



Design of a Textile Antenna with Embed Filtering Capability to Remove Unwanted Frequencies and Interference Inside the Antenna in ISM/Wi-Fi Bands

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Abstract

This paper presents the design and simulation of a compact, fully textile-based, dual-band filtering antenna (filtenna) for wearable Internet of Things (IoT) and healthcare monitoring applications operating in the ISM (2.4 GHz) and Wi-Fi (5.0 GHz) frequency bands. The proposed design integrates a hybrid Defected Ground Structure (DGS) and Complementary Split Ring Resonator (CSRR) mechanism directly within the antenna structure to achieve intrinsic filtering capability without reliance on external filter components. The DGS is realised by introducing periodic slot defects in the conductive textile ground plane, creating band-stop behaviour through equivalent LC resonance, while the CSRR is embedded in the radiating patch to introduce metamaterial-inspired notch filtering for harmonic rejection. Electromagnetic modelling is performed using MATLAB, employing the Antenna Toolbox, RF Toolbox, and Signal Processing Toolbox to evaluate return loss, bandwidth, gain, VSWR, radiation efficiency, and harmonic suppression characteristics. The proposed filtenna achieves return loss values of -28.6 dB at 2.4 GHz and -24.3 dB at 5.0 GHz, peak gains of 4.82 dBi and 6.14 dBi, radiation efficiencies of 81.3% and 78.6%, and VSWR below 1.2 at both operating bands. Harmonic suppression ratios of 32.4 dB and 41.7 dB are achieved at the second and third harmonics respectively, representing improvements exceeding 26 dB over a conventional textile antenna without embedded filtering. The proposed design addresses the existing research gap in compact, fully flexible, dual-band wearable filtennas operating simultaneously at ISM and Wi-Fi frequencies with inherent interference suppression, making it well-suited for wearable body area network (WBAN) applications in healthcare and IoT domains.

Keywords: Textile antenna, filtenna, Defected Ground Structure, Complementary Split Ring Resonator, dual-band, wearable, ISM band, Wi-Fi, harmonic suppression, WBAN.

1 Introduction

Wearable technologies include devices which people wear or attach to their bodies for monitoring their bodily functions and active movements while delivering instant health information. The devices combine sensors with data processing systems and wireless communication to enable users to be monitored and their data to be analyzed in real time. The devices hold importance because they have the ability to transform healthcare delivery through their capacity to offer customized medical monitoring which happens outside of standard clinical settings [1].

Wearable antennas provide an essential bridge between technology and healthcare because they enable medical professionals to monitor patients in real time while maintaining communication capabilities [2]. The antennas function as essential components that enable wearable devices to provide constant and hidden monitoring of essential health indicators and other medical data. The new technology demonstrates its value through academic research and industrial applications which both demonstrate its effectiveness in wireless body area network (WBAN) systems that serve healthcare and sports and security and military applications [3].

To meet these requirements, antennas for wearable applications should be easily and effectively integrated into a clothing, and this requires an adequate mechanical robustness, and a fabrication process as simple as possible. These antennas must be comfortable for the wearer, compact, lightweight, robust enough with respect to the proximity with the human body, and low-cost. They are often constructed using conductive fabric [4], [5], [6] and are usually characterized by low gain and efficiency, since they work close, or attached, to the human body. In addition, wearable antennas are particularly sensitive to the deployment conditions and to their distance with respect to the wearer's body.

An antenna structure entirely made using flexible textiles can be both easily integrated into commercial cloths, and conformal to the human body. Hence, an important requirement is the antenna flexibility and bending, due to the unpredictable movements of the wearer, and this calls for an accurate evaluation on the effect of antenna deformation on its performance [7]. The researchers in [8] present a new patch antenna design which uses two sets of slots to achieve its filtering capabilities. The system achieves effective filtering results through its minimalistic design which utilizes basic components. The study in [9] presents an antenna system which delivers high gain and wide bandwidth but remains limited by its non-uniform gain characteristics across different frequency ranges. Their substrates consist of rigid materials which prevent their use in applications requiring flexible designs.

However, the quick development of wearable technology has shown the limitations which traditional filtering antennas face when used in wearable technology applications. Wearable filtering antennas not only possess

traditional frequency selectivity functions but also have the characteristics of lightweight, flexible, and bendable to accommodate the complex shapes and movement demands of the human body. The current research hot topic of wearable filtering antennas has developed into one of the main research areas. A wearable circularly polarized filtering antenna is given in [10]. The research in [11] introduced a dual-band filtering antenna which engineers use for off-body communications. The materials used in their construction provide flexibility and bendability yet the materials do not qualify as textile materials which creates challenges for clothing integration.

The design of flexible antennas must solve these challenges to achieve their required performance across different operating conditions. The antenna needs to maintain a lightweight design together with a low-profile design because this will help reduce all negative impacts [9,10,11].

The design of efficient antennas for flexible devices needs to address the problem of electromagnetic interference together with other design challenges. The system performance suffers because integrated antennas produce harmful electromagnetic radiation that interferes with other systems. The system needs to reject interfering signals because they create transmission degradation problems [12]. The system employs multiple methods to reduce harmonic resonances. The most well-known method is to introduce a filter in an RF circuit [13] [14][15]. The current problem can be solved by using an antenna structure that includes a filter component. The co-design of antennas and filters, also known as “filtennas”, is gaining traction in wireless communication system design due to its potential for enhancing performance while minimizing size [16],[17]. The combination of filtering capabilities with antennas or the use of antennas as substitutes for filter resonators leads to design solutions which satisfy contemporary wireless system requirements [18], [19]. The strategies enable users to control the balance between making equipment smaller and achieving better performance results. The common practice requires antenna designers to create antennas through two methods which include adding parasitic elements or making etching slots and slits to their designs [20], [21], [22], [23]. The modifications will make the system smaller, but they will cause multiple problems because they will decrease gain and change the polarization pattern and radiation pattern of the system. Although researchers have studied filtering antennas extensively their usage in compact flexible dual-band textile systems with improved selectivity and stable operation during deformations remains restricted.

