

Compact Patch Antenna on Structurally Modified Magnetodielectric Substrate

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Abstract—Magnetodielectric substrate gives a new dimension for reducing the size of the planar antennas. In this article, the patch size is reduced by taking a substrate with nano-sized nickel ferrite inclusions in LDPE polymer matrix. The antenna is made to operate in X and Ku bands by engraving T slots along the resonant length of the patch. Structural modification of the substrate geometry as a step profile is incorporated along the slotted patch edges to enhance performance. The T-slots, along both the resonating lengths with the magnetodielectric stepped substrate show four resonant frequencies in both X- and Ku-bands with $S_{11} < -15$ dB and a maximum -10 dB bandwidth of 22.4%. A miniaturization factor of 2.97 is obtained.

1. INTRODUCTION

Integration of more communication standards in one microwave wireless device has created demand on developing compact, low-cost, and robust multi-band microwave components. Microstrip patch antennas (MPA) are an important transreceiving transducer in microwave devices, and low profile of this component is desirable. Miniaturization in MPA, denoted by factor, n , is given as $n = \sqrt{(\epsilon_r \mu_r)}$, where, ϵ_r is the complex permittivity and μ_r the complex permeability of the substrate [1]. Major shortfalls of using high ϵ_r substrates are lowering of radiation efficiency, pattern degradation (due to excitation of surface waves) and lowering of impedance bandwidth [2, 3]. Miniaturization can also be achieved by modifying the other parameter μ_r . Bulk ferrites, generally, have high saturation magnetization and dispersive magnetic losses [4–6] and needs strong external dc-bias fields to alter its permeability property [7], making it unsuitable for compact applications. Further, shift of operational frequency of antennas on ferrite substrates on application of external bias [8, 9] causes difficulty in integrating it with other systems. Lately, artificial magnetodielectric substrates are used to overcome issues of high loss in ferrites. Non-magnetic materials can be engineered with embedded circuits to achieve magnetic permeability [10]. However, the process of developing engineered artificial magnetic materials is complex [11–13]. Nano-sized ferrites are reported to have low saturation magnetizations and low eddy current losses [14, 15]. Composites made using nano ferrite inclusion in polymers can result in natural magnetodielectric materials with low magnetic losses. ϵ_r and μ_r of the composite can be altered by varying the amount of the inclusion to achieve the desired performance [16].

The work carried out is focussed on developing a single patch miniaturized antenna for operation in X- and Ku-bands, primarily used in satellite, radar, space and terrestrial communications. A magnetodielectric composite with natural nano ferrite inclusions is developed as the substrate material for microstrip patch antenna miniaturization.

Modern wireless communications impose the need for design and development of efficient antenna elements used in systems that will operate in contemporary multi-service urban environments, in which

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several different networks coexist and interoperate. These antennas should necessarily function in multi-band modes [17]. Modifying the patch using slots, stubs and loading is a common technique for achieving multi-frequency operation [18]. However, stubs and loading techniques typically increase the antenna size, either in the antenna plane or along its thickness. Slots can enhance performance without increasing the dimension of the patch. L-, U-, E-, T-, H-shaped slots [19–23] are common slot geometries reported in literature. A T-slot, as compared to others, is easy to incorporate onto the rectangular patch. In addition, the various sections of the T-geometry provides the flexibility to optimize the structure as per the requirement. In the current work, T-slots are engraved along the resonating length as shown in Fig. 2 and their performance studied.

The authors in their earlier work [24] modified the structure of a substrate in the form of a stepped profile to obtain multifrequency resonance with improved performance for a simple rectangular patch. The stepped substrate geometry studied reduces the surface waves and enhances the return loss characteristics. The performance of the T-slotted patch is studied with stepped structure of the substrate. Similar studies are carried out using a standard dielectric substrate $FR4$ ($\epsilon_r=4.3$, $\tan \delta=0.021$), to test the feasibility of the structure.

