Additively Manufactured Stress-strain Dependant Frequency Reconfigurable Antenna for Pressure Sensor Applications

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A novel additive-manufactured antenna for stretchable sensor application is designed, simulated and measured. The fully transparent antenna has air as a substrate and a conductive aluminium metal sheet as a patch. The layers are defined with thin Thermo Poly Urethane (TPU) material, as its flexible/stretchable property doesn't disturb the actual property of air. The air substrate is locked within the flexible TPU with a thickness of 200 microns, and the conducting patch is also dimensioned with the 3D printing method. The stretchable antenna is fabricated with 3D printing technology, considered a dielectric medium, and the conducting medium is a conducting aluminium sheet. Re-configurability is achieved with the pressure level applied over the air–substrate antenna. Hence, the minimal change in shape changes the dielectric constant, thus changing the antenna parameter and radiation pattern. The antenna achieves improved size and performance with a gain of 7.2 dB, a directivity of 7.574 dB, a radiation efficiency of 95.67 %, and a 12:509 front-to-back ratio. The fabricated antenna is tested for its resonant characteristics and radiation properties. This reconfigurable antenna can be used for various applications, including Wireless Local Area Network (WLAN) communication.
*Keywords:*3D printing, flexibility, air substrate, reconfigurable, sensors.

1. INTRODUCTION

Wireless technology plays a crucial role in data transmission of power, making flexible and stretchable electronics extend towards implantable biomedical applications and further. The number of researchers is increasing for stretchable electromagnetic applications since they are beneficial in developing compact communication systems like cellular, bio applications, radar applications, etc. Stretchable electromagnetics is very helpful in achieving reconfiguration properties. The Ethyl Vinyl Acetate (EVA) substrate is used along with conductive, stretchable silver fabric. The EVA antenna is measured in unstretched and stretched modes for its electromagnetic properties [1]. An effective substrate for the stretchable and reconfigurable antenna is the stretchable fabric Lycra. The variation in the stretch level of the material shows variation in its dielectric properties; hence, the resonance frequency varies accordingly. A defective ground surface helps achieve broadband characteristics, improving the antenna parameters such as gain, efficiency and bandwidth [2]. Reconfiguration based on stretchable antennas has certain advantages such as ease of fabrication, effective application on humans in biological applications, a single device is enough for tenability in reconfiguration, the researcher is liberal to choose the dielectric and conductive materials out of his own need [3]. Textile antennas can be used in wearable electronic applications. The fabrication procedures, the fabrication challenges, and its application areas are discussed [4]. An 800% stretchable fabric acts as a substrate, and a stretchable conductive ink is screen-printed over the substrate for the simulated dimensions. The silver conductive stretchable ink combines a binder, polyurethane and a stretch binder, ethyl cellulose, with silver ink. The resulting conductive ink lasts its stretchability of up to 500 cycles [5].

A boon of microfluid-based stretchable devices is also reported. This technique uses conductive liquid metals as conductive and polymer-based stretchable dielectric substrates [6]. Preparation and characterization of printable conductive wirings with stretch properties using silver flakes and elastomers are reported in [7]. The copper metal and conductive rubber act in alternating layers to make an Radio Frequency (RF) antenna. But, when copper is stretched, cracks may form, and they can be filled using conductive rubber to fill up the discontinuities [8]. Various implementation techniques in different applications such as Satellite, MIMO, Cognitive radio and mobile terminals were presenetd in [9]. Methods to modify the properties of the substrate using air cavity was described in [10].

All the above techniques use operating frequency at narrowband resonances. A combination of stretchable surfaces forms a new stretchable substrate [11]. Extensively, adhesion technology is crucial in various pre-formed solid flexible structures [12]. Water can be used as a conductor for frequency-reconfigurable applications. Reconfiguration is made through fluidic tuning. The full words (EM) parameters were reached with the channel length, depth, width and position.[13].

