Deployable reconfigurable antenna with intrinsic strain sensing capabilities for stretchable soft robotic applications

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Frequency reconfigurable antennas play a prominent role in telecommunication technologies. This paper presents a reconfigurable antenna that could define the stretch properties in association with the intrinsic strain sensing capabilities. The stretchable resin is synthesized using Magnesium Nitrate Hexahydrate, Aluminium Nitrate Nanohydrate, the mixture was reduced and polymerized and finally made conductive stretchable resin with the help of CNT's (Carbon Nano Tubes). The solution is characterized by the help of SEM and EDAX measurements. The conducting stretchable polymer resin could elongate upto 100% along with the fabric dielectric, Lycra. The electrical conductivity of the resin is 8 S/m. The precise dimension of the antenna was done with the help of a micro-cutter. The inverted S shape of the antenna helps to achieve bandwidth. The fabricated antenna operates within 4GHz and 8GHz with a gain of up to 3.3dB, Front to the Back ratio of 7.42. It is experimented by varying the strain to achieve frequency reconfiguration ranging from 0% to 75%. The fabrication and characterization of extremely efficient stretchable and reconfigurable antenna for C band frequency applications are described. As a potential application, the work can be demonstrated with the use of a highly stretchable and deformable antenna for deployable soft robotic applications.

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1. Introduction

Stretchable antennas are commonly employed in reconfigurable applications such as space exploration, search and rescue operations, sports and re-habilitation and furthermore. The increase in the use of Body Area Networks, Body Sensor Networks has drawn the attention of researchers toward reconfigurable devices such as antennas, sensors, etc., which also helps to understand physiological parameters as well. Some other applications include prosthetics and soft robots for human-machine interactions [1, 2]. Reconfiguration plays a major role in modern communication systems where multiple antennas are required. This makes the wireless communication technology enhanced in both space-effective and cost-effective aspects. The flexible/stretchable behavior of the antenna simplifies the reconfiguration. i.e., the change in physical properties of the dielectrics makes further changes in input and output impedances and henceforth the gain and efficiency changes as well [3-5].

The preparation and usage of functional devices have been increasing in demand in recent years. Hence, there is a necessity of making the functional dielectric as well as a functional conductor [6-12]. Depending upon the increase in the number of devices, high demand for integration also persists which results in furthermore higher costs as well as component requirements. Hence, a system with better functionality and better efficiency with a much lesser complexity is required. When considering this, a multifunctional device (e.g., sensing as well as communication) is generally preferred [13, 18]. The devices such as antennas would carry forward an interesting study.

In wearable antenna systems, the wearable antenna comprises both stretchable as well as flexible behavior which responds to the changes in physical properties due to deformation. This could be observed with the changes in frequency as well as radiation properties with that of the deformation [19-21, 14, 15-17]. This reveals the reconfiguration potential due to the deformation with decreased number of components without actually sacrificing the efficiency and gain parameters and commensuration of integration challenges [22-26].

The flexible and stretchable functional materials are enabled by novel materials and/or a new integration approach with structural changes. Moreover, replacing the conventional rigid surfaces with elastomeric substrates the conductive part, as it complies with the radiation characteristics must also comprise stretchable and flexible connections. It may also include liquid metals [32], conductive textiles, elastomeric conductive fillers [33], conductive films [27] stretchable and flexible structures from conductive metals. The antenna performances strongly depend upon the resonance frequency, radiation efficiency; gain and radiation pattern [28-31]. In this regard, the flexible and stretchable antennas in the burgeoning field with plenty of challenges there is the need for small-sized antennas with low cost, easily tunable antennas with better performance characteristics.

The preparation of the conductors, as well as dielectric materials for the conformal as well as stretchable applications, remains a difficult task. The gap between the human and machine is filled with soft conductive materials like liquid metals, conductive fabrics, and engineered materials etc which help in the revolution for artificial intelligence [35-38]. In accordance with the stretchable conductor, along with conductivity, the material must also be soft and stretchable [34]. This tendency can be achieved by either introducing soft regions to make morphological modifications for conjugated conductive co-polymers, or by adding plasticizing agents as well as flexible segments in between [39-41]. It can also be achieved by the blend of conductive components with stretchable network insulators, which is essentially necessitated to make conductive paths with insulating networks [42].

However, with the essence of compatibility which remains a crucial role in between the conductive domains and the nearby elastomeric networks as it leads to poor electro-mechanical performance [43, 44]. It addresses the challenges in elastic networks which remain a major problem. As an example, the chemically/physically treated conductive polymers show restricted stretch-ability which results from intrinsic incompatibility in rigid structures with flexible domains. The stretchable insulating polymers blended with conductive materials like liquid metals, conductive salts, and rigid conjugated polymers that result in percolating conductive paths make impedance changes in conductive networks during deformation. It causes irreversible damage when stretched. Despite electronically conductive materials, the ionic electrolytes do not effectively get bounded with polymer networks may provide environmental instability like evaporation, freezing and potential leakage of resins during deformation [46]. Inspired by conductive materials, it is important to synthesize a soft conductive material and make coupling action with dynamically cross-linked networks.