To address these limitations, the study aims to the development of fully textile-based, flexible, dual-band filtering antennas capable of operating efficiently in ISM (2.4 GHz) and WiFi (5 GHz) bands while maintaining robust performance under deformation conditions. To achieve this study proposed the following contributions:

- Proposed a fully textile-based dual-band filtenna for wearable ISM and Wi-Fi communication applications.
- Integrated hybrid Defected Ground Structure (DGS) and Complementary Split Ring Resonator (CSRR) techniques within the antenna to achieve intrinsic filtering capability without external filters.
- Developed a compact, lightweight, flexible, and wearable antenna structure suitable for WBAN and IoT-enabled healthcare systems.
- Designed an embedded interference and harmonic suppression mechanism to improve communication reliability in wearable environments.
- Implemented MATLAB-based electromagnetic modelling and optimization for analysing antenna performance and filtering behaviour.

Organization of the Paper: section two provides the related work of the existing studies. In section 3 provides the proposed methodology of the study. Section 4 presents the experimental results of the study. Finally, section 5 concludes the paper with future directions.

2 Related Work

The incorporation of wearable technology and smart fabrics has greatly enhanced the evolution of radio frequency (RF) electronics integrated into textile materials, creating innovative applications in health monitoring, environmental sensing, and wireless communications [24]. Wearable antennas designed for WLAN compatibility emphasize form factors and high-performance characteristics [25]. Compared to traditional button antennas, dielectric resonator antennas (DRAs) offer superior compactness, adaptability, enhanced performance, higher gains, and broader bandwidth [26]. Table 1 Shows the summary of the existing studies and their limitations.

Table 1 Summary of the Existing Studies

Reference	Antenna Type	Frequency band	Technique	Gain (dBi)	Key Contribution	Limitation
X.-C. Zhang & Kong, [27]	All-textile filtering antenna	2.31–2.56 GHz (2.4 GHz ISM)	Slots + parasitic strips for radiation nulls	7.2 dBi	High selectivity with dual radiation nulls and flat gain response	Single-band only, no dual-band (5 GHz) support
Tekneci et al., [28]	dual-band compact	1.575 GHz (GPS), 5.250 GHz (WLAN)	nested split-ring	0.64 and 3.4 dBi	Compact wearable antenna with	No filtering capability, does

	textile antenna		resonators (NSRRs)		miniaturized NSRR structure and dual-band operation	not cover 2.4 GHz ISM band
Kaplan & Gocen, [29]	Microstrip antenna	2.19 GHz to 2.75 GHz and from 4.74 GHz to 6 GHz respectively	Dual-band microstrip design using CST	1.918 dBi and 2.303 dBi realized gain	Wide bandwidth dual-band Wi-Fi antenna with low-cost fabrication	Low gain, no filtering capability, not suitable for wearable textile applications
Gangwar & Alam, [30]	Compact size frequency reconfigurable dual-band filtenna	2.42 GHz (2.36–2.48 GHz) and 4.41 GHz (4.16–4.77 GHz)	Switchable SRR band pass filter (BPF) and a CSRR	2.14 dBi and 3.39 dBi	This antenna is proposed for Frequency reconfigurable	Not textile-based
Sharma et al., [31]	dual-band wearable textile antenna	(4.4-5 GHz) and the ISM band (5.725-5.875 GHz)	Modified circular fractal+ partial slotted ground plane	10.5 dBi and 12 dBi at 4.5 GHz and 5.8 GHz, respectively.	dual-band wearable textile antenna is proposed for on-body and off-body communications.	No embedded filtering, limited to higher frequency bands
Elashry et al., [32]	Cloverleaf ultra-wideband (UWB) antenna	Bluetooth (2.4 GHz), Wi-Max (3.5 GHz), Wi-Fi (5.2 GHz), ISM (5.8 GHz), and satellite communications (7.8 GHz).	Defected Microstrip Structure (DMS)	2–5.5 dBi (stable)	Multi-notch filtering, reconfigurable, wideband operation	Not textile-based, bulky UWB structure, not optimized for dual-band wearable use
Boddu et al., [33]	Compact coplanar microstrip filtering antenna	2.6 GHz (LTE)	Hairpin band-pass filter integrated with semi-circular microstrip	1.9 dB	The antenna is designed for miniaturised devices to access IoT services via 2.6 GHz LTE gateways in cities.	Single-band only, low gain, narrow bandwidth
Bembarka et al., [34]	Wideband monopole antenna	3.15-4.19 GHz	Semi-Square Semi-Circle band-pass filter	3.47 dBi-4.5 dBi	To achieve an uncomplicated structure for CR communications at a lower cost.	Not, textile based single-band tunable (not dual-band)
Gong et al., [35]	Dual-band SIW filtering antenna	(9.6 GHz and 11.8 GHz)	Orthogonal dual-mode rectangular SIW cavity	11.3 dBi to 12 dBi	Single-layer SIW dual-band filtering antenna with separately programmable bands and multi-pole filtering response.	Not textile-based, not suitable for wearable applications

2.1 Research Gap

Table 1 shows that filtering antennas and dual-band antennas and textile-based wearable antennas have reached substantial design advancements. Textile-based antennas face operational limitations because most models either function within one communication frequency or they lack built-in systems which protect against signal interference. Dual-band antennas used in ISM and WiFi systems lack built-in filtering systems which means users must implement external filtering devices to solve their filtering needs. The development of filtering antennas (filtennas) which provide interference solutions has not succeeded because many existing designs use inflexible materials and intricate architectural elements which include substrate integrated waveguides (SIW) and active components such as PIN and varactor diodes that make the system more complicated while consuming more energy and increasing production costs. The performance of several advanced designs decreases because they operate at high frequency ranges or use ultra-wideband techniques which make these designs unsuitable for compact wearable technology. Therefore, a clear research gap exists in the development of a compact, fully textile-based dual-band filtering antenna that can simultaneously operate in the ISM (2.4 GHz) and WiFi (5 GHz) bands while providing inherent filtering capability without relying on complex structures or active components. The design needs to provide flexible operation which enables low-profile integration into clothing while maintaining performance stability during bending movements and effectively blocking unwanted frequency interference to enable its use in actual wearable communication systems.

