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MOBILE & WIRELESS HEALTH

An Effective Design of Wearable Antenna with Double Flexible Substrates and Defected Ground Structure for Healthcare Monitoring System

Ameena Banu Mustafa[1] **· Tamilselvi Rajendran**[1]

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Abstract
Due to the development of modern wearable mobile devices, the need of antenna with smaller size and internally flexible to fit becomes necessary. Miniaturization of Micro Strip Patch (MSP) antenna increases its employability for communication in different aspects. The use of flexible material for the fabrication of MSP antenna still improves its use for Wireless Body Area Networks (WBAN) which includes devices for monitoring systems in military, surveillance and medical applications. The devices designed specifically in Industrial Scientific Medical (ISM) band are used for communication in these applications. Defected Ground Structure (DGS) is adopted as an emerging technique for improving the various parameters of microwave circuits, that is, narrow bandwidth, cross-polarization, low gain, and so forth. In this paper, the design of compact micro strip patch antenna using different flexible substrate materials with DGS is proposed to resonate the antenna at 2.45GHz ISM band which can be used as biomedical sensors. Felt and Teflon with dielectric constant 1.36 and 2.1respectively are chosen as flexible substrate material among various flexible materials like cotton, rubber, paper, jeans etc. Using CST studio suite software, the designed antenna is simulated and the fabricated antenna is tested with Vector Network Analyzer (VNA). The performance parameters like return loss, gain, directivity and Voltage Standing Wave Ratio (VSWR) of the antenna are analyzed.

Keywords CST software · ISM band · WBAN · Defected ground structure · VNA · Return loss · Directivity · Gain · Flexible dielectric materials · Teflon · Felt

Introduction

Antenna plays vital role in communication for transmission and reception of electromagnetic waves in free space. The design of an efficient antenna providing low return loss and high gain for recent wireless applications is a major challenge. Micro strip antennas are widely used for its low profile, easy manufacturability, simple structure, low cost and omni directional radiation patterns [1, 2]. These features provide a great advantage over the traditional ones. Modern mobile devices can be used as Cordless phones, Near Field Communication (NFC) devices, Monitoring System and Wireless Computer networks. While designing the antennas for these applications particularly for monitoring devices, the flexibility of the material is quite important. Hence, the substrate layer of MSP can be designed with flexible materials like Cotton, Felt, Teflon etc. While choosing the flexible dielectric material for antenna design many of its characteristics are being considered like dielectric constant, loss tangent, adhesive property, temperature coefficient, mechanical strength, recyclability etc. High value of dielectric constant increases the level of miniaturization at the same time increases the spurious radiation also. Therefore, optimum value of dielectric material is preferred. Similarly while considering about mechanical strength if it is too rigid it cannot be used as flexible material and hence with enough strength but be flexible is required.

These Flexible Substrate Antennas (FSAs) designed at particular resonant frequency should unaffected under bending, stretching and twisting. Even when it is embedded with fabrics and bandages, they should function normally [3–6]. When

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✉ Ameena Banu Mustafa
am_banu@yahoo.com; ameenabanuece@sethu.ac.in

Tamilselvi Rajendran
rts.ece@gmail.com

[1] Department of ECE, Sethu Institute of Technology, Pulloor, Virudhunagar District, Tamilnadu 626115, India

Fig. 1 Wearable antenna applications

the micro strip patch antennas made with flexible substrates, they provide the possibility of wearing it for communication purposes like tracking, navigation and for public safety purposes [7, 8]. The design of wearable devices for medical applications having several challenges like [9].

- Safety and Reliability
- Compactness
- Power requirement
- User acceptability
- Environment where it is used like home, hospital etc.

Some of the wearable antenna applications are shown in Figure 1 [10].

For medical applications, the antenna used as wearable device may have dual polarization i.e. either linear polarization or circular polarization. When circular polarization is preferred, for some human beings it may cause skin diseases when there is a radiation towards skin. As a whole, a linear polarized antenna may be preferred for medical wearable devices [11, 12].

The main challenge of designing of this kind of antenna is impedance matching which also sometimes confines its applications. In order to conquer these shortcomings, some new technologies have been introduced. One such technique that can be used to overcome these limitations is using Defected Ground Structure (DGS) [13–15]. As the name Defected Ground Structure suggests, intentionally mistakes like slots or defects integrated on the ground layer of MSP. The structure may consist of single DGS unit or multiple DGS unit. When multiple number of DGS units used, they may be arranged horizontally or vertically. Sometimes concentric circles also introduced. The periodic repetition of unit DGS cells gives much variation in the performance of the antenna. DGS exhibits negative permittivity and permeability. These structures are realized by etching off a simple shape defect from the ground plane of micro strip patch antenna. The simple shapes used as Defected Ground Structure may be circular, rectangular, dumbbell, etc. At the same time, the structures shown in Fig. 2 also be used based on the design requirements [16, 17].

