Hindawi
Advances in Materials Science and Engineering
Volume 2021, Article ID 8905489, 9 pages
https://doi.org/10.1155/2021/8905489

Review Article

Characterization of Composite RFID Antennas Based on Thermal Properties: A Survey

Chitra Varadhan[1] **Fekadu Ashine Chamatu**[2] **and S. Arulselvi**[1]

[1]*Department of ECE, Bharath Institute of Higher Education and Research, Chennai 600 073, Tamilnadu, India*
[2]*Department of Chemical Engineering, College of Biological and Chemical Engineering, Addis Ababa Science and Technology University, Addis Ababa 16417, Ethiopia*

Correspondence should be addressed to Chitra Varadhan; chitralaya@gmail.com and Fekadu Ashine Chamatu; fekadu.ashine@aastu.edu.et

Received 25 July 2021; Revised 17 August 2021; Accepted 19 August 2021; Published 16 September 2021

Academic Editor: Samson Jerold Samuel Chelladurai

In this paper, a comprehensive survey on thermal and geometric design parameters of composite materials utilized in the fabrication of modern RFID systems has been discussed mainly due to its advantages such as lightweight and high strength. Designing of RF antenna setup requires careful consideration of material, geometric and fabrication parameters. Polymer materials were chosen as the substrate and subjected to extensive studies to determine and predict the capability of the miniaturized RFID antenna. The effect of the polymer matrix composite (PMC) material on the antenna parameters such as gain, bandwidth, and return loss is analyzed and realized that improvement in bandwidth and perfection in impedance matching can be further accomplished by employing fractal structure. It is also discovered that the thermal properties affect the impedance and operating frequencies, thus enabling multilayer PMC deploying fractal structured RFID antennas to be used for many applications such as logistics, aerospace, biomedical, and mining.

1. Introduction

Recent trends in the field of composites involve vigorous research in composite materials-based radio frequency identification (RFID) antennas. RFID comprises of two important elements, reader and tag. The radio waves are travelling from the reader, whereas tag has the ability to respond accordingly. The tag/reader is capable for both transmission and receiving the data by means of RF antennas. The major features of RFID technology are primarily the contactless transmission of data and nonline of sight between reader and tag. There tag encounters various environmental challenges such as grime, paint, fog, snow, ice, and bottles with chemicals while in storage. A massive utilization of UHF-RFID tag/readers in the day-to-day life such as item movement tracing, railway rolling stock identification, theft prevention, tracking library books, toll collections, vehicle parking access control, building access control, retail stock managements, proximity cards, and vehicle immobilizer systems.

Electro-civil industries such as aerospace or shipbuilding are widely using carbon-based materials in the fields as they demonstrate superior properties such as higher corrosion resistivity, long life time, and high stability within a wide temperature domain. Due to the extensive properties of carbon-based materials which are highly incorporated in resonators, filters, transmission lines, and high gain antenna designs, Aixin et al. communicated on composite metamaterials, exhibiting abundant properties in the microwave starting from 1 GHz to 100 GHz [1]. RFID system communicating through antenna includes the substrate sandwiched between the patch and ground plane. The substrate of the RFID antenna can be fabricated using a flexible heat sensitive polymer or a rigid heat retardant polymer based on the user application. Designing planar antennas is precisely dependent on the dielectric constant values such as loss tangent (Tan δ) and relative permittivity (ε_r). An increase in value of dielectric constant results in decrease of the antenna size yielding a narrow bandwidth, due to capacitive load influenced in RF energy [2]. Similarly, the thermal conductivity will influence the effects during the usage of antenna, resulting in shift in operating frequency, thus affecting the read range of the antenna. Design of RFID antenna is crucial and RFID engineers must have a broad vision about the temperature range experienced on the substrate during usage such that the selection of composite material should not deteriorate the overall performance of antenna.

Multilayered composite materials comprising of cardboard, gypsum, and natural flaked graphite were considered. The fundamental definite characters of radio-absorbing materials are influenced by the working range of the radiation wavelengths and thickness of the composite material. Composite absorbing materials can be employed in the RFID antenna as substrate, as well as radiating element to decrease the weight of the antenna, to improve the durability and to enhance the thermal expansion. The objective of the utilization of composite material is to enhance the performances such as gain and directivity, meanwhile suppressing interferences among the elements of antenna and performing with excellent transmission features in extensive RFID antenna frequency ranges. Bucky paper (single-walled carbon nanotube) is one of the most extremely conductive materials.

The remainder of the paper is organized as follows. Session 2 initiates with composite materials in RFID as a radiating element and elaborates on antenna substrates. Section 3 showcases the thermal conductivity measurement setup followed by the thermal conductivity in RFID, and conclusion is presented in Section 4.

2. Composite Material in RFIDs as Radiating Element and Substrates

Creation of optically transparent antennas appropriate for RFID systems can be adapted to various forms through the usage of conductive polymers [3,4]. In earlier days, RFID technology applications implemented nonconventional materials such as silver-ink, due to reasonable price. However, they are impractical for flexible RFIDs and are conformal as conductive polymers with the limitation of operation in low frequency applications. Literature surveys are proving that the composite materials used in RFID antenna have equivalent radiation characteristics to that of a traditional metal model. A popular fabrication method suggested in the literature survey is to coat the graphene on a nonplanar surface of the antenna.

