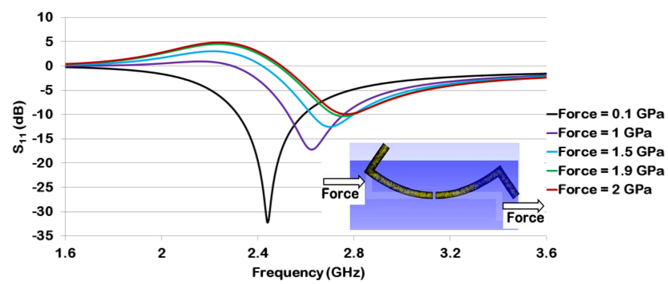
The electromagnetic solver CST microwave studio is used to design and analyse the performance of the proposed sensing antennas. The strain effect on the structure is provided by the CST mphysics studio. Later, simulation results from both the solvers are combined to analyse the sensing performance under certain applied strain.



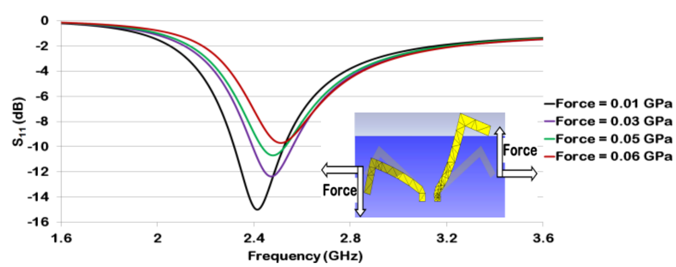
(a) Deformed monopole antenna and its sensing response in terms of return loss



(b) Deformed dipole antenna and its sensing response in terms of return loss



(c) Deformed opposite bent dipole antenna and its sensing response in terms of return loss



(d) Deformed Flying bird dipole antenna and its sensing response in terms of return loss

Fig. 3. Deformed sensing antennas and their return loss variation under different applied strain

Fig. 3 shows the deformed sensing antennas and their s-parameter response under different strain conditions. The purpose of this study is to provide a comparative analysis on the maximum tolerance level of applied force that the designed antennas can handle under various loads and strain orientations. Here, the strain effect on the substrate material is not considered since all the antennas are designed on the same substrate. The traction force with different orientations is applied on the edges of the resonating structure.

A. Monopole Antenna

Fig. 3(a) shows the sensing response of the monopole antenna under a shear force. It can be seen that the antenna resonates at 2.395 GHz with a traction force of 1 GPa (Giga Pascal) which depicts a deviation of 200 MHz from its original resonance frequency 2.415 GHz as shown in Fig. 1(a). As the traction force increases, the antenna resonance frequency keeps deviating further and the quality factor also starts to deteriorate. With force applied up to 19 GPa, the antenna keeps operating with return loss greater than 10 dB, however, the resonance frequency further deviates to operate at 2.25 GHz. At 20 GPa traction, the antenna stops operating completely as the impedance matching becomes very poor with a return loss of slightly greater than 8 dB. Therefore, it can be said that the monopole antenna with a shear strain can tolerate up to an applied force of 19 GPa while compromising the resonance frequency. As long as the practical aspects of strain applications such as the soil strain measurement and structural health monitoring are concerned, it is not always feasible to consider only the shear force on a sensing device. Here, the strain can be encountered from literally any arbitrary direction. Therefore, several other strain orientations are also taken into account. Table I shows the simulated results of maximum strain tolerance level of monopole and dipole antennas under different types or orientations of applied force. The monopole antenna can handle a maximum strain of up to 20 GPa under shrinking force which is quite similar to that of the shear force. However, in this case, the resonance frequency increases to 2.6 GHz due to the shrinkage in size of the antenna. If a one dimensional force is applied, the monopole can handle up to 27 GPa with the maximum resonance at 2.26 GHz. With a two dimensional force, the tolerable strain encounters a significant reduction with a value of 450 MPA (Mega Pascal) due to the deviation of arm orientation and structural deformation.

B. Conventional Dipole Antenna

Fig. 3(b) shows a shrinking stress applied on the conventional dipole antenna in order to determine its sensing behavior and maximum strain tolerance. As expected, due to the reduction in the dipole arms under increasing stress, the resonance frequency keeps shifting to the higher frequencies compared to its original resonance 2.45 GHz depicted in Fig. 1(b). Though the antenna deviates from the original resonance, it can be observed from Fig. 3 (b) that it can handle a high amount of stress (up to 36 GPa) before its operability gets seized. From Table I, it is evident that this antenna handles a high amount of strain (up to 24 GPa) with a shear force too. With a one dimensional force, the maximum strain tolerance of dipole amounts to a huge value of 994 GPa since at this strain type, the resonator dimension remains the same even with high amount of traction force. This is because, when one arm of the antenna is pulled with a certain force; the other arm is pushed with the same amount to maintain the similar shape of the symmetrical arms. However, if a two dimensional strain is applied; the force handling capability (400 MPa) of this antenna also gets reduced to the similar level of that of the monopole antenna.

