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Electrically Small Antenna for Sensing Application: A Review

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Abstract: This study focuses on the electrically small antennas (ESAs) tailored for sensing applications. Recognizing the critical role of antenna size and performance in modern sensing systems, the research employs advanced simulation and optimization techniques to explore various configurations. Additionally, discussions on potential enhancements, such as meta material, Dielectric resonating antenna, meander line antenna, etc. integration and reconfigurable structures, provide insights for future developments in compact antenna technology for wireless sensing systems. Thus, in In this paper, a comprehensive overview of various types of electrically small antennas (ESAs) is presented, along with their significance in enhancing performance and their application in 5G and 6G communication systems.

Keyword: Advanced simulation, potential enhancement, optimization techniques, metamaterial,

I. INTRODUCTION

The miniaturization of wireless communication systems has become advantageous due to the increasing demand for small and compact equipment. Antennas, too, are subject to this trend. Although "small" can be interpreted in various ways, antennas are typically designed for comparative purposes. Unfortunately, reducing the size of antennas often leads to a compromise in performance. Conventional methods for designing small antennas for low frequencies often result in larger antenna sizes. This becomes problematic at lower operating frequencies, as the size of the antenna significantly impacts both the systems and their portability[5].The design and development of electrically small antennas for sensing applications represent a pivotal exploration in modern antenna engineering. In response to the escalating demand for compact and efficient wireless sensing devices, the pursuit of miniature antennas has gained prominence. The term "electrically small" denotes antennas with dimensions much smaller than the operating wavelength, making them suitable for applications where space is limited. This introduction delves into the significance of designing such antennas, addressing the challenges and opportunities in crafting compact yet high-performing solutions for sensing.

As technological advancements continue to push the boundaries of miniaturization, the quest for electrically small antennas opens new frontiers in the realm of sensor technology, promising innovations with profound implications for diverse sensing applications.

II. LITERATURE REVIEW

Designing ESAs for sensing applications, various factors must be considered, including antenna geometry, substrate material, and feeding techniques. Common ESA configurations include monopoles, dipoles, loops, and microstrip patches, each offering different advantages depending on the specific sensing requirements [1]. The choice of substrate material, such as printed circuit boards (PCBs) or specialized dielectrics, significantly impacts antenna performance in terms of bandwidth, efficiency, and radiation pattern [2]. Fabrication methods, including traditional PCB manufacturing processes and microfabrication techniques, play a crucial role in achieving desired antenna characteristics [3].

Evaluating the performance of ESAs in sensing applications requires accurate measurement techniques and simulation tools. Parameters such as impedance bandwidth, radiation efficiency, directivity, and sensitivity are critical metrics for assessing ESA performance. Measurement setups often involve anechoic chambers, near-field scanning, or network analyzers, while simulation software such as CST Microwave Studio or HFSS facilitates predictive modeling of ESA behavior [4].

ESAs find applications across various domains, including wireless sensor networks, IoT devices, biomedical sensors, environmental monitoring systems, and industrial sensing applications. In IoT devices, ESAs enable compact and energy-efficient wireless communication, while in biomedical sensors, they facilitate non-invasive monitoring of physiological parameters. Environmental monitoring systems leverage ESAs for remote sensing of atmospheric conditions, while industrial applications utilize ESAs for process control and asset tracking [5].

Despite their potential, ESAs face challenges in sensing applications, such as limited bandwidth, low efficiency, and susceptibility to environmental interference.

Future research directions aim to address these challenges through innovative antenna designs, advanced materials, and signal processing techniques. Integration with emerging technologies like machine learning, Metamaterials, and reconfigurable antennas holds promise for enhancing ESA sensing capabilities further [6].

III. MEANDER LINE ANTENNA

Meander lines are widely recognized as the ideal solution for a range of wireless communication applications, such as , mobile phones, USB dongles, Bluetooth headsets, RFID tags, and more [14]. In numerous applications, meander-line antennas have been studied for their potential in miniaturization [15]. By affecting the propagation time of an electromagnetic wave from the feed point to the antenna's end, this miniaturization technique can lead to even smaller antennas[16]. Monopole antennas offer several benefits, such as high radiation efficiency, wide impedance bandwidth, low profile, cost-effectiveness, and simple structure. Consequently, they can be easily incorporated into applications like WLANs, high-resolution radars, imaging systems, military communication, and cognitive radio systems [17]. Various methods have been documented in the literature for shrinking the size of monopole antennas, including the meander line technique. Meander line antennas are well-suited for sensing applications due to their compact size, wideband or multiband operation, directional capabilities, and ease of fabrication. Their low profile and robust construction make them ideal for integration into small devices or systems, while their ability to operate over a broad frequency range enables sensing across various signals of interest. Additionally, their directional characteristics allow for precise spatial coverage, crucial for applications requiring specific sensing areas. Overall, the versatility, customizability, and practicality of meander line antennas make them a popular choice for a wide range of sensing applications, including wireless sensor networks, RFID systems, IoT devices, remote sensing, and biomedical sensing.