Nicholas et al. [4] fabricated the antenna in copper as well as conductive polymer, Clevios PH500 PEDOT-PSS, through description; the selected conductive polymer has conductivity of 300 S/m. To optimize the conductivity, 10% dimethyl sulfoxide (DMSO) is combined with polymer, and to decrease the surface tension, 2% surfactant (Tween-21) is added. On simulation of both the RFID antennas, it was observed that the modified antenna shows conductivity closely equal to 5×10^5 S/m, which is nearer to the conductivity of copper 5.9×10^7 S/m. For the substrate, polyethylene terephthalate (PET) was chosen and the improvised RFID antenna was fabricated on the conductive polymer, with the dielectric constant of 3.8 and the thickness of 0.5 mm. Since dipole antenna does not require ground plane, the antenna is transparent, easy to design, and flexible in nature. Few properties and its corresponding values of graphene which is used as metal surface in the RFID antenna are listed in Table 1.

Biocomposite materials such as wood plastic composite (WPC) are served as antenna substrate, especially for the frequencies 1–20 GHz. One of the popular selection of WPC is polypropylene (PP) and Leucaena Leucocephala wood filler used as an adhering (laminate) substrate for RFID antenna. The WPC is a desirable material as it is commonly available in nature and cost-effective with thermal resistance up to 180°C of melting point. The hot and cold pressing methods are used to construct the antenna substrate. During the progression, certain gap dispute arises due to the formation of internal blisters due to heat transmission. Measurement of thermal distribution and dielectric properties inside the substrate measurement is difficult to perform. However, the study of temperature and pressure required for hot/cold pressing, material moisture content, venting time, and humidity are essential, since the water absorption leads to the formation of air bubble inside the prototype, therefore resulting in degradation of RF signal. The literature says that the thermal properties of wood are mostly affected by denseness, wood structure, fibre, moisture, and carbon contents. Therefore, wood filler with polypropylene as RFID substrate is laminated to provide tolerance to moisture absorption and also raise the immunity to the thermal conductivity.

In polymer thick film technology, the usage of conductive paste as substrate is due to improved electrical performance of printed RFID antennas even though the conductive paste gives rise to increase in resistance [5]. This technology works well at low temperatures on cost-effective substrates, especially in membrane keyboards and electromagnetic shielding to avoid electromagnetic interferences in the miniaturized electronic devices. Most commonly used conductive pastes are copper oxide and silver oxide. The particle density of the conductive silver paste provides substantial increase in paste properties, as the resistance of copper oxide paste is substantially increased after curing when compared with silver oxide which remains invariable irrespective of change in environmental conditions. The resistivity of conductive paste can be decreased by 70%; reliability improved around 2.4 times and also reduction in area compared to conventional smart labels when particle density is increased. Due to compression process, the conductive silver particles create a contact with substrate material and produce better performance compared to copper engraved smart labels.

The composite materials are associated in injectable RFID antenna; a passive RFID antenna is embedded at the bottom of the skin to transfer the data for monitoring the glucose level and orthopaedic identification. The antenna is printed on plastic sheets as stickers and is fixed subdermally. In traditional methods, the antenna includes conductive inks and paints submerged inside the skin. This results in occurrence of imperfection due to ageing. Recent research on

Table 1: Properties of graphene-composite metal antennas [3].

Parameters	Brass	Zoltek Px 35	Aluminium
Tensile strength	450	4137	100
Tensile modulus	100	242	75
Density	8500	1810	2700
Electrical resistivity	6×10^{-8}	15.5×10^{-6}	3×10^{-8}
Temperature of melting (decomposition) of metal (GCM) (°C)	900	>650	650
Coefficient of thermal expansion	19.1×10^{-6}	8×10^{-8}	23.8×10^{-6}

polymer engineering development has devised injectable nanocomposite hydrogel material which is solid at body temperature [6–9]. The muscles act as ground plane and the antenna injected on the fat gives accurate results compared to conventional injectable skin antennas. This modified RFID antenna provides sufficient substitution for the future generation work on subdermal RFID antennas.

Mobile antennas can be realized using polymer magnetuo-dielectric (MD) material and copper coating as radiating element. A schematic representation of polymer-based mobile antenna is shown in Figure 1. Polycarbonate is used as a substrate and the performances are evaluated and compared with conventional FR 4 [10]. It is observed that there is a difference in wavelength between the antenna substrate and human body. This causes a shift in resonant frequency, which is moderated by the usage of MD substrate, resulting in greater efficiency. It was also detected that the regression of performance of the antenna is reduced by implementation of MD material when compared with conventional material. The weight of the magneto-dielectric antenna is 2.88 g, which is slightly more compared with traditional mobile antenna weighing 1.41 g.

In recent years, anisotropic conductive adhesives (ACAs) are very popular in applications of RFID flip chip packaging. The ACAs are having enormous advantages when compared with conventional bonding materials due to minimal cost, less processing steps, and lower processing temperature for large scale RFID tag inlays manufacturing. Majorly there are two types of ACAs, one is anisotropic conductive pastes (ACPs) and another is anisotropic conductive films (ACFs). Fabrication of a flexible RFID antenna with polymer adhesive continues to prove as a struggle. Compared to ACPs, the cost of ACFs is much higher and the stability of RFID tags is low. ACAs are structured by blending micro-sized spherical silver components with possible curing agent into a thermos-set epoxy resin. On aluminium blended with polyethylene terephthalate (PET), the RFID chips were fabricated, silver/PET was printed, and silver/paper antenna was printed through hot-press bonding process. Reliability tests are performed and flip chip on flex association were calculated [11] in which it was discovered that during the hot-press process, the polymer matrix is unstable and nonuniform. Hence, post-curing was suggested to improve the stability of the antenna substrate. The RFID tags adhering to the substances which contain conductive materials result in degradation of radiation properties such as impedance mismatch, shifting in operating frequency, changes in radiation pattern, and reflection in radiating RF energy (S_{11}). These variations

