Development of nano ferrite coated miniaturised jute antenna for wireless applications

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ABSTRACT – REZUMAT

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In this work, a microstrip patch antenna is designed using a novel Ytterbium doped Cu-Mn Nano ferrite coated jute substrate for S band (2-4 GHz) applications. The prepared material is characterised by structural and electromagnetic properties to examine and analyse the effect of material factors on antenna substrate suitability. The antenna is designed and simulated using Computer Simulation Technology (CST) software. The antenna parameters such as gain are improved by employing super formula and meander line techniques. The fabricated antenna also shows better performance with return loss, Voltage Standing Wave Ratio (VSWR) and gain values.

Keywords: *coating, composites, technical textiles, textile, thermal conductivity*

Dezvoltarea antenei din iută în miniatură acoperită cu nanoferită pentru aplicații wireless

În această lucrare, a fost proiectată o antenă cu patch-uri cu microbandă folosind un nou substrat de iută acoperit cu nanoferită de Cu-Mn, dopat cu iterbiu pentru aplicații în bandă S (2-4 GHz). Materialul realizat este caracterizat pentru proprietăți structurale și electromagnetice, cu scopul de a examina și a analiza influența factorilor de material asupra adecvării substratului antenei. Antena este proiectată și simulată folosind software-ul Computer Simulation Technology (CST). Parametrii antenei, cum ar fi amplificarea, sunt îmbunătățiți prin folosirea tehnicilor cu superformule și a liniilor tip spirală. În plus, antena fabricată prezintă performanțe superioare în raport cu pierderile de retur, raportul undei staționare de tensiune (VSWR) și valorile de amplificare.

Cuvinte cheie: *acoperire, compozite, textile tehnice, textil, conductivitate termică*

INTRODUCTION

New and innovative materials are being developed continually in the field of materials science [1]. This leads to the advancement of existing products and technologies or the introduction of new technologies for the development of society and the environment, either directly or indirectly. Among various materials, Nano ferrites attracted the attention of researchers, scientists and technologists due to their wide range of applications in the fields of electronics, communication, drug delivery, sensors, actuators etc. The size of the antenna in electronics is a major bottleneck in further reducing communication package sizes at the very high-frequency band (VHF) [2]. The growing demand for small antennas in defence, aerospace, and mobile devices necessitates antenna miniaturisation. Antenna miniaturisation is a difficult problem because antenna gain and bandwidth [3] are constrained by fundamental limits based on antenna size.

Because of the wide extent of the field of composites, the necessity to discover a replacement for glass fibre-reinforced composites, which are non-biodegradable, is essential. A primary component of interest has been the development of a high-performance composite employing natural fibres.

RELATED WORKS

The following are some of the works focussed on flexible antennae using Nanomaterial material as substrate.

Xu et al. [4] prepared LiZnTiBi ferrites with high permeability dispersed into a PDMS film to use as a flexible substrate for the patch antenna. The ferrite material is ground and synthesized. After dispersed on the Polydimethylsiloxane film, shows desirable normalized characteristic impedance ($(\mu'/\varepsilon')1/2\eta_0 = 0.95\eta_0$) and miniaturization factor ($(\mu'\varepsilon')1/2 = 5.26$) for miniaturized flexible antenna application at 100 MHz. However, there is no simulation-level design of an antenna with such a substrate for miniaturization.

Hasan et al. [5] prepared a nanomaterial mixture consisting of nickel zinc ferrite (NZF) nanopowder with linseed oil, m-xylene and α-terpineol. The final nanopowder is sonicated and in liquid form applied on the surface of FR-Material. Then the square patch antenna is designed using the nano-composite substrate and silver patch. The simulated results show there is a significant reduction in Return loss (–10.97 dB at 6.42 GHz) and bandwidth for patch antenna using Nano-composite substrate when compared to patch antenna with FR-4 substrate which has higher return loss (–8.2 dB at 6 GHz) and reduced bandwidth.

Nevertheless, considerable challenges still need to be addressed before nano composite substrate-based patch antennas can be widely used in various wireless applications. The nano-composite substrate possesses the following issues: the cost of the composite material such as FR4, epoxy glass, RT-Duroid etc., is high, and there are more rigidity, and design issues when applicable to conformal antennas, wearable antennas etc. These issues can be overcome by employing nanomaterials on flexible substrate materials such as textiles, foam etc.

