

Lycra fabric as an effective stretchable substrate for a compact highly efficient reversibly deformable broadband patch antenna

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This paper describes the design and numerical simulation of a highly efficient broadband antenna on stretchable substrate. The reversibly deformable and stretchable antenna proposed here uses the stretchable fabric Lycra which is known for its exceptional elasticity. The DGS mentioned in this antenna helps to achieve broadband operation of 23.8% in 10dB impedance bandwidth with enhanced efficiency of 97.389% with the size reduction of 40.06%. In general, textiles present a very low dielectric constant that reduces the surface wave losses and increases the impedance bandwidth of the antenna. Multiway stretchable fabric helps to achieve multiple frequency bands. Hence the more stretchable lycra fabric is used here. The radiation characteristics of the designed antenna are analyzed for variation in number of slots and different levels of stretchability. The proposed design for various stretchability levels are simulated using HFSS EM simulation software and the results are discussed. This antenna is meant to be utilized for S and C (2 to 6 GHz) band wireless applications.

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1. Introduction

There is an increasing need for the wireless networks and microelectronic circuits that provides conformable, stretchable and reversibly deformable structures. As the tensile strain is applied, the substrate stretches. As the substrate stretches, the patch also stretches and deforms to the same level. The change in structure changes the dimensions of patch thereby changing the frequency. Therefore, the operating frequency depends on the geometry of the patch. As the resonant frequency is the function of applied tensile strain, the antenna is considered as reconfigurable.

Designing a reconfigurable antenna requires that the reconfiguration property and reconfiguration technique are determined at the beginning of the design process. There are four different kinds of reconfiguration properties that an antenna can attain. An antenna can achieve either of frequency reconfiguration, radiation pattern reconfiguration, polarization reconfiguration or a combination of any of these properties [1, 2].

As for the selection of the reconfiguration technique based on reconfigurable antenna property, there are a few reconfiguration systems that have been proposed since the ascent of reconfigurable antennas. Accordingly, Electrical, Optical, Mechanical and Material change are the four major categories [1, 2].

Thermal switches have also been used for reconfiguration in antennas [3]. Other reconfigurable techniques are based on graphene plasmonics [4], liquid crystals [5], and mechanical [6]-[9]. In the application of cognitive communication, switch and switchless antennas

are controlled by software [10].

The structural configuration of conductor lines optimizes the frequency response of microelectronic circuits and components. Since the ground plane of these components, which is typically made up of metal sheet like copper, it does not provide any degree of freedom in the design phase. An alternate solution to improve the radiation characteristics of microcomponents is DGS (Defected Ground Structure) (DGS) which is based on coplanar waveguides (CPW) and microstrip lines [11]. A few DGS structures have been studied and reported in the literature [12,13]. The DGS is sited underneath a microstrip line or antenna and is allied for proper coupling with the microstrip antenna or microstrip line [14]. In the DGS, the EM wave gets the characteristics of band pass and bandstop, henceforth getting a slow wave structure [15]. There are two main categories of DGS: Single defect and group of small defects. The defects can be periodic or non-periodic [16]. A conventional microstrip patch antenna and a microstrip antenna array coupled with two-element E-plane employing a DGS [17].

The litheliety in electronics has confined to the growth flexible and weightless devices which have extensive applications such as solar cells, wearable electronics, conformal antennas, flexible sensors, bio-medical applications. When we use conformal or flexible antennas, the device gets damaged and losses occur during bending action. This can be reduced by using a conductive rubber and an optimal metal. The Theory, simulation and fabrication of antennas for stretchable substrates were studied [18]. Apart from high sensitivity level and fast computation in antennas, the request gets similarly expanded for conforming for complex shapes and

deformation [19, 20]. A request for the mechanical execution is the current advancement of integrated circuits. The most stipulated form of deformation among various modes (e.g., bending, twisting and stretching) is stretching as it easily includes tensile strain to the larger extent. Various stretchable components can sustain tensile strains depending on the acquiescence of elastomeric substrate and initial nano-topography of the metal film on silicone [21]. A new approach for stretchable electronics is being developed, just like injecting a liquid metal alloy into channels made of elastomeric micro-structures [22]. Stretchable antenna design considerations and performance metrics are discussed [23].