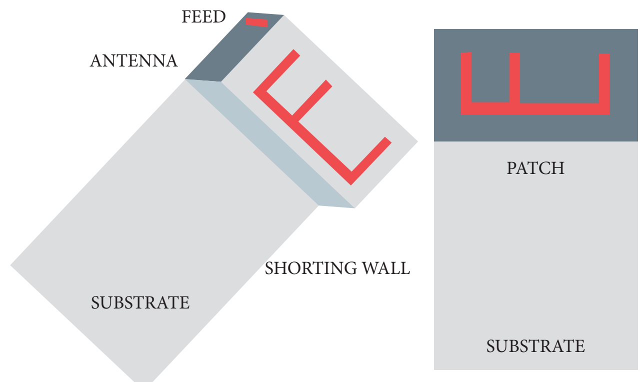

Figure 1: Polymer-based mobile antenna on polycarbonate substrate.

depend on the shape, size, and antenna distance from the conductive material [11]. Thus, selection of composite materials is very essential to improve the RFID reader/tag antenna parameters.

3. Thermal Conductivity in RFID

RFID technology depends on common parameters, such as pressure, luminosity, humidity, deformation, and temperature. Due to measurement inaccuracy of the above parameters, the antenna performance is compromised. Accuracy of antenna is of utmost importance in critical applications and increase in temperature induces degradations in performance of RF signals. Temperature is nothing but heat intensity present in any element or body. Therefore, thermal analysis has become mandatory for commercial applications of RFID antennas. As from the literature surveys, parameters like operating frequencies and impedances decline due to increased temperature in metallic parts and substrate of the tag antenna [12, 13]. This results in impedance mismatch between reader and tag; this discrepancy can be avoided by self-tuning circuit in the RFID chip. The self-tuning circuits are used for acquiring values from chip memory bank for acknowledged input temperature values and a RFID tag can be regulated and worked as a temperature sensing element. This method can be adopted only for fixed RFID tags, since the input impedance is a function of received power. Thus, the self-tuning circuit can be activated to accomplish various values of known input power [14]. Table 2 presents association between the thermal expansion coefficient and the thermal coefficient of relative permittivity.

Table 2: Input impedance of the three RFID chips as function of temperature [12].

Temperature (°C)	Real part of impedance (Ω)			Imaginary part of impedance (Ω)		
30	6.85	8.03	7.45	−139	−134	−132
40	7.4	7.34	7.46	−138	−135	−132
50	7.53	8.5	7.81	−138	−133	−131
60	7.69	8.6	8.16	−138	−133	−131
70	7.9	8.66	8.23	−134	−134	−131
80	8.52	8.79	9.34	−138	−133	−131

In the design consideration, RT6010.2LM is used as a substrate ($\varepsilon r = -$ 425 ppm/°C), which gives high thermal coefficient. The RFID tag is activated with a very low power sensor providing extraordinary read range, accomplished with smaller size. The electrical performance is directly proportional to the reading distance; hence, a low antenna resistance is necessary, especially for long range systems, e.g., airline baggage handling or parcel services. There are 2 methods to decrease the resistance: (1) increasing the track height by repeated print of the coil structure or (2) increasing the particle density within the paste by applying a compression process. Due to its economic and ecological advantages, the second method can be adopted. The thermal modification of substrate contributes overall sensitivity of tag. Konstantinos et al. described that the variation in temperature results in slight increase of input impedance by very little amount on real part while the imaginary part remains unaffected. Due to the presence of self-tuning circuit, the imaginary part remains almost constant in the UHF-RFID chips. Some properties of commonly used substrate are listed in Table 3. The substrates and its corresponding coefficient of thermal expansion and temperature coefficient of relative permittivity are tabulated.

A UHF passive RFID temperature sensor tag antenna is designed and simulated using EM software. A cavity backed slot antenna is proposed in this design as a RFID tag antenna. Polytetrafluoroethylene (PTFE) material is realized as temperature sensing material due to its high thermal expansion around 140 ppm/°C. In the centre of the slot antenna, a copper-layered PTFE pole is employed and is vicinity to the cavity ceiling. Thus, between cavity ceiling and PTFE surface, a loaded capacitor is induced. When temperature increases, PTFE approaches cavity ceiling, thus there is a change in frequency of slot antenna due to the thermal expansion. The expansion results in a frequency deviation of 30 MHz/10°C and of 10.5 m read range with the calculated value. Figure 2 shows the linear relationship between thermal displacement vs temperature variations [15–19]. Generally, the thermal expansion can be realized at moderate temperatures. The effects of thermal expansion can also be experimented in metallic nanostructures through 5 nm-wide RFID slot antenna by providing additional degree of freedom in the nanostructure results in improved functionality in thermal modulation. The effects of thermal variation are established by comparing the features of air-filled slot antenna and spacer-filled slot antennas.

The EM software and coupled mode method (CMM) were used to simulate and measure the modulation in resonant frequency at different temperature. The temperature deformation of slot antenna is embedded on glass substrate. During the increase of heat gradually from 25°C to 190°C, it is observed that the width of slot antennas is diminished from 5 nm to 2 nm due to thermal expansion. During heating, the slot antenna thickness increases linearly. Thus, variation in frequency of operation can be reduced by impregnating the nanostructures with active materials, for example, vanadium dioxide-based nanostructures.

3.1. Thermal Monitoring Measurement Setup. The thermal properties were measured using thermal property analyser. The antenna under test (AUT) is experimented by perfectly insulating the small antennas in the Fresnel region and the temperature is monitored [20–24]. The cold temperature measurement setup which is maintained under −100 °C can be extended to full cold-hot temperature spectrum. The liquid nitrogen is filled in the bottom part to cool the AUT; the heat conduction mechanism is designed without affecting the performance reduction build up on the surface of AUT in a laboratory setup with a material under test (MUT). MATLAB was used to develop the model and the flowchart of thermal prognostic cycle is shown in Figure 3.