2. SYNTHESIS AND STUDY OF MAGNETODIELECTRIC MATERIAL

In our current study, particulate composites with nickel ferrites (NiFe_2O_4) nano-magnetic inclusions in a low density poly ethylene (LDPE) polymer matrix is developed as the substrate for the antenna. Nickel ferrite (NiFe_2O_4) is chosen as it is known to handle high microwave powers without affecting its magnetic properties as its Curie temperature is $\sim 500^\circ\text{C}$ [25]. The polymer base of the composite system gives shape and flexibility to the substrate with reduced weight. The mechanical properties of LDPE are those between rigid materials such as polyester and limped polymers as vinyls. Moreover, it has low dielectric loss at microwave frequencies and is thus a suitable host matrix for microwave substrate applications.

NiFe_2O_4 crystallites are synthesized by co-precipitation technique using nickel (II) nitrate hexahydrate (98% pure), iron (III) nitrate nonahydrate (98% pure) as precursors in stoichiometric amounts described in the previous work done by the authors [25]. X-ray diffraction studies show the crystalline size to be ~ 12 nm. The particle size is determined using transmission electron microscopy (TEM) and found to be ~ 30 nm. The image is shown in Fig. 1. Nano-sized NiFe_2O_4 crystallites are dispersed in low density polyethylene (LDPE) to develop magnetodielectric substrate with varying volume fraction. Volume fraction (VF) of the nickel ferrite beyond 5% makes the composite brittle and fragile, and the sinkage of ferrite inclusions occurs as the host polymer reaches the percolation limit. The magnetodielectric materials are morphologically tested for dispersion uniformity by scanning electron microscopy (SEM). Magnetic characterizations are carried out using vibrating sample magnetometry and microwave characterizations using Nicolson-Ross techniques [26]. The 5% VF nickel ferrite/LDPE substrate ($\epsilon' = 7.385$, $\epsilon'' = 9.9 \times 10^{-3}$ at 10 GHz and $\mu' = 1.1998$, $\mu'' = 0.88$ at 9.86 GHz and 4π Ms as 1.87 emu/g) is chosen for showing the best performance in terms of S_{11} and -10 dB bandwidth. In the study to follow, the 5% VF nickel ferrite/LDPE substrate is termed as ‘magnetodielectric’, while the standard $FR4$ substrate is termed as ‘dielectric’.

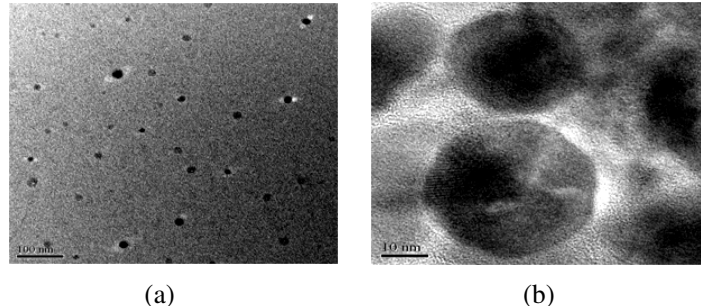


Figure 1. Transmission electron microscope image of NiFe_2O_4 nanoparticles with scale factor of (a) 100 nm, (b) 10 nm.

3. DESIGN AND FABRICATION OF T SLOTTED STEP PROFILE ANTENNA

A simple rectangular patch is designed using standard design equations based on transmission line model (TLM) [27]. The length (L) and width (W) of the patch resonating at 9 GHz obtained for a substrate height, $H' = 2$ mm are tabulated in Table 1.

Table 1. Simple rectangular patch dimension at 9 GHz using TLM.