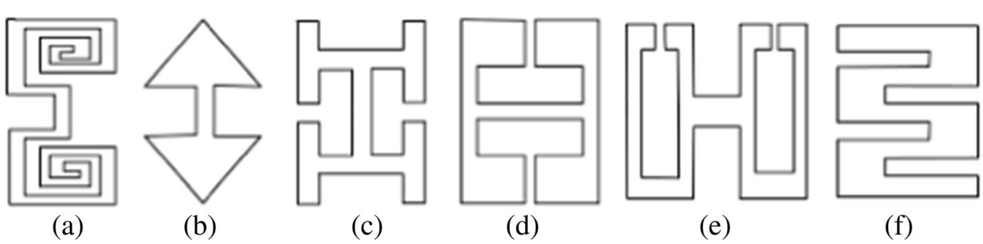


Fig. 2 Different shapes of DGS

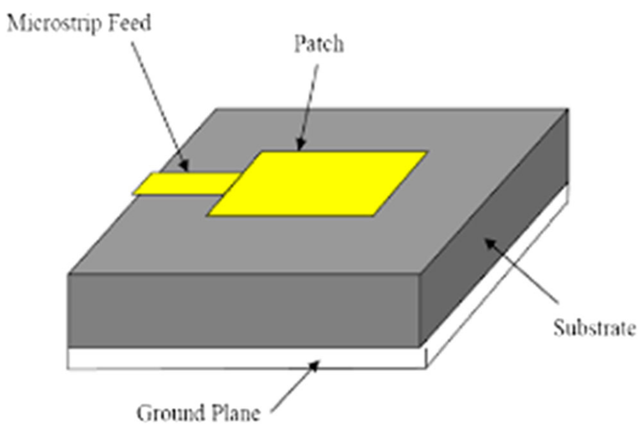


Fig. 3 Micro strip patch antenna structure

Due to its simple structural design, this method is preferred as compared to different feeding techniques (https://www.researchgate.net/.../Comparison-of-PBG-EBG-and-DGS_tbl1_313253370) like Electromagnetic Band Gap (EBG) and Photonic Band Gap (PBG) to enhance the performance of the antenna in terms of suppression of higher order harmonics, mutual coupling between the nearby elements and cross-polarization to improve the radiation characteristics. A microstrip antenna with diagonal square shaped DGS is used.

Vector Network Analyzers (VNA) are used to test component specifications and verify design simulations to make sure systems and their components work properly together. VNA contains both a source, used to generate a known stimulus signal, and a set of receivers, used to determine changes to this stimulus caused by the device-under-test or DUT. The stimulus signal is injected into the DUT and the VNA measures both the signal that's reflected from the input side, as well as the signal that passes through to the output side of the DUT. It performs two types of measurements – transmission and reflection. Transmission measurements pass the VNA stimulus signal through the device under test, which is then measured by the VNA receivers on the other side. Comparatively, reflection measurements measure the part of the VNA stimulus signal that is incident upon the DUT, but does not pass through it. Instead, the reflection measurement measures the signal that travels back towards the source due to reflections. The most common reflection S-parameter measurements are S_{11} and S_{22} (https://www.tek.com/dokument/primer/what-vector-network-analyzer-and-how-does-it-work).

Table 1 List of substrate materials with their dielectric constant

Substrate Material	Dielectric Constant ε_r
Polymide	3.4
Rubber	7
PTFE/Teflon	2.1
Felt	1.36
Jeans	1.6
Paper	1.4

Table 2 Dimensions of proposed antenna

Parameters	Values in mm
Patch length L	36.27
Patch width W	36.27
Patch height h	0.035
Substrate thickness	1.6
Ground length	72.54
Ground width	72.54
Ground height	0.035

Related work

Many researchers have designed the micro strip patch antenna with flexible materials. Sankaralingam S and Gupta B [18] developed the MSP with wash cotton and curtain cotton as substrate material and they have achieved the return loss of −15.6 dB with wash cotton and -16 dB with curtain cotton. Under bending conditions, the return loss was reduced. Researchers Tanaka, M., Jae-Hyeuk, J [19], Santas, J.G., Alomainy, A., Yang, H [20] and Corchia, L., Monti, G., De Benedetto, E. and et al. [21], described the design of antenna in which the conductive spray consists of copper with gas used along any flexible material. Humberto C. C. Fernandes, José L. Da Silva And Almir Souza E S. Neto [22] explained the use of defected ground structure in design of patch antenna which resonates at around 3GHz, in which FR4 was used as substrate