At room temperature, it attains −105°C and the resonant frequency is measured with the help of RF cable. The temperature is monitored by the thermistors and data logger. Multiprobe system is used to measure the RF changes with respect to the variation in the temperature. Thus, it determines the RF dependency with respect to changes in temperature within the same setup. This testing method leads to a very efficient and cost-effective thermal testing. It is focused on three important parameters, volume heat capacity, thermal diffusivity, and thermal conductivity with respect to the temperature. SVR algorithm is used to find the probable temperatures; using this algorithm, a prognostic model is established. Irregularities in temperature along with the joints of RF power cables are compared with the output temperature. Thus, the degradation can be analyzed and corrected.

3.2. Performance Evaluation of Thermal Sensitivity between Composite and Traditional Materials. For the performance evaluation of RFID reader/tag antennas, monitoring the thermal sensitivity is a very essential parameter. Yang et al. [25] identified two important sensing approaches for thermal monitoring which are electrical and thermal properties of sensing materials. The temperature-dependent electrical properties are sensed with water and high density polyethylene-Ba0.3Sr0.7TiO3 (HDPE-BST). The thermal expansion properties are measured with mercury and polytetrafluoroethylene (PTFE). In antennas, the patch is constructed for electrical properties, due to narrow bandwidth characteristics, favourable for sensing operations. To determine electrical sensing properties, initially water is embedded as substrate of patch antenna to reconfigure the antenna resonant frequency with temperature ($\Delta f/\Delta T$);

Table 3: Properties of frequently used substrate [12].

Substrate	Coefficient of thermal expansion ($x/y/z$ axis)	Thermal coefficient of relative permittivity (εr)
RT6010.21.M	24/24/27 ppm/°C	−425 ppm/°C
RT6006	47/34/117 ppm/°C	−410 ppm/°C
RO4350 B	10/12/32 ppm/°C	+50 ppm/°C
RO4003 C	11/14/46 ppm/°C	+40 ppm/°C
RT5870	22/28/173 ppm/°C	−115 ppm/°C
RT5880	31/48/237 ppm/°C	−125 ppm/°C

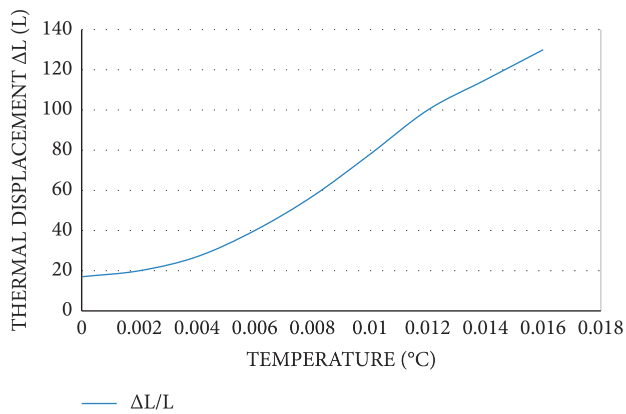

Figure 2: Comparison between thermal displacement and temperature.

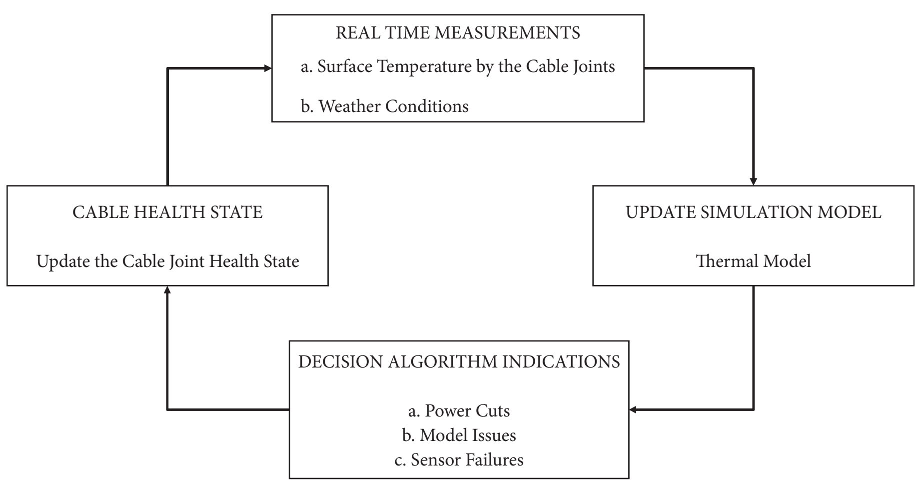

Figure 3: Thermal monitoring flowchart.

permittivity of water reduces from 80 at 20°C to 67 at 60°C. To find the sensitivity of the antenna, the parameters such as frequency shift/temperature, gain realization, and bandwidth are calculated [26–32]. Thus, the observed result is 3.2 dB realized gain with 4.33% bandwidth and 4 MHz/10°C frequency shift.

Since water inside the substrate is difficult to control and low reliability of the design, a novel composite material HDPE-BST was proposed to integrate with the patch as a substrate. The measurement of the antenna material parameters such as loss tangent and relative permittivity was studied under different temperatures. Due to small observed gain, it was noted that there is a significant decrease of read range to 4.2 m at 16 °C. The read range is calculated by using Friis transmission equation. The designed antenna is simulated using HFSS software and the results are compatible with the calculated results. The design is fabricated and the prototype is measured in the anechoic chamber. In Figure 4, structure of slot antenna HDPE-BST sensing antenna is depicted.