In addition to this, Nano ferrite materials have an impressive dielectric strength and negligible losses at high frequencies, making them suitable for high-frequency applications. Microstrip patch antennas mounted on ferrite substrates have several advantages over dielectric materials. On the other hand, the nano ferrites mixed with textile materials can do even better when comes to bending applications. Thus, the designed antenna can even be applicable for wearable applications. For this reason, this work focuses on the development of Nano ferrite materials and their mixing in the flexible substrate jute for the miniaturized design and performance improvement for wireless applications. For further improvement of the antenna performance, enhancement techniques like Super shape and meander line techniques are proposed.

The main contributions of the proposed work include:

- Primary approach to use nano-ferrites coated on the jute fabric as a substrate for the patch antenna.
- Antenna miniaturization with reduced return loss, better Voltage Standing Wave Ratio (VSWR) and improved gain by employing super formula and Meander line techniques.

The rest of the paper has been organised as follows: 3^{rd} section deals with the steps involved in the development of flexible antennae such as material synthesis and characterisation, antenna design, simulation, fabrication and measurement. 4^{th} section involves the results and discussions. The simulated and measured values under various conditions are plotted and analysed. Finally, 5^{th} section provides a conclusion and suggests the future work that can be done in the proposed work.

PREPARATION OF NANO-FERRITE MATERIAL

Researchers investigated that the combination of Copper and Manganese nano ferrites has developed a non-conducting behaviour [5, 6]. Moreover, when added with rare earth metal, the combination will further improve the dielectric property overall. The choice of rare earth metal chosen is Ytterbium. Ytterbium is being used in a variety of applications, including memory devices and optoelectronic applications [7]. It can also serve as an industrial catalyst and is increasingly being used to replace conventional catalysts which are too toxic and polluting [8, 9].

Synthesis and characterisation of nano ferrites

The synthesis procedure is done using the sono chemical reactor process as shown in figure 1. For this process, metal nitrates are employed as a source material. Metal nitrates and citric acid were initially dissolved 1:1 in deionized water. For two hours, the blended solution was sonicated. The sonication process was conducted at a constant temperature of 80°C. The pH value was adjusted to 7 using NH_4OH after sonication, which was added drop-by-drop to the produced solution by stirring at room temperature, and then dried for 24 hours at a constant temperature of 80°C in a hot-air oven. As a result, the