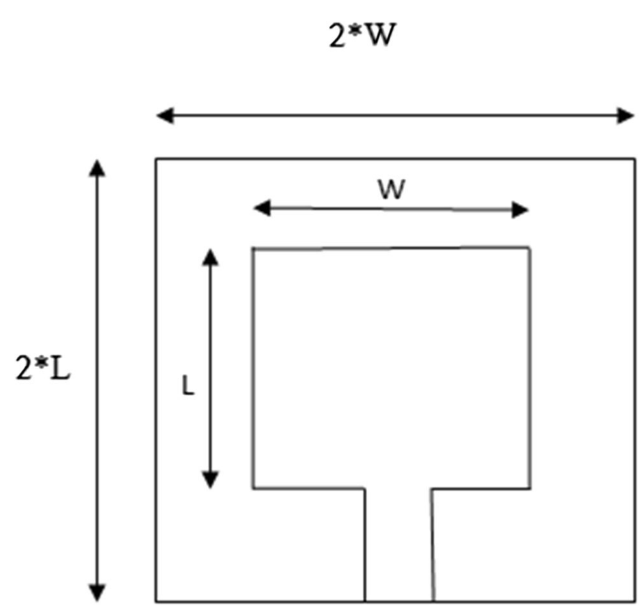


Fig. 4 Top view of proposed antenna

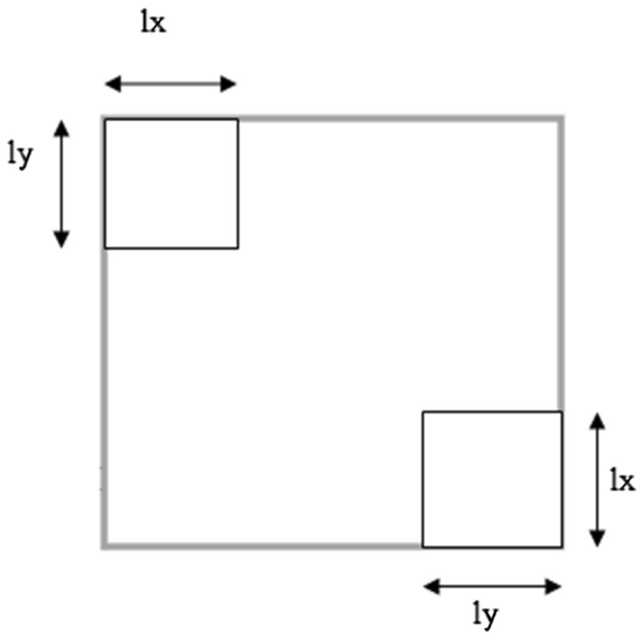


Fig. 5 Bottom view of proposed antenna with DGS

material. They have achieved the return loss of -19 dB at 3.3GHz and also resonate at multiple frequencies.

H. Elftouh and et al. [23] developed a patch antenna with one unit and double unit DGS for resonating at 5.7GHz, where FR4 is used as substrate. But, the fabricated antenna resonated at 3.3GHz with one unit DGS and at 3GHz with double unit DGS. Alix rivera and Balanis [24] inserted a ferrite ring at the mid of substrate so that substrate layer was divided in to two layers of dielectric-ferrite and ferrite-dielectric. Even the performance of the antenna was satisfied at the specified frequency, the cost and design complexity of the antenna was increased due to the use of ferrite materials. Sumit Majumder, Tapas Mondal and M. Jamal Deen [25] described the progress in low-power, compact wearables (sensors, actuators, antennas,) used for monitoring the different parts and functions of the body pave the way for low-cost, unobtrusive, and long-term health monitoring system.

The above studies on design of micro strip patch antenna with different materials and different techniques elaborated the advantages of use of flexible and multiple substrate materials. When the FR4 is used for fabricating the antenna, the flexibility became questionable at the same time the availability and cost of the flexible material used should be considered. Hence, we authors getting interested in designing an antenna with flexible substrate material such as Felt, Teflon and Jeans as dielectric substrate which can extend its use for wearable applications and combination of different substrate materials as single substrate layer to enhance the performance of the antenna at the desired resonant frequency.

Table 3 Dimensions of diagonal square in ground layer

Parameters	Values in mm
Length of the upper square	10
Width of the upper square	10
Length of the lower square	10
Width of the lower square	10
Height of the two squares	0.035

Antenna design

A micro strip patch antenna consists of ground layer, substrate layer and conducting layer. The ground and conducting layers are normally copper and for substrate layer, a material with low dielectric constant is preferred to improve the radiation property of the antenna. The dimensions of all the three layers were calculated for the preferred resonant frequency and dielectric constant of the substrate material. The basic structure of micro strip patch antenna is presented in Fig. 3 which consists of ground, substrate and radiating patch.

While designing the antenna, initially the resonant frequency was chosen according to the frequency band of operation. Since, we aimed for ISM band applications, the resonant frequency was chosen as 2.4GHz.The patch dimensions width and length is calculated as below [26].

Width

The width of the patch is calculated by using eq. (1)

$$W = \frac{C}{2f_0\sqrt{\frac{(\in r+1)}{2}}}\,[\mathrm{mm}] \tag{1}$$

where C is the velocity of light in free space, f_o is the resonant frequency and ε_r is the dielectric constant of the substrate material.