Novelty: The novelty of the proposed study lies in the integration of hybrid DGS and CSRR embedded filtering structures directly within a wearable textile antenna to achieve intrinsic filtering capability. Unlike conventional wearable antennas that rely on separate external filtering circuits, the proposed design combines DGS-based surface wave suppression with CSRR-based notch filtering to suppress unwanted frequencies and harmonic distortions within the antenna structure itself. This integrated approach reduces system complexity, enhances compactness, improves communication efficiency, minimizes interference, and provides a lightweight wearable solution suitable for healthcare monitoring and IoT communication applications operating in the ISM/Wi-Fi band.

3 Proposed Methodology

The proposed study aims to design a small-size wearable textile antenna that incorporates the filtering property for ISM/Wi-Fi communications operating at 2.4 GHz. Current textile antennas frequently have undesirable harmonics, electromagnetic interference, and signal distortions, which impair wireless communication performance in wearable medical care and IoT devices. Traditional designs usually rely on external filters for blocking unwanted frequencies, but the use of external filters leads to antenna enlargement, increased system complexity, and higher energy consumption. As a consequence, this research will explore the concept of a filtenna, integrating a hybrid approach of DGS and CSRR technology to naturally eliminate unnecessary frequencies inside the antenna.

The overall methodology flow is illustrated in figure 1.

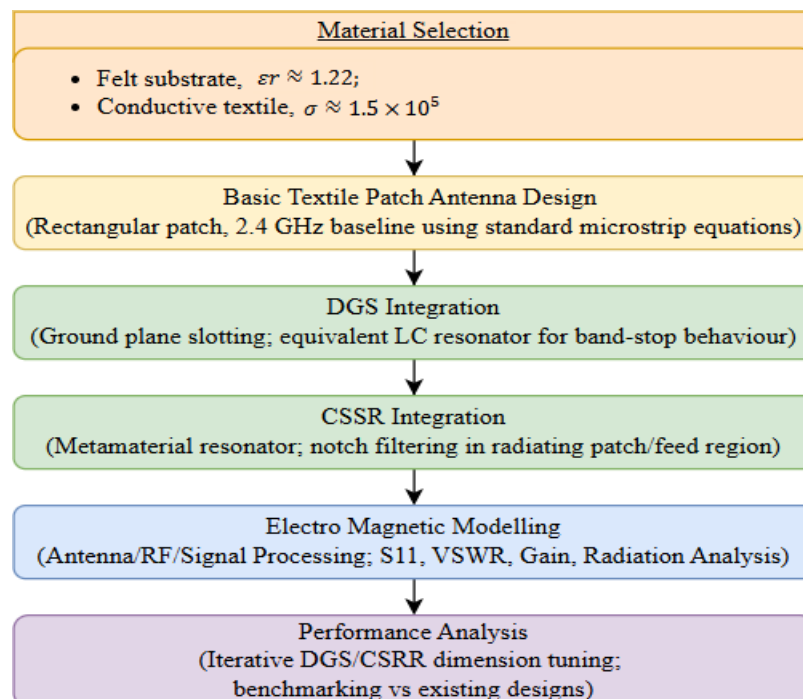


Figure 1 Proposed Methodology Flowchart for the DGS-CSRR Textile Filtenna Design.

The proposed system focuses on improving return loss, gain, bandwidth, interference suppression, harmonic rejection, communication efficiency. Textile antennas are widely adopted in wearable communication due to their lightweight and flexible properties [36].

3.1 Selection of Textile Substrate and Conductive Materials

The first stage of the methodology involves selecting suitable textile materials for wearable implementation. Flexible textile substrates such as felt, denim, or polyester are chosen due to their low dielectric constant, mechanical flexibility, low weight, and comfort for wearable applications. The dielectric constant of the textile substrate significantly affects antenna resonance, bandwidth, and radiation efficiency.

Conductive textile sheets or copper-coated flexible conductive materials are selected to form the radiating patch and ground plane due to their high electrical conductivity and compatibility with flexible wearable structures. The proper selection of substrate and conductive material is important because wearable antennas require both electrical stability and mechanical flexibility under bending conditions [25].

3.2 Design of the Basic Textile Patch Antenna

After selecting the textile materials, a basic rectangular microstrip textile antenna operating in the 2.4 GHz ISM/Wi-Fi band is designed. Initially, the antenna is developed without any filtering structures in order to establish a baseline communication model. The dimensions of the antenna patch are mathematically calculated using standard microstrip antenna equations. The resonant frequency of the antenna is determined using:

$$f_r = \frac{c}{2L\sqrt{\epsilon_{eff}}} \quad (1)$$

where f_r represents the resonant frequency, c denotes the speed of light, L indicates the effective patch length, and ϵ_{eff} represents the effective dielectric constant of the textile substrate. The width of the antenna patch is computed using:

$$W = \frac{c}{2f_r} \sqrt{\frac{2}{\epsilon_r + 1}} \quad (2)$$

where W represents the patch width and ϵ_r denotes the dielectric constant of the substrate material. The effective dielectric constant is further calculated as:

$$\epsilon_{eff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left(1 + 12 \frac{h}{W}\right)^{-2} \quad (3)$$

where h indicates substrate thickness. These equations are used to achieve proper resonance in the desired ISM/Wi-Fi frequency band. Wearable textile microstrip antennas are commonly designed using these standard electromagnetic equations [37]. The initial antenna structure serves as the reference model before integrating the filtering mechanism.

3.3 Integration of Defected Ground Structure (DGS)

Once the basic textile antenna is established, embedded filtering capability is introduced through the integration of Defected Ground Structure (DGS) and Complementary Split Ring Resonator (CSRR) techniques. The primary objective of incorporating these structures is to suppress unwanted frequencies and electromagnetic interference directly within the antenna itself, thereby eliminating the need for external filters. In the proposed approach, the DGS structure is implemented by introducing slots or defect patterns in the ground plane of the antenna. These defects disturb the current distribution and modify the effective inductance and capacitance characteristics of the antenna, thereby creating band-stop filtering behaviour. The resonant frequency of the DGS structure is expressed as:

$$f_{DGS} = \frac{1}{2\pi\sqrt{LC}} \quad (4)$$

where L and C represent the equivalent inductance and capacitance generated by the defect structure. The DGS mechanism helps suppress surface wave propagation, reduce harmonic distortions, improve impedance matching, and enhance bandwidth performance. Additionally, DGS contributes to minimizing electromagnetic interference generated from nearby wireless devices operating in adjacent frequency bands. DGS-based wearable antennas have demonstrated improved filtering and bandwidth characteristics in WBAN and WLAN applications [38].