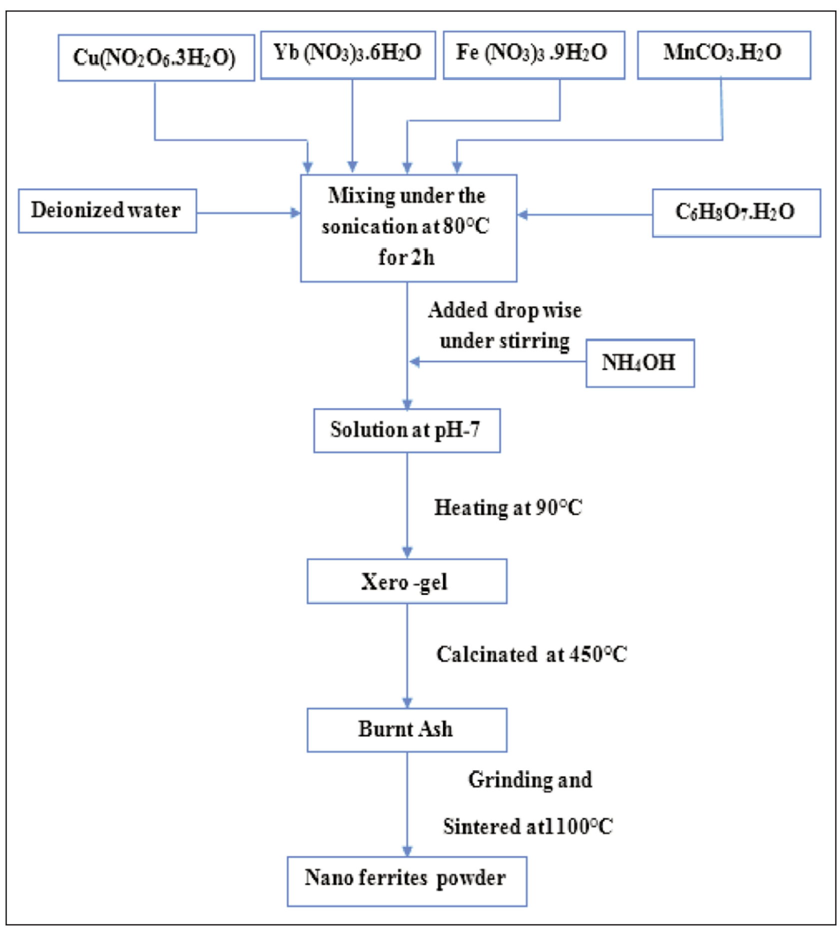


Fig. 1. Synthesis of nano ferrites

residue formed was collected and subjected to calcination at 400°C for three hours before it was ground into a homogenous mixture and sintered for 24 hours at 1000°C in atmospheric air. Further characteristic studies were performed with sintered powders. To meet the objectives of this research, the following materials were prepared using the above-mentioned sono chemical methods:

$$Cu_{0.5}\,Mn_{0.5}\,Yb_{X}\,Fe_{1.8}\,O_4 \text{ (X = 0.2, 0.4 and 0.8) nano ferrites}$$

Characterisation of nano ferrites

The Ytterbium doped Cu-Mn Nano ferrite particles are characterized for structural and electromagnetic properties to examine and analyse the effect of material factors on antenna substrate suitability.

The phase formation of the synthesized ytterbium-doped manganese copper nano ferrite is confirmed by their X-ray diffraction patterns, which were recorded on a Schmadzu 7000S powder X-ray diffractometer (XRD). The crystallite sizes of $Mn_{0.5}Cu_{0.5}Yb_{0.15}Fe_{1.85}O_4$ (MCYFO) nano ferrites were determined from the unit cell software. The XRD pattern of the MCYFO nano ferrite is shown in figure 2, *a*.

The observed XRD peaks are matched with the JCPDS card No: 74-1482 (orthorhombic structure) and 74-2072 (cubic structure) for $YbFeO_3$ and $MnCFe_2O_4$, respectively [10]. The crystallite size of MCYFO nano ferrite is 97.57 nm. Moreover, the lattice constant and volume of the prepared nano ferrite is 8.417 Å and 596.51 (Å)^3. Thus, the prepared $Mn_{0.5}Cu_{0.5}Yb_{0.1}5Fe_{1.8}5O_4$ nano ferrite is at the nano level.

Morphology, size and elements of the MCYFO nano ferrite were analyzed by scanning electron microscopy (SEM) [11] with energy-dispersive X-ray spectroscopy (EDS) (ULTRA 55; Zeiss, Germany). The SEM image of the MCYFO nano ferrite is shown in figure 2, *b*. This SEM image exhibited a condensed arrangement of regular material with a spherical shape. The nanoferrite size is 97.14 nm which is in good agreement with the crystallite size calculated from the XRD pattern. However, a lot of voids are seen in the SEM image. This may be due to delamination or accumulation of active impurities. This can be minimized by careful synthesis of the nanomaterials.

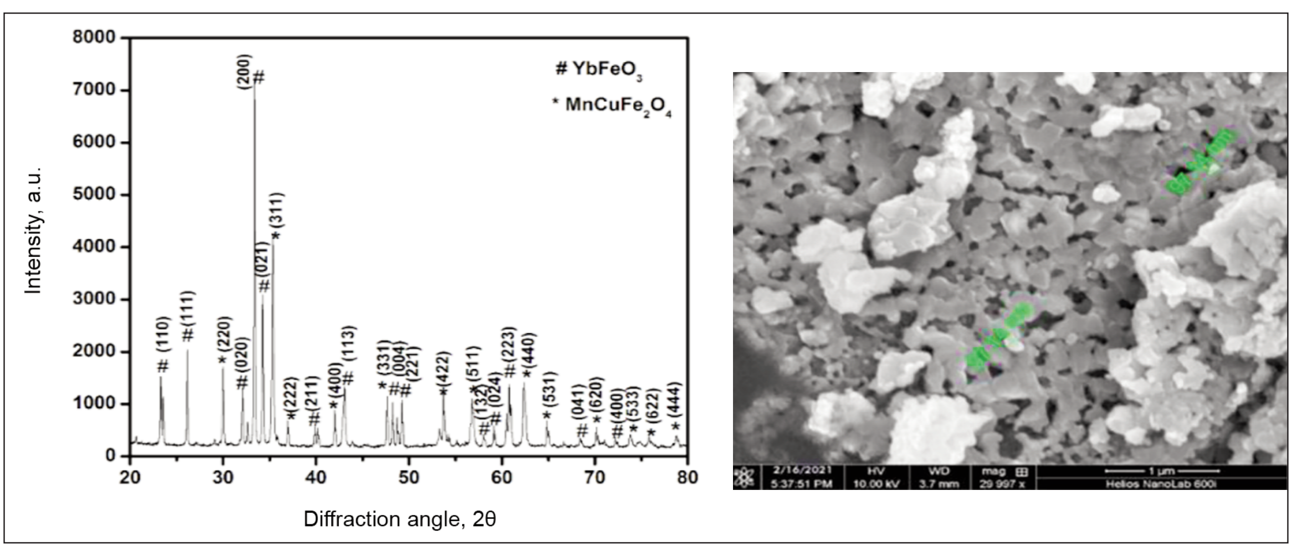
Preparation of antenna substrate material