Herein, we propose a kind of intrinsically stretchable conductors by making a solution of Magnesium Nitrate Hexahydrate and Aluminium Nitrate Nanohydrate [49]. This makes sense, that we create an intrinsically stretchable conductor which consists of polyzwitterions that assemble conductive nano-channels to reduce the possibility of electrolyte leakage [45]. Dynamic networks are made with the conductive nano-channels to serve reliability in structural integrity, deformation stability and environmental adaptability [46, 47].The advantage of polydimethylsiloxane (PDMS) [48] in flexible wear-resistant product materials is demonstrated by employing two different methodologies to confirm the equivalent isotropic dielectric constant and loss tangent. Developers of space and airborne applications are attracted to CNTs [50] due to their excellent temperature stability, mechanical robustness and less vulnerable to environmental factors.

Reconfigurable antenna is one among the emerging technologies in various fields ranging from sports, health care, military, air surveillance, navigation, etc. These antennas help to read and monitor the physiological factors of the human body. This work encompasses the wearable antenna which reconfigures based upon the stretch applied to it. The conductive resin was made which could stretch upto 100%. This was deposited upon the pre-treated Lycra dielectric. Then the fabricated antenna was studied for its dielectric properties measurements and radiation properties measurements.

2. Synthesis and characterization of stretchable conductive resin

2.1. Materials used

Cyanoacrylate $C_6H_7No_2$, Magnesium nitrate hexahydrate $(Mg(No_3)_2.6H_2O)$, Aluminium nitrate Nanohydrate $(Al(No_3)_3.9H_2O)$, Hydroxyapatite$(Ca_{10}(PO_4)_6(OH)_2)$, Sodium Carbonate (Na_2CO_3), Sodium Hydroxide (NaOH), CNT.

2.2. Method

Synthesis of the work was done by the preparation of three different types of solutions. In the first solution, 2g of Magnesium nitrate hexahydrate along with 0.75g of Aluminium nitrate Nanohydrate were mixed with 25ml of DI (De-ionized) water in a 4:1 molar ratio. Then 0.25g of Sodium hydroxide was mixed with 0.5g of sodium carbonate in 25ml of DI water. Next, a dispersion medium consisting of 2g of hydroxyapatite with 25ml of de-ionized water. During synthesis, the mixture of $(Mg(No_3)_2.6H_2O)$ with $(Al(No_3)_3.9H_2O)$ is added to the (Na_2CO_3), mixture at the rate of 6ml/min under constant stirring. The final solution is again mixed with the pre-prepared dispersion medium.Then the product was mixed with Cyanoacrylate $(C_6H_7NO_2)$ and CNT and thoroughly mixed. The resultant dispersion was then combined with the PDMS resin under stirring at room temperature.

2.2.1. Step-by-step demonstration

Fig. 1 details the step-by-step demonstration of the synthesis.

Step1: In the first solution, 2g of Magnesium nitrate hexahydrate along with 0.75g of Aluminium nitrate Nanohydrate were mixed with 25ml of DI water in a 4:1 molar ratio.

Step2: Then 0.25g of Sodium hydroxide was mixed with 0.5g of sodium carbonate in 25ml of DI water.

Step3: A dispersion medium consisting of 2g of hydroxyapatite with 25ml of de-ionized water.

Step 4: During synthesis, the mixture of $(Mg(No_3)_2.6H_2O)$ with $(Al(No_3)_3.9H_2O)$ is added to the (Na_2CO_3), mixture at the rate of 6ml/min under constant stirring. The final solution is again mixed with the pre-prepared dispersion medium.

Step 5: The product was mixed with Cyanoacrylate ($C_6H_7NO_2$) and CNT and thoroughly mixed. Then the resulting dispersion was mixed with the PDMS resin under stirring at room temperature.

2.3. X- ray diffraction (XRD) analysis of MWCNTs

The XRD analysis of Multi-walled CNTs is displayed in Fig. 2. Presence of crystalline nature can be examined using XRD patterns. Samples were collected at diffraction angles between 15° and 80°. The diffraction plane according to 2θ shows that the characteristics peaks at 26.5° and 43° match the plane 002 and 100, respectively.