For identifying thermal properties, cavity backed slot antennas are created to integrate mercury as sensing material inside the cavity. For temperature monitoring, the large coefficient of thermal expansion of mercury (180 ppm/°C) is appropriate. Tunable cavity resonators can be used to change the tuning gap between cavity ceiling and the metal post in cavity effectively. This results in small variation (Approx.

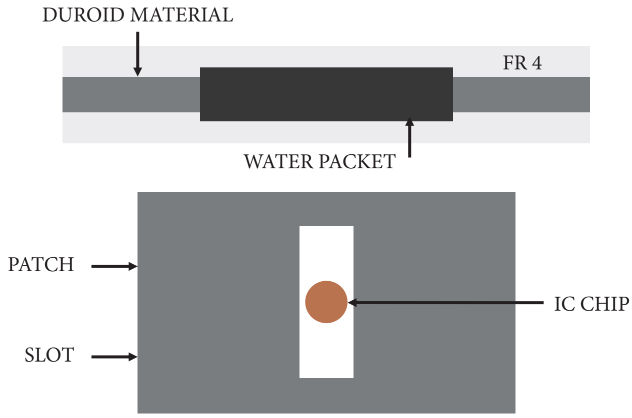

Figure 4: Structure of the HDPE-BST sensing antenna.

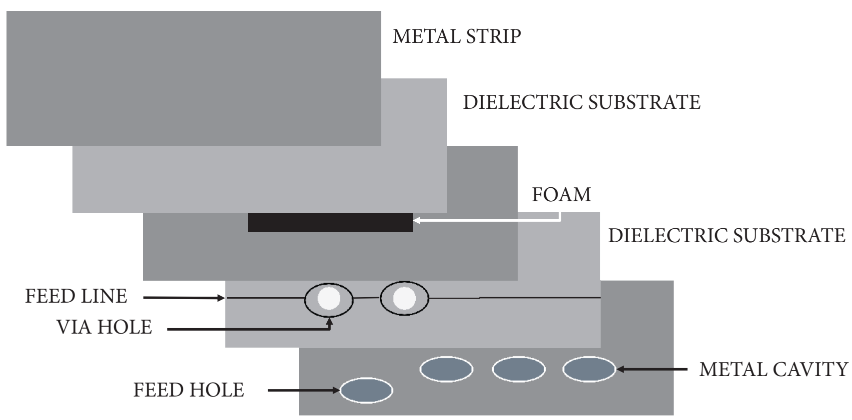

Figure 5: Capacitive loaded cavity backed RFID slot antenna structure.

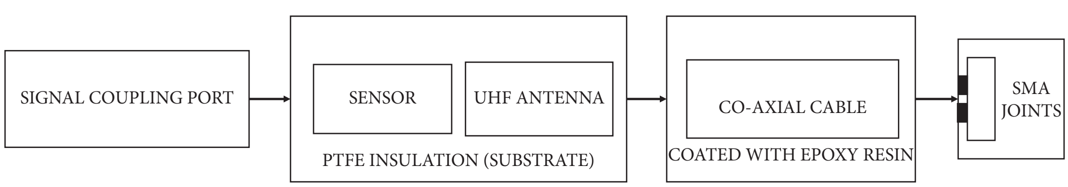

Figure 6: Structure of PTFE sensing antenna.

13 MHz/10 °C) in the order of μm, which effectively causes changes in frequency transformation in MHz. The sensing material forms a huge capacitive loaded with cavity backed in the slot antenna. According to the change in temperature, a change in gap thickness is created, which produces change in resonant frequency of the RFID slot antenna, as shown in Figure 5.

Since integration of mercury as liquid is difficult inside the cavity, an alternative sensing element based on PTFE was proposed. Due to the solid state of PTFE, higher sensitivity was achieved by close proximity to the ceiling of the cavity [33–38]. The prototype antenna, fabricated with PTFE, observed 40 MHz/10°C with read range of 14 m, which is the best option for sensing elements compared to the other proposed designs, thus making composites to be highly desirable as sensing antennas in practical applications [39–43]. For a constant temperature, the read range follows a normal distribution with a sharp peak at the resonant frequency. However, as the temperature increases, the graph is skewed with the same normal distribution with slightly lesser read range values [44–54]. General structure of PTFE sensing antenna is depicted in Figure 6.

4. Conclusion

In this communication, the properties of composite materials used in modern RFID system have been discussed and studied due to its appreciable properties such as lightweight and high strength. Thermal properties and structural design specifications of the substrate materials have been reviewed and discovered that the thermal properties affect the impedance and operating frequencies. Designing of RF passives antenna requires consideration of material, structure, fabrication parameters, and other uncertainties. The effects of composite material have been studied in detail and the performance of the compact multiband RFID antenna was forecasted using the models. By extending this approach, investigation of the behavior of complete setup can be calculated, containing other prime parameters, such as RFID antenna size, structure, and losses in material, and thermal variation with frequency. Based on the parameters, the gain of the antenna, bandwidth, and reflection coefficients can be inferred. For further improvement, miniaturization can be attained by deploying suitable fractal geometry RFID antennas with composite material. The composite material-based antennas can be used for many applications such as biomedical, satellite, and mining applications.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

Chitra Varadhan received her Bachelor degree in Electronics and Communication Engineering from Regional Engineering College (NIT, affiliated with Bharathidasan University, Trichy, Tamil Nadu, India) in 1996 and completed Master of Engineering in College of Engineering, Anna University, Guindy, Chennai, in 2008. Currently, she is pursuing PhD in Design of Fractal RFID Antennas in BIHER (Bharath Institute of Higher Education and Research, Chennai, Tamil Nadu, India). Arulselvi is working as an associate professor in BIHER (Bharath Institute of Higher Education and Research, Chennai, Tamil Nadu, India). Her areas of specialization include networking and communications. Currently, she is guiding Chitra Varadhan in the area of Fractal RFID Antennas. The authors declare that they have no conflicts of interest.

