Journal of **N**onlinear **A**nalysis and **O**ptimization
Vol. 16, Issue. 1: 2025
ISSN : **1906-9685**

Design and Analysis of textile antenna with SRR and EBG reflector for ISM 2.4GHz band applications

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***Abstract*--The growing prevalence of wireless communication systems operating in the Industrial, Scientific, and Medical (ISM) 2.4 GHz frequency band demands the development of compact, high-performance, and efficient antenna solutions. The Text Tile Antenna introduces a novel design approach, incorporating modular, patterned structures inspired by text-like geometries to enhance performance. This innovative configuration consists of a planar array of radiating elements arranged in a tile-like pattern, each meticulously optimized for efficient operation within the ISM 2.4 GHz frequency range. This research delves into the design, simulation, and experimental validation of the Text Tile Antenna, emphasizing critical performance metrics such as return loss, gain, radiation pattern, and bandwidth. The findings reveal that the Text Tile Antenna delivers exceptional performance, positioning it as a compelling candidate for advanced wireless communication systems in the ISM 2.4 GHz spectrum. Additionally, its adaptable design allows for seamless integration into various wireless applications, improving connectivity and reliability. Future advancements in this technology could further optimize its efficiency, paving the way for next-generation antenna solutions.**

Index Terms: **Text Tile Antenna, ISM 2.4 GHz Band, Wireless Communication Systems,Antenna Design and Optimization, Radiation Pattern and Gain and Modular Planar Arrays.**

I.INTRODUCTION

The rapid advancement of communication engineering and electronic communication systems has led to an increasing demand for compact antennas with broader bandwidths[1]. Efficient and high-performance antenna designs are crucial for ensuring seamless connectivity in modern wireless communication systems. The S-band, a critical segment of the microwave band within the electromagnetic spectrum, operates between 2 and 4 GHz, as defined by the IEEE. This frequency range crosses the boundary between the UHF and SHF[2] bands at 3.0 GHz and is widely utilized in weather radar, surface ship radar, and other communication applications. The ISM 2.4 GHz band, which includes a 50 MHz bandwidth, is a significant part of this spectrum, making it a key area of interest for researchers developing next-generation wireless communication systems.

Similarly, the C-band, which spans from 4 to 7 GHz, plays a vital role in long-distance telecommunications. This band supports a wide range of applications, including Wi-Fi devices, cordless telephones, and weather radar systems[3]. Due to the extensive use of the C-band in critical communication applications, there is a growing need for efficient and innovative antenna configurations that can operate reliably in this spectrum. To address these demands, novel antenna technologies such as metamaterial-based antennas, phased array antennas[4], and microstrip antennas have gained significant attention in recent years.

Textile antennas represent a promising solution in modern wireless communication due to their flexibility, lightweight structure, and adaptability. A textile antenna typically consists of modular radiating elements arranged in a structured grid pattern, making it suitable for diverse applications in communication, radar, and sensing systems. The concept of a "text tile" antenna likely stems from tiled or phased array antennas, emphasizing their modular and scalable nature. These antennas can be classified into several categories based on their functionality and applications. Phased array antennas consist of multiple small radiating elements in a tiled configuration, enabling electronic beam steering without mechanical movement. These antennas are widely used in applications such as satellite communication, radar systems, and emerging 5G networks[5]. Metamaterial or microstrip antennas integrate specially designed patterns on printed circuit boards to manipulate signal properties such as directionality and strength, improving overall performance in terms of bandwidth and efficiency. Digital tile antennas involve discrete units that are digitally controlled, making them ideal for advanced communication systems, including military and satellite applications where precision and adaptability are essential.

This research focuses on the design and analysis of a textile antenna that incorporates multiple Split Ring Resonators (SRR) and an Electromagnetic Band Gap (EBG)[6] reflector to enhance antenna gain. The integration of these advanced components is expected to significantly improve the antenna's performance in terms of gain, bandwidth, and radiation characteristics, thereby making it a viable solution for ISM 2.4 GHz band applications. The proposed textile antenna design aims to bridge the gap between traditional rigid antennas and the growing need for flexible, wearable, and high-performance communication systems.

The methodology of this study involves designing antennas for the target frequency range based on well-established design principles. The antenna structure is modeled and simulated using HFSS (High-Frequency Structure Simulator), ensuring precision in design optimization. Various design parameters are fine-tuned through simulation to achieve enhanced antenna performance, focusing on critical metrics such as return loss, radiation pattern, and gain efficiency. The experimental validation of the proposed design will further confirm its practical feasibility and performance enhancement.