The application of microstrip patch antennas in the construction industry helps engineers automate the systems efficiently and straightforwardly. A microstrip patch antenna is designed over the construction material, of which the aluminium acts as a substrate. The frequency changes are studied with the help of the bent occurred on the substrate [14]. The dielectric material, even though it is capable of being a substrate for an antenna when it fails due to its permeability properties, modifications are made

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on the substrate by coating low viscous stretchable resin to get optimistic results [15]. Stubborn materials when they act as a substrate for a microstrip patch antenna in stretchable applications. Modifications are done upon the substrate to help achieve a stretchable and flexible antenna that could be more useful for wireless applications [16]. reconfigurable and stretchable antennas are done with the help of intelligent surfaces like Ethyl Vinyl Acetate. With this substrate, the configuration and reconfiguration could be achieved with precision values [17]. A survey of the Reconfigurable antennas is useful for many kinds of sensor applications like air sensors, water sensors, pressure sensors, and humidity sensors [18].

The flexible, reconfigurable antenna with Frequency Spread Spectrum (FSS) for IoT applications has been studied. The antenna operates in three modes of operation, and each mode operates with the help of a PIN diode attached to the antenna surface [19]. A flexible antenna with small dimensions and a simple layout for making pattern reconfigurable structures in making wireless communication systems applications [20]. Application of the flexible frequency reconfigurable antenna with a conductor as a stretchable conductive silver fabric with a double braided structure. The antenna can act as a strain sensor that has the capability of measuring the movements as well as the bending angle [21]. Hence, antenna switching with the help of the stress-strain method will be more advantageous than the conventional diode switching methods due to its low cost and ease of fabrication. Air is the least dielectric constant material. Hence, this work focuses on utilizing air as the antenna substrate. The 3D printing method could make an envelope of Thermo Poly Urethrane (TPU) layer around the air layer. As the thickness of the TPU layer is 200 microns, the dielectric constant changed to 1.385.

The design procedure includes the material selection, preparation of the substrate, study of dielectric properties for the substrates and conductivity properties of the conductors, antenna design formulas, simulation of the antenna, antenna fabrication and measurement.

In this paper, a frequency reconfigurable antenna printed using a 3D printed technique is presented. The frequency reconfiguration was done by varying the dielectric properties of the substrate as per the requirements, which would be beneficial for many communication applications. The variation in dielectric properties was achieved by applying pressure on the surface. The conductive aluminium sheet was used for the conductive patch and the ground. The proposed antenna covers a minimal space, 31 mm × 32.5 mm, in a confined environment and can be modified in accordance with the space availability. The antenna dimensions are discussed in the geometric discussion. The fabrication method implemented is described in the fabrication section. The evaluation of the fabricated antenna with the simulation results is described in the Evaluation section, and the paper's main points are discussed in the conclusion. The operation of the antenna based on the strain levels is discussed.

2. GEOMETRIC DISCUSSION

The conductive aluminium sheet has a tensile strength of 16 lbs/inch with 56 N/20 mm conductivity of $3.77 \times 10^7\ \Omega$. The aluminium conductive sheet is chosen so that it is coated with a conductive adhesive coating on one side. Hence, when we use these in our experiment, the materials used alone should not disturb the actual properties. So, a highly flexible material with reasonable dielectric properties, TPU is used as a layer of separation between the conducting and dielectric mediums. The additively manufactured 3D printed antenna fabricated with a stretchable TPU layer is simulated using High Frequency Spread Spectrum (HFSS) 12 with the dimensions are shown in Fig 1.