Meander line antennas are widely used in sensing applications due to several advantageous characteristics:

1) Compactness: Meander line antennas are inherently compact due to their folded structure, making them suitable for integration into small devices or systems where space is limited.
2) Multi-band Operation: By adjusting the dimensions and layout of the meander lines, these antennas can be designed to operate at multiple frequencies, enabling multi-band sensing applications without the need for additional antennas.
3) Wideband Operation: Meander line antennas can be operate to over a wide frequency range, allowing sensing across a broad spectrum of signals or frequencies of interest.
4) Directionality: Depending on the design, meander line antennas can exhibit directional characteristics, which can be advantageous for sensing applications requiring specific coverage or spatial resolution.
5) Robustness: Meander line antennas are often printed on PCBs (Printed Circuit Boards) or fabricated using other robust materials, making them durable and suitable for various environmental conditions, including harsh industrial environments or outdoor deployments.
6) Low Profile: The flat, planar nature of meander line antennas results in a low profile, making them suitable for applications where antenna height needs to be minimized, such as in portable or embedded sensing devices.
7) Ease of Fabrication: Meander line antennas can be fabricated using standard PCB manufacturing techniques, which are cost-effective and well-established, facilitating mass production for large-scale sensing deployments.
8) Customizability: Design parameters such as the number of meander segments, the spacing between them, and the overall dimensions can be adjusted to tailor the antenna's performance to specific sensing requirements, including frequency range, impedance matching, and radiation pattern.

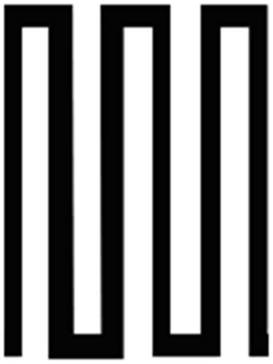

Figure 1: Overview of meander line antenna

These characteristics make meander line antennas a versatile choice for various sensing applications, including but not limited to wireless sensor networks, RFID (Radio Frequency Identification) systems, IoT (Internet of Things) devices, remote sensing, and biomedical sensing. They offer a balance of performance, compactness, and ease of integration that aligns well with the requirements of modern sensing systems.

IV. DIELECTRIC RESONATOR ANTENNA

Dielectric resonators are increasingly utilized today due to their advantages, including minimal metallic losses, wide bandwidth, low dielectric losses, high gain, and the ease of achieving circular polarization (CP) at higher modes. Circularly polarized (CP) antennas are preferred over linearly polarized antennas due to reduced multipath fading, improved signal reception, and lower polarization losses.

The fabrication of rectangular dielectric resonator antennas (DRA) is comparatively straightforward when compared to cylindrical DRAs, which have garnered extensive attention in literature due to differing mathematical interpretations. A primary focus of theoretical studies on DRAs revolves around dielectric resonators with a permittivity (εr) greater than 10, owing to the numerous advantages associated with high-permittivity resonators, such as improved coupling and greater energy storage. In a comparative analysis between low-permittivity DRAs ($\varepsilon r = 5$) and high-permittivity DRAs ($\varepsilon r = 10$), Scholars determined that a lower permittivity dielectric resonator antenna (DRA) is advantageous for improving bandwidth, despite resulting in a larger DRA size. The DRA design proposed in reference [12] involves a conventional FR-4 substrate serving as the dielectric resonator, combined with a circular loop featuring four feeds. The use of a circular ring microstrip line with four feeds facilitates the excitation of the $TE_{11\delta}$ mode within the dielectric resonator. Notable achievements of this project include a straightforward design (eliminating the need for slot or probe feed), compact dimensions, and cost-effectiveness. The proposed DRA operates within the 24-27 GHz frequency band, demonstrating a consistent gain of approximately 8.6 dBi and a 3 dB axial ratio bandwidth of approximately 1 GHz. Figure 2 presents the simulated and fabricated DRA. Antenna design simulations were carried out using HFSS software, while mathematical computations were performed using MATLAB software.