As mentioned earlier, Microstrip patch antennas mounted on ferrite substrates have several advantages over other dielectric materials. On the other hand, the nano ferrites mixed with textile materials can do even better when comes to bending applications. The textile material chosen is jute fabric. Even though jute is a significant fabric, its application in microwave antennas has been limited [12]. It is one of the cheapest natural fibres and the second most commonly used fibre after cotton [13]. Jute has the advantage of not wrinkling as easily or wearing away as cotton. It also eliminates pollutants from the environment [14].

The process involved in the development of the nano-ferrite-coated jute material is shown in figure 3. In this process, the first step is to prepare the nano ferrites powder in liquid form by mixing it with deionized water and leaving it for 24 hours and then continuously stirring using a magnetic stirrer as in figure 3, *a*. Then the jute sheet is dipped with the solution using dip coating equipment as in figure 3, *b*. Using this method, the solution will be evenly mixed and coated into the jute sheet. After dipping, the fibre is dried for 24 hours. The resultant material is a nanocomposite fibre material as shown in figure 3, *c* which is flexible, unlike nanocomposite glass material.

Measurement of dielectric properties of the nanocomposite substrate material

The dielectric properties of the Nano-ferrite Jute substrate are tested using a Broadband Dielectric Spectrometer (BDS) of NOVOCONTROL Technologies GmbH & Co. Germany and model Concept 80. The



a *b*

Fig. 2. Images of: *a* – RD pattern of the MCYFO nano ferrite; *b* – SEM image of MCYFO nano ferrite

Fig. 3. Steps involved in the development of nano-ferrite doped Jute substrate: *a* – preparation of the nano ferrites powder in liquid form; *b* – jute sheet dipping; *c* – nanocomposite fibre material

dielectric constant and the tangent loss for the prepared substrate are measured in the range of 1 MHz to 3 GHz as shown in figures 4 and 5.