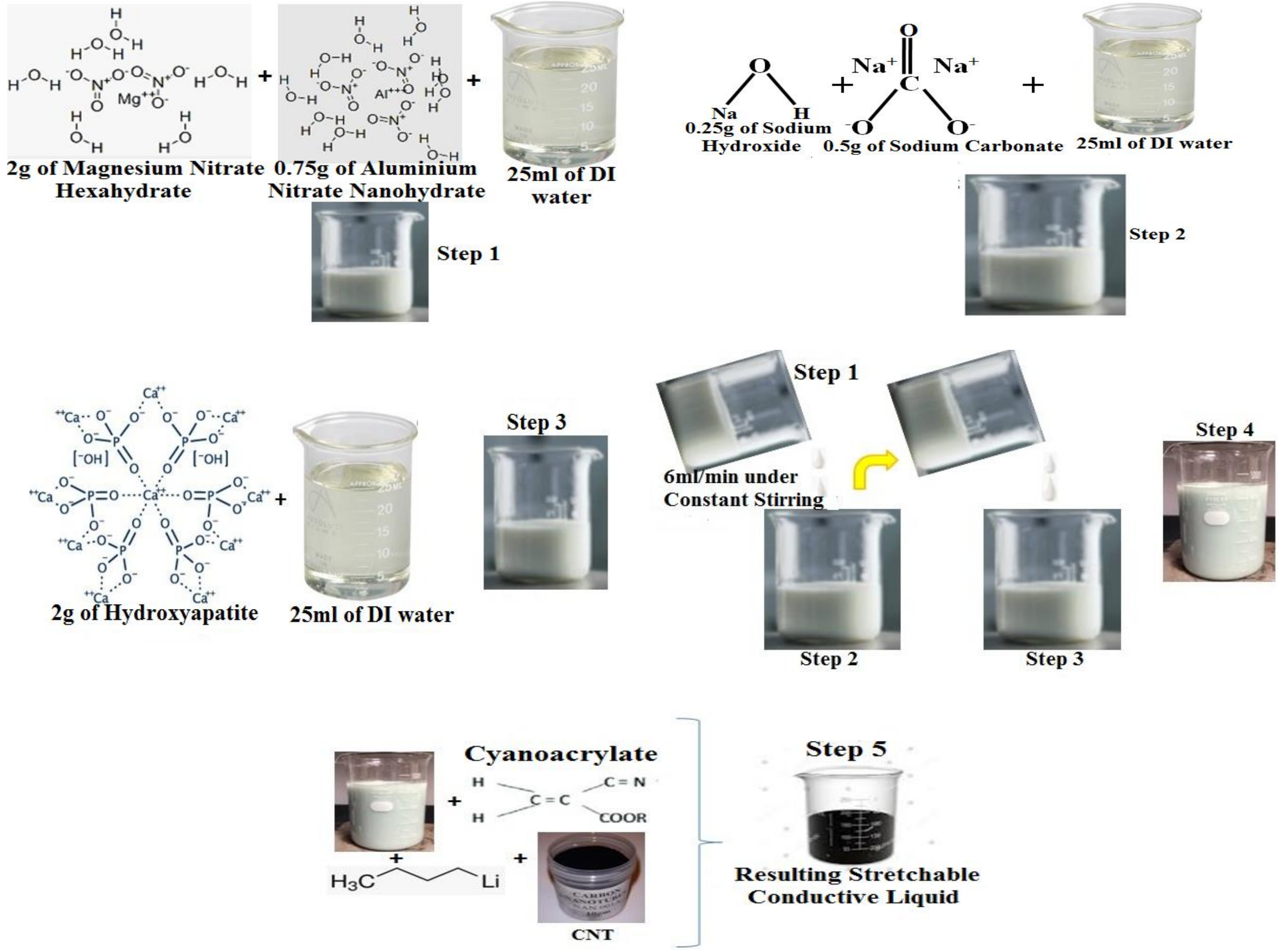


Fig. 1. Synthesis of Stretchable conductive resins (color online)

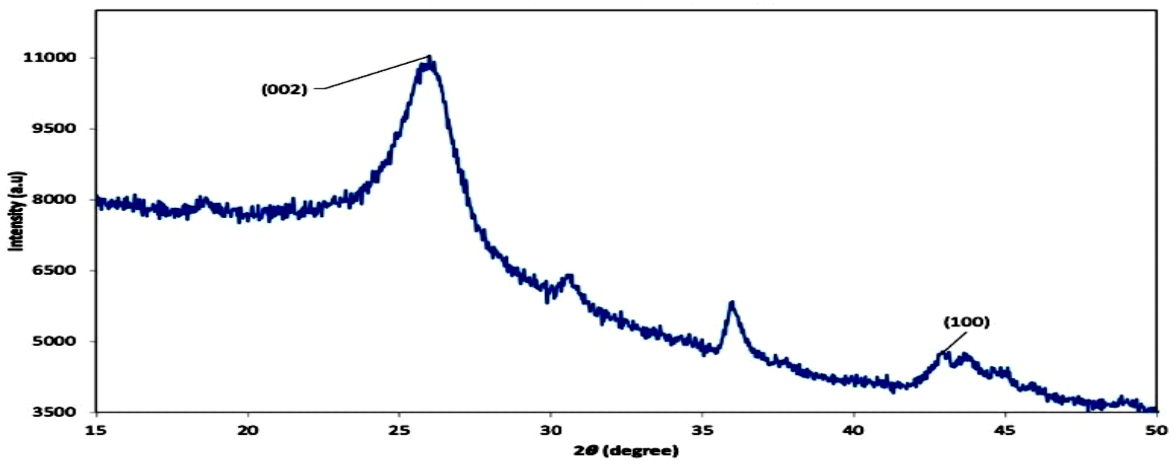


Fig. 2. XRD analysis of Multi-walled Carbon Nano Tubes (MWCNTs) (color online)

3. SEM and EDAX measurements

The prepared resin was subjected to Scanning Electron Microscopy Measurements (SEM) for the structural morphology test, in order to find out the level of mixing of Carbon Nano-tubes upon the prepared stretchable resin. Fig. 3a and Fig. 3b represent the SEM image of 35 KX and 65 KX magnifications of Multi-walled Carbon Nano-tubes. Fig. 3c represents the CNTs are in good mixing composition with the resin under the magnification of 13.62KX and Fig. 3d expresses the distribution of CNTs in the dispersion medium under 500X magnification.