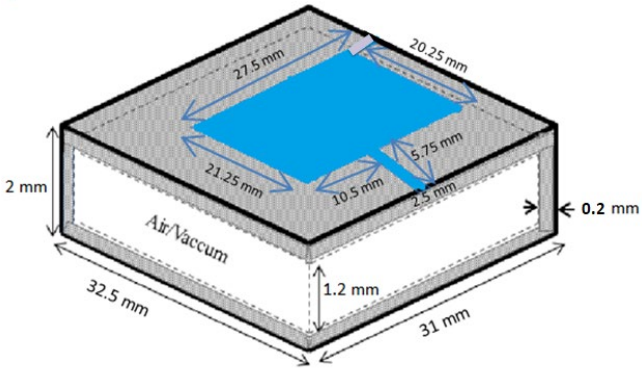

Fig. 1. Geometry of the proposed 3D printed antenna

It can be used for multiple frequency limits, 3.6 GHz to 4.2 GHz and broadband applications. The overall dimension of the antenna is 31 mm × 32.5 mm. The antenna is connected to the Virtual Network Analyzer (VNA) via an SubMiniature Version A (SMA) connector, and its corresponding s_{11} and radiation properties are measured by mounting it onto the anechoic chamber. This idea greatly helps future researchers to develop highly stretchable electronic devices using additive manufacturing techniques. Fig. 2 shows the change in dimensions of the antenna when pressure is applied over it. When external pressure is applied on the substrate from one direction, the air cavity present in the centre of the substrate tends to move towards the other direction. Hence, the substrate deforms, which leads to a change in the dimensions of the substrate. As the length, width, and height of the substrate change, the dielectric properties also tend to change accordingly.

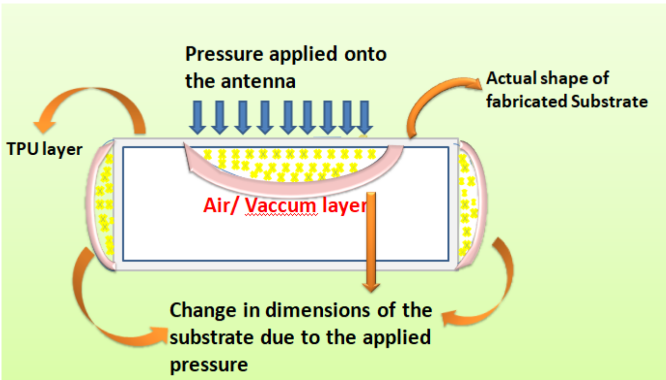

Fig. 2. Representation of the change in the physical dimensions of the antenna with applied pressure

3. SIMULATION AND FABRICATION

The antenna was modelled using HFSS'12 by making a 200-micron-thick TPU layer around the air. The overall dimensions of the antenna are 31 mm × 32.5 mm. The Perfect E sheet is applied on either side for the patch and ground layers. The antenna simulation results concerning frequency and E and H plane radiation patterns during the actual state and stretched state are shown in Fig. 3.

The proposed Air-Water patch antenna requires a super-flexible TPU to separate the layers of air and water.TPU chosen for this work has a dielectric constant of 5.8 and a dielectric loss tangent of 0.05. As the air-filled TPU layer is used for this experiment, the dielectric constant changes due to the impact within the TPU. The derivative verification of the change in dielectric properties between the air, TPU and the air-filled TPU are studied with the formulas listed in Table 1.

Table 1. Dielectric properties of the materials used and their combinations

Material	Dielectric constant ε_r	Loss tangent δ
TPU	5.8	0.05
Air	1	Vary with weather
Fabricated TPU-Air combination	1.385	0.068

Hence, the air-filled flexible 200 microns TPU substrate was 3D printed with a creality 3D Ender 3 machine with a 0.2 mm nozzle for the designed dimensions, shown in Fig. 5. These dielectric properties were found with the experimental evaluation with the suspended ring resonator method followed by numerical derivation. When pressure is applied to the substrate, the physical properties change, resulting in a change in dielectric properties, whereas the radiation properties also tend to change. In this work, the change in dielectric properties for the change in physical properties is noted down using the suspended ring resonator method.