A transparent, mechanically reconfigurable and flexible Zeroth-Order Resonant (ZOR) antenna is discussed using stretchable micromesh structure [24]. A large RF bias network is needed to operate the switches and the nonlinear effect and parasitic parameters affect the switches. On the other hand, as it is linearly tunable to wide range of frequencies, the mechanical tunability could be exploited [25-27].

Elastane fibres show rubber like deformable behavior and are extremely stretchable [28]. The moisture elastic plated fabric with superfine polypropylene fibre inside, cotton yarn outside and lycra at center [29]. The use of textiles in wearable antennas requires the characterization of their properties and material properties of Lycra fabric [30].

This paper is organized as follows. Section II describes the Conventional single patch antenna design for the proposed substrate and its associated parameters. Section III describes the Transformation towards the proposed structure. Section IV describes the Stretchable patch antenna for DGS. The parametric study of DGS dimension unit and its impact on antenna characteristics such as frequency, Return Loss, efficiency, gain, and directivity, which finally gives rise to optimized proposed DGS structure. Section V describes the Antenna parameters and comparison for various stretchability levels. Comparison of return loss, gain and directivity for various levels of stretchability for the substrate with proposed DGS.

2. Single patch antenna design for lycra substrate

Lycra fabric (for its exclusive stretchability) is used as substrate dielectric material ($\epsilon_r = 1.5$, $h = 1.5$, $\tan \delta = 0.0093$). The dimensions of ground plane are 80mm*90mm. The dielectric properties of the substrate

are as listed below:

Table 1. The dielectric properties of the lycra substrate

Substrate	Dielectric Constant (ϵ_r)	Loss Tangent ($\tan \delta$)	Thermal Conductivity (W/m-k)
Lycra	1.5	0.0093	0.0060

The following formulas are used for calculating the dimensions of the microstrip patch. For an efficient radiator operating at frequency f_r , with dielectric thickness h and permittivity ϵ_r , the actual width is given by

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

Substituting the velocity of light, $c = 3 \times 10^8 \text{ m/s}$, $\epsilon_r = 1.5$, $f_r = 2.4 \text{ GHz}$, we get $W = 55.9 \text{ mm}$. The effective dielectric constant is:

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

Putting $\epsilon_r = 1.5$, $W = 55.9 \text{ mm}$ and $h = 1.5 \text{ mm}$, we get $\epsilon_{eff} = 1.467$. Patch length extension at the two open ends due to fringing fields can be calculated as:

$$\Delta L = 0.412h \frac{(\epsilon_{eff} + 0.3) \left(\frac{W}{h} + 0.264 \right)}{(\epsilon_{eff} - 0.258) \left(\frac{W}{h} - 0.8 \right)} \quad (3)$$

Replacing ϵ_{eff} , W , h by their values, we get $\Delta L = 0.929$. Patch length can be calculated as

$$L = \frac{C}{2f_r \sqrt{\epsilon_{eff}}} - 2(\Delta L) \quad (4)$$

Putting $\epsilon_{eff} = 1.467$, we get $L = 49.2 \text{ mm}$.