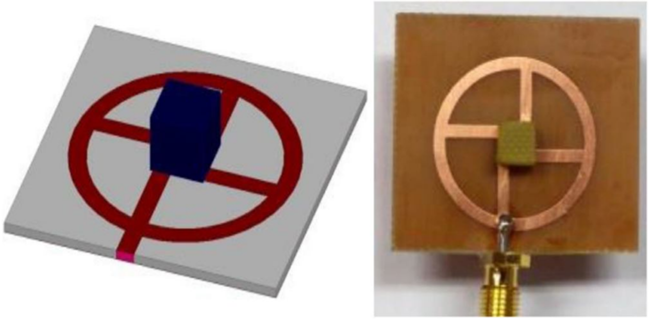

Figure 2: DR Antenna prototype

At present, exclusively high-permittivity dielectric resonators (DR) are employed due to their myriad benefits. In microwave image sensing, cost plays a crucial role as the sensor is typically complemented by signal processing circuitry, thereby influencing the overall system cost. In microwave image sensing applications, it is essential for the device to exhibit high and consistent gain. The proposed dielectric resonator antenna (DRA) fulfills all the essential criteria of such a sensor. It offers a broad impedance bandwidth and axial ratio (AR) bandwidth, which are desirable attributes for the sensor.

V. DUAL FUQUENCY COMMUNICATION ANTENNA

A dual-frequency communication system operates concurrently on two distinct frequencies, offering improved reliability and performance. By employing diversity techniques, these systems can counteract fading and multipath propagation effects, thereby enhancing communication link robustness. Moreover, dual frequencies enable interference mitigation, facilitating seamless frequency switching to sustain communication amidst interference or congestion. This approach also broadens available bandwidth, enabling higher data throughput and accommodating multiple communication channels. Dual-frequency systems find utility across various domains, including wireless, satellite, and military communications.

Effective implementation necessitates thoughtful consideration of factors such as frequency selection, modulation techniques, and signal processing algorithms to optimize performance and ensure compliance with existing standards and regulations. Overall, dual-frequency communication systems present a dependable and adaptable solution for diverse communication requirements.

The system consists of two antennas: one dedicated to fixed-band communication and the other for sensing purposes. These antennas are combined to operate as a single-port device. The main objective of the system is to detect various materials under test (MUTs) without impacting the operational bandwidth of the communication antenna. To achieve this objective, a frequency-selective multipath filter (FSMF) is designed, comprising an input port and two output ports. The antennas are integrated at each output port of the FSMF [13].

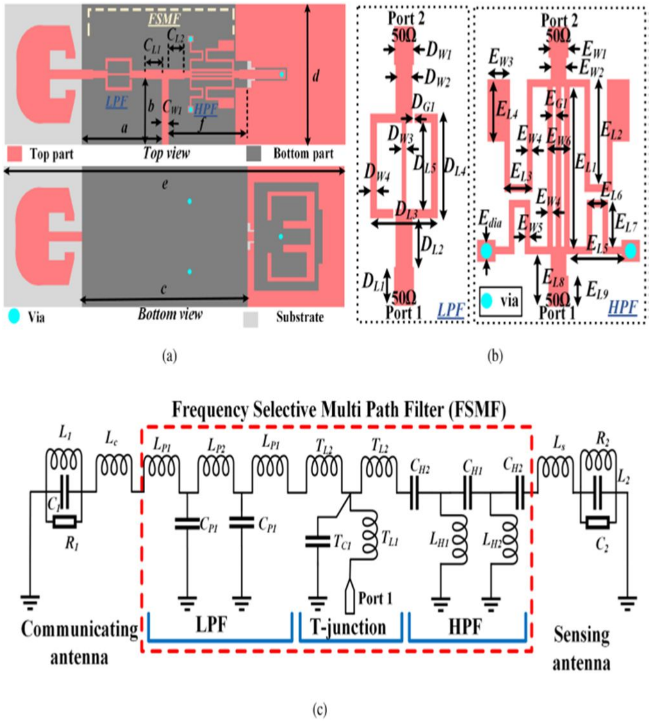

Figure 3: Example Dual frequency communication antenna

The performance of the dual-functional system is evaluated using various PCB substrate blocks and in the presence of ice/water, with both simulated and measured results showing good agreement. Observations indicate that the presence of materials under test (MUTs) only affects the resonance frequency of the antenna sensor, leaving the operational bandwidth of the communicating antenna unchanged. The fixed-band communicating antenna, designed for Wi-Fi application at 2.45 GHz, is integrated into the proposed dual-functional system, while a narrowband antenna sensor is employed for ice/water detection. Additionally, the efficacy of the antenna sensor is confirmed for sensing different materials (substrate blocks) with permittivity ranging from $\varepsilon r = 2.2$ to 6.15. Importantly, this concept holds promise for various simultaneous sensing and communication applications [13].