References

[1] L. Martin, D. Staiculescu, H. Li, S. L. Ooi, C. P. Wong, and M. M. Tentzeris, "Investigation of the impact of magnetic permeability and loss of magnetic composite materials on RFID and RF passives miniaturization," in *Proceedings of the 2007 Workshop on Computational Electromagnetics in Time-Domain*, pp. 1–4, Perugia, Italy, October 2007.

[2] N. Dugin, T. Zaboronkova, and E. Myasnikov, "Using carbon-based composite materials for manufacturing C-range antenna devices," *Latvian Journal of Physics and Technical Sciences*, vol. 53, no. 5, pp. 17–23, 2016.

[3] N. J. Kirsch, N. A. Vacirca, E. E. Plowman, T. P. Kurzweg, A. K. Fontecchio, and K. R. Dandekar, "Optically transparent conductive polymer RFID meandering dipole antenna," in *Proceedings of the 2009 IEEE International Conference on RFID*, pp. 278–282, Orlando, FL, USA, April 2009.

[4] M. Luniak, M. Roellig, and K. J. Wolter, "A technology enabling improved properties of polymer conductive pastes," in *Proceedings of the 26th International Spring Seminar on Electronics Technology*, pp. 104–107, High Tatras, Slovakia, May 2003.

[5] A. M. Chrysler, C. M. Furse, K. L. Hall, and Y. Chung, "Effect of material properties on a subdermal UHF RFID antenna," *IEEE Journal of Radio Frequency Identification*, vol. 1, no. 4, pp. 260–266, 2017.

[6] S. Amendola, R. Lodato, S. Manzari, C. Occhiuzzi, and G. Marrocco, "RFID technology for IoT-based personal healthcare in smart spaces," *IEEE Internet of Things Journal*, vol. 1, no. 2, pp. 144–152, 2014.

[7] Z. Xiao, X. Tan, X. Chen et al., "An implantable RFID sensor tag toward continuous glucose monitoring," *IEEE Journal Biomedical Health Information*, vol. 19, no. 3, pp. 910–919, 2015.

[8] S. Milici, S. Amendola, A. Bianco, and G. Marrocco, "Epidermal RFID passive sensor for body temperature measurements," in *Proceedings of the IEEE RFID Technology Application Conference (RFID TA)*, pp. 140–144, Tampere, Finland, September 2014.

[9] J. Jungyub Lee, J. Juhyang Lee, K. Yonghun Cheon, and Y. Cheon, "Miniaturized antennas with reduced hand effects in mobile phones using magneto-dielectric material," *IEEE Antennas and Wireless Propagation Letters*, vol. 13, pp. 935–938, 2014.

[10] X.-H. Cai, B. An, Y.-P. Wu, F.-S. Wu, and X.-W. Lai, "Research on the contact resistance and reliability of flexible RFID tag inlays packaged by anisotropic conductive paste," in *Proceedings of the 2008 International Conference on Electronic Packaging Technology & High Density Packaging*, pp. 1–5, Shanghai, China, July 2008.

[11] K. Zannas, H. El Matbouly, Y. Duroc, and S. Tedjini, "Self-tuning RFID tag: a new approach for temperature sensing," *IEEE Transactions on Microwave Theory and Techniques*, vol. 66, no. 12, pp. 5885–5893, 2018.

[12] M. C. Caccami and G. Marrocco, "Electromagnetic modeling of self-tuning RFID sensor antennas in linear and nonlinear regimes," *IEEE Transactions on Antennas and Propagation*, vol. 66, no. 6, pp. 2779–2787, 2018.

[13] M. C. Caccami and G. Marrocco, "Electromagnetic characterisation of self-tuning UHF RFID tags for sensing application," in *Proceedings of the 2016 IEEE International Symposium on Antennas and Propagation (APSURSI)*, pp. 1273-1274, Fajardo, PR, USA, June 2016.

[14] F. Amato, C. Miozzi, S. Nappi, and G. Marrocco, "Self-tuning UHF epidermal antennas," in *Proceedings of the 2019 IEEE International Conference on RFID Technology and Applications (RFID-TA)*, pp. 380–383, Pisa, Italy, September 2019.

[15] Q. Qiao, L. Zhang, F. Yang, Z. Yue, and A. Z. Elsherbeni, "A high sensitivity capacitively-loaded UHF RFID temperature sensor tag using PTFE material," in *Proceedings of the 2014 IEEE Antennas and Propagation Society International Symposium (APSURSI)*, pp. 1310-1311, Memphis, TN, USA, July 2014.

[16] M. Dhaouadi, M. Mabrouk, T. P. Vuong, A. C. de Souza, and A. Ghazel, "A capacitively-loaded loop antenna for UHF near-field RFID reader applications," in *Proceedings of the 2015 IEEE Radio and Wireless Symposium (RWS)*, pp. 193–195, San Diego, CA, USA, January 2015.

[17] Q. Liu, Y. Yu, and S. He, "Capacitively loaded, inductively coupled fed loop antenna with an omnidirectional radiation

pattern for UHF RFID tags," *IEEE Antennas and Wireless Propagation Letters*, vol. 12, pp. 1161–1164, 2013.

[18] Y.-K. Jung and B. Bomson Lee, "Capacitively loaded loop antenna fed by wideband metamaterial balun," in *Proceedings of the 2009 IEEE Antennas and Propagation Society International Symposium*, pp. 1–4, North Charleston, SC, USA, June 2009.