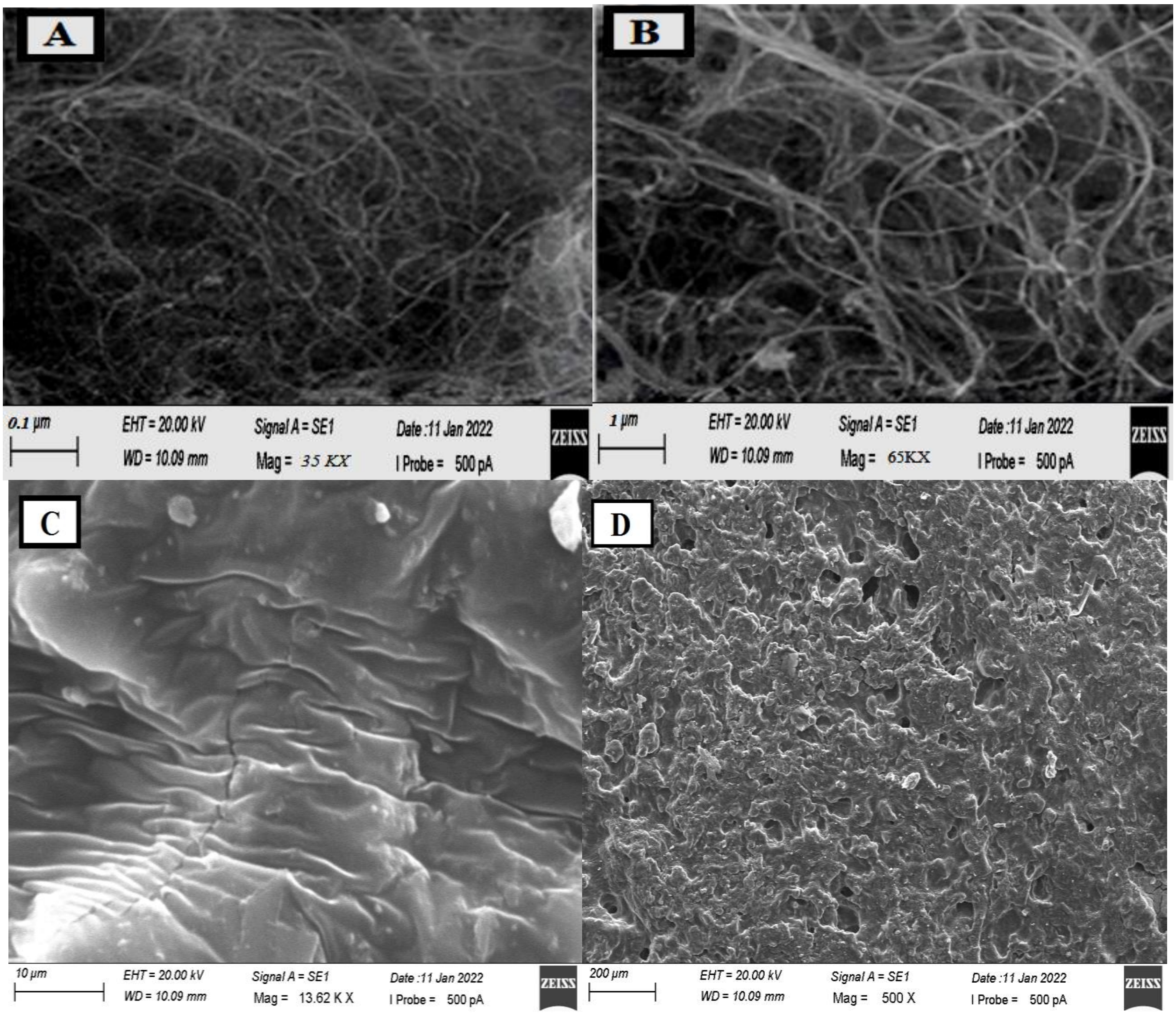


Fig. 3. SEM measurements for stretchable conductive resin (A) 35KX magnified MWCNT (B) 65 KX magnified CNT (C)Appearance of conductive CNT of the resin 13.62KX magnification (D)Distribution of CNT in the dispersion medium(500X magnification)

The Energy Dispersive X-ray Analysis (EDAX) measurements were taken for the sample to study the elemental composition of materials. The stretchable conductive resin was supposed for the EDAX study to experiment with the presence and level of CNT's in the resin prepared. Fig. 4 represents the Carbon particles are found in higher levels, as expected for the application of stretchable conductive resin.