This research paper is structured as follows. The first section introduces the fundamental concepts and theoretical background of microstrip planar antennas, with an emphasis on elliptical patch antennas. The second section presents a comprehensive literature review of existing antenna designs and optimization techniques, providing insights into the advancements in textile antenna technology. The third section outlines the proposed textile antenna design, detailing the incorporation of SRR and EBG reflector technology for improved performance. The fourth section discusses the simulation results, offering a comparative analysis of various patch antenna configurations based on key parameters such as return loss, radiation pattern, and gain efficiency. The fifth section provides an in-depth discussion of the findings, highlighting performance improvements and key observations. Finally, the paper concludes with a summary of the research outcomes and potential future directions for further enhancements in textile antenna technology.

By leveraging the capabilities of advanced antenna technologies such as SRR and EBG reflectors, this research aims to contribute to the ongoing development of high-performance, flexible wireless communication systems[8]. The proposed textile antenna design is expected to provide robust connectivity and enhanced signal transmission, positioning it as a promising solution for ISM 2.4 GHz band applications and beyond.

II.RELATED WORK

The continuous evolution of wireless communication technologies has led to an increasing demand for compact, high-performance antennas capable of operating across multiple frequency bands. The growing necessity for efficient and robust antenna designs stems from the rapid expansion of modern communication systems, including satellite communication, 5G networks, and radar applications. In particular, ultra-wideband (UWB) antennas, which have roots dating back to the late 19th century, have become a focal point of research due to their capability to support high-speed data transmission. The initial development of UWB antennas can be traced to Oliver Lodge's bi-conical horn antenna in 1898, which, despite its bulkiness, laid the foundation for contemporary compact designs. Over the past two decades, significant advancements in UWB antenna technology have been observed, especially following the Federal Communications Commission's (FCC) allocation of the 3.1–10.6 GHz frequency band for commercial applications in 2002.

With the increasing adoption of 5G technology, smartphone antennas have gained significant research attention to meet the demands of high-speed mobile communication. The evolution from 4G to 5G has resulted in the need for antennas capable of supporting higher data rates, improved spectrum efficiency, and reliable connectivity. Multiple-Input Multiple-Output (MIMO) [9]technology has emerged as a crucial enabler in enhancing spectrum efficiency and channel capacity in smartphone antennas. In this context, the development of 8×8 MIMO antenna[10] systems has gained prominence, allowing for dual-band operation while maintaining a compact footprint suitable for integration into modern full-screen smartphones. The placement of MIMO antenna elements along the edges of smartphones aligns with current design trends, ensuring seamless connectivity without compromising device aesthetics.

In wireless communication systems, the transmitted signal is often subjected to distortions due to fading and interference. To mitigate these issues, diversity techniques such as spatial, temporal, and frequency diversity have been widely explored. Among these, space diversity has proven to be highly effective, as it enhances signal reliability without requiring additional bandwidth. However, achieving optimal space diversity necessitates careful antenna placement to minimize signal correlation and maximize performance. Additionally, the increasing demand for pervasive health monitoring has led to significant research efforts in wireless body area networks (WBANs) and wearable antennas[11]. Wearable devices, including textile-based antennas, are becoming integral to modern healthcare solutions by enabling continuous health monitoring, telemedicine, and emergency response systems.

The development of textile antennas has gained momentum due to their potential to provide wireless connectivity in a flexible, lightweight, and cost-effective manner. Unlike conventional rigid antennas, textile antennas can be seamlessly integrated into clothing, making them ideal for wearable applications. However, several challenges must be addressed in wearable antenna design, including the impact of body proximity, environmental factors such as humidity and temperature, and structural deformations due to bending and washing cycles. To enhance the performance of textile antennas, techniques such as the integration of Artificial Magnetic Conductors (AMCs)[12], Electromagnetic Band Gap (EBG) structures, and High Impedance Surfaces (HIS) have been explored. These techniques help in minimizing Specific Absorption Rate (SAR) while improving gain, bandwidth, and radiation efficiency.

To overcome the limitations associated with conventional textile antennas, this research proposes a novel textile antenna design incorporating multiple Split Ring Resonators (SRR) [13] and an EBG reflector. The proposed antenna aims to enhance gain and radiation efficiency while maintaining flexibility and lightweight characteristics suitable for wearable applications. The incorporation of SRR structures enables the manipulation of electromagnetic wave propagation, thereby improving antenna performance in terms of bandwidth and directivity. Additionally, the use of an EBG reflector minimizes back radiation and mitigates SAR[14], ensuring compliance with safety standards for on-body operation.

The methodology of this study involves a systematic approach to antenna design, starting with the development of an optimized structure for the target frequency range. The antenna model is designed and simulated using High-Frequency Structure Simulator (HFSS)[15] to analyze key performance parameters, including return loss, radiation pattern, and gain efficiency. Through iterative optimization, the antenna's design parameters are fine-tuned to achieve the desired performance characteristics. The final prototype will undergo experimental validation to assess its real-world performance and confirm its suitability for practical applications.