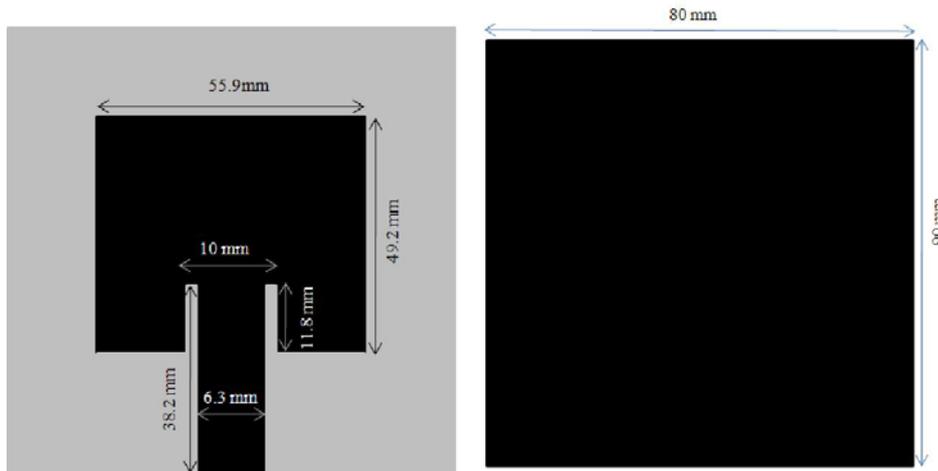


Fig 1. Conventional microstrip patch antenna

Fig. 1 shows the conventional microstrip antenna with no DGS plane which is designed to operate at S and C band operating frequencies (2GHz to 8 GHz). The Microstrip feed is used to excite the antenna. The return loss level is affected with respect to the depth of inset; hence it is set accordingly to get its best return loss level. Table 2 shows the simulation results of conventional Microstrip Patch Antenna with no DGS and properly set inset feed.

Table 2. Simulation results of conventional Microstrip Patch Antenna with no DGS

Parameters	Frequency (GHz)	Band width (dB)	Return Loss (S11)	Radiation Efficiency (%)	Gain (E Plane)	Directivity (H Plane)
Values	2.35	0.05	11.06	70.70	4.80	6.80

3. Transformation towards proposed structure (stretchable patch antenna with DGS)

The Defected Ground Structure (DGS) is an etched, periodic or non-periodic configuration defect in the ground of a planar transmission line which disturbs the shield current distribution in the ground plane which helps to reduce unwanted response in antennas. Meanwhile, the DGS also helps to achieve the required response which can be measured by antenna parameters. Table 3 shows the transformation of antenna parameters from no DGS structure to the proposed stretchable patch antenna with DGS structure (highly efficient, Enhanced Bandwidth).

Table 3. Transformation in terms of antenna parameters

Design	Frequency (GHz)	Return loss (dB)	Radiation efficiency (%)	Gain (dB)	Directivity (dB)
tr				e-plane	h-plane
Proposed Pattern	2.2	-11.5	97.389	2.3074	2.3729
Pattern 2	1.1	-10.07	75.63	2.0097	2.6573
Pattern 3	1.05	-9.77	82.38	2.2098	2.6825
Pattern 4	2.2	-12.43	74.153	2.95	3.98
Pattern 5	2.25	-11.78	80.05	3.20	4.00
Pattern 6	1.4	-11.45	76.88	2.79	3.63
Pattern 7	1.8	-10.2876	90.98	2.15	2.37
Pattern 8	8.2	-1.56	90.53	2.17	2.40
Pattern 9	2.0	-2.597	90.13	2.17	2.39
No DGS pattern	2.35	-11.06	70.70	4.80	6.80