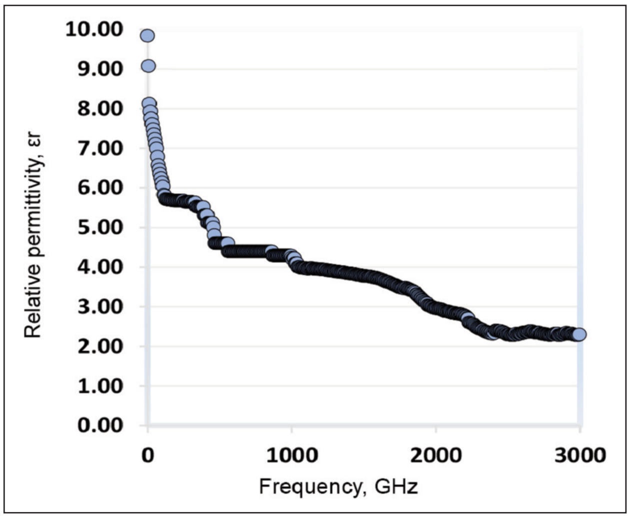


Fig. 4. Relative permittivity vs Frequency

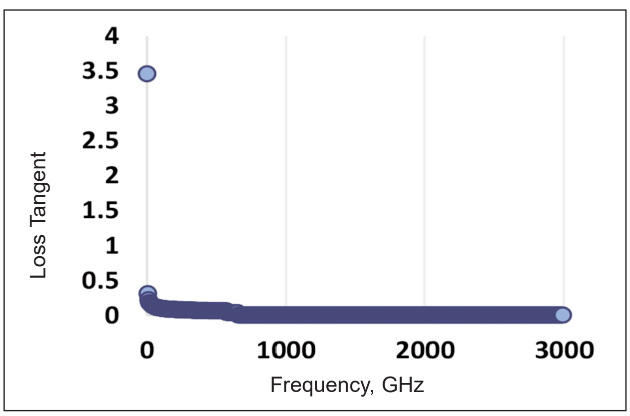


Fig. 5. Loss tangent vs Frequency

From figure 4, the relative permittivity is taken as 2.306. From figure 5, the loss tangent is reducing from 0.00102 beyond 1 GHz. The final value i.e., loss tangent is taken as 0.00102.

Thermal conductivity (K)

The thermal conductivity (K) of any material is a parameter that determines how well it can conduct heat. This term refers to the amount of heat, Q that passes through a thickness L in a plane normal to its surface area A with temperature difference T under steady state when the temperature gradient is the only factor affecting heat transfer. It is given by equation 1:

$$K = \frac{Q \times L}{A \times \Delta T} \tag{1}$$

By substituting the thickness of the substrate, L = 1 mm, heat transfer as 27 W, temperature difference (2 K to 400 K) as 398 K and Area (circle sheet of 13 mm diameter) as A = 132.66 mm^2, the K = 0.511 W/K/m.

Table 1 shows the comparison of the values of dielectric properties i.e., relative permittivity and loss tangent and patch dimensions of Jute and nano-ferrite doped Jute material. This shows that the higher loss tangent value jute is compensated which is reduced by dipping it with nano ferrite material. Even though the dielectric constant is higher for new substrate material, there is no compromise in the flexibility of the substrate. From the patch dimensions also, it is understood that the patch size is minimized.

Design and simulation of antenna

Microstrip patch antennas [15] were chosen for the antenna design because they have several advantages over traditional microwave antennas in terms of simple design, smaller dimensions, low profile, and ease of fabrication. The width and length of the patch

Table 1

DIELECTRIC PROPERTIES AND PATCH DIMENSIONS OF JUTE AND NEW SUBSTRATE MATERIAL

Substrate	Dielectric Constant	Frequency (GHz)	Loss tangent	Material density (Kg/m^3)	Thermal conductivity (W/K/m)	Length of the patch (mm)	Width of the patch (mm)
Jute	1.87	3.2	0.052	0.0015	0.4273	33.66	39.10
Nano ferrite coated Jute material	2.306	3.2	0.00102	0.0021	0.511	30.44	36.47

Table 2

COMPARISON OF ANTENNA PARAMETERS OF PATCH USING JUTE AND NANO FERRITE COATED JUTE					
Antenna structure	**Frequency (GHz)**	**Return loss S_{11} (dB)**	**VSWR**	**Gain (dB)**	**Directivity (dBi)**
Rectangular patch with Jute as substrate	3.22	–15.465	1.40	–2.34	6.77
Rectangular patch with Nano ferrite coated Jute as substrate	3.19	–17.17	1.32	5.351	7.057

are calculated from the standard design equation of the rectangular patch antenna [16] as 36.44 mm and 30.44 mm respectively.

The structure of a conventional rectangular patch antenna with new material as substrate at 3.2 GHz with inset feed [17], layout of the antenna structure with dimensions simulated in Computer Simulation Technology (CST) Studio Suite® 2019 version software as shown in figure 3. The length and width of the substrate and ground plane as 36.46 mm and 42.49 mm respectively. The thickness of the copper sheet used for the patch and ground plane is 0.035 mm.

Table 2 shows the comparison of antenna parameters of the rectangular patch using Jute and Nano ferrite coated Jute. The result shows that all the parameters are improved when the jute substrate is coated with ferrite material compared to simply jute. This result shows that the antenna parameters can be improved further when employing some enhancement techniques such as meander line, super formula techniques etc.