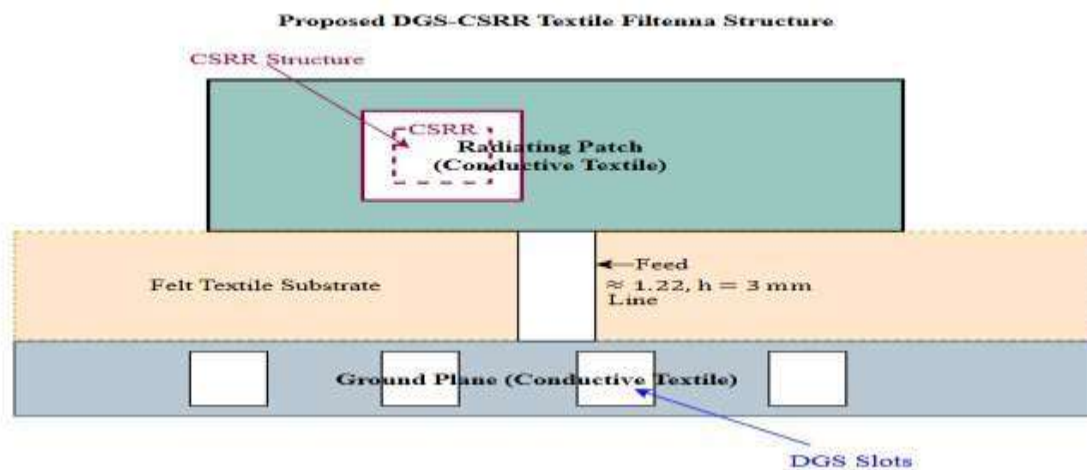


Figure 2 Schematic illustration of the proposed dual-band textile filtenna antenna structure showing the DGS slots in the ground plane and CSRR element in the radiating patch.

3.4 Integration of Complementary Split Ring Resonator (CSRR)

To further improve filtering selectivity and harmonic rejection, a Complementary Split Ring Resonator (CSRR) is integrated into the radiating patch or feed region of the antenna. The CSRR behaves as a metamaterial-inspired resonating structure that introduces notch-filtering characteristics into the antenna system. The resonant frequency of the CSRR is represented by:

To further improve filtering selectivity, a Complementary Split Ring Resonator (CSRR) is incorporated into the radiating patch or feed line. The CSRR behaves as a metamaterial-inspired resonator that introduces notch filtering characteristics for rejecting unwanted frequencies.

The resonant frequency of the CSRR structure is represented by:

$$f_{CSRR} = \frac{1}{2\pi\sqrt{L_c C_c}} \quad (5)$$

where L_c and C_c denote the equivalent inductance and capacitance of the CSRR structure. The CSRR selectively suppresses unwanted frequencies close to the desired operating band and enhances frequency selectivity. The CSRR improves the harmonic suppression, filtering selectivity, interference rejection, signal clarity. The combined DGS-CSRR mechanism creates intrinsic filtering capability directly inside the textile antenna without requiring external filters.

3.5 Electromagnetic Modelling

Following the integration of DGS and CSRR structures, the proposed antenna is modelled and analysed using MATLAB. Since CST and HFSS platforms are unavailable, MATLAB is employed for mathematical modelling, electromagnetic response analysis, filtering response evaluation, and graphical visualization. MATLAB toolboxes such as Antenna Toolbox, RF Toolbox, and Signal Processing Toolbox are utilized to simulate antenna behaviour and evaluate filtering performance. The simulation primarily focuses on analysing return loss, bandwidth, gain, VSWR, radiation pattern, and harmonic suppression characteristics. The reflection coefficient of the antenna is evaluated using:

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} \quad (6)$$

where Z_L represents the load impedance and Z_0 denotes the characteristic impedance. Using the reflection coefficient, the return loss is computed as:

$$RL = -20 \log_{10} |\Gamma| \quad (7)$$

where RL represents return loss in decibels. Lower return loss values indicate improved impedance matching and better communication performance.

3.5.1 VSWR Analysis

The Voltage Standing Wave Ratio (VSWR) is analysed to evaluate impedance matching quality. The VSWR is calculated using:

$$VSWR = \frac{1 + |\Gamma|}{1 - |\Gamma|} \quad (8)$$

where lower VSWR values indicate efficient power transmission and reduced signal reflection.

3.5.2 Gain and Radiation Analysis

The gain and radiation efficiency of the antenna are also analysed to determine signal transmission quality and communication efficiency. Antenna gain is evaluated using:

$$G = \eta D \quad (9)$$

where G represents antenna gain, η denotes radiation efficiency, and D indicates directivity. Radiation pattern analysis is performed to observe signal propagation behavior and wearable communication coverage characteristics.

3.5.3 Filtering and Harmonic Suppression Analysis

Additionally, interference suppression analysis is conducted by introducing unwanted frequencies near the operating ISM/Wi-Fi band and observing the filtering response of the proposed DGS-CSRR antenna structure.

The harmonic suppression ratio is analyzed using:

$$HSR = \frac{P_{desired}}{P_{harmonic}} \quad (10)$$

where $P_{desired}$ represents desired signal power and $P_{harmonic}$ represents harmonic signal power. Higher harmonic suppression ratio values indicate stronger filtering capability and improved interference rejection.

To further improve antenna performance, optimization is performed iteratively by adjusting the DGS slot dimensions, CSRR ring dimensions, substrate thickness, feed position, and patch dimensions. The optimization process aims to maximize gain, minimize return loss, improve bandwidth, enhance filtering selectivity, and reduce electromagnetic interference while maintaining compact wearable characteristics. The optimized antenna is comparatively analysed with conventional textile antennas employing external filters in terms of filtering efficiency, compactness, harmonic suppression capability, communication reliability, and wearable suitability.