Substrate Material	Permittivity ϵ'	Permeability μ'	Length (L) (mm)	Width (W) (mm)
5% VF nickel ferrite/LDPE (magnetodielectric)	7.385	1.198	5.34	8.20
FR4 substrate (dielectric)	4.4	1	7.1	10.2

The miniaturization factor, n , can be calculated from the equation, $n = \sqrt{(\epsilon_r \mu_r)}$ [1] where ϵ_r is the real part of complex permittivity and μ_r the real part of complex permeability of the substrate. For magnetodielectric substrate with $\epsilon_r = 7.385$, $\mu_r = 1.198$, $n_{\text{NF/LDPE}} = 2.97$, while for standard dielectric substrate with $\epsilon_r = 4.4$, $\mu_r = 1$, $n_{\text{FR4}} = 2.09$. Thus, the miniaturization factor of the patch on the magnetodielectric substrate to that on the dielectric substrate is equal to 1.42, i.e., $n_{\text{NF/LDPE}}/n_{\text{FR4}} = 1.42$.

The dimensions of the T-slots are obtained by optimizing the width and length of the slots for the antenna using CST microwave studio[®] software. T-slots are placed symmetrically at the center of the resonating length. Two patch configurations are studied with T-slot (i) one of the non-radiating edges and (ii) both the non-radiating edges, referred as single T-slot and double T-slots, respectively. The schematic of the designed T-slot with dimensions is given in Fig. 2.

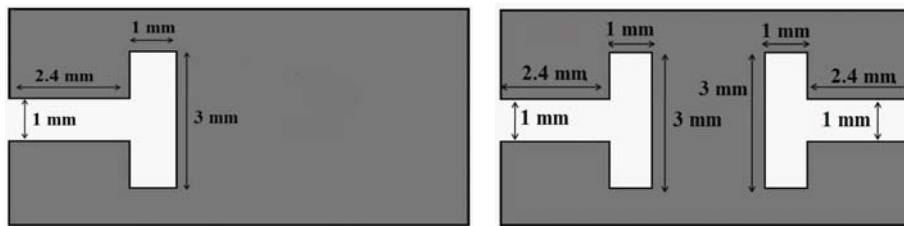


Figure 2. Single T slot and double T slot dimensional schematic.

In a previous work done by the authors in [24], a stepped profile was introduced in substrate geometry to enhance antenna performance. The substrate was laterally removed in vicinity to the radiating edge of the patch. Schematic diagrams of the step profile are shown in Figs. 3(a), (b) and (c). The studies were conducted by varying the step riser height, h' , and step tread length, $L + 2w'$. A parametric analysis was conducted with an equivalent circuit model proposed in the same paper. Step configuration with $h' = 1.5$ mm and $w' = 1$ mm showed the best performance in terms of the S_{11} characteristics and multiresonance. The same step configuration was employed in this work for both the magnetodielectric and dielectric substrates.

A stepped structure in the dielectric (FR4) substrate is fabricated by gradually grinding the lateral parts. A grinding machine of least count 0.01 mm with a grinding wheel attachment of 12 mm diameter is used for the purpose. The substrate is held tightly with a metallic holder, and the movement of the wheel is kept in one direction to maintain flatness and to avoid chipping of the substrate. In the case of the magnetodielectric (5% VF nickel ferrite/LDPE) substrate, a stepped mould of desired dimension