$$\varepsilon_{reff} = \varepsilon_{cavity}\left[\frac{L + 2\Delta L \dfrac{\varepsilon_{fringe}}{\varepsilon_{cavity}}}{L + 2\Delta L}\right], \quad (1)$$

where $\varepsilon_{\mathrm{reff}}$ is the effective dielectric constant; $\varepsilon_{\mathrm{cavity}}$ is the dielectric constant of the cavity; L is the Leength of the Patch;. $\varepsilon_{\mathrm{fringe}}$ is the Dielectric constant in fringe effect; Whereas, in measurement, the dielectric constant of the material is calculated by,

$$\sqrt{\varepsilon_r} = \frac{C}{2 f_r L}, \quad (2)$$

where ε_{r} is the dielectric constant of the material; C is the speed of the light; f_r is the resonant frequency measured from the peak; L is the length of the substrate used. The loss tangent (tan δ) is calculated by

$$\tan\delta = \frac{1}{Q}, \quad (3)$$

where Q is the quality factor, and

$$Q = \frac{f_{res}}{f_{3dB,U} - f_{3dB,L}}, \quad (4)$$

where f_{res} is the resonant frequency; $f_{3dB,H}$, $f_{3dB,L}$ are 3dB frequency upper and lower limit.

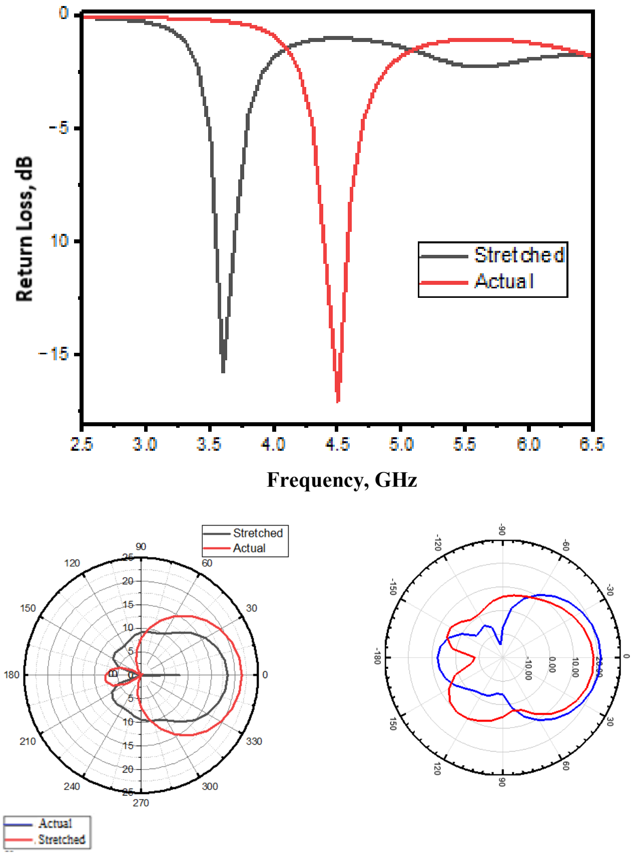

Fig. 3. Comparison of frequency, E and H plane radiation pattern of the simulated antenna

When the pressure/stress is applied from the z-axis, the air layer present within the substrate tends to move in all possible directions, leading to the stretch in the x and y-axes. The strain caused by the substrate will tend to change the dimensions of the antenna, which results in a change in dielectric properties. After the application of the strain, the dielectric constant is increased, and the loss tangent is decreased. Hence, the antenna frequency reconfigures at this stage. When the stress is released, the antenna again configures to its actual state.

Fig. 3 represents the radiation frequency, E plane and H plane radiation pattern of the simulated antenna. The antenna initially radiates at 4.5 GHz. The reconfiguration achieved on the application of 23 % strain is 3.6 GHz. From the figure, the comparison of the E and H planes displays the antenna's radiation pattern outcomes. The Left Hand Side (LHS) of the figure shows the E plane (ϕ = 0°) radiation pattern for the actual state, which is displayed in red colour, directed at 0°, and the radiation pattern for the stretched state is displayed in black colour, directed at 0°.