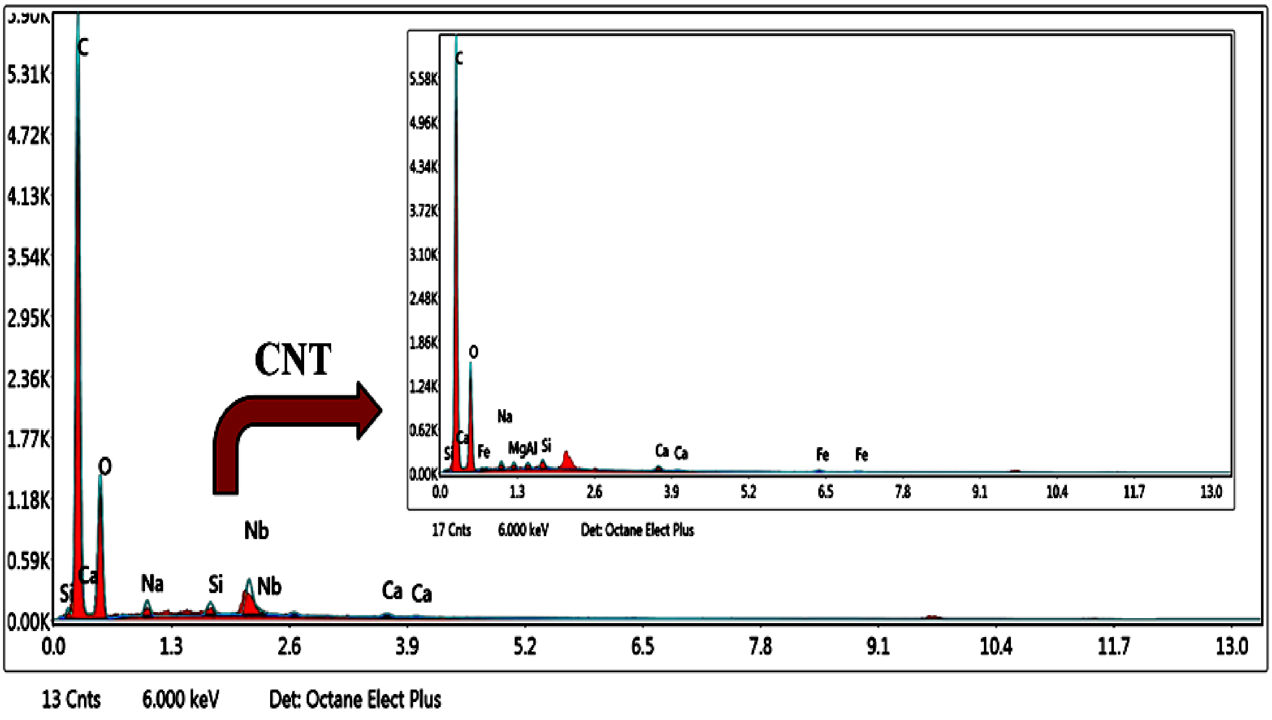


Fig. 4. EDAX for the presence of Carbon particles for stretchable conductive resin (color online)

4. Antenna design and fabrication

The proposed stretchable polymer resin conductor in a stretchable and reconfigurable antenna for soft robotic applications is depicted schematically in Fig. 5. The substrate Lycra's physical and dielectric properties are listed in Table 1.

Table 1. Lycra fabric substrate's dielectric properties

Substrate material	Thickness of the material	Value of dielectric constant	Loss tangent (tanδ)
Lycra	0.4 mm	3.38	0.045

Being known for its high elasticity, fabric Lycra serves as a dielectric substrate. To prepare the RF dielectrics, the substrate was first boiled with 1.0 mol/L Sodium Hydroxide (NAOH) aqueous solution for 1hour and then, it was washed using DI (De-Ionized) water, then dried at 100°C in the hot air oven to remove the surface impurities, if present. To prevent the fabric from varying environmental disturbances, the functional coating was made upon the fabric, i.e., a thin film of the coating was made on either side of the fabric using Doctor-blade technology. The prepared substrate was precisely tailored with the help of a micro-cutter. The dielectric properties of the substrate Lycra were noted down in Table 1.

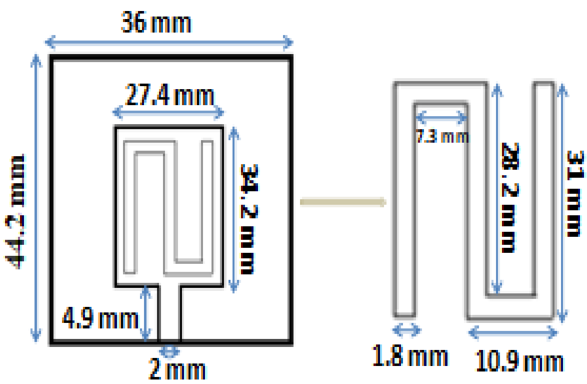


Fig. 5. Dimensions of the Microstrip patch antenna designed using HFSS 13 (color online)

The micromachining for the fabrication of conducting patch is an important criteria, in which the perfection is achieved with the precise drawing of the patch inclusive of the slot with the help of coral draw software and machining was done with the help of a micro-cutter. Then, the prepared stretchable conductive resin was applied onto the substrate by doctor blade technology. The other side of the substrate, i.e., the ground also applied with the conductive resin coating (Fig. 6). The antenna thus fabricated is air-dried for 6 hours.