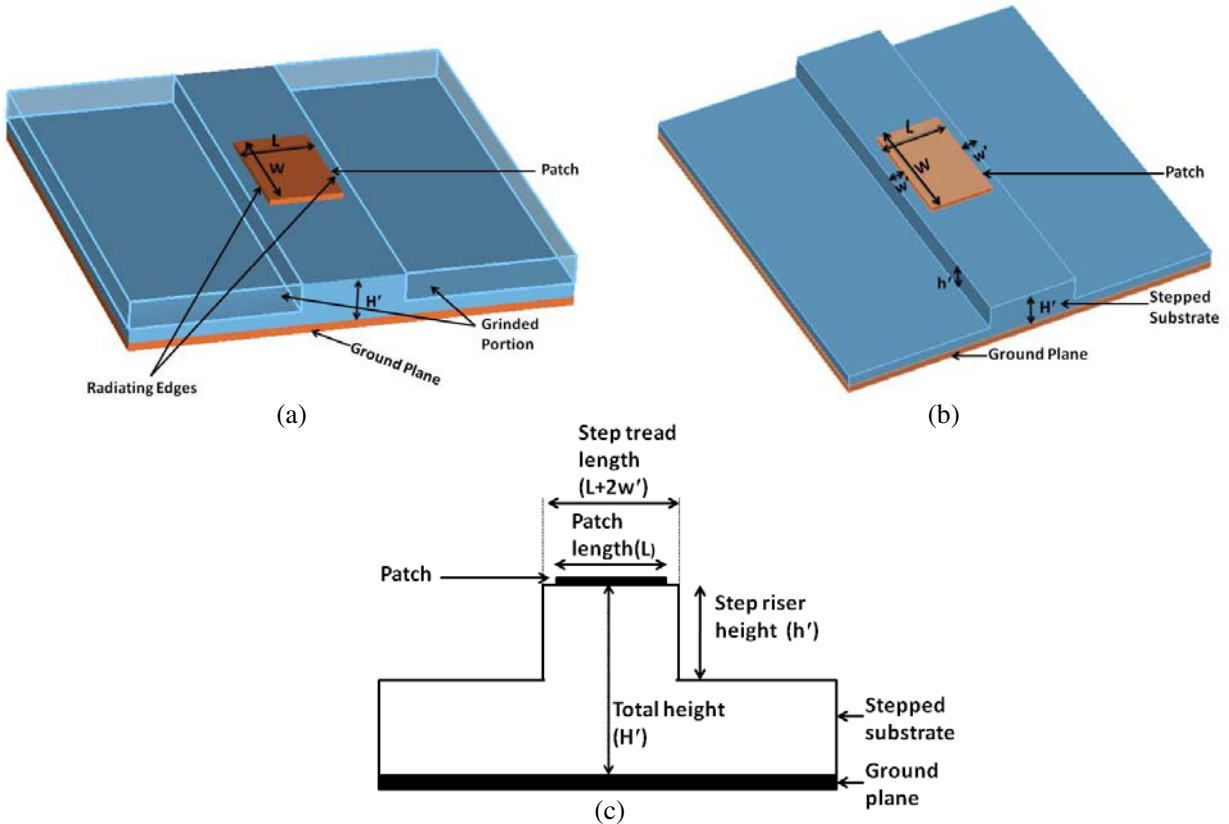


Figure 3. Schematic of antenna profile (a) before removing the lateral portion of the substrate, (b) with the stepped substrate, (c) showing detailed side view of the step.

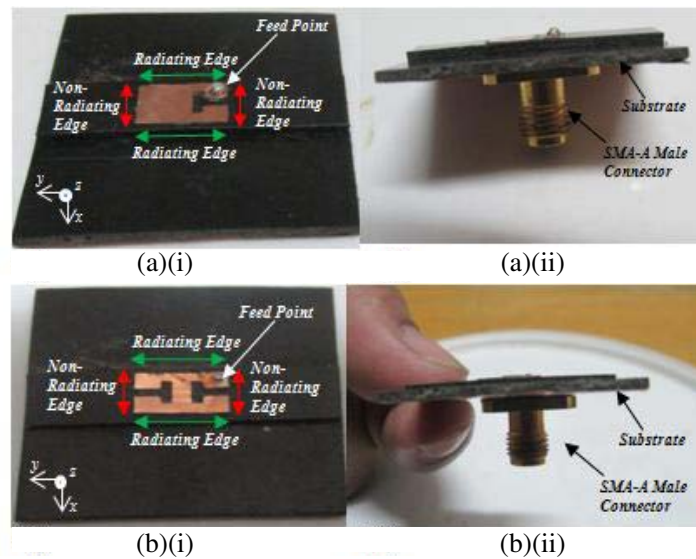


Figure 4. Photographs of the (i) top view, (ii) side view of (a) single T-slot antenna stepped magnetodielectric substrate and (b) double T-slot antenna on stepped magnetodielectric substrate.

is used. The LDPE powder is dissolved in cyclohexane (99%) and stirred continuously at 70°C to make a homogenous mixture. The synthesized nickel ferrite nano particles are added in required percentage volume fraction in the polymer matrix. The composite is then stirred for 2–3 hours to get uniform

blending. The homogenous viscous composite is slowly poured into the mould and allowed to cool gradually at room temperature.