Length

The length of the patch is calculated by using eq. (2)

$$L = L(eff) - 2\Delta L\ [\mathrm{mm}] \tag{2}$$

where

$$L(eff) = \frac{C}{2f0\sqrt{\in(reff)}}\,[\mathrm{mm}] \tag{3}$$

and

$$\in r(eff) = \frac{\in r+1}{2} + \frac{\in r-1}{4}\left(1+\frac{12h}{W}\right)^{-1/2} \tag{4}$$

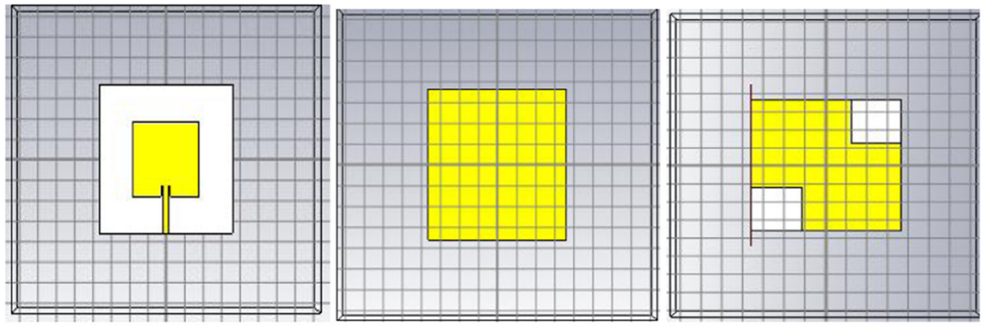


Fig. 6 **a** Front view **b** Back view **c** Back view with square DGS

where **h** is the height and **W** is the width of the patch. The patch antenna dimensions **L** and **W** are obtained for the resonating frequency of 2.45GHz. The length of the patch is calculated with the aid of effective dielectric constant $\varepsilon_{r(eff)}$ which is lower than the actual dielectric constant of the material, since it includes the fringing effect also. The height **h**of the patch and the ground is kept as 0.035 mm.

Substrate

For flexible antenna [27], Cotton, Polyester, Jeans, Felt, Teflon etc. may be used as substrate material. Some of the flexible substrate materials and their relative permittivity (dielectric constant) are given in Table 1.

While choosing the dielectric material for substrate, the clear understanding of effect of dielectric constant ε_r on radiation efficiency is required. If a material with high dielectric constant is preferred, the antenna size may get reduced at the same time the radiation efficiency also gets reduced. When the antenna used as an implantable device for WBAN networks, the size must be small and its efficiency should be high. Hence in this proposed design, the materials with moderate dielectric constant like felt and Teflon with $\varepsilon_r = 1.36$ and 2.1 respectively are preferred for substrate. The thickness of each substrate material is 1.6 mm for single substrate design and 0.8 mm each for double substrate design [28–32], with the dimension of 36.27(L) × 36.27(W) mm^2.

Table 4 Return loss with single substrate (Simulation Results)

Substrate	DGS	Frequency (GHz)	Return loss S_{11} (dB)
Felt	without	2.9	−9
Felt	with	2.95	−9.7
Teflon	without	2.48	−3.7
Teflon	with	2.40	−20

Dimensions of the ground plane and substrate layer are generally taken as 2 times the dimension of the patch to avoid the finite ground effect. The thickness of the ground plane and patch are taken as 0.035 mm. The dimensions of the antenna are given in Table 2.

Finally the Defected Ground Structure is being implemented with diagonally opposite squares in the ground layer of the antenna. Now the antenna consists of ground layer of Copper with DGS, substrate of Teflon, substrate of Felt and conducting layer with patch of Copper. According to the resonant frequency and the selected dielectric constants of the substrate materials, the length and width of the patch were same. The top view of the antenna was explicitly given in Fig. 4 and the bottom view of antenna with DGS of diagonally opposite squares is shown in Fig. 5.

Table 3 below shows the diagonal square dimensions introduced in ground plane as defect.

Feed point

The feed point was placed at mid point along either side of the antenna to produce linear polarization. Regarding polarization, since the device is to be attached with the human body, the back radiation towards human body should be avoided and hence circular polarization is not preferred. For impedance matching, the location of feed point can be optimized. When the antenna was designed using CST software, the above measurements were used to fix the dimension of the antenna and the simulated structures were given in Fig. 6.

Results and discussion

The performance of designed patch antenna with single and double substrate (with and without DGS) is analyzed using CST studio suite software. The antenna parameters Return lossS_{11}, VSWR, Directivity and Gain are observed from the plots and compared.

Table 5 Gain and directivity with single substrate (simulation results)

Substrate	DGS	Gain (dB)	Directivity (dB)
Felt	without	2.83	7.21
Felt	with	2.41	5.8
Teflon	without	5.9	6.4
Teflon	with	6.38	7.11

Table 4 shows the value of resonant frequency and return loss for single substrate antenna with and without square DGS and Table 5 shows the gain and directivity under the same conditions.

Based on the simulated results of the antenna with single flexible substrate material with and without square DGS, the return loss of around -10 dB was achieved. While taking into consideration, the values of gain and directivity are satisfied for an antenna. For further improving the performance of the antenna in terms of return loss at the specified resonant frequency, the double substrate method is introduced. Figure 7 shows the return loss graph of proposed antenna without DGS and Fig. 8 shows the same when square DGS is used. From this Fig. 7, it is observed that the antenna resonated at 2.4GHz and the return loss was around -4 dB.