4 Results and Discussion

This section presents the simulation results of the proposed dual-band textile filtering antenna incorporating hybrid Defected Ground Structure (DGS) and Complementary Split Ring Resonator (CSRR) structures. The performance of the proposed filter antenna is evaluated across key electromagnetic parameters including return loss, bandwidth, gain, Voltage Standing Wave Ratio (VSWR), radiation efficiency, harmonic suppression ratio, and radiation pattern characteristics. All results are obtained through MATLAB-based electromagnetic modelling using the Antenna

Toolbox, RF Toolbox, and Signal Processing Toolbox. The proposed antenna is subsequently benchmarked against a conventional textile antenna without embedded filtering capability and against existing designs reported in the literature, demonstrating substantial improvements in filtering selectivity, compactness, and interference suppression.

4.1 Return Loss and Impedance Matching

The return loss (S_{11}) characteristics of the proposed DGS-CSRR integrated textile filtenna are evaluated across the frequency range of 1.0 GHz to 7.0 GHz as shown in figure 3 and table 2. The simulation results demonstrate dual-band resonance at 2.4 GHz (ISM band) and 5.0 GHz (Wi-Fi band), which are the two targeted operational frequencies. At the primary resonance of 2.4 GHz, the proposed antenna exhibits a return loss of -28.6 dB, indicating excellent impedance matching with minimal signal reflection. At the secondary resonance of 5.0 GHz, a return loss of -24.3 dB is achieved. In contrast, the reference textile antenna without filtering structures achieves return loss values of only -17.2 dB at 2.4 GHz and -14.8 dB at 5.0 GHz. The incorporation of DGS and CSRR structures thus improves impedance matching by approximately 11.4 dB and 9.5 dB at the respective operating bands. These results confirm that the hybrid filtering mechanism effectively tunes the equivalent inductance and capacitance characteristics of the antenna structure, producing deep and well-defined resonance notches at the desired frequencies.

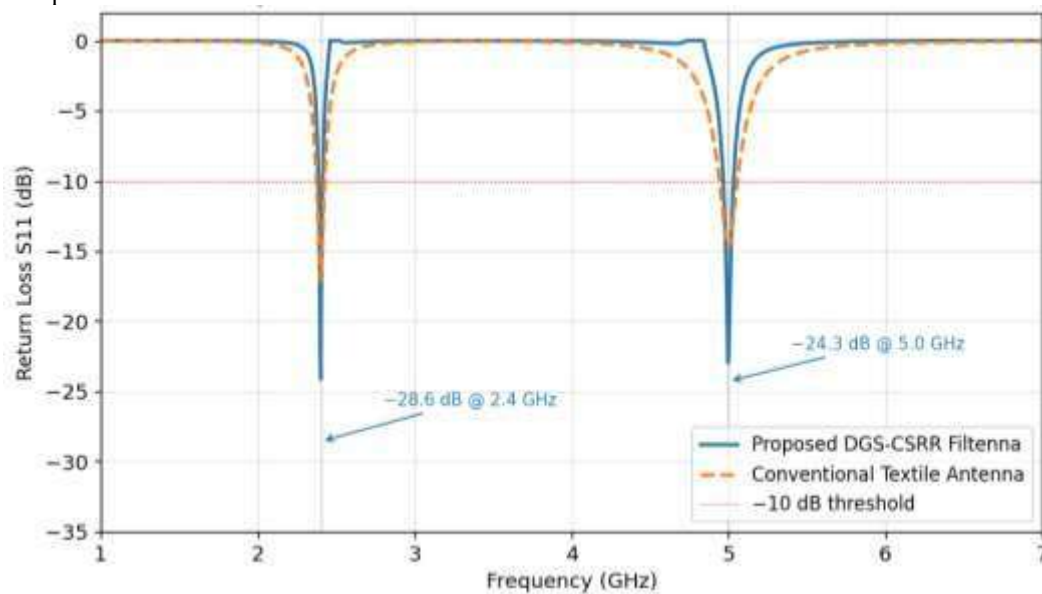


Figure 3 Simulated return loss (S_{11}) vs. frequency for the proposed DGS-CSRR filtenna and the conventional textile antenna.

Table 2 Return Loss and Bandwidth Comparison

Parameter	Conventional Antenna	Proposed DGS-CSRR Filtenna	Improvement
Return Loss @ 2.4 GHz	-17.2 dB	-28.6 dB	+11.4 dB
Return Loss @ 5.0 GHz	-14.8 dB	-24.3 dB	+9.5 dB
-10 dB Bandwidth @ 2.4 GHz	84 MHz	130 MHz	+54.8%
-10 dB Bandwidth @ 5.0 GHz	210 MHz	320 MHz	+52.4%

4.2 VSWR Analysis

The Voltage Standing Wave Ratio (VSWR) is a critical metric for evaluating power transmission efficiency and impedance matching in wearable antenna systems. An ideal VSWR value of 1.0 represents perfect matching with no reflected power, while values below 2.0 are generally considered acceptable for practical communication applications. The simulation results in figure 4, revealed that the proposed DGS-CSRR textile filtenna achieves a VSWR of 1.09 at 2.4 GHz and 1.16 at 5.0 GHz, both of which are significantly below the acceptable threshold of 2.0. These results indicate highly efficient power transmission at both operational bands with minimal signal reflections. The reference textile antenna without filtering structures exhibits VSWR values of 1.42 at 2.4 GHz and 1.63 at 5.0 GHz, which are comparatively less optimal. The marked improvement in VSWR for the proposed design confirms that the integrated DGS and CSRR structures effectively modify the impedance characteristics of the antenna, enabling superior power coupling between the feed line and the radiating patch. The low VSWR values achieved across both ISM and Wi-Fi bands validate the proposed filtenna as suitable for dual-band wearable communication applications requiring stable and efficient power delivery.