The fabrication of a copper patch on the magnetodielectric composite substrate is performed by rolling technique. The substrate is cleaned with acetone to remove oil and grime from the surface. The substrate is dried at 30°C in a vacuum oven. A copper adhesive tape of thickness 0.03 mm is used to fabricate the patch and the ground plane of the rectangular microstrip patch antenna. The designed artwork, of the patch, as shown in Fig. 2, is transferred to the adhesive copper tape using hot press technique. The copper tape with the artwork printed on it is then dipped into an etching solution for sufficient time until the etching process is completed. The etched tape is washed with double distilled water and then dried to remove any traces of the etchant. The tape, after etching, is then rolled over the substrate at a pressure of 6 torr for two hours. The fabrication on the stepped dielectric is done by a similar technique. In this case, copper laminated dielectric stepped substrate is used. The patch artwork is first transferred onto the copper laminated substrate using hot press technique, which is then etched in an etching solution.

Figures 4(a)(i) & 4(b)(i) and Figs. 5(a)(i) & 5(b)(i) show photographs of the fabricated patch antennas on both the stepped magnetodielectric and dielectric substrates.

The MPA is excited by coaxial feeding technique using a single miniature type-A female coaxial connector having an impedance of 50 ohms, at 1 mm from one of the radiating edge and 1.5 mm from the non radiating edge, as shown in Figs. 4(a)(ii) & 4(b)(ii) and Figs. 5(a)(ii) & 5(b)(ii).

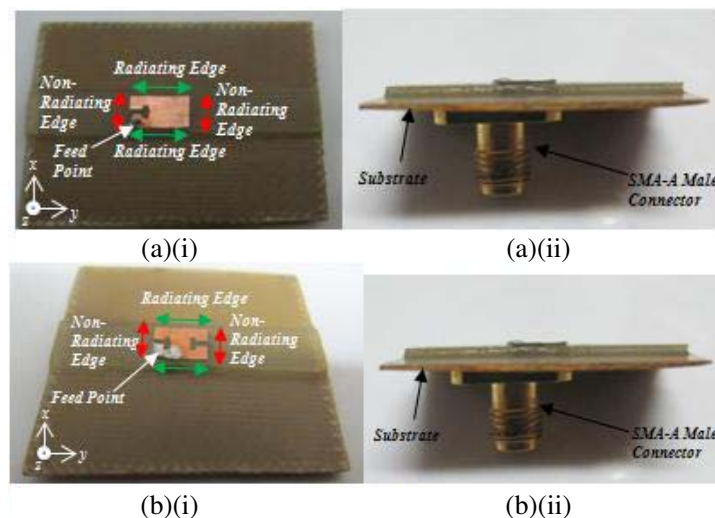


Figure 5. Photographs of the (i) top view, (ii) side view of (a) single T-slot antenna stepped dielectric substrate and (b) double T-slot antenna on stepped dielectric substrate.