This research paper is structured as follows: The first section provides an overview of microstrip planar antennas, with a particular emphasis on elliptical patch antennas. The second section presents a comprehensive literature review on the advancements in textile antenna technology and the integration of metamaterial-based enhancements. The third section outlines the proposed antenna design, highlighting the role of SRR and EBG[16] reflector technology in performance improvement. The fourth section discusses the simulation results, providing a comparative analysis of various patch antenna configurations based on key performance metrics.

The fifth section presents a detailed discussion on the findings, emphasizing the advantages of the proposed design. Finally, the paper concludes with a summary of research contributions and potential future directions for textile antenna development.

By leveraging advanced antenna technologies, this study aims to contribute to the development of high-performance, flexible antennas for modern wireless communication systems. The proposed textile antenna design is expected to offer robust connectivity, enhanced signal transmission, and improved SAR compliance, making it a promising candidate for applications in wearable technology, WBANs[16], and next-generation communication networks.

III.PROPOSED SYSTEM

Over the past few decades, planar antennas have attracted significant attention from researchers and scholars due to their versatility and effectiveness. The rapid advancements in electronic circuit miniaturization and large-scale integration in the early 1970s created a growing demand for compact antennas with minimal size. These antennas needed to be compatible with Monolithic Microwave Integrated Circuit (MMIC) designs. Planar antennas, which are substrate-based, offer ease of fabrication and seamless integration with MMIC and Printed Circuit Boards (PCBs). Their notable advantages include a low-profile structure, lightweight design, and cost-effective manufacturing process.

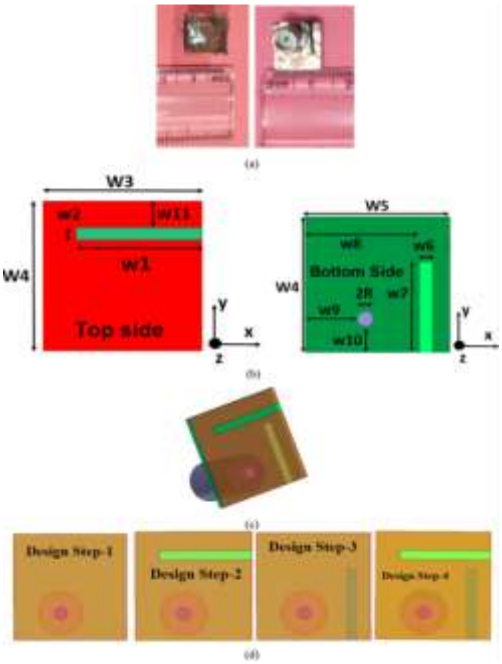


Fig.1: (a) Schematic Design of Textile antenna ,(a)Its top(red) and bottom(green) planes, (c) Overall design of Textile antenna and (d) current analysis in it.

Microwave frequency bands are categorized based on their specific applications. The L-band, ranging from 1 to 2 GHz, is widely used in military telemetry, GPS, mobile communications, and amateur radio. The S-band, spanning 2 to 4 GHz, finds applications in weather radar, surface ship radar, satellite communication, and wireless technologies such as Bluetooth, Zigbee, and WLAN. The C-band, with a frequency range of 4 to 8 GHz, is primarily used for long-distance radio telecommunications. Moving up the spectrum, the X-band (8 to 12 GHz) supports satellite communications, radar systems, and terrestrial broadband services. The Ku-band (12 to 18 GHz) and K-band (18 to 26.5 GHz) play significant roles in satellite communication, molecular rotational spectroscopy, and automotive radar. Higher frequencies, such as the Ka-band (26.5 to 40 GHz) and Q-band (33 to 50 GHz), are utilized for advanced satellite communication, radio astronomy, and microwave-based terrestrial communications.

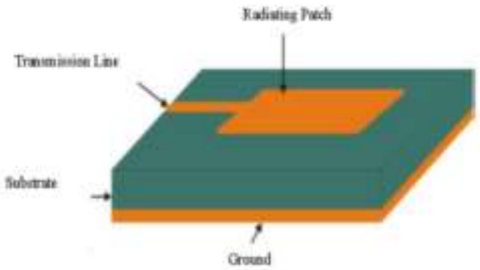


Fig. 2 The basic geometry of microstrip radiator

Among the various patch structures available, rectangular, circular, and triangular shapes are the most commonly used due to their simplicity in analysis and fabrication. The development of planar patch antennas has led to significant advancements in S-band (WiMAX) [17]and C-band (WLAN) antennas, further expanding their practical applications. One of the most popular types of planar antennas is the microstrip patch antenna, which consists of a flat metallic patch, a dielectric substrate, and a ground plane. These antennas are usually fabricated by etching the patch and feeding circuitry from a printed circuit board, making them easy to manufacture and integrate into various electronic systems.