The Right Hand Side (RHS) of the figure shows the H plane ($\phi = 90°$) radiation pattern for the actual state is displayed in blue, directed at 0°, and the radiation pattern for the stretched state is displayed in red, directed at 0°. As displayed in the figures, the radiation patterns have unidirectional outcomes at both planes with good trends concerning the actual state and stretched state.
The simulation for reconfiguration could not be precisely carried over with software, as the pressure application on the axis tends to change the shape of the antenna. When the pressure is applied on the *z*-axis, the *x*-axis and *y*-axis increase in length and the *z*-axis decreases. It results in a change in frequency and radiation properties with the pressure applied. In HFSS, a scale-up option is available. So, the work progressed to experimental evaluation. The comparison analysis of the proposed antenna with similar ones is listed in Table 2. Table 2 shows the comparison analysis of the antenna with previous works with respect to the substrate used, size, frequency, material type, gain and efficiency.

The size and performance of the proposed work were found to be much better than that of other similar works, and hence, it exhibits its superiority.

3D printing technology is an upcoming trend in many fields, ranging from making duplicates of images to prosthetics in complicated surgeries. The replica of an object can easily be made using this technology by specifying the requirements. Even with this, replicas are mostly possible with hard structures like plastic, etc.; flexible/stretchable materials fabrication is under study. The most commonly available flexible filament is thermo-poly urethane. However, it does not have stretchable properties. Hence, it is made stretchable by introducing an air/vacuum layer in between. As the air layer is sandwiched between the 200 microns thick TPU layers, the overall structure stretches with pressure applied over the substrate. The flowchart for the 3D printing technology using the Creality 3 Ender 3 machine is shown in Fig. 4.

An RF antenna constitutes two parts: a conductive patch and ground and a dielectric substrate. The conductive part is a conductive aluminium sheet; hence, to hold it with specified dimensions for the conducting patch, the conductive patch area is designated with TPU borders for the simulated dimensions.

The actual dimensions of the antenna and dimensions of the antenna with strain are listed in the table below. substrate lengths ($L1, L2$), substrate widths ($W1, W2$), substrate heights ($H1, H2$), patch lengths ($Pl1$, $Pl2$), patch widths ($Pw1$, $Pw2$), ground lengths ($gl1$, $gl2$), ground widths ($gw1$, $gw2$), feed lengths ($fl1, fl2$), feed widths ($fw1$, $fw2$).

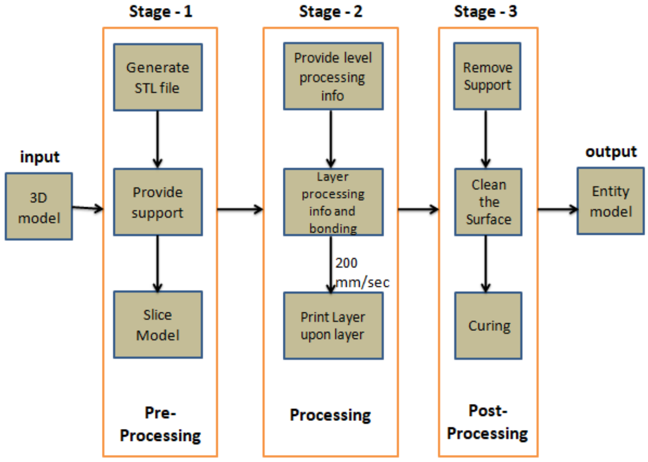

Fig. 4. Flowchart of printing technology using creality 3 ender 3 printer

Fig. 5 a represents the patch of the fabricated antenna, Fig. 5 b represents the ground of the fabricated antenna, and Fig. 5 c represents the lateral side of the fabricated antenna.