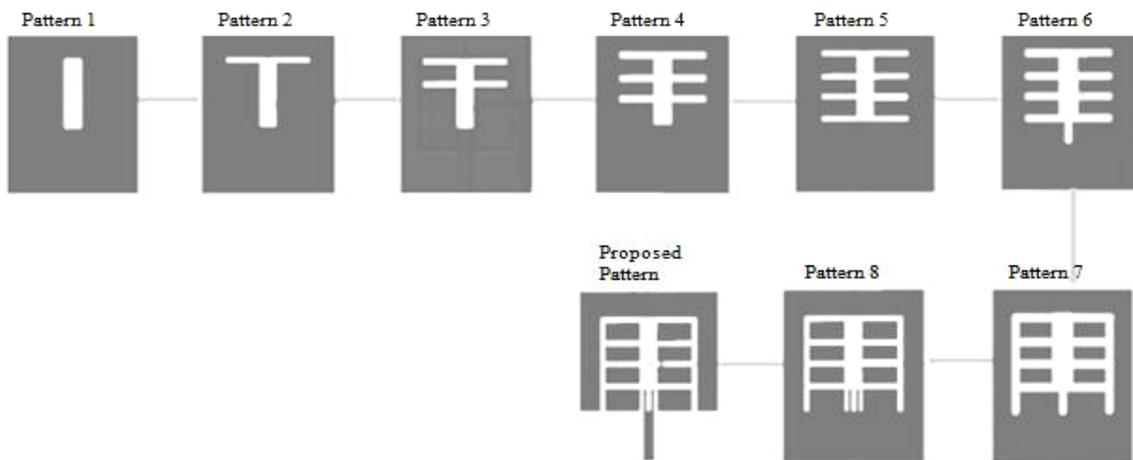


Fig 2. Transformation in terms of design

Of all the structures shown in Fig. 2, the conventional structure (NO DGS Pattern), the pattern in the intermediate designing process (Pattern 5) and proposed structure are taken and their results are compared for antenna parameters, return loss, gain and directivity patterns. Hereafter, the patterns will be mentioned as

- NO DGS Pattern → Design,
- Proposed Design → Design 1,
- Pattern 5 → Design 2

The comparison of gain and directivity at 2.4 GHz is plotted in Fig 3(a) and Fig 3(b). Fig 3 shows the return loss comparison of conventional microstrip patch antenna with proposed DGS antenna and the antenna in the intermediate designing process.

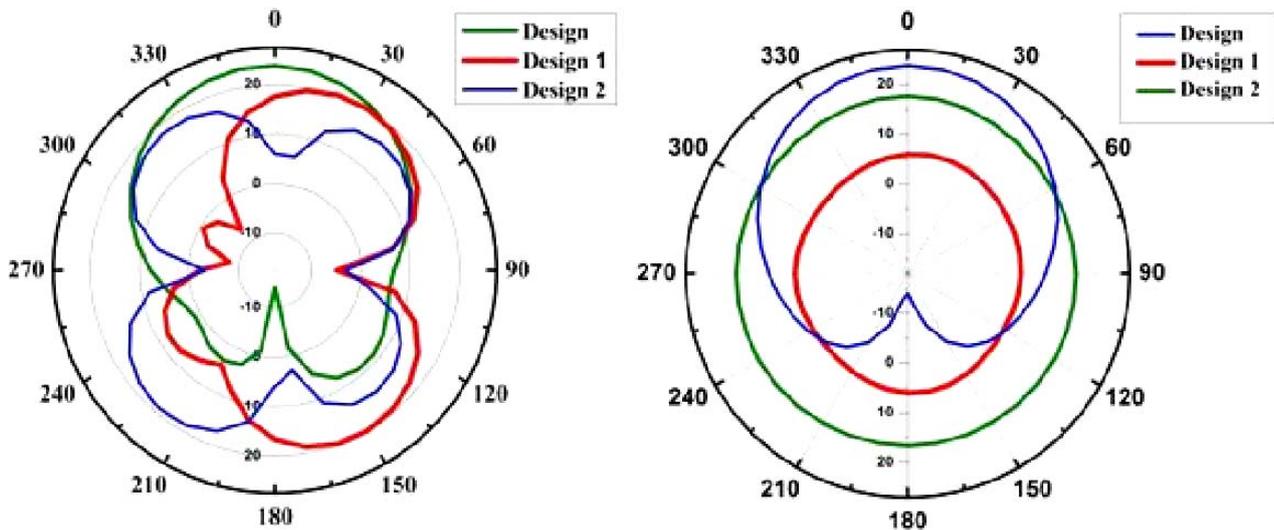


Fig 3. Comparison of (a) gain and (b) directivity with respect to No DGS, pattern 5 and proposed DGS antenna

From the Fig. 4, it is evident that the proposed DGS antenna has higher bandwidth (23.80%) than that of the conventional NO DGS antenna (0.85%) and the antenna in intermediate designing process i.e pattern 5 (2.85%).