[19] P. Cheong, S. N. Lam, Y. Q. Qui, W. W. Choi, and K. W. Tam, "A tunable antenna-filter module for simultaneous UHF RFID-based power facility monitoring and partial discharge measurement," in *Proceedings of the 2010 International Conference on Applications of Electromagnetism and Student Innovation Competition Awards (AEM2C)*, pp. 182–186, Taipei, Taiwan, August 2010.

[20] A. Giacomini, R. Morbidini, L. J. Foged et al., "Thermal testing of small antennas in multi-probe spherical near-field systems," in *Proceedings of the 2017 Antenna Measurement Techniques Association Symposium (AMTA)*, pp. 1–6, Atlanta, GA, USA, October 2017.

[21] L. J. Foged, A. Giacomini, and R. Morbidini, "Thermal testing of small antennas in spherical near field system," in *Proceedings of the 2011 IEEE International Conference on Microwaves, Communications, Antennas and Electronic Systems (COMCAS 2011)*, pp. 1–7, Atlanta, GA, USA, October 2011.

[22] C. Bencivenni, M. Gustafsson, A. Haddadi, A. U. Zaman, and T. Emanuelsson, "5G mmwave beam steering antenna development and testing," in *Proceedings of the 2019 13th European Conference on Antennas and Propagation (EuCAP)*, pp. 1–4, Krakow, Poland, March 2019.

[23] C.-Y. Tsai, H. E. Chen, I. Hu, D.-L. Chen, D. Tarng, and C. P. Hung, "System thermal analysis of RF SiP module in smartphone," in *Proceedings of the 2020 15th International Microsystems, Packaging, Assembly and Circuits Technology Conference (IMPACT)*, pp. 165–167, Taipei, Taiwan, October 2020.

[24] D. Sato, N. Yamada, and K. Tanaka, "Thermal characterization of hybrid photovoltaic module for the conversion of sunlight into microwave in solar power satellite," in *Proceedings of the 2015 IEEE 42nd Photovoltaic Specialist Conference (PVSC)*, pp. 1–4, New Orleans, LA, USA, June 2015.

[25] F. Yang, Q. Qiao, L. Zhang, Z. Yue, and A. Z. Elsherbeni, "High-sensitivity RFID sensing antennas: from sensing mechanism selections to antennas structure designs," in *Proceedings of the 2014 XXXIth URSI General Assembly and Scientific Symposium (URSI GASS)*, pp. 1–4, Beijing, China, August 2014.

[26] K. Chang, Y.-h. Kim, Y.-j. Kim, and Y. Yoon, "Patch antenna using synthesized polyimide for RFID sensing," in *Proceedings of the 2006 European Conference on Wireless Technology*, pp. 83–86, Manchester, UK, September 2006.

[27] S. Manzari, A. Catini, C. Di Natale, and G. Marrocco, "Ambient sensing by chemical-loaded UHF-RFIDs," in *Proceedings of the 2013 7th European Conference on Antennas and Propagation (EuCAP)*, pp. 1718–1720, Gothenburg, Sweden, April 2013.

[28] X. Song, G. Wang, and Y. He, "Design of the high-sensitivity RFID sensor tag with MOEA/D-DE," in *Proceedings of the 2016 International Symposium on Antennas and Propagation (ISAP)*, pp. 950-951, Okinawa, Japan, October 2016.

[29] M. Wagih and J. Shi, "Wireless ice detection and monitoring using flexible UHF RFID tags," *IEEE Sensors Journal*, 2021.

[30] B. Wang, M.-K. Law, J. Yi, C.-Y. Tsui, and A. Bermak, "A −12.3 dBm UHF passive RFID sense tag for grid thermal monitoring," *IEEE Transactions on Industrial Electronics*, vol. 66, no. 11, pp. 8811–8820, 2019.

[31] K. Pan, L. Teng, L. Ting, X. Zhou, A. A. Stokes, and Z. Hu, "Soft wireless battery-free UHF RFID stretchable sensor based on microfluidic technology," *IEEE Journal of Radio Frequency Identification*, vol. 3, no. 4, pp. 252–258, 2019.

[32] A. A. Aziz, A. Mursyidi, R. Tahir, and A. Rahman Nurul, "Measurement of dielectric and thermal properties of Leucaena Leucocephala bio composite substrate with different composition mixture," *Journal of Engineering and Science Research VL*, vol. 2, 2018.

[33] C. Pelvillain, P. Cussac, S. Diaham, Z. Valdez-Nava, M.-L. Locatelli, and T. Lebey, "Dielectric and thermal properties of parylene N and D films for power electronic surface insulation," in *Proceedings of the 2015 IEEE 11th International Conference on the Properties and Applications of Dielectric Materials (ICPADM)*, pp. 508–511, Sydney, Australia, July 2015.

[34] X. Huang, P. Peng, W. Peng, J. Yu, F. Liu, and P. Jiang, "Thermal conductivity and dielectric properties of epoxy composites with hyperbranched polymer modified boron nitride nanoplatelets," in *Proceedings of the 2012 IEEE International Conference on Condition Monitoring and Diagnosis*, pp. 1089–1092, Bali, Indonesia, September 2012.

[35] Suwarno and F. Salim, "Effects of electric arc on the dielectric properties of liquid dielectrics," in *Proceedings of the 2006 IEEE 8th International Conference on Properties & applications of Dielectric Materials*, pp. 482–485, Bali, Indonesia, June 2006.

[36] N. Rahman, S. Chen, K. A. Korolev, M. N. Afsar, R. Cheung, and M. Aghion, "Millimeter wave complex permittivity measurements of high dielectric strength thermoplastics," in *Proceedings of the 2008 IEEE Instrumentation and Measurement Technology Conference*, pp. 2146–2149, Victoria, Canada, May 2008.