VI. METAMATERIALS ANTENNA

Metamaterials possess distinctive features such as sub-wavelength operation and phase manipulation, making them highly valuable across a spectrum of applications, including 5G communication systems. The evolving landscape of 5G devices demands attributes such as high efficiency, rapid data rates, computational prowess, cost-effectiveness, compactness, and low power consumption. Achieving these objectives necessitates a reevaluation of antenna designs to enable wideband operation, high gain, multiband capability, compact size, reconfigurability, absorption, and ease of fabrication. Materials integrated with antennas or standalone metamaterials offer these sought-after characteristics, driving advancements to meet the needs of users. Numerous studies in the literature focus on designing metasurfaces capable of enhancing bandwidth, gain efficiency, and reducing antenna size and cost. These intelligent metasurfaces can be tailored for reconfiguration in terms of frequency and polarization. Moreover, absorbers loaded with metamaterials are customized to enhance absorption percentages, particularly beneficial for radar applications.

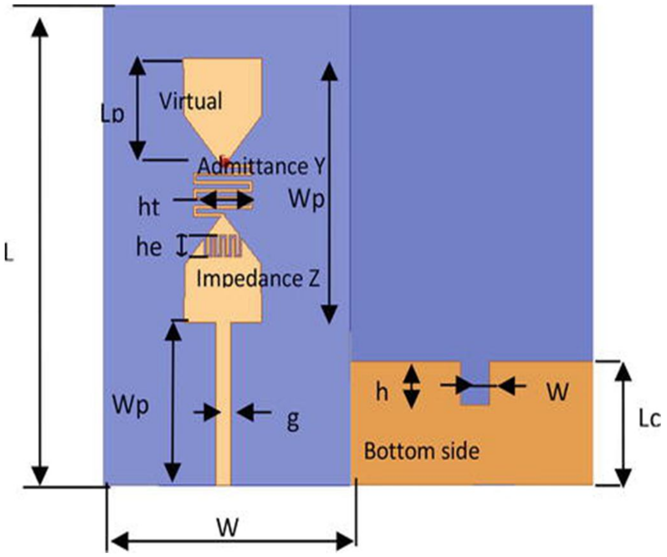

Figure 4: Example of metamaterial

Considerable focus has been directed towards metamaterial structures, including split ring resonators (SRRs), complementary split ring resonators (CSRRs), and complementary right-left hand (CRLH) structures, which are grounded in transmission line technologies and zero-order resonators (ZORs). This study offers a historical overview of the emergence, development, and application of metamaterials. It explores the physical properties of metamaterials and introduces various types of metamaterials (MTMs), encompassing materials with negative permeability (MGN), negative dielectric (ENG), and double-negative electric and magnetic components (DNG).

The first discussed application of metamaterials involves an ultrawide-band monopole antenna loaded with zero-order resonators (ZORs), designed for WLAN, WiMax, and X-band applications. Comparative analysis with three similar ZOR antennas reveals that loading monopole antennas with ZORs can elevate gain to 1.8 dBi and enhance impedance bandwidth by 148% compared to the original antenna. Furthermore, adjusting the inductor length or capacitor value can shift the resonant frequency towards lower or higher operating frequencies.

The second application features a highly compact sensor utilizing CRLH resonator and CSRR for identifying liquid mixtures. Simulation using HFSS software demonstrates the sensor's competitive sensitivity compared to existing literature. Additionally, the sensor's dimensions and testing surface are compact.

In conclusion, metamaterials exhibit the potential to enhance microwave structures' performance, whether by increasing antenna gain or impedance bandwidth, or by improving the sensitivity of electromagnetic sensors [18].

VII. FUTURE SCOPE

The future of electrically small antennas (ESAs) is on the brink of significant expansion and innovation across multiple industries. As technological advancements persist, the demand for compact, efficient, and adaptable antenna solutions is escalating. ESAs offer a promising avenue for meeting these demands, given their small size and ability to uphold performance in constrained spaces. In the realm of wireless communication, ESAs are anticipated to play a pivotal role in the proliferation of Internet of Things (IoT) devices, wearable technology, and 5G networks. These antennas will facilitate seamless connectivity in various domains such as smart homes, industrial automation, and healthcare monitoring.