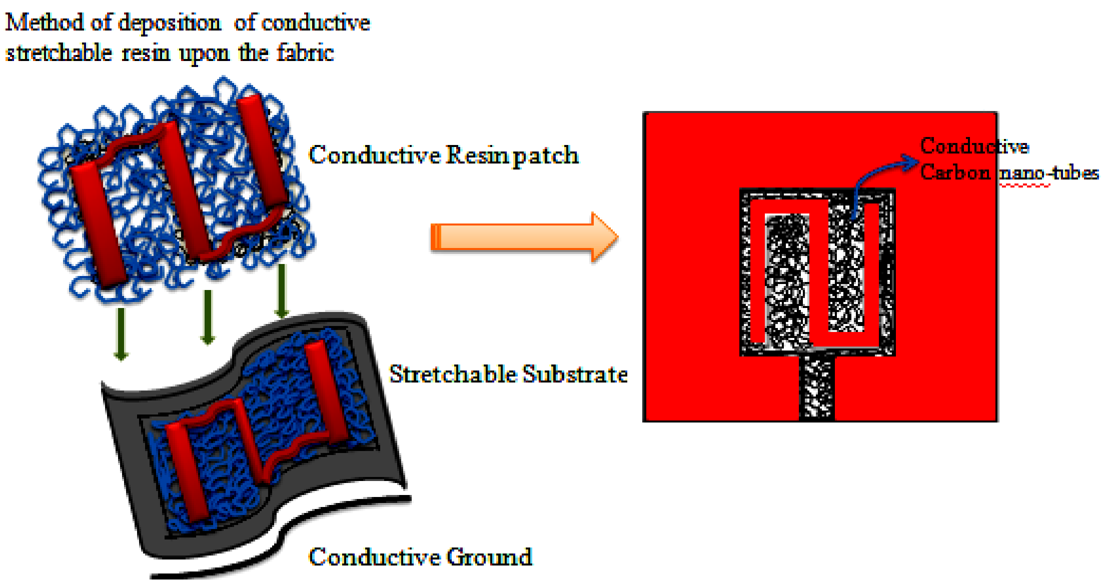


Fig. 6. Method of deposition of conductive stretchable resin upon the fabric (color online)

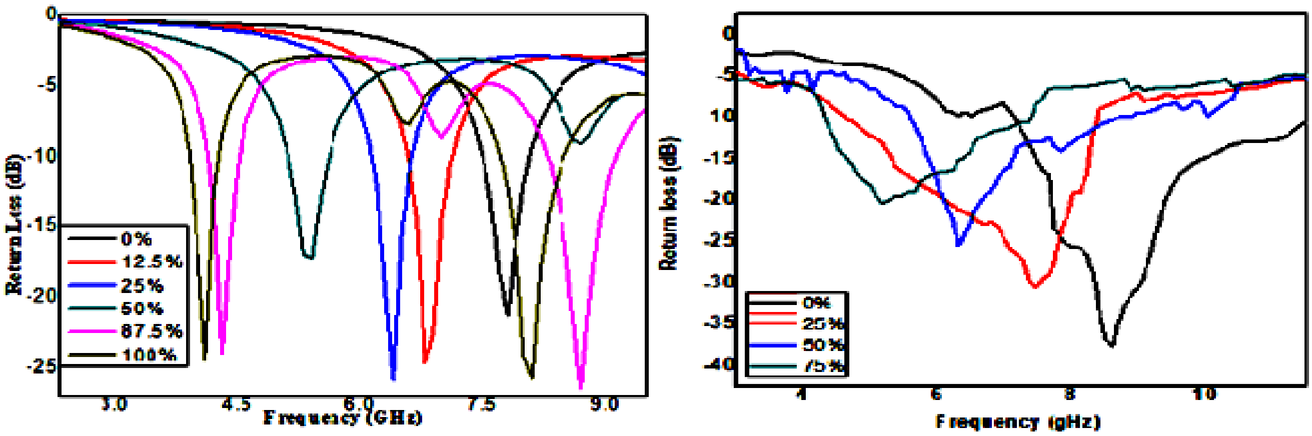
Tensile strength measurements for the fabricated antenna were carried out in accordance with ASTM D 1776 standard using the UTM (Universal Testing Machine), with the force applied 33N in the loading rate of 10 mm/min. The fabricated antenna was loaded into the UTM and stretched in accordance with the loading rate. The process proceeded until the fabric ripped. The tension applied at the time of rip is recorded. The results of breaking force and elongation of the fabric samples were obtained by the computer interfaced with this testing machine.The antenna's elastic modulus was found to be 3.36411 N/mm^2. The Lycra fabric ripped with a tensile strength of 14.14N/mm^2, whereas the fabricated antenna ripped at a tensile strength of 4.72 N/mm^2. On further application of force, the fabric tends to lose its elasticity and breaks down at the maximum ductility of the fabric at which the fabric torn.

Fig. 7. Fabricated Antenna mounted on VNA (Vector Network Analyzer) (color online)

The fabricated antenna is mounted upon the Vector Network Analyzer as depicted in the Fig. 7 and reflection coefficient parameters were taken for the levels of stretch-ability ranging from 0% to 75%.