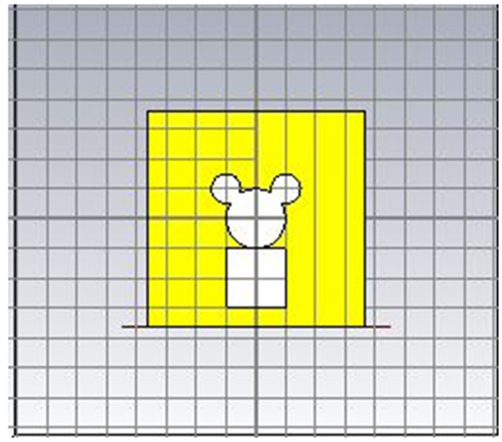


Fig. 9 Back view of antenna with doll shaped DGS

From Figs. 7 and 8, it is observed that the return loss of the antenna was improved to -23 dB when square DGS is introduced at the ground plane ant it resonates at the frequency of 2.42GHz. To emphasize the importance of introduction of DGS in antenna design, a doll like different structure as in Fig. 9 is used and analyzed as earlier.

The following Fig. 10 shows the return loss characteristics of the antenna with doll shaped DGS.

Fig. 7 Return loss graph of proposed antenna without DGS

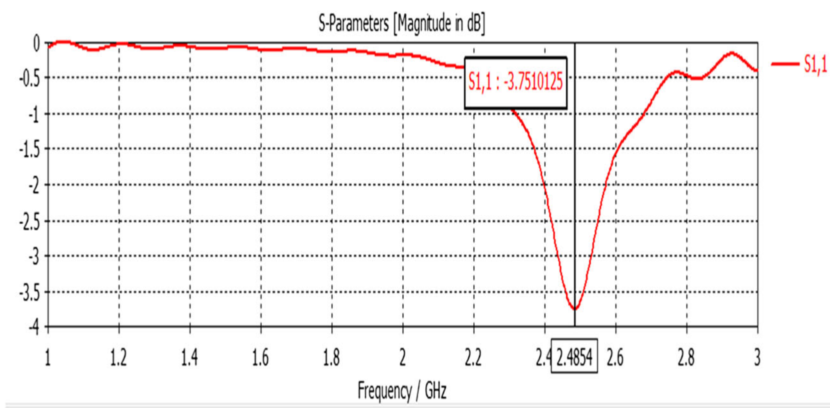
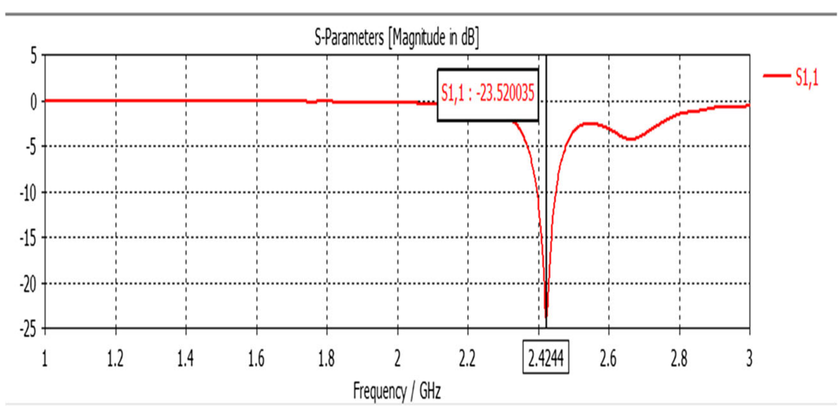


Fig. 8 Return loss graph of proposed antenna with Square DGS



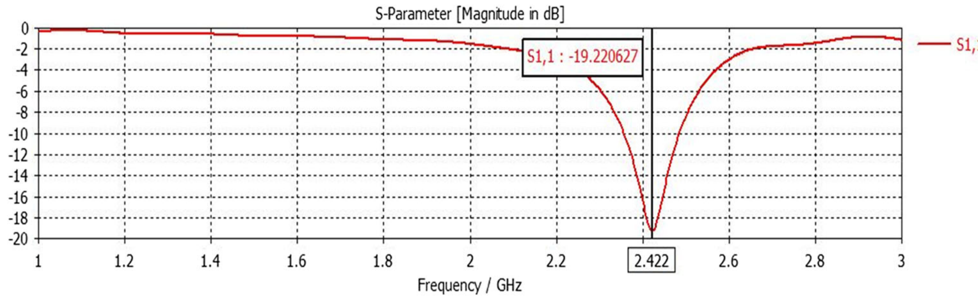


Fig. 10 Return loss graph of proposed antenna with Doll shaped DGS

Table 6 Simulation results with double substrate (Teflon & Felt)

Substrate	DGS	Freq. (GHz)	Return loss S_{11} (dB)	VSWR
Felt & Teflon	without	2.40	-4	4.79
Felt & Teflon	with Square DGS	2.42	-23	1.143
Felt & Teflon	with Doll DGS	2.42	−19	1.245