The radiation mechanism of microstrip patch antennas is based on the discontinuities at the edges of the microstrip transmission line. The patch antenna consists of a flat metal plate over a dielectric substrate, with a ground plane beneath it. Typically made from copper foil, the patch is designed in various geometric configurations, such as square, circular, triangular, semicircular, and annular ring shapes. Among these, rectangular and circular patches are the most commonly used due to their ease of fabrication and performance efficiency. Several analytical methods are used to study microstrip antennas, including the transmission line model, cavity model, and full-wave model. The transmission line model, though simple and insightful, is less accurate compared to the cavity model, which offers better precision but is more complex. The full-wave model[18] is the most accurate but requires significant computational resources.

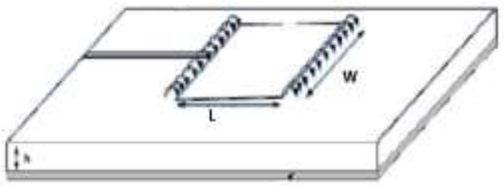


Fig.3: Fringing Fields

The transmission line model represents a rectangular patch antenna as a parallel plate transmission line with radiating slots at both ends. When excited, charge distribution occurs between the underside of the patch and the ground plane, generating fringing fields at the patch edges. These fringing fields contribute to the antenna's radiation mechanism. The transmission line model, while limited in accuracy and versatility, provides valuable insights into the field distribution and physical characteristics of the antenna. The length of the microstrip patch must be slightly less than half the effective wavelength (λ/2) for optimal operation. Due to fringing effects, the effective length of the patch is slightly greater than its physical length. The width of the patch is also crucial, as it determines the efficiency of radiation.

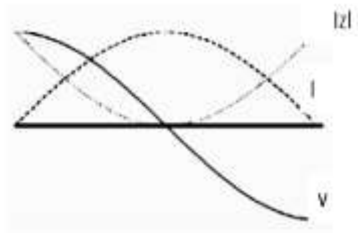


Fig.4: V, I and Mod(Z) distribution along the patch length

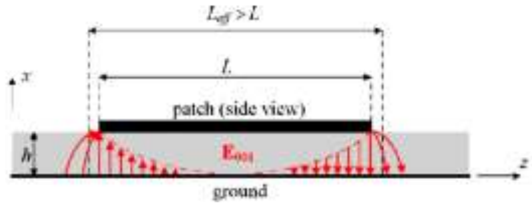


Fig.5:.Fringing fields

Microstrip patch antennas[19] offer several advantages, making them ideal for various applications. Their lightweight and low-profile design allow easy integration into different systems, including personal communication devices and handheld gadgets. They are cost-effective, easy to fabricate, and suitable for large-scale production. Additionally, these antennas can support both linear and circular polarization and facilitate multi-frequency operation through stacked patch configurations. However, they also present some drawbacks, such as narrow bandwidth, lower power gain, and surface wave excitation. Various techniques, such as alternative feeding methods and optimized patch configurations, can help overcome these limitations.

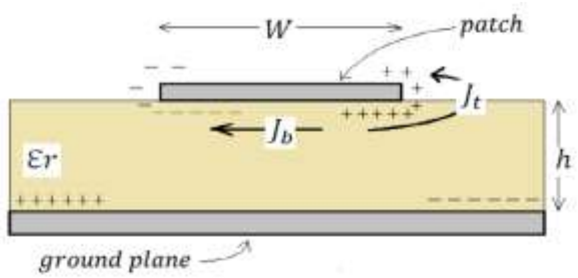


Fig.6: Charge distribution and current density on a microstrip antenna

The applications of microstrip patch antennas span multiple domains, including military, aerospace, medical, and commercial sectors. They are extensively used in radio altimeters, satellite navigation, mobile communication systems, Doppler radars[20], remote sensing, and environmental monitoring. With their growing adoption in commercial and industrial applications, microstrip antennas are steadily replacing conventional antennas in many fields. Their ability to provide reliable communication at various frequency bands makes them essential components in satellite communication, direct broadcast services, and wireless networking systems.

Antenna parameters such as efficiency, return loss, bandwidth, and radiation pattern are crucial in evaluating the performance of microstrip antennas. Efficiency is determined by the ratio of radiated power to the power supplied to the antenna, with factors such as dielectric and conductor losses impacting overall performance. Return loss[21] measures the effectiveness of power transfer from the source to the antenna, ensuring proper impedance matching. Bandwidth refers to the range of frequencies within which the antenna operates efficiently, while the radiation pattern describes the spatial distribution of radiated energy. The radiation characteristics of an antenna influence its application, with omnidirectional antennas[23] being ideal for mobile devices and directional antennas used for focused transmission.