5. Resonant characteristics and radiation properties measurement

The fabricated antenna was mounted onto the Vector Network Analyzer (VNA) as illustrated in Fig. 7, and the corresponding return loss (S11) was noted down for every level ranging from 0% to 100%. It is observed that, at the level of 0% stretch applied, the frequency measured was 8.2 GHz with a return loss of -38dB. Likewise, when 25% stress has applied, the frequency was 7.6 GHz with a return loss of -32dB. With 50% and 75% of stress was applied, the resonated frequencies are 6.1 GHz and 5.4 GHz with the corresponding return losses -26dB and -19dB respectively. The frequencies re-configure with the level of stress applied to it. The simulated, as well as measured frequencies for the proposed antenna are shown in Fig. 8a and Fig. 8b.

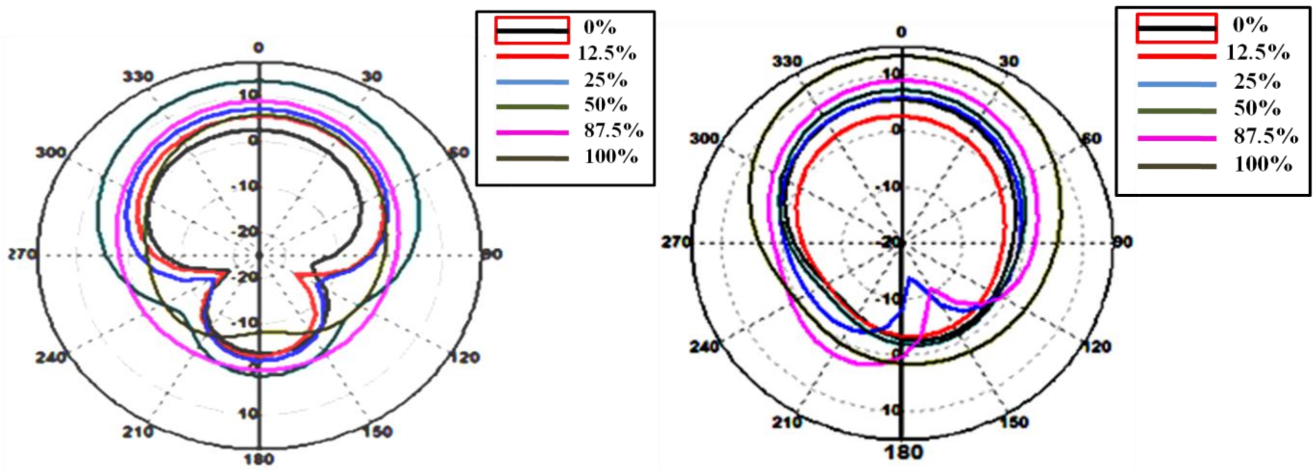


(a) (b)

Fig. 8. (a) Simulation results for Reflection Co-efficient (S_{11}); (b) Measurement results for Reflection Co-efficient (S_{11}) (color online)

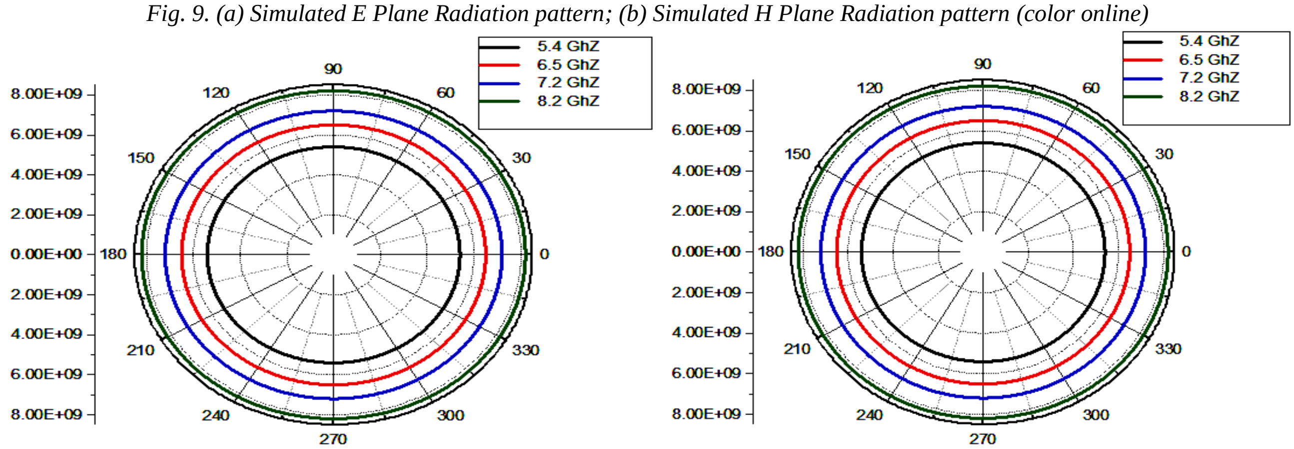
The E and H plane radiation pattern for both the simulation as well as the measured values are as noted in the Fig. 9a and Fig. 9b and Fig. 10a and Fig. 10b. The radiation pattern also changes in accordance with the amount of stress applied onto the substrate and therefore the gain as well as the efficiency changes.