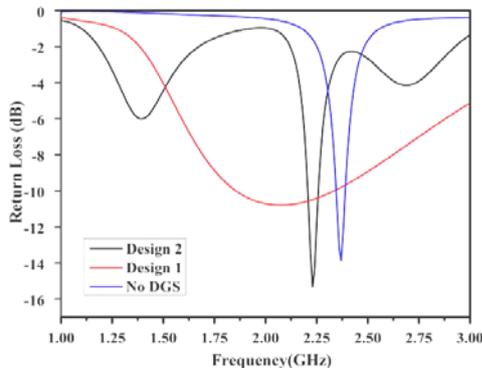
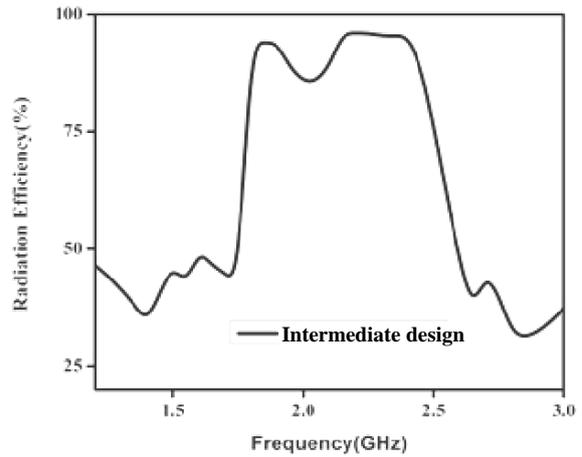
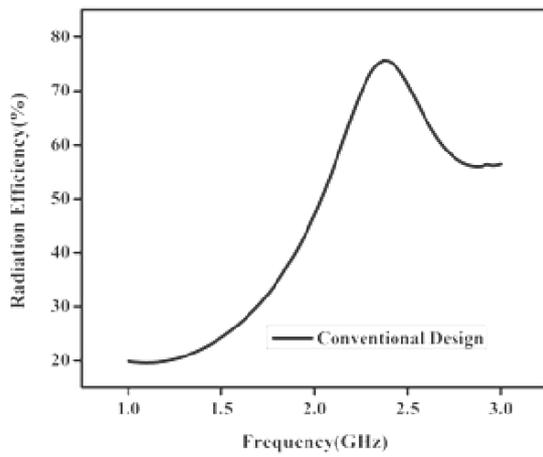


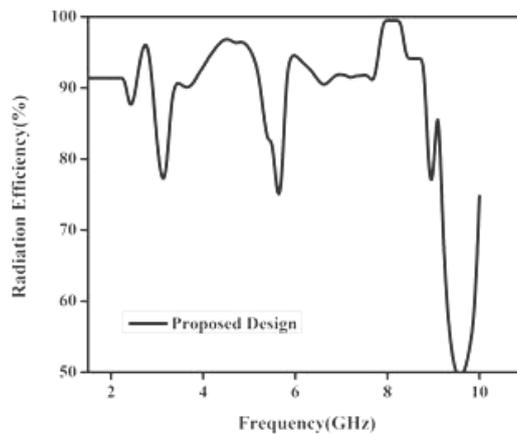
Fig. 4. Comparison of return loss (s_{11}) with respect to No DGS, pattern 5 and proposed DGS antenna

The radiation patterns are computed and their efficiencies are calculated. The proposed DGS structure shows the highest efficiency of 97.389% when compared with the conventional NO DGS antenna (70.70%) and the antenna in intermediate designing process i.e pattern 5 (80.05%) as shown in Fig 5.



(a)

(b)



(c)

Fig. 5. Efficiencies of (a) conventional microstrip antenna; (b) antenna in the intermediate designing process (c) proposed antenna

4. Stretchable patch antenna with DGS

The main characteristic of Reconfigurable antenna is adjusting its working frequency in a certain range. In this paper, the reconfiguration is achieved by using a stretchable substrate Lycra, an elastic polyurethane fabric

which is known for its exceptional elasticity. The DGS with periodic defects have been introduced in order to achieve high efficiency and to enhance the bandwidth, but the front side is a normal patch antenna with inset feed is designed and remains undisturbed.