The superformula technique [18] on microstrip antennas allows for reduced size and high-gain antenna designs by developing new structures. The meandering line technique in antennae is nothing but the design made by a succession of sets of right-angled compensating bends [19]. Electrically, a meander antenna is a compact antenna. Meander line antennas [20] are made up of horizontal and vertical lines. Turns are formed by combining horizontal and vertical lines. As the number of turns rises, so does the efficiency. Figure 6 shows the step-by-step process of the proposed antenna. The size of the superformula shape as in figure 6, *a* can be reduced by employing meandered lines with the remaining portion in the superformula shape removed as shown in figure 6, *b*. The horizontal and vertical lines are adjusted such that the operating frequency will be 3.2 GHz. Using the meandering line, nearly 50% patch size is reduced as shown in figure 7.

Table 3 shows the dimensions of the antenna. An Inset feed line is used for better antenna performance. Its advantages are its ease of fabrication, simplicity of modelling, and ability to match impedances. Figure 8 shows the simulation results of the antenna parameters of the proposed antenna. Using the Meander line technique, the antenna resonates at dual frequencies 2.19 GHz and 3.2 GHz. The S_{11} value was also very much reduced to –35 dB

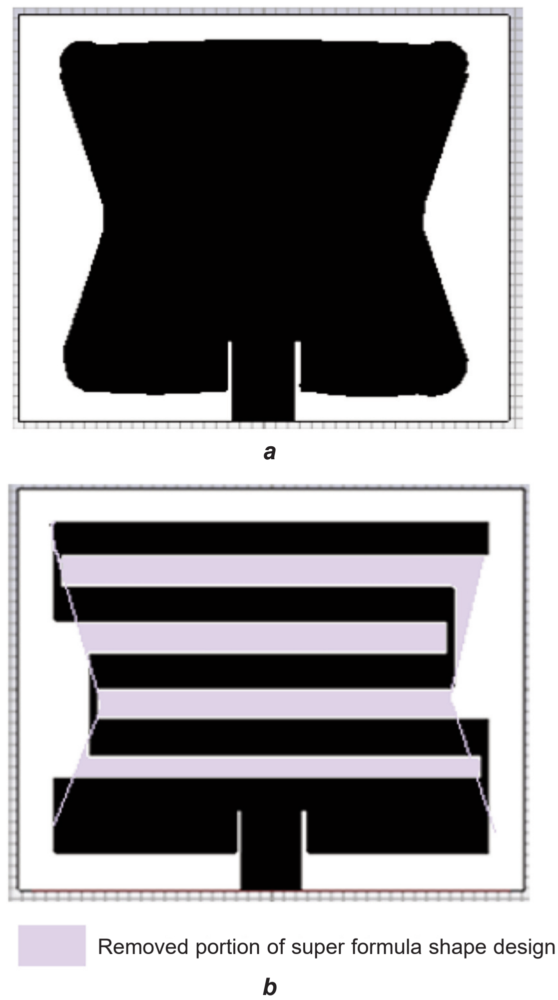


Fig. 6. Step-by-step process of proposed antenna: *a* – antenna structure 2 using super formula shape; *b* – meandered line in antenna structure 3

Table 3

DIMENSIONS OF THE PROPOSED ANTENNA	
Parameters	**Dimensions (mm)**
Width of the patch Wp	36.47
Meander line M1	3
Meander line M2	0.5
Meander line M3	2
Meander line M4	6
Length of the patch Lp	30.44
Feed line width F1	5
Inset feed gap	0.5

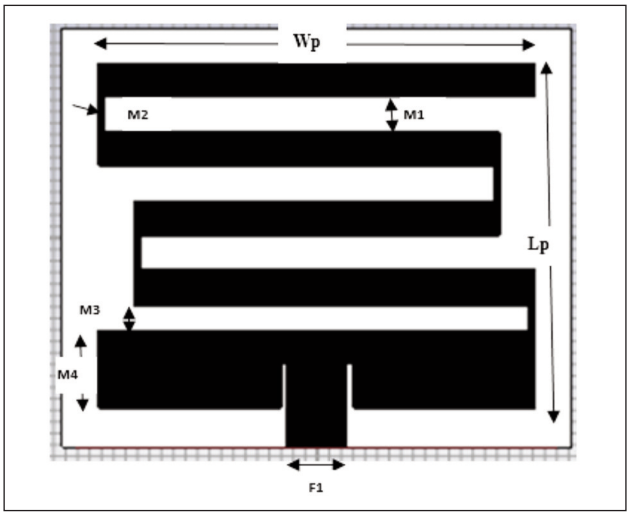


Fig. 7. Proposed Antenna Structure

at 3.2 GHz which is very low compared to a rectangular patch antenna (–17.17 dB) using the same substrate material. Overall, the gain also improved from 5.351 dBi to 8.366 dBi.