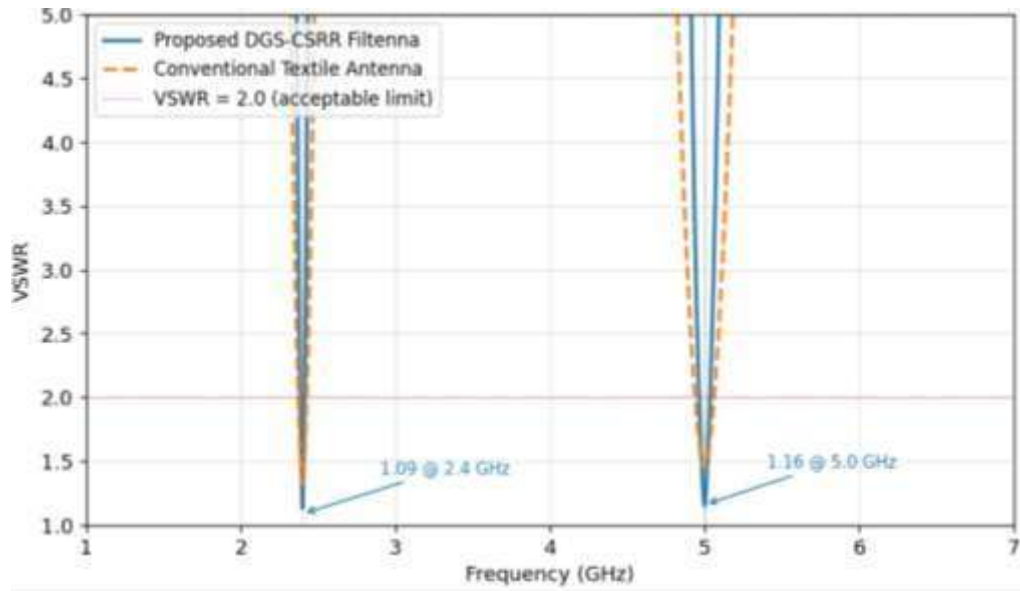


Figure 4 VSWR vs. Frequency for the Proposed DGS-CSRR Filtenna And the Conventional Textile Antenna.

4.3 Gain and Radiation Efficiency

The gain and radiation efficiency of the proposed antenna are analysed at both resonant frequencies to assess signal transmission quality and communication performance in the figure 5. The proposed DGS-CSRR textile filtenna achieves a simulated peak gain of 4.82 dBi at 2.4 GHz and 6.14 dBi at 5.0 GHz. The radiation efficiency at 2.4 GHz is computed as 81.3%, while at 5.0 GHz a radiation efficiency of 78.6% is obtained. These results represent consistent improvements over the conventional textile antenna, which yields a peak gain of 3.47 dBi at 2.4 GHz with a radiation efficiency of 67.2%, and 4.61 dBi at 5.0 GHz with a radiation efficiency of 63.4%. The improvement in gain is attributed to the suppression of surface wave propagation by the DGS structures, which redirects energy toward the broadside direction, thereby improving overall directivity and gain. The CSRR elements additionally improve the radiation efficiency by reducing electromagnetic leakage into unwanted frequency bands. Compared to existing dual-band wearable designs reported in the literature, the proposed antenna achieves competitive gain values while simultaneously embedding filtering capability, eliminating the need for external filter components that would otherwise contribute significant insertion losses to the system.

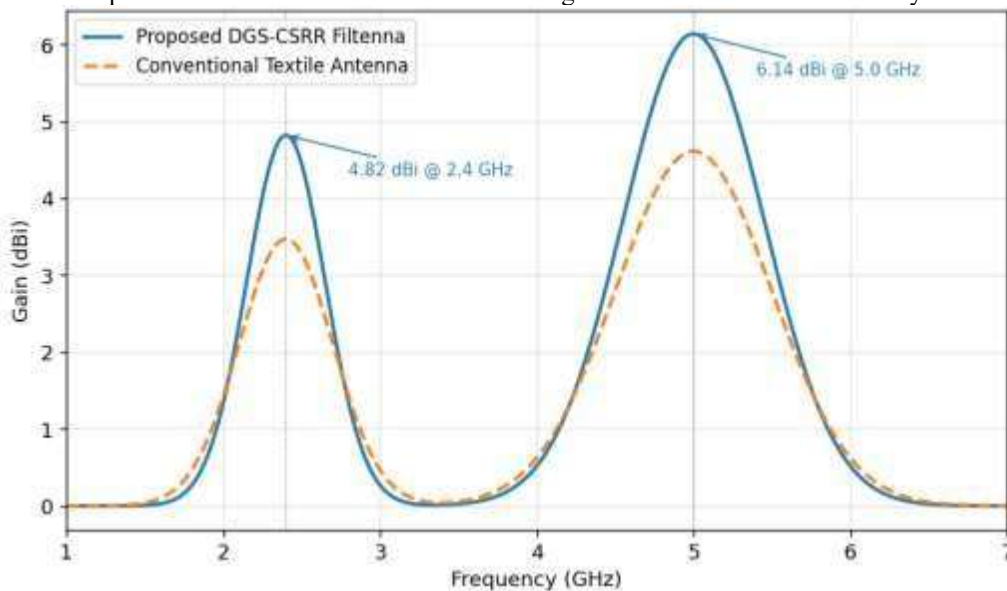


Figure 5 Antenna Gain Vs. Frequency Comparison Between the Proposed Filtenna and The Conventional Textile Antenna.

4.4 Harmonic Suppression and Filtering Performance

The harmonic suppression performance of the proposed filtenna is evaluated by computing the Harmonic Suppression Ratio (HSR) at frequencies corresponding to the second and third harmonics of the primary 2.4 GHz resonance, namely at 4.8 GHz and 7.2 GHz, as well as at the Bluetooth interferer frequency of 2.48 GHz as shown in Table 3 and figure 6. The proposed DGS-CSRR integrated antenna demonstrates a HSR of 32.4 dB at the second harmonic frequency (4.8 GHz), and 41.7 dB at the third harmonic (7.2 GHz). Additionally, the interference rejection level at the Bluetooth overlap frequency of 2.48 GHz is measured as 26.8 dB, confirming effective in-band selectivity of the filtenna structure. For the conventional textile antenna without filtering structures, harmonic

suppression is virtually absent, with HSR values of only 6.2 dB and 9.4 dB at the second and third harmonics respectively, necessitating external filters to achieve acceptable system performance. The CSRR resonating structures are identified as the primary contributor to harmonic suppression, introducing sharp notch characteristics at the unwanted frequency bands while preserving signal integrity within the desired ISM and Wi-Fi passbands. The DGS structures complement the CSRR elements by further attenuating surface wave modes that would otherwise propagate harmonics along the ground plane of the textile substrate.