[37] H. S. Yun, J. Jeong, D. Kim, and D.-S. Kim, "Active thermal control of 5 nm gap terahertz antennas," in *Proceedings of the 2018 43rd International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz)*, pp. 1-2, Nagoya, Japan, September 2018.

[38] J. Castellon, H. Yahyaoui, O. Guille, E. David, M. Guo, and M. Fréchette, "Dielectric properties of POSS/LDPE and MgO/LDPE nanocomposites compounded by different techniques," in *Proceedings of the 2017 IEEE Conference on Electrical Insulation and Dielectric Phenomenon (CEIDP)*, pp. 457–460, Fort Worth, TX, USA, October 2017.

[39] X. Chen, J. Liu, J. Zheng et al., "Insulation property analysis of cross-linked polyethylene based on density functional theory," in *Proceedings of the 2018 12th International Conference on the Properties and Applications of Dielectric Materials (ICPADM)*, pp. 347–350, Xi'an, China, May 2018.

[40] K. Wu, Y. Wang, X. Wang, M. Fu, and S. Hou, "Effect of space charge in the aging law of cross-linked polyethylene materials for high voltage DC cables," *IEEE Electrical Insulation Magazine*, vol. 33, no. 4, pp. 53–59, 2017.

[41] H. Ren, L. Zhong, W. Zhao et al., "Influence of crosslinking byproducts on DC conductivity of HVDC XLPE cable insulation," in *Proceedings of the 2018 IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP)*, pp. 90–93, Cancun, Mexico, October 2018.

[42] A. Hedir, O. Jbara, M. Moudoud, F. Slimani, S. Rondot, and F. Bellabas, "Behaviour of cross-linked polyethylene used as high voltage power cables insulation due to environmental constraints," in *Proceedings of the 2018 International*

Conference on Electrical Sciences and Technologies in Maghreb (CISTEM), pp. 1–4, Algiers, Algeria, October 2018.

[43] G. Gherbaz, G. Chen, and A. S. Vaughan, "Polyethylene/ Dibenzylidene Sorbitol: effect of composition on space charge of polymeric insulation systems," in *Proceedings of the 2008 Annual Report Conference on Electrical Insulation and Dielectric Phenomena*, pp. 161–164, Quebec, Canada, October 2008.

[44] J. Ryoo, J. Choo, I. Park, J. Hong, and J. Lee, "Full wave simulation of flip-chip packaging effects on RFID transponder," in *Proceedings of the 2007 IEEE International Conference on RFID*, pp. 37–40, Grapevine, TX, USA, March 2007.

[45] M. Barahona, D. Betancourt, and F. Ellinger, "Using UWB IR radar technology to decode multiple chipless RFID tags," in *Proceedings of the 2016 IEEE International Conference on Ubiquitous Wireless Broadband (ICUWB)*, pp. 1–6, Nanjing, China, October 2016.

[46] M. Barahona, D. Betancourt, F. Ellinger, K. Haase, G. C. Schmidt, and A. C. Hübler, "Automatic IR UWB chipless RFID system for short range applications," in *Proceedings of the 2017 IEEE-APS Topical Conference on Antennas and Propagation in Wireless Communications (APWC)*, pp. 274–279, Verona, Italy, September 2017.

[47] V. H. Nguyen, H. P. Phan, M. H. Hoang et al., "Improving radiation characteristics of UHF RFID antennas by zigzag structures," in *Proceedings of the 2011 International Conference on Advanced Technologies for Communications (ATC 2011)*, pp. 102–105, Da Nang, Vietnam, August 2011.

[48] G. Tarapata, H. T. Hui, J. Weremczuk, R. Jachowicz, C. W. P. Shi, and X. Shan, "Comparison of performance of four RFID sensor antennas fabricated on different substrates," in *Proceedings of the 2009 Asia Pacific Microwave Conference*, pp. 614–617, Singapore, December 2009.

[49] C. Chihyun Cho, H. Ikmo Park, and I. Park, "Design of novel RFID tag antennas for metallic objects," in *Proceedings of the 2006 IEEE Antennas and Propagation Society International Symposium*, pp. 3245–3248, Albuquerque, NM, USA, July 2006.

[50] H. Sun, G. Xiao, S. Lang, Z. Zhang, and Y. Tao, "Screen printed HF RFID antennas on polyethylene terephthalate film," *IEEE Journal of Radio Frequency Identification*, vol. 3, no. 2, pp. 91–97, 2019.

[51] W. Pachler, I. Russo, W. Bösch, G. Hofer, G. Holweg, and M. Mischitz, "A silver ink-jet printed UHF booster antenna on flexible substratum with magnetically coupled RFID die on-chip antenna," in *Proceedings of the 2013 7th European Conference on Antennas and Propagation (EuCAP)*, pp. 1730–1733, Gothenburg, Sweden, April 2013.

[52] Y. Liu, M. Yu, L. Xu, Y. Li, and T. T. Ye, "Characterizations and optimization techniques of embroidered RFID antenna for wearable applications," *IEEE Journal of Radio Frequency Identification*, vol. 4, no. 1, pp. 38–45, 2020.

[53] K. Saarinen and L. Frisk, "Reliability of UHF RFID tags in humid environments," in *Proceedings of the 2012 IEEE 14th Electronics Packaging Technology Conference (EPTC)*, pp. 180–184, Singapore, December 2012.

[54] D. Betancourt, R. Nair, K. Haase et al., "Square-shape fully printed chipless RFID tag and its applications in evacuation procedures," in *Proceedings of the 2015 9th European Conference on Antennas and Propagation (EuCAP)*, pp. 1–5, Lisbon, Portugal, April 2015.