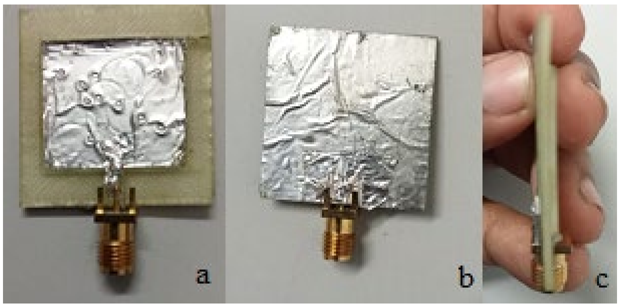

Fig. 5. 3D fabricated antenna: a – patch; b – ground; c – lateral view of antenna

The dimensions of the antenna during the actual size and during the application of pressure are shown in Table 3. The pressure is applied to the antenna from the top end towards the air-filled layer present within the TPU.

Table 2. Comparison analysis of the antenna with similar works

Ref.	Substrate	Dimensions, mm	Frequency, GHz	Material	Gain, dB	Efficiency, %
[2]	Lycra	80 × 90	2-6	Stretchable	2.3074	97.389
[4]	PDMS	–	4.5	Stretchable	-0.94	50.4
[16]	Silicone	26.4 × 20.4	5	Flexible	3.1225	77.1
[17]	EVA	80 × 29.4	3.6	Stretchable	2.3	81
[19]	Rogers	30 × 30	2.4 3.5	Flexible	6.5 7.5	–
[20]	Rogers	40 × 50	1-65 – 2.51	Flexible	2.2	80
This work	3D printed substrate	35 × 32.5	3.6 GHz 4.4 GHz	Stretchable	7.2	95.67

Table 3. Antenna dimensions

Actual		Strain applied	
*L*1	32.5 mm	*L*2	32.75 mm
*W*1	31 mm	*W*2	34.65 mm
*H*1	2 mm	*H*2	1.54 mm
*Pl*1	24.5 mm	*Pl*2	24.25 mm
*Pw*1	27.5 mm	*Pw*2	28.5 mm
*gl*1	32.5 mm	*gl*2	32.75 mm
*gw*1	31 mm	*gw*2	34.65 mm
*fl*1	5.75 mm	*fl*2	5.75 mm
*fw*1	2.5 mm	*fw*2	2.6 mm

At the time of pressure applied, the stretch level of the substrate (the combination of TPU and air) increases with a change in dielectric properties, and henceforth, a change in resonant characteristics as well as a change in radiation pattern characteristics also takes place. This change helps in effective reconfiguration, i.e., switching between one frequency to the other and then back to the former one.

4. EXPERIMENTAL EVALUATION

The fabricated antenna is studied for its electromagnetic properties by mounting it on a VNA for its S_{11} parameters and also mounted on the anechoic chamber for its radiation properties. These properties were analyzed for the antenna in normal conditions and with an external pressure applied to it. From the experimental results in Fig. 6, the return loss values are within the range of -10 dB up to -40 dB, which denotes 90 % to 99.9 % power absorbed into it. That means only 0.01 % – 10 % of power is reflected back.

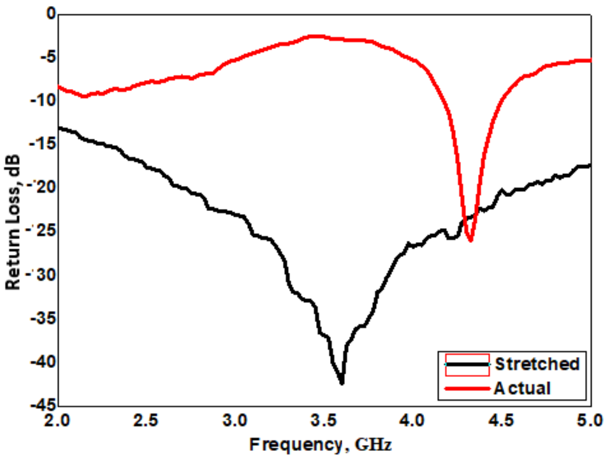

Fig. 6. Measured S_{11} parameter using no stress and stress applied to the air layer