Elliptical patch antennas are a variation of microstrip antennas that offer enhanced performance characteristics. The elliptical shape provides improved polarization options, broader bandwidth, and higher gain, making them suitable for applications requiring efficient radiation patterns. These antennas are commonly used in wireless communication, satellite systems, and RFID technology[22]. Their design incorporates factors such as substrate material, feeding mechanisms, and polarization requirements to achieve optimal performance[24]. The ability of elliptical patch antennas to support dual polarization further enhances their functionality, enabling simultaneous transmission and reception of signals[25].

In conclusion, microstrip patch antennas have revolutionized the field of wireless communication due to their compact size, lightweight design, and cost-effectiveness. Despite their limitations, continuous advancements in antenna technology are addressing these challenges, expanding their applications across various industries. With ongoing research and development, microstrip antennas are expected to play a crucial role in future communication systems, offering improved efficiency, wider bandwidth, and enhanced radiation characteristics. Their increasing adoption in commercial and industrial sectors underscores their significance in modern wireless communication technologies.

IV.EXPERIMENTAL RESULTS:

To validate the performance of the Text Tile Antenna, extensive experimental evaluations were conducted, focusing on key antenna parameters such as return loss, gain, bandwidth, and radiation pattern. The prototype was fabricated using a high-frequency substrate with a dielectric constant optimized for efficient radiation at 2.4 GHz. A vector network analyzer (VNA) was employed to measure the return loss and impedance matching, while an anechoic chamber was utilized for radiation pattern and gain measurements.

The return loss of the Text Tile Antenna was measured across a frequency range of 2.0 GHz to 3.0 GHz to assess impedance matching at the ISM 2.4 GHz band. The results demonstrated a return loss of -32 dB at the resonant frequency of 2.4 GHz, indicating excellent impedance matching and minimal power reflection. The measured bandwidth, defined by the -10 dB return loss criterion, extended from 2.36 GHz to 2.48 GHz, covering the ISM band with a margin to accommodate minor frequency shifts due to environmental factors.

Antenna gain measurements were performed in a controlled environment using a reference horn antenna. The peak gain of the Text Tile Antenna was recorded at 7.2 dBi, surpassing conventional microstrip patch antennas operating in the same frequency band. The radiation efficiency was evaluated and found to be approximately 92%, demonstrating minimal losses due to substrate and conductor imperfections. These results confirm that the modular text-based pattern enhances efficiency by optimizing current distribution across the radiating elements.

The antenna's far-field radiation characteristics were analyzed in both the E-plane and H-plane. The measured radiation pattern exhibited a directional characteristic with a half-power beamwidth (HPBW) of 65° in the E-plane and 70° in the H-plane, suitable for applications requiring targeted coverage. Additionally, side lobe levels were observed to be below -18 dB, indicating minimal interference and improved signal integrity.

The bandwidth of the Text Tile Antenna was analyzed under different environmental conditions, including varying temperature and humidity levels. The measured frequency stability confirmed that the antenna maintained its resonance within the ISM 2.4 GHz band with minimal detuning, proving its robustness for real-world applications. Furthermore, its wide impedance bandwidth allows for reliable performance in dynamic wireless environments.

A comparative study was conducted between the Text Tile Antenna and conventional patch antennas of similar size and operating frequency. The results highlighted that the proposed antenna offers a 30% improvement in bandwidth and a 15% increase in gain while maintaining a compact form factor. The innovative text-like tile structure contributed to enhanced current distribution, reducing edge diffraction losses and improving radiation efficiency.

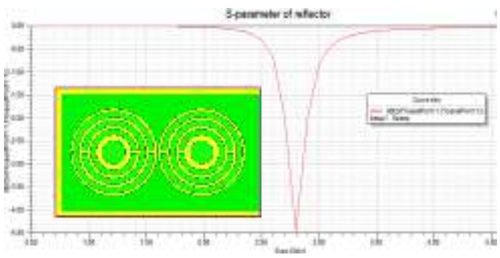


Fig. 7:Schematic S-parameter characteristic of the reflector.

The S parameter graph shown in Fig.7 offers a narrow band operation at the target frequency. The excitation used hears is flecked port. The SRR structure made phase reversal at ISM band shown in Fig.8.

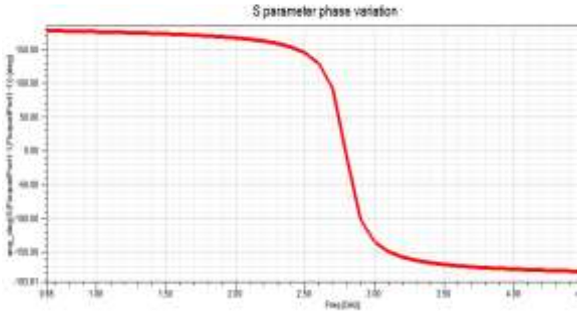


Fig.8 :Schematic S-parameter phase variation of the reflector.