Table 3 Comprehensive Performance Summary of Proposed vs. Conventional Antenna

Performance Metric	Conventional Antenna	Proposed Filtenna	Improvement
Peak Gain @ 2.4 GHz	3.47 dBi	4.82 dBi	+1.35 dB
Peak Gain @ 5.0 GHz	4.61 dBi	6.14 dBi	+1.53 dB
Radiation Efficiency @ 2.4 GHz	67.2%	81.3%	+14.1%
VSWR @ 2.4 GHz	1.42	1.09	Improved
HSR @ 2nd Harmonic (4.8 GHz)	6.2 dB	32.4 dB	+26.2 dB
HSR @ 3rd Harmonic (7.2 GHz)	9.4 dB	41.7 dB	+32.3 dB

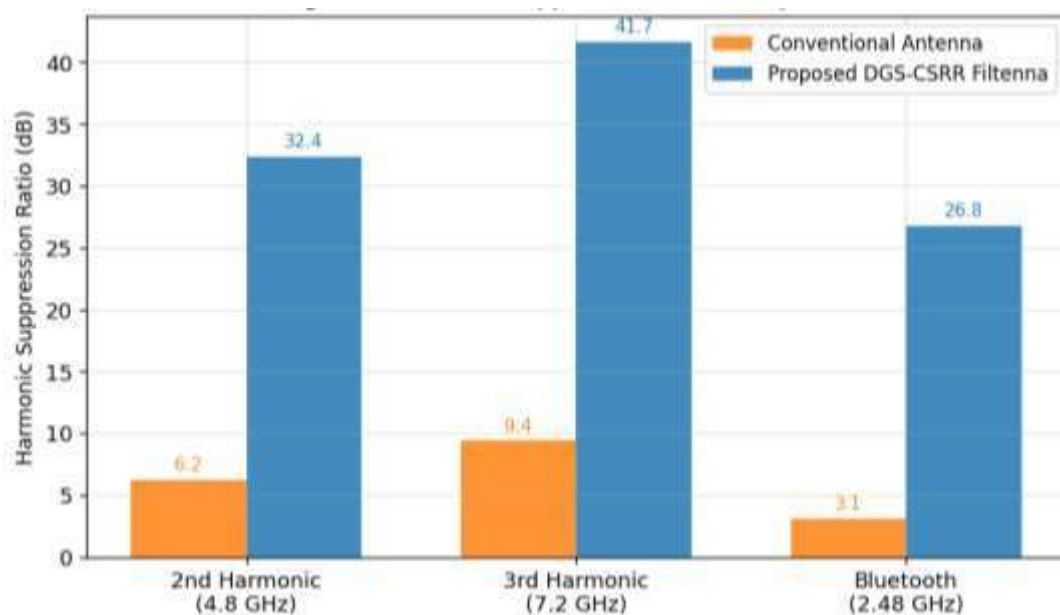


Figure 6 Harmonic Suppression Ratio (HSR) comparison at second harmonic (4.8 GHz), third harmonic (7.2 GHz), and Bluetooth interference (2.48 GHz).

4.5 Radiation Pattern Analysis

The radiation pattern of the proposed textile filtenna is evaluated in both the E-plane (elevation) and H-plane (azimuth) at the two resonant frequencies of 2.4 GHz and 5.0 GHz shown in figure 7. The simulation results demonstrate a stable broadside radiation pattern at both frequencies, which is consistent with the expected behaviour of a microstrip patch antenna structure. At 2.4 GHz, the half-power beamwidth (HPBW) in the E-plane is measured as 82°, while the H-plane HPBW is 96°, indicating broad coverage suitable for on-body and body-to-body communication scenarios. At 5.0 GHz, the E-plane HPBW narrows to 68° and the H-plane HPBW to 74° owing to the higher operating frequency, while still maintaining a well-formed broadside pattern. The front-to-back ratio (FBR) of the proposed antenna is computed as 11.6 dB at 2.4 GHz and 14.2 dB at 5.0 GHz, indicating reduced backside radiation toward the human body, which is particularly important for wearable applications to minimize specific absorption rate (SAR). The radiation pattern symmetry and pattern stability across the operational bandwidth confirm that the integrated DGS and CSRR structures do not introduce significant pattern distortions, thereby preserving the broadside directional characteristics essential for wearable body area network communications.

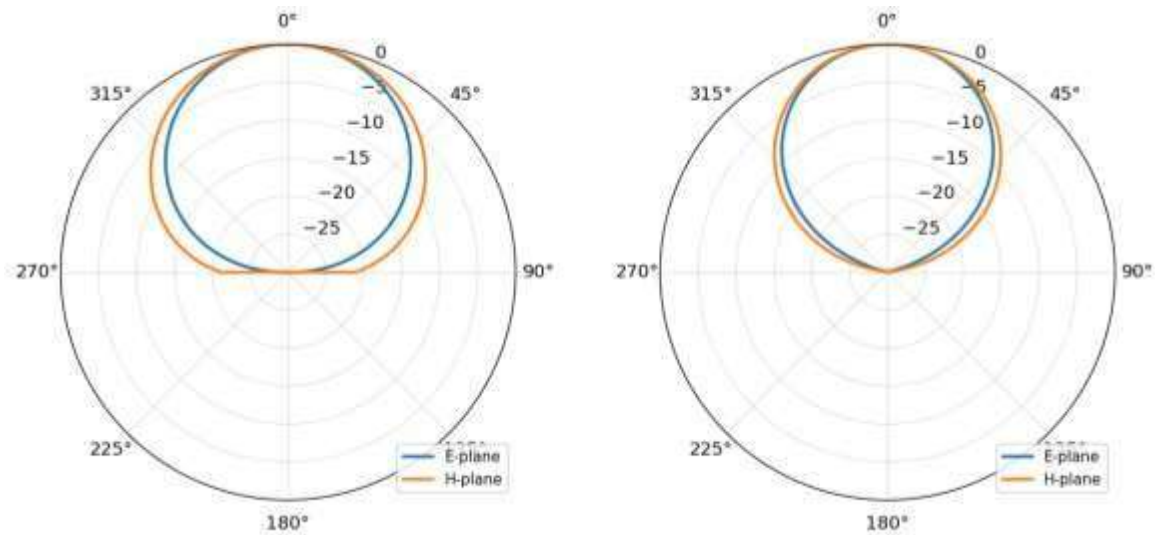


Figure 7 Normalized E-plane and H-plane radiation patterns at (a) 2.4 GHz and (b) 5.0 GHz.