TABLE I. MONOPOLE AND DIPOLE ANTENNA PERFORMANCE AT DIFFERENT STRAIN TYPES

Strain Force Type	Monopole		Dipole	
	Max Strain tolerance (GPA)	*Resonance at Max Strain (GHz)*	*Max Strain tolerance (GPa)*	*Resonance at Max Strain (GHz)*
Shear	19	2.25	24	2.19
Shrinking	20	2.6	36	2.855
One Dimensional	27	2.26	994	2.32
Two Dimensional	0.45	2.245	0.4	2.245

TABLE II. Opposite Bent DIPOLE ANTENNA AND FLYING BIRD PERFORMANCE AT DIFFERENT STRAIN TYPES

Strain Force Type	Opposite Bent Dipole		Flying Bird Dipole	
	Max Strain tolerance (GPA)	*Resonance at Max Strain (GHz)*	*Max Strain tolerance (GPa)*	*Resonance at Max Strain (GHz)*
Shear	3.5	2	0.4	2.155
Shrinking	0.6	2.49	0.06	2.465
One Dimensional	1.9	2.755	0.7	2.3
Two Dimensional	0.5	2.145	0.05	2.48

C. Opposite Bent Dipole Antenna

Fig. 3 (c) shows the effect of strain on the opposite bent dipole antenna. Here, a one dimensional traction force is considered. As it is evident from the figure, the orientation of the resonating structure gets changed with increasing strain due to oppositely placed arms. This instigates a quality factor deviation along with impedance mismatch which results in a deterioration in antenna performance. The antenna can handle up to an external force of 1.9 GPa. At 2 GPa, the return loss becomes less than 10 dB and the resonance frequency shifts up to 2.75 GHz which illustrates a deviation of about 300 MHz from its original resonance 2.43 GHz as shown in Fig. 1(c). TABLE II shows the simulated results of maximum strain tolerance level of the opposite bent dipole and flying bird dipole antennas under other types of applied force. The maximum strain tolerance of the opposite bent dipole under shear force is a bit higher than that of the one dimensional force. At this condition, it can tolerate up to 3.5 GPa though the resonance frequency shifts to 2 GHz. When a shrinking force is applied on this antenna, the maximum resonance frequency (2.49 GHz) due to strain does not change much from the original resonance and it only handles a maximum strain of 600 MPa. If a two dimensional strain is applied, this tolerance level reduces further to 500 MPa and due to antenna structure variation, the resonance frequency shifts to 2.145 GHz.

D. Flying Bird Dipole Antenna

For a two dimensional strain on the flying bird dipole antenna, the maximum tolerable stress reduces substantially which is evident from Fig. 3 (d). Here, the strain is applied on both the arms of the antenna. Due to the increasing two dimensional forces, the structure of the antenna gets completely deformed and hence it can only tolerate a traction force of up to 50 MPa before the return loss becomes less than 10 dB. Eventually, the resonance frequency also does not shift much (2.48 GHz) and it only deviates a mere 55 MHz from the original resonance (2.425 GHz).This antenna is not capable of handling much traction force even at the other types of strain which is evident from Table I. The shrinking force effects this sensing antenna in a similar way to that of the two dimensional force where the maximum strain tolerance is only 60 MPa. The shear force increases the length of the antenna and hence the resonance at the maximum strain reaches to 2.155 GHz. In this case, the strain tolerance reaches to a value of 400 MPa which is slightly better than the two dimensional or shrinking forces. For one dimensional strain, this antenna can handle the highest amount of force (700 MPa), however, in comparison to the other types of sensing antennas, this strain handling capacity is considerably small.

Table I and II also show the maximum deviation range of resonance frequency of the all the designed antennas from their respective original resonances. The monopole antenna ranges from 2.245-2.6 GHz considering different types of applied strain which indicates a maximum deviation of 0.185 GHz from the original resonance 2.415 GHz. The operating range is comparatively higher in case of dipole with 2.19–2.855 GHz. This designates a maximum resonance deviation of 0.405 GHz from the original. For opposite bent dipole, the maximum resonance under tolerable strain ranges from 2 to 2.755 GHz. Here the maximum resonance deviation is slightly higher than the conventional dipole with a value of 0.43 GHz. The flying bird dipole has a dynamic range starting from 2.155-2.48 GHz indicating a maximum deviation of 0.27 GHz from its original resonance 2.425 GHz. The above analysis illustrates that the designed sensing antennas can be interrogated with a wideband signal ranging from 2-3 GHz to obtain their sensing response. This also helps determining the suitable sensors for specific strain sensing applications. The applications areas such as structural health monitoring or soil strain monitoring, where the object or structure is exposed to less external traction force and the sensing needs to be performed over a long period of time, the opposite bent and flying bird dipole can be tremendous solutions for those sectors. On the other hand, the monopole and the conventional dipole sensors are mostly suitable for the applications that involve excessive loading such as manufacturing process and construction, mechanical equipment and early crack detection.

IV. Conclusion

This paper has focused on the design and analysis of four conventional and printed monopole and dipole antennas as chipless RFID strain sensors. A novel concept of interrelating the analysis of structural mechanics to the microwave problems is proposed here. The mechanical deformation due to applied strain is utilized to extract the resonance frequency or quality factor deviation in the microwave domain. All the designed antennas are analyzed for different orientations of applied strain in order to cater for pratical considerations. The maximum strain tolerance level along with the resonance frequency deviation are calculated to determine the feasibility of the designed sensors to be used for different strain applications. The future research will include the strain effect on the susbtrate materials along with the resonating elements. It will also involve a sensitivity analysis in terms of applied strain vs resonance frequency shift. Another aspect of further research involves the incorporation of ID in such sensors to keep track of them in a largely deployed sensor network. This can be achieved by adding mutually coupled resonators near the antenna feed line. The fabrication of the proposed sensing antennas will also be carried out as a part of the future work. These antennas are extremely low cost and robust, therefore, the implementation of such sensors would be a great milestone for the chipless RFID based sensors and hence a tremendous contribution to the RFID and wireless sensor research community.

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