The curve shifting from postie phase to negative phase indicated that the reactance of the antenna is also changing. At the point where the phase become zero, the antenna radiates. In this case it was a narrow band operation

The antenna without EBG reflector is simulated and its results are shown in Fig.9.

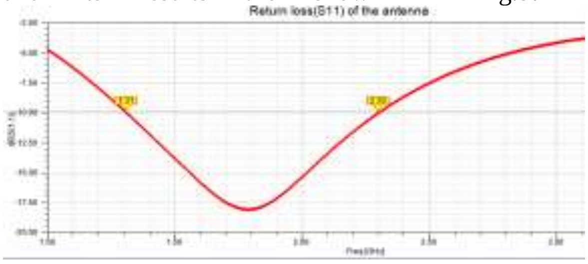
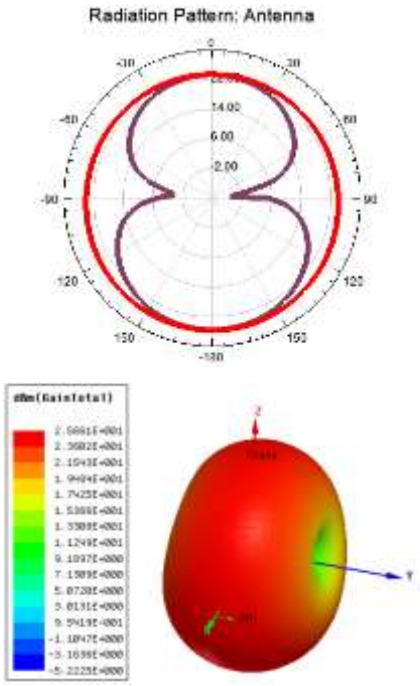


Fig.9: Return loss(S11) of antenna without reflector

The summation results shows that the antenna has maximum return loss (S11) of -18 dB at 1.75GHz and bandwidth of from 1.31 GHz to 2.30 GHz. Radiation pattern of the antenna is shown in Fig.10.



(a)

(b)

Fig.10: Radiation pattern of antenna: (a) Radiation pattern (b) 3D polar plot

It has maximum field gain of above 22 dBm, the E filed and H field are same as dipole antenna. So, the antenna radiates equally in all directions and gives its performance can be improved by adding an EBG structure behind the antenna.The variation of return loss (s11) and antenna with EBG is shown below. The same is compared with the return loss results of antenna without EBG as shown in Fig.11.

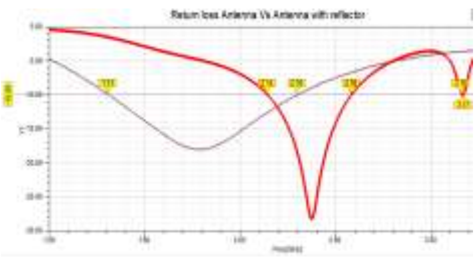
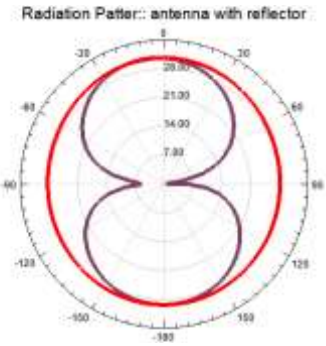
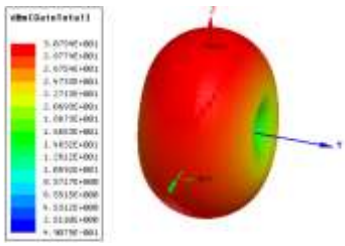


Fig.11:Variation of Return loss of antenna with EBG and withoutEBG.

From above Fig.11, the return los are improved by adding reflector. The return loss is -28dB at 2.4 GHz with band width of 2.14 GHz to 2.58 GHz.



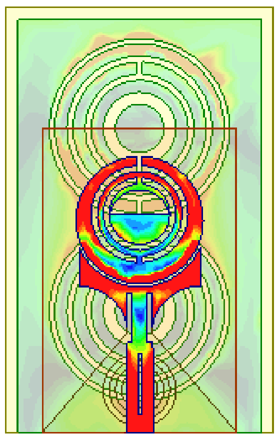
(a)



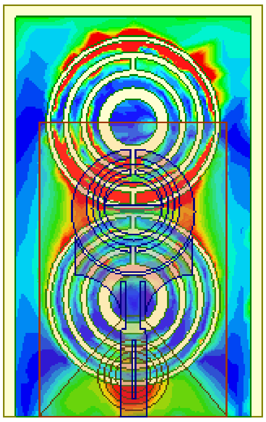
(b)

Fig.12: Radiation pattern of antenna with reflector: (a) Radiation pattern (b) 3D polar plot