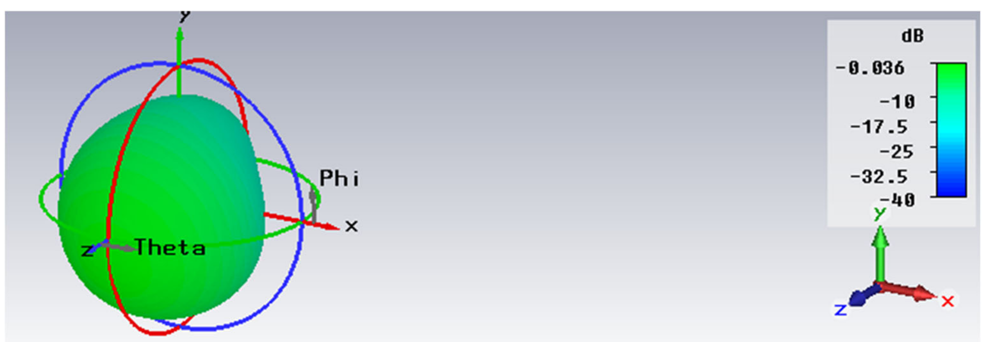


Fig. 11 Gain for double substrate antenna without DGS

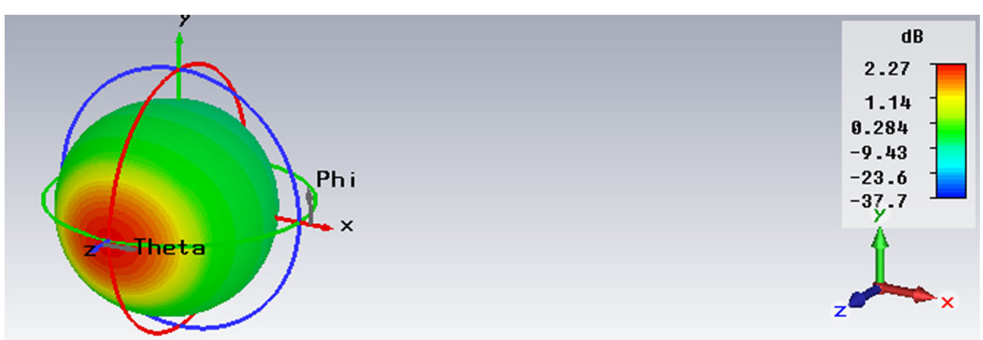


Fig. 12 Gain for double substrate antenna with DGS

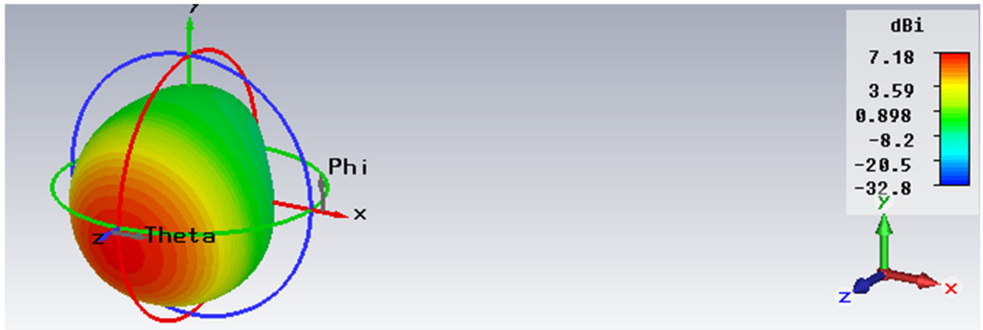


Fig. 13 Directivity for double substrate antenna without DGS

Fig. 14 Directivity for double substrate antenna with DGS

Table 7 Simulation results with double substrate (Jeans & Felt)

Substrate	DGS	Freq. (GHz)	Return loss S_{11} (dB)	VSWR
Felt & Teflon	with Square DGS	2.42	−23	1.143
Felt & Jeans	with Square DGS	2.87	−18	1.296

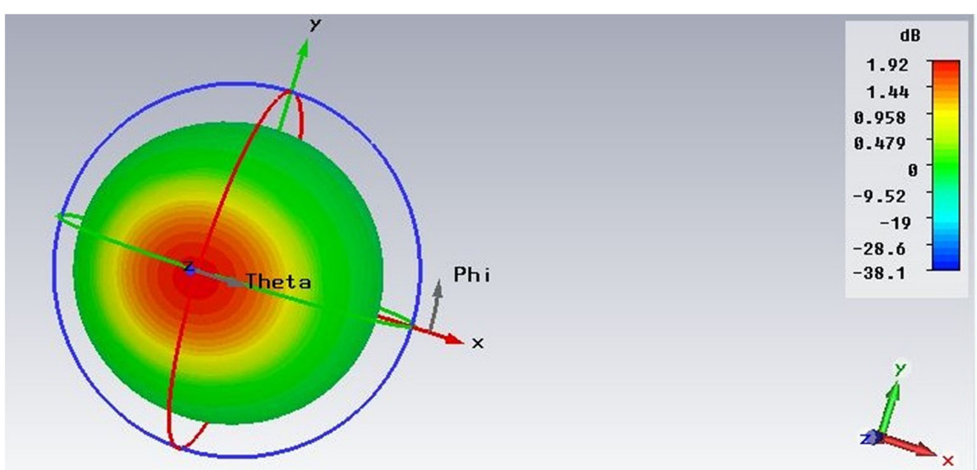


Fig. 15 Gain for double substrate antenna with DGS (Jeans & Felt)