Equivalent circuit model

The proposed antenna design is modelled using a Lumped network equivalent model with capacitor and Inductor and simplified as shown in figure 9. In this, by using the resonant frequency equation as in equation 2, the frequency is calculated as 2.13 GHz and 3.169 GHz.

$$f_r = \frac{1}{2\Pi\sqrt{L_{eq}\cdot C_{eq}}} \tag{2}$$

Antenna fabrication and measurement

The proposed antenna is fabricated with the same dimension as in the simulated model and measured. To assess the values of performance parameters acquired with the antenna designed using simulation software, the fabricated antenna is connected with the Vector Network Analyzer (VNA) for *S* parameter measurement and microwave set up for gain measurement as shown in figure 10. The *S* parameter is measured as –26.42 dB. The gain of the test antenna is calculated as 5.47 dB.

COMPARATIVE RESULT ANALYSIS

Table 4 shows the comparison of the simulated and measured results of the various antenna parameters of nano-ferrite doped flexible patch antenna with flat as well as bending of 20 degrees. The measured values are very well matched with the simulated values. The gain obtained in the fabricated antenna is also greater than 5dB. Moreover, the results indicate that the proposed antenna has achieved better performance when compared to the works done in [5] in which the nanomaterial is deposited on FR-substrate which is rigid and in [4] that employs oil palm empty fruit fibre (OPEFF) mixed with nickel oxide (NiO) nanoparticles reinforced with polycaprolactone (PCL) which has return loss of –11.93 dB, –14.2 dB and –16.3 dB for three patch antennas designed. In the above table, the results show that there is a gradual deviation in the performance of the antenna when it undergoes bending. The performance also depends on the dimension of the antenna. Because for a compact antenna, it is enough to bend the antenna to a certain limit. No need to bend the antenna fully due to the small size of the antenna. The overall performance of the nano ferrite mixed jute antenna is very much improved when compared to the performance of the jute-only antenna. The length and width of the proposed antenna are smaller than those of the conventional rectangular microstrip antenna.