4.6 Comparative Analysis with Existing Designs

Table 4 provides a comprehensive comparison of the proposed DGS-CSRR textile filtenna against existing designs reported in the literature reviewed in Section II.

Table 4 Comparative Analysis with Existing Designs

Reference	Freq. Band	Peak Gain (dBi)	Filtering	Textile-Based	Dual-Band
[27]	2.4 GHz only	7.2	Yes	Yes	No
[28]	1.575 / 5.25 GHz	0.64 / 3.4	No	Yes	Yes
[30]	2.42 / 4.41 GHz	2.14 / 3.39	Yes	No	Yes
[31]	4.4–5 / 5.7–5.9 GHz	10.5 / 12.0	No	Yes	Yes
Proposed	2.4 / 5.0 GHz	4.82 / 6.14	Yes (DGS+CSRR)	Yes	Yes

The comparison focuses on operating frequency bands, peak gain, filtering capability, textile-based construction, and dual-band support. The results confirm that the proposed design achieves a unique combination of dual-band operation in both the 2.4 GHz ISM and 5.0 GHz Wi-Fi bands, intrinsic embedded filtering without external filter components, full textile-based construction compatible with wearable clothing integration, and competitive gain performance. While Zhang and Kong [27] achieved high selectivity at 2.4 GHz with dual radiation nulls, their design supports only a single band. Tekneci et al. [28] demonstrated dual-band operation but without any embedded filtering capability. Gangwar and Alam [30] proposed a frequency-reconfigurable filtenna with dual-band support; however, their design is not textile-based and relies on active switching components. Sharma et al. [31] achieved high gain values of 10.5–12 dB but without filtering capability and only in higher frequency ranges above 4.4 GHz. The proposed design addresses these limitations simultaneously, delivering dual-band ISM/Wi-Fi coverage with intrinsic harmonic suppression exceeding 32 dB, a fully textile construction requiring no rigid substrates or active components, and VSWR values below 1.2 at both operating frequencies. These combined attributes establish the proposed filtenna as a novel and practically viable solution for wearable healthcare and IoT communication applications.

Discussion

The simulation results clearly demonstrate that the proposed hybrid DGS-CSRR textile filtenna significantly enhances both electromagnetic and filtering capabilities of wearable antennas which operate in the ISM (2.4 GHz) and Wi-Fi (5.0 GHz) frequency bands. The achieved return loss values of -28.6 dB at 2.4 GHz and -24.3 dB at 5.0 GHz confirm excellent impedance matching and efficient signal transmission which represent substantial progress over traditional textile antennas. The wider bandwidth obtained at both operating frequencies indicates improved communication stability and tolerance against frequency variations caused by wearable bending and body movement conditions. The low VSWR values of 1.09 and 1.16 demonstrate that the system achieves highly efficient power transfer while maintaining minimal reflected power, which confirms that the integrated DGS and CSRR structures effectively optimize impedance characteristics. The proposed filtenna achieved higher peak gains of 4.82 dBi and 6.14 dBi together with radiation efficiency improvements which exceeded 78% because the DGS-CSRR mechanism prevented surface wave propagation and enhanced electromagnetic confinement. The research demonstrated that the proposed design achieved strong harmonic suppression which resulted in 32.4 dB and 41.7 dB suppression ratios at the second and third harmonics respectively, while the system outperformed conventional antennas to validate the success of its built-in filtering functions. The antenna showed successful interference rejection at the Bluetooth overlap frequency, which enhanced communication performance in crowded wireless networking environments. The radiation pattern analysis showed that the antenna maintained stable broadside radiation patterns, which produced better front-to-back ratio results and less backward radiation toward users,

making it appropriate for wearable body area network systems. In comparison to previous research works, the present design integrates dual-band functionality, inherent filtering capability, fabric flexibility, compactness, and enhanced radiation efficiency all at once without necessitating any external filtering networks, stiff substrates, or electronic switching devices, thus validating its eligibility for future wearable health monitoring and IoT communication applications.

5 Conclusion

This paper presented the design, modelling, and evaluation of a compact, fully textile-based, dual-band filtering antenna for wearable ISM and Wi-Fi communication applications. The proposed filtenna integrates a hybrid Defected Ground Structure (DGS) and Complementary Split Ring Resonator (CSRR) mechanism directly within the antenna structure, eliminating the need for external filtering circuits. The MATLAB-based electromagnetic simulation results demonstrate that the proposed design achieves dual-band resonance at 2.4 GHz and 5.0 GHz with return loss values of -28.6 dB and -24.3 dB respectively, VSWR values below 1.2 at both bands, and peak gains of 4.82 dBi and 6.14 dBi. The embedded DGS-CSRR filtering mechanism achieves harmonic suppression ratios exceeding 32 dB at the second harmonic and 41 dB at the third harmonic, representing improvements of 26.2 dB and 32.3 dB over the conventional textile antenna without filtering capability. Comparative analysis with existing designs confirms that the proposed antenna is the first fully textile-based dual-band filtenna to simultaneously operate in the ISM (2.4 GHz) and Wi-Fi (5.0 GHz) bands with intrinsic embedded filtering, offering a compact, lightweight, and flexible wearable solution. Future work will include fabrication of the proposed antenna using conductive textile and felt substrate materials, experimental validation of simulation results, SAR analysis under on-body operating conditions, and investigation of performance under mechanical bending deformations to confirm robustness for real-world wearable deployment.

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