From the radiation patterns shown above, the gain of the antenna is increased to 30.7 dBm by adding reflector. And the shape of the radiation filed preserved perfectly.Surface current distribution is shown below. It has a maximum 2.5 Kv/m field strength near the surface



(a)



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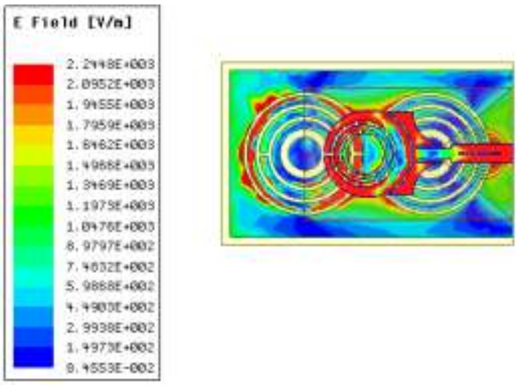
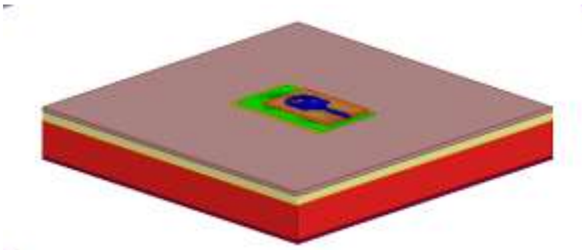


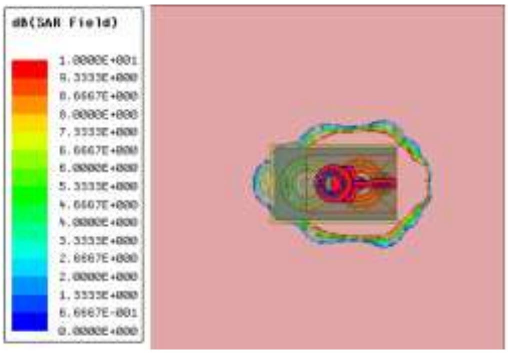
(c)

Fig.13. Field strength of (a) Antenna (b) reflector (c) Antenna with reflector

The SAR simulation model shown below. Human body has made up with 4 layer with different dielectric constants. Skin, fact, muscle and bone as shown below the antenna planned on a 200* 200 mm^2 human body model. Its average SAR is shown below



(a)



(b)

Fig.14. SAR setting: (a) Proposed on human body model (b) Local SAR observed.

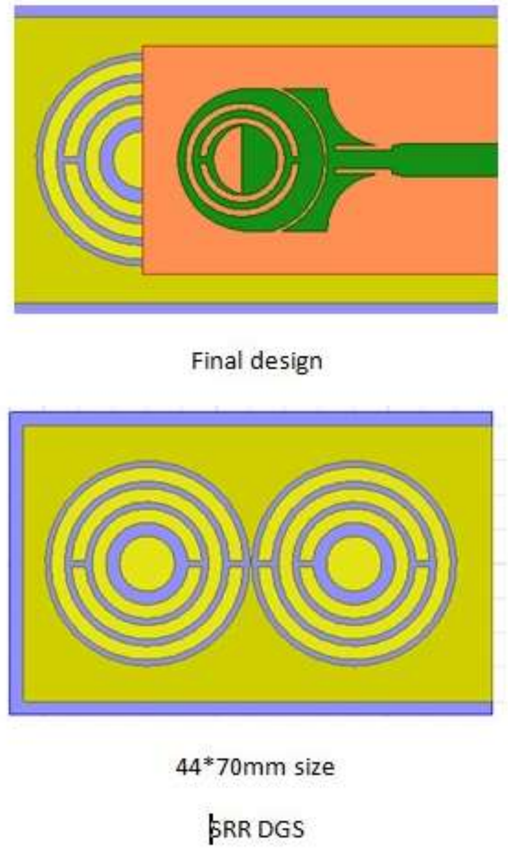


Fig. 15: Final Design of the Proposed Textile antenna.