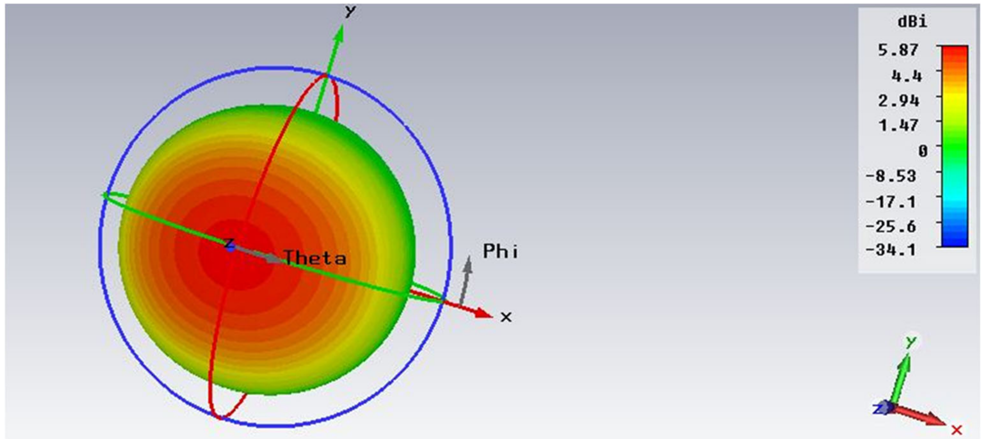


Fig. 16 Directivity for double substrate antenna with DGS (Jeans & Felt)

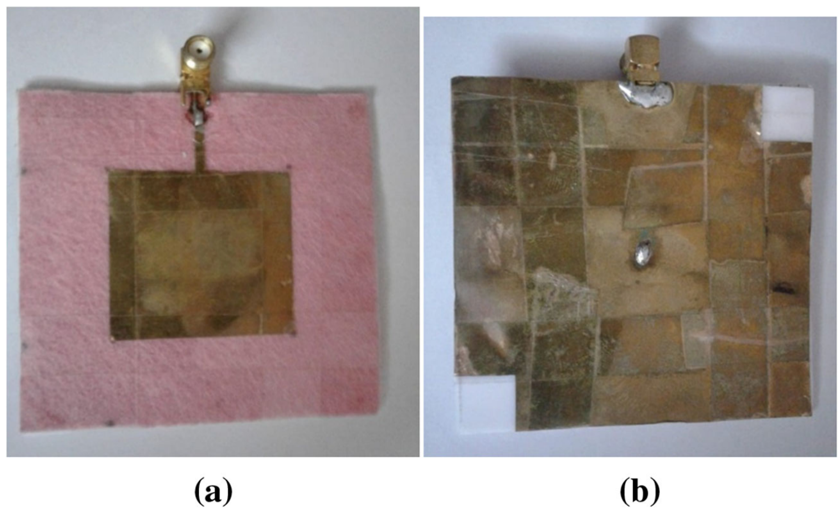


Fig. 17 **a** Top view of the fabricated antenna **b** Bottom view of the fabricated antenna with DGS

Table 6 shows the resonant frequency, return loss and VSWR of double substrate MSP with and without DGS.

When the values of return loss and VSWR were compared, it is observed that both the parameters have been improved as compared without using DGS. But still when different design DGS were considered, the antenna with square DGS produced better performance with simple design, and hence the other parameters were analyzed for the same design.

The 2D Polar plots and 3D patterns of gain (dB) and directivity (dB) of the antenna with Square DGS are simulated with CST. If the value of gain and directivity is greater than one, it is said to be that the performance of the antenna is acceptable. The gain achieved by double substrate patch antenna without DGS is shown in Fig. 11 and with DGS is shown in Fig. 12.

From the above 3D gain plots Figs. 11 and 12, the change in the gain of the antenna with DGS is experimentally recognized. When the antenna has regular ground structure, it has negative gain, but when defect is introduced in the ground the gain has been improved well. The directivity of double substrate patch antenna without DGSis shown in Fig. 13 and with DGS is shown in Fig. 14.

From the above directivity plots Figs. 13 and 14, it is observed that the directivity of the antenna is maintained in the positive level even when defect is introduced in the ground plane.