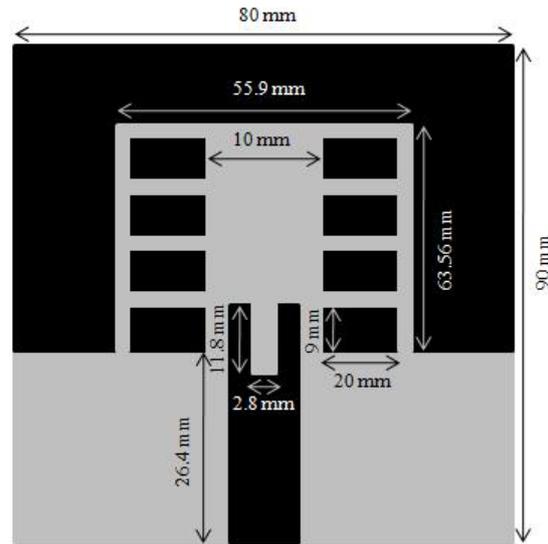
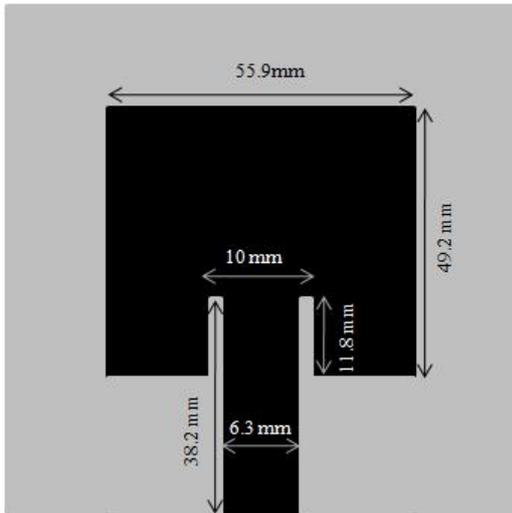


Fig 6. (a) Front view and (b) rear view of proposed antenna with DGS structure

Fig. 6(a) shows the front view of the proposed antenna. The front view is nothing but the conventional microstrip antenna which is left undisturbed, and the rear view Fig 6(b) shows the proposed DGS structure made at the exact rear side of the patch, which consists of slots on the ground surface which makes 8 independent rectangles which are located on either sides in the rear side of microstrip feed line, with parallel spacing of 10mm and vertical spacing of 2.8mm between them. A slot is made at the centre of the microstrip feed line with the dimension of 2.8mm 11.7625mm. The spacing between this structure discussed and the ground surface is 2.8mm. This is for getting better efficiency with reasonable return loss. The ground surface placed below the location of the patch is etched out except at the location of the feed line in order to get the best possible bandwidth and efficiency.

Return Loss, Efficiency, Gain (E-Plane) and Directivity (H-Plane) are comparatively discussed.

5. Antenna parameters comparison for various stretchability levels

Lycra, which is known for its exceptional elasticity is used as the substrate. This helps to vary the levels of stretchability (in HFSS, Scaling option is used for stretchability). In this structure, the levels of stretchability are varied (25%, 50%, 100% and 200%) and the corresponding antenna parameters such as Frequency,

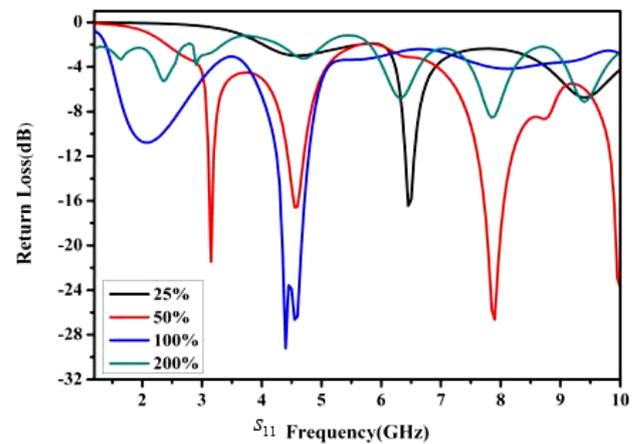


Fig. 7. Comparison of return loss (s_{11}) with respect to various levels of stretchability

Fig 7 shows the return loss comparison of various levels of stretchability of the substrate. On reading the graph, it is evident that the return loss varies from 2.2 GHz to 6.3GHz. Hence, this antenna works in S and C band.