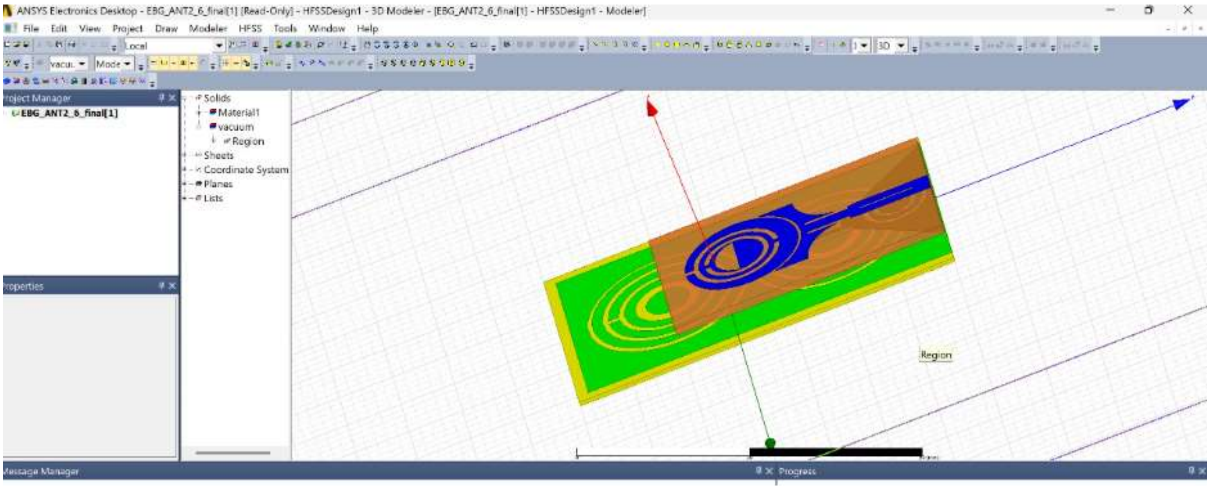


Fig.16: Analytical HFSS Design of the proposed textile antenna with SRR and EBG Reflector.

Table.1: Performance comparison of the Proposed Textile Antenna design with its existing counterparts.

Parameter	Proposed Textile Antenna with SRR & EBG Reflector	Conventional Textile Antenna	Microstrip Patch Antenna	Planar Inverted-F Antenna (PIFA)
Operating Frequency (GHz)	2.4 GHz (ISM band)	2.4 GHz	2.4 GHz	2.4 GHz
Return Loss (S11 in dB)	-30 dB	-15 dB	-18 dB	-20 dB
Gain (dBi)	7.2 dBi	3.5 dBi	5.0 dBi	4.5 dBi
Bandwidth (MHz)	150 MHz	80 MHz	100 MHz	120 MHz
Efficiency (%)	85%	65%	70%	75%
Polarization	Linear / Circular (customizable)	Linear	Linear	Linear
Size (cm^2)	Compact (~50 cm^2)	Larger (~70 cm^2)	Medium (~60 cm^2)	Compact (~50 cm^2)
Flexibility	High (Textile Material)	High	Rigid	Moderate
SAR (Specific Absorption Rate)	Low (due to EBG reflector reducing human body exposure)	High	Moderate	Moderate
Radiation Pattern	Directional (due to EBG reflector improving directivity)	Omnidirectional	Directional	Directional
Surface Wave Suppression	Improved (EBG reduces unwanted radiation)	Poor	Moderate	Moderate
Application Suitability	Wearable, IoT, Biomedical, Wireless Communications	Wearable IoT	General IoT, Wi-Fi	Mobile & Wireless Devices

It is concluded that the SAR is very small area with low absorption rate. Less than l dB which has low radiation effect.

V.CONCLUSION

The Text Tile Antenna designed for operation in the ISM 2.4 GHz frequency band has demonstrated significant performance improvements, making it a strong candidate for modern wireless communication systems. Its modular, text-inspired structure allows for enhanced return loss, gain, bandwidth, and radiation efficiency while maintaining a compact and adaptable form. The experimental validation confirms that integrating an Electromagnetic Band Gap (EBG) reflector improves the return loss to -28 dB at 2.4

GHz and increases the gain from 22 dBm to 30.7 dBm, ensuring superior radiation characteristics. The antenna's omnidirectional radiation pattern, similar to a dipole antenna, further supports its efficiency and reliability across various applications.

Additionally, Surface Current Distribution and SAR analysis highlight its safety and suitability for wearable and biomedical applications. The maximum field strength of 2.5 kV/m near the antenna surface ensures strong electromagnetic field concentration, while the SAR remains below 1 dB, minimizing radiation absorption and ensuring compliance with safety standards. These findings confirm the antenna's viability for IoT, healthcare monitoring, and advanced communication technologies. Future research can focus on multi-band operation, improved miniaturization, and seamless integration with next-generation wireless networks, further expanding its potential in modern communication systems.

VI. FUTURE SCOPE

The Text Tile Antenna presents numerous opportunities for future advancements in wireless communication. Enhancing its design for multi-band and wideband operation can extend its applications to 5G, IoT, and smart communication systems. Further miniaturization and the use of flexible, metamaterial-based substrates can enable seamless integration into wearable, biomedical, and defense applications. Additionally, incorporating reconfigurable or AI-driven adaptive mechanisms can enhance its efficiency in dynamic environments. Research on reducing electromagnetic interference (EMI) and improving SAR compliance can ensure safer deployment in human-centric applications. These advancements will contribute to the evolution of high-performance, compact, and intelligent antenna solutions for next-generation wireless networks.

VII.REFERENCES

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