Stretchable devices are being developed in a continuous fashion in accordance with various functionalities. In this study, we prepare a stretchable conductive resin to realize the overall reliability of the connections. The stretchable conductive resin was prepared based upon 2g of Magnesium nitrate Hexahydrate along with 0.75g of Aluminium nitrate Nanohydrate. The mixture was then reduced and polymerized. Finally, the polymerized mixture was made collectively conductive by the addition of Multi-walled Carbon Nanotubes.



(a) (b)

Fig. 9. (a) Simulated E Plane Radiation pattern; (b) Simulated H Plane Radiation pattern (color online)



(a) (b)

Fig. 10. (a) Measured E Plane Radiation pattern; (b) Measured H Plane Radiation pattern (color online)

The stretchable conductive polymer has shown superior adaptability to stretchable substrates due to excellent stretchability (maximum tensile strain: 75%) and the ability of electrical conductivity in deformation (ΔR/R < 16) at a tensile strain of 75%. A stretchable antenna was fabricated using the prepared stretchable polymer resin and measured for the reconfiguration with respect to the change in dielectric properties in accordance with the stress applied. The antenna again resonated to its original value, when deformed.

The antenna resonates at 8 GHz with a return loss of -38dB before the tensile strain is applied. The 10 dB measured values provided a bandwidth of 2 GHz which represents broadband behaviour. Similarly, the properties tend to vary with the level of stress applied. The variable behaviour is dependent upon the tensile strength provided to the substrate. This can be calculated by using Eq. 1.

$$\text{Tensile strain (\%)} = \frac{I-I_0}{I_0} * 100 \quad (1)$$

where 'I_0' is length of the patch antenna without external strain and 'I' is the patch antenna length with external strain.

Table 2.Comparison of measured performance parameters

Applied Tensile Strain (%)	Broadband range	Frequency of Operation (GHz)	Antenna Efficiency (%)	Antenna Gain (dB)
0	7-11	8	78.94	2.63
25	4.5-8	7.3	77.23	3.15
50	5.8-9.2	6.2	84.51	3.27
75	4.4-6.6	5.5	74.93	2.20

When the external strain is applied, the dielectric properties of the material vary and in accordance, the frequency, as well as radiation pattern, changes. This methodology was used by the proposed structure to achieve re-configuration. The designated dimensions support wideband operation along with the stretchable characteristics. The comparison of the measured performances is noted down in Table 2.

Table 3 summarizes the comparison of the proposed antenna with other reconfigurable antennas.

Table 3. Comparison of proposed antenna with other reconfigurable antennas

Ref	Antenna Type	Method to Reconfigure	Materials used	Freq (GhZ)	Gain (dB)	Efficiency (%)	Dimension (mm^2)	Thickness (mm)
This paper	Patch	Stretchable	Lycra fabric and CNT conductive resin	4 – 8	2.2 – 3.3	74.93 – 84.51%	44.2 x 36	0.4
[51]	Patch	Electrical switching	Felt and Shield it super	1.57 – 2.55	0.2 – 4.8	17 – 47%	113 x 99	1.7
[52]	Patch	Geometry morphing	Denim	2.45 – 5	1.9 – 3.2	82.8 – 97%	45 x 33	0.13
[54]	Patch	Parasitic patch	Polymer, conductive fabric	2.3 – 2.68	2.9 – 3.3	40.3 – 46.1%	59.8 x 59.8	5.46
[55]	Slot antenna	Injectively charging the permittivity	FR4, PDMS and Copper	3.05 – 7.9	N/A	N/A	N/A	N/A
[53]	Dipole	Microfluid based	S-glass, copper tape, EGaIn	3.84 – 5.34	N/A	N/A	N/A	N/A

The authors of [51] designed a circularly polarised reconfigurable antenna for the frequency range of 1.5 to 2.55 GHz utilising electrical switching technology. In [52], a flexible frequency reconfigurable antenna is proposed with the dual-polarized operation (2.45 GHz, 5GHz) using denim material as a substrate. The authors of [53] demonstrated that liquid conductor-filled micro fluidic channels work well as switches for reconfigurable antennas for the frequency range 3.84 to 5.34GHz. The authors of [54] have successfully demonstrated a strong, flexible, frequency-reconfigurable, and wearable antenna using the conductive fabric technology incorporated in PDMS. By integrating a fluidic structure to the antenna's surface, the authors of [55] designed a tunable multi frequency slot antenna for the frequency range 3.05 – 7.9GHz.

6. Conclusions

This study reports the preparation of stretchable conductive polymer resin that could elongate >75%. It also encompasses the elongated resin that deforms along with the material on which it is deposited onto. Three solutions were made and are mixed in the proper molarity mixing ratio and the final polymer is mixed with the multi-walled Carbon Nano-tubes. The conductive polymer has proven stability with maximum tensile strain (>75%), and electrical conductivity (~8 S/m). The fabricated antenna works in C band frequencies ranging from 4 to 8 GHz. It can be useful for GPS, Wireless computer Networks and Soft Robotic applications.

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