With no stress applied to the fabricated antenna, the frequency is 4.4 GHz. And with 23 % stress applied to it, the measured frequency is 3.6 GHz. The stress applied to it is measured using the tensile strain formula,

$$TensileStrain(\%) = \frac{I - I_0}{I_0} X100 \quad (5)$$

where *I* represent the patch length with no external strain applied; I_0 represents the length of the patch with 23 % pressure applied over it. Similarly, the change in radiation properties is also measured with the stress applied onto the substrate. The strain applied over the substrate is measured using *S* parameters, as shown in Fig. 7 and radiation parameters, as shown in Fig. 7 a and b.

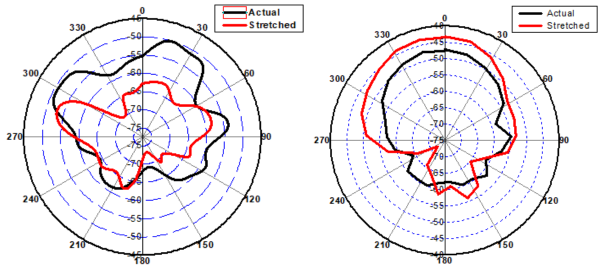

Fig. 7. Measured radiation pattern: a – E plane measurements; b – H plane measurements

From the measured values varying from I_0 to the stretched value *I*, the resonant frequency decreased from 4.4 to 3.6 GHz. It implies that the antenna can be used in multiple frequency modes based on the stress applied to it. Fig. 6 shows the measurement results of the frequency reconfigurable antenna. The antenna initially radiates at 4.4 GHz. On the application of external pressure over the *z*-axis, the antenna stretched in the direction of length and width and shrunk in the direction of height. This change in the dimensions leads to a change in the dielectric properties of the substrate, which further tends to switch the frequency. Hence, this way, the frequency reconfiguration is achieved. The achieved reconfiguration by the application of 23 % strain is 3.6 GHz. Fig. 7, the comparison of the E and H planes, displays the antenna's radiation pattern outcomes. The LHS of the figure shows the E plane (ɸ = 0°) radiation pattern for the actual state is displayed in red, and the radiation pattern for the stretched state is displayed in black. The RHS of the figure shows the H plane (ɸ = 90°) radiation pattern for the actual state is displayed in blue colour, directed at 0^0, and the radiation pattern for the stretched state is displayed in red colour, directed at 0°. As displayed in the figures, the radiation patterns have unidirectional outcomes at both planes with good trends with respect to the actual state and stretched state. The electric and magnetic field parameters are found satisfactorily, associated with a gain of 7.2 dB, directivity of 7.5743 dB and radiation efficiency of 95.67 %, along with a 12:509 front-to-back ratio. Future research on this work can be switching between frequency bands for aerospace applications.

5. CONCLUSIONS

Fabrication and experimental verification of 3D printed additively manufactured antenna that works in S and C bands were performed. The patch antenna utilizes air, the natural dielectric as substrate, and is fabricated using 3D printing. The layers of substrate and patch are defined using TPU, an elastomeric polymer. The antenna is simulated using HFSS'12 and fabricated by utilizing 3D printing technology. Reconfiguration is achieved by the stress applied over the air gap substrate. Configuration level based on resonant frequency can be determined with the amount of stress applied over it. The novel antenna is simulated using HFSS, fabricated and experimentally verified for 0 % and 23 % pressure applied over it. The dielectric parameters and radiation parameters were found to be best suited to a microstrip patch reconfigurable antenna. The antenna is best suited for automobile industries, construction industries and other WLAN (Wireless Local Area Networks) applications. However, in the future, stretchable materials with less viscosity can be used for 3D printers with pointed nozzles reducing the thickness of the TPU which further helps in improving the antenna's performance.

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