The MSP with multilayer substrate in which Teflon and Felt are used as dielectric material, the performance is satisfied. Even it is satisfactory, to describe the effect of material chosen for substrate layer, Teflon can be replaced by Jeans and the performance is analyzed with the help of CST software. The results obtained with this combination of substrate materials are given in Table 7. Figures 15 and 16 show the gain and directivity plots for this case.

Table 8 Double substrate MSP antenna with Square DGS (comparative results)

Parameter	Simulated Values	Measured Values
Resonant Frequency	2.42GHz	2.4GHz
Return Loss	-23 dB	-18 dB
VSWR	1.143	1.86

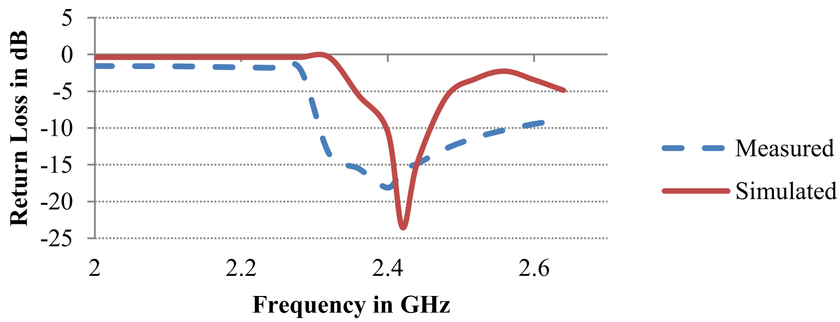


Fig. 18 Simulated Vs measured return loss S_{11} in dB

While comparing the results of the MSP (Jeans and Felt) with the results of MSP (Teflon & Felt), the later type produced better performance in terms of return loss, VSWR, gain and directivity. Hence, the antenna was fabricated with the aid of copper as ground layer with DGS and Teflon and Felt as substrate layer based on the design procedure. The feed point was connected at the midpoint and it is important that the air gaps should be avoided. The following Fig. 17a shows the top view of the antenna in which felt material is used as top layer of the substrate and Fig. 17b shows the bottom view of the antenna with diagonally opposite two square defects in ground layer which is below the Teflon material.

In order to evaluate the values of performance parameters obtained with the simulation of the designed antenna, the fabricated antenna was linked with the Vector Network Analyzer for return loss and VSWR measurement. A Vector Network Analyzer is the test system that enables the analysis of performance of RF and microwave devices in terms of network scattering parameters.

Table 8 shows the comparative values of simulated and measured results of the parameters of double substrate micro strip patch antenna with DGS.

Figure 18 shows the comparison of simulated and measured values of the return loss. From the graph, it is observed that the fabricated antenna resonate at 2.4GHz with return loss of around -18 dB.

study proven that the performance of the micro strip patch antenna using DGS with double flexible substrate material was improved.

The parameter VSWR is a measure that numerically describes how well the antenna is impedance matched to the radio or transmission line it is connected to. If the VSWR is smaller, it depicts that the antenna is perfectly matched to the transmission line and more power is delivered to the antenna. Also the return loss is the loss of power in a signal that can be reflected back by the transmission line. The lower the return loss, it is said that the devices and lines are properly matched. When the typical values of return loss and VSWR considered for satisfactory working of an MSP antenna, the proposed double substrate antenna exhibits improved performance which is resonated almost at the specified frequency.

When the antennas are used for Wireless Body Area Networks as sensors for security and as health monitoring device for biomedical applications, the primary requirement of the antenna is that it should have linear polarization to avoid the back radiation towards human or animal body which in turn increases the radiation efficiency in terms of low return loss. The antenna design proposed here produces very much appropriate grades in this aspect and hence this may be used for wearable applications. Also the issues on using wearable devices such as cost, acceptability with human body, recycling property of the material used for fabrication are considered.

Conclusions

The performance parameters of the antenna like return loss, VSWR, gain and directivity are obtained with the use of CST software under different conditions. The antenna with different substrate material, combination of materials to form substrate layer and the development of defected ground structure are considered for the analysis. It is observed that from Fig. 8 and Table 6, as compared to single substrate patch antenna (with and without DGS), the double substrate patch antenna with square DGS has improved return loss of around −23 dB at the frequency of 2.42 GHz. These simulated results are then compared with measured values of the parameters obtained with the help of Vector Network Analyzer. The comparative study proven that the performance of the micro strip patch antenna using DGS with double flexible substrate material was improved.

Future scope

The growth of advanced techniques in the field of medical image processing, health monitoring system and so on increases the interest on research of design of wearable devices for such applications. At the same time, the study on material selection, design methods also becoming significant to make simpler the usage of such devices.

Compliance with Ethical Standards

Conflict of interest The Authors and Co-Authors have no conflicts of Interests. The Paper is not submitted to any other Journals. This is solely submitted to this Journal.

Ethical approval (involving human participants and/or animals) This article does not contain any studies with human participants or animals performed by any of the authors.

Informed consent No humans or animals were involved. All applicable international, national, and/or institutional guidelines for the care and use of animals were followed.

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