Furthermore, ESAs hold substantial promise in space applications, where constraints related to size, weight, and power are paramount. They can support communication in small satellites, CubeSats, and other space missions, thereby aiding in Earth observation, satellite internet provision, and scientific exploration. Moreover, ESAs are expected to find applications in automotive systems, medical devices, defense technology, and rapid prototyping, driven by advancements in additive manufacturing and flexible electronics.

As ongoing research and development in antenna design, materials, and manufacturing techniques continue to advance, electrically small antennas stand poised to revolutionize connectivity and pave the way for innovative solutions across diverse fields.

VIII. CONCLUSION

In this paper, some of the antenna having potential to used as s sensor for the measurement application has been discussed. It has been observed that the metamaterial used for the design of the compact size with enhance performance antennas which has the potential to use for the sensing application.

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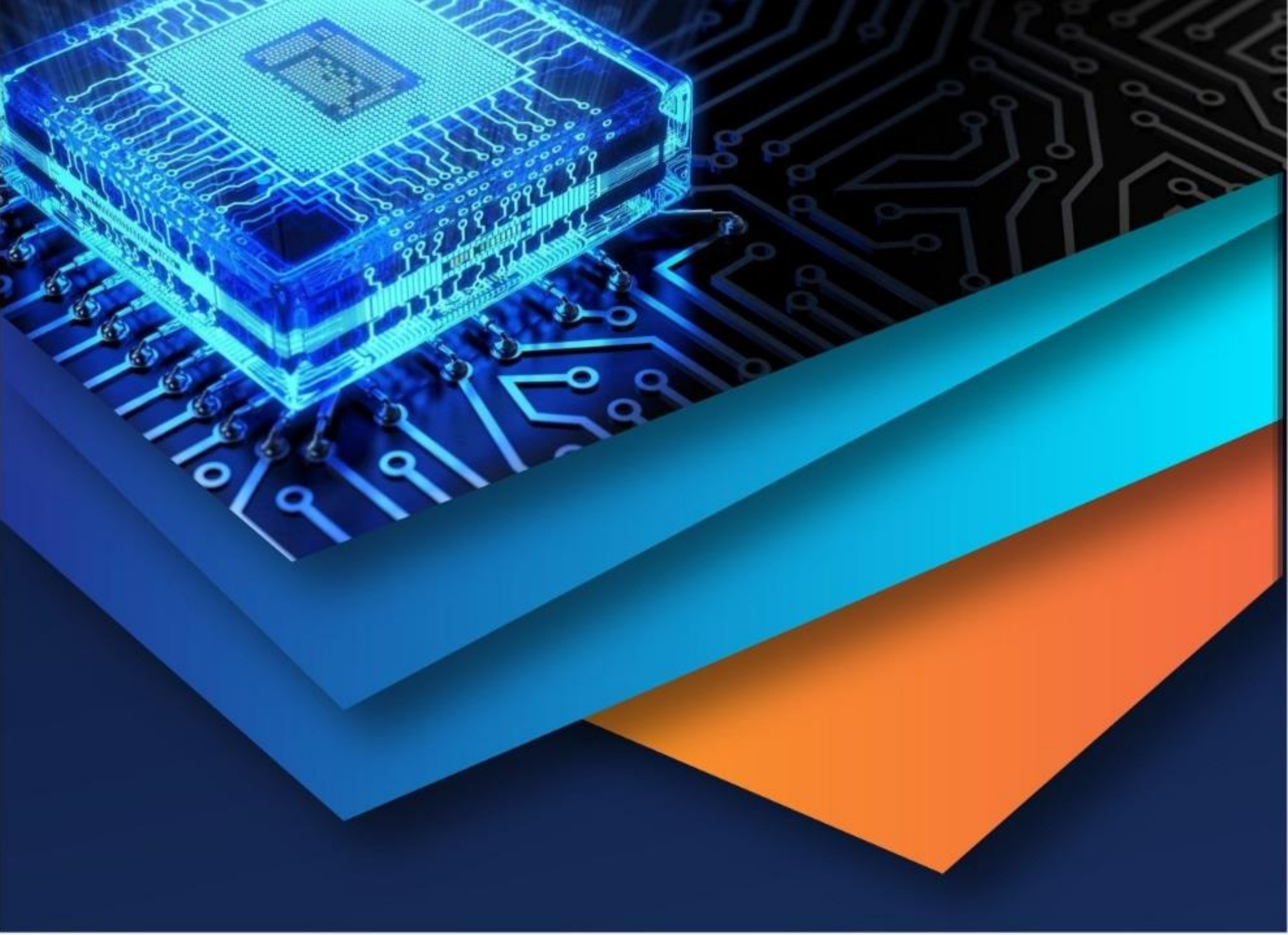

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