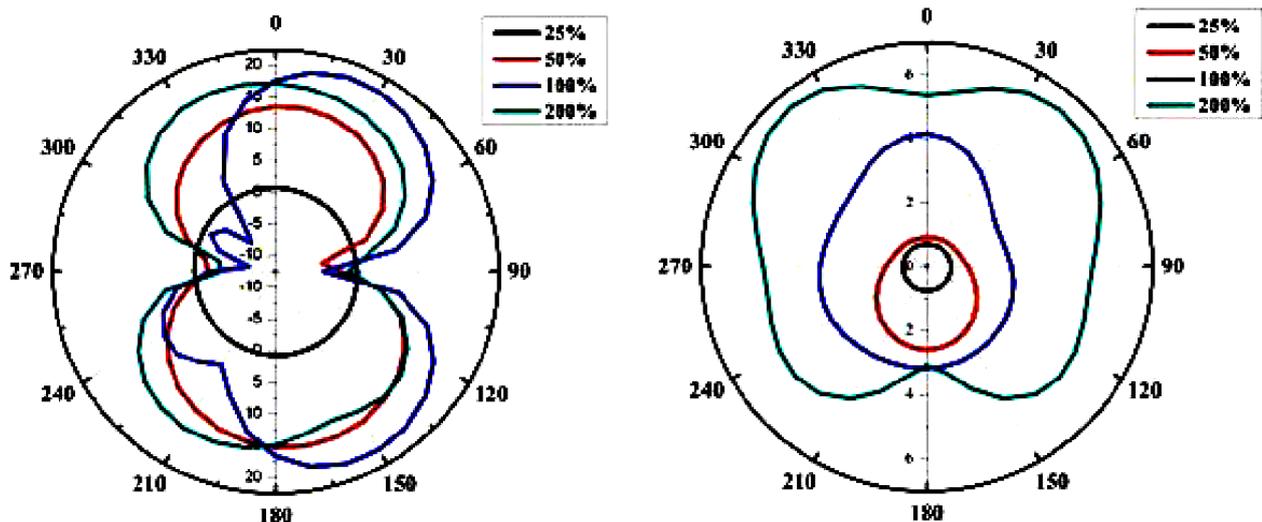


Fig 8. Comparison of (a) Gain and (b) Directivity with respect to various levels of stretchability

Fig. 8 (a) and Fig. 8 (b) show the comparison of gain and directivity results of various levels of stretchability of the substrate. Whereas, the gain pattern is bidirectional and has less number of side lobes and the directivity pattern has Omni directional pattern.

The conventional Microstrip Patch antenna resonates at 2.4 GHz. After integrating with proposed DGS, the resonating bandwidth starts at 1.8GHz. When we design an antenna for this frequency, the antenna dimension should be 66.8×74.5 mm. On comparing, the proposed DGS antenna has achieved the size reduction of 40.06%. Hence a compact antenna with miniature size is achieved.

6. Conclusion

In this work, a comprehensive investigation of a DGS, its various configurations and its impact on stretchable Lycra substrate, also with various levels of stretchability is presented. It is observed that the conventional Microstrip Patch antenna has the very narrow bandwidth and its maximum efficiency was limited. So, the partial ground plane concept is utilized to enhance its performance in terms of its widened bandwidth and high efficiency.

The conventional Patch antenna has the limited efficiency of 70.70%. After integrating with the proposed DGS, the efficiency has increased to 97.389%. The conventional patch has a very narrow bandwidth of 0.85%. And the modified proposed DGS-based antenna has obtained the bandwidth of 23.80%. It is also observed that the conventional Microstrip Patch antenna resonates at 2.4 GHz, after integrating with proposed DGS, the resonating bandwidth starts at 1.8GHz. Hence, miniaturization of the patch antenna is also achieved.

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