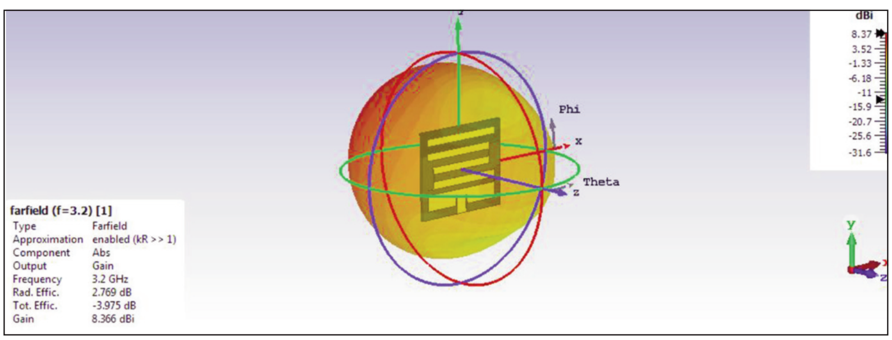


Fig. 8. The simulated gain value of the proposed antenna

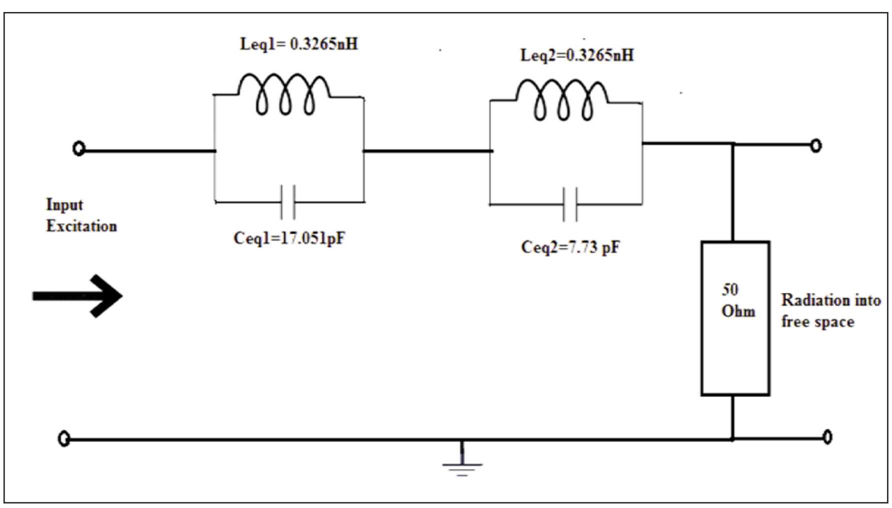


Fig. 9. Equivalent circuit model of the proposed antenna

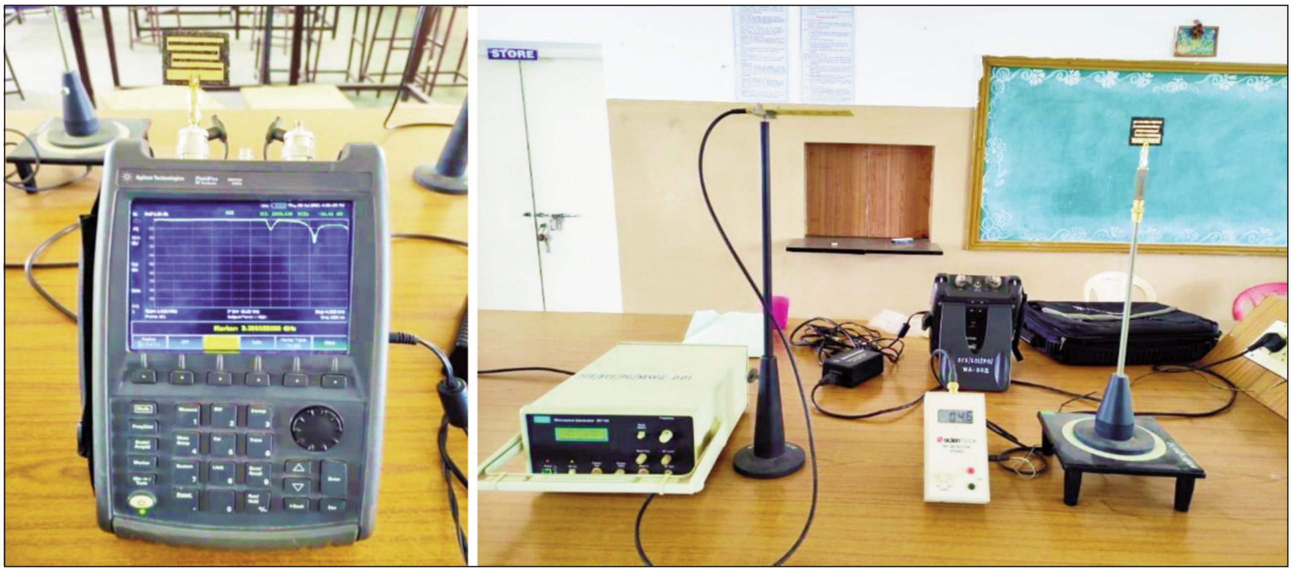


Fig. 10. Testing of fabricated antenna – S_{11} (left) and Gain(right) measurements

Table 4

COMPARISON OF SIMULATED AND MEASURED PARAMETERS OF THE PROPOSED ANTENNA

Parameter	Simulated values	Measured values
Resonant frequency (GHz)	3.20	3.30
Return loss (dB)	–35.07	–26.42
VSWR	1.03	1.23
Bandwidth (MHz)	20	250
Gain (dB)	8.366	5.47

CONCLUSION AND FUTURE WORKS

The patch antenna is designed by depositing the newly prepared strong dielectric nanomaterial Ytterbium doped Copper-Manganese Nano Ferrites in the jute fabric for miniaturization, to avoid the air gap and for better performance. Also, the antenna is designed with varied meandered line patches using a super formula technique for improving the antenna performance. The performance is improved with reduced reflection coefficient, VSWR, Directivity and gain.

Comparatively, the gain of the antenna is enhanced to a very good level (greater than 5 dB) than the previous approaches. The fabricated antenna also shows better under free space and bending conditions. This paves the way to achieve the needs and develop portable devices for various applications such as aircraft, spacecraft, satellites, missiles, mobile, GPS, Wi-Max and radio locations, especially in Ground Radar (3.1–3.4 GHz) with the help of a low-cost flexible antenna. In future, the antenna can be designed using thin film nanomaterial as a substrate with flexible properties for wearable applications.

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