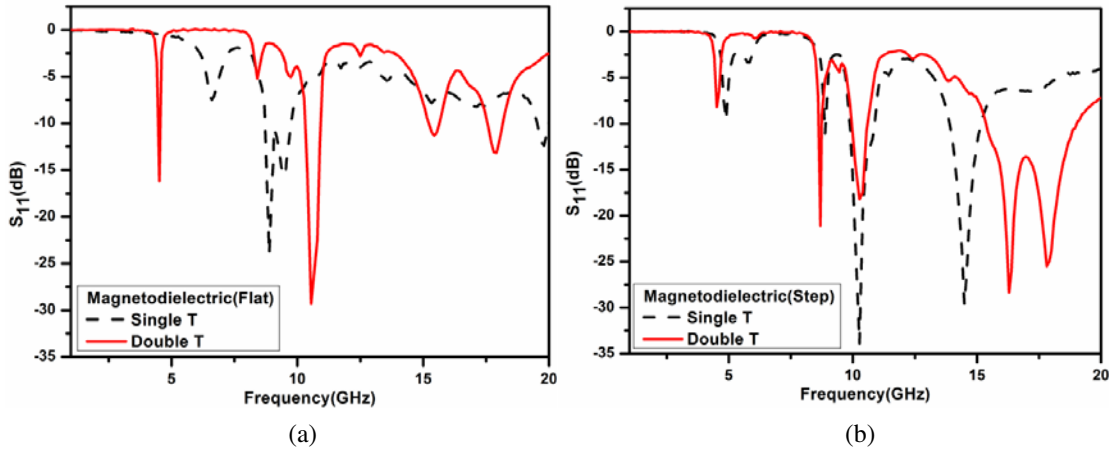
4. PERFORMANCE STUDIES OF THE T SLOTTED ANTENNA

Return loss measurements are carried out over the range 1 GHz to 20 GHz using Agilent PNA series vector network analyzer (VNA) E8362C. The S_{11} plots for the single T-slot antenna and double T-slot antenna on the magnetodielectric substrate for both flat and stepped configurations are shown in Figs. 6(a) and 6(b), respectively. Figs. 7(a) and 7(b) show S_{11} for the same slotted configurations on the dielectric substrate. The results are summarized in Table 2.

The antenna on the magnetodielectric substrate with the flat profile exhibits two frequency notches for a single T configuration, one at 8.89 GHz ($S_{11} = -24.1$ dB) and the other at 9.5 GHz ($S_{11} = -15.3$ dB). Double T configuration shows two prominent notches at 4.54 GHz ($S_{11} = -16.3$ dB) and at 10.5 GHz ($S_{11} = -29.1$ dB). Flat profile antenna on the dielectric substrate shows frequency notches at 9.45 GHz ($S_{11} = -24.43$ dB) and at 13.85 GHz ($S_{11} = -25.34$ dB) for single T and at 6.69 GHz ($S_{11} = -25.08$ dB) and at 13.53 GHz ($S_{11} = -30.67$ dB) for double T configuration. Single

Table 2. Table for the S_{11} plot results.

Antenna Profile	F_r (GHz)	S_{11} (dB)	-10 dB% Bandwidth
Magnetodielectric			
Single T-slot(Flat)	8.8	-24.0	11.5
	9.5	-15.3	10.7
Double T-slot(Flat)	4.54	-16.33	4.6
	10.5	-29.1	5.8
Single T-slot (Step)	10.2	-33.5	9.9
	14.4	-29.6	8.9
Double T-slot(Step)	8.6	-21.2	1.8
	10.31	-18.34	4.0
	16.29	-28.43	22.4
	17.86	-25.42	20.4
Dielectric			
Single T-slot(Flat)	9.45	-24.43	1.9
	13.85	-25.34	15.0
Double T-slot(Flat)	6.69	-25.08	2.5
	13.53	-30.67	9.6
Single T-slot (Step)	7.11	-15.28	5.9
	7.34	-33.02	5.7
	13.04	-14.98	8.4
Double T-slot(Step)	6.80	-36.11	2.5
	12.17	-16.11	5.0
	14.16	-30.44	6.3

**Figure 6.** S_{11} plots for the T-slot configuration on (a) flat, (b) stepped magnetodielectric substrate.

T patch on the magnetodielectric substrate shows -10 dB impedance bandwidth more than 10% for both the lower and higher resonant frequencies, while the dielectric substrate shows only for the higher resonant frequency.

Introducing step geometry in the substrate structure tends to shift the resonance frequency towards higher side because of decrease in effective permittivity and permeability. The decrease in effective permittivity of the substrate due to the step design lowers the surfaces waves [24], hence enhancing the performance. From Fig. 6 and Fig. 7, it is evident that the stepped geometry improves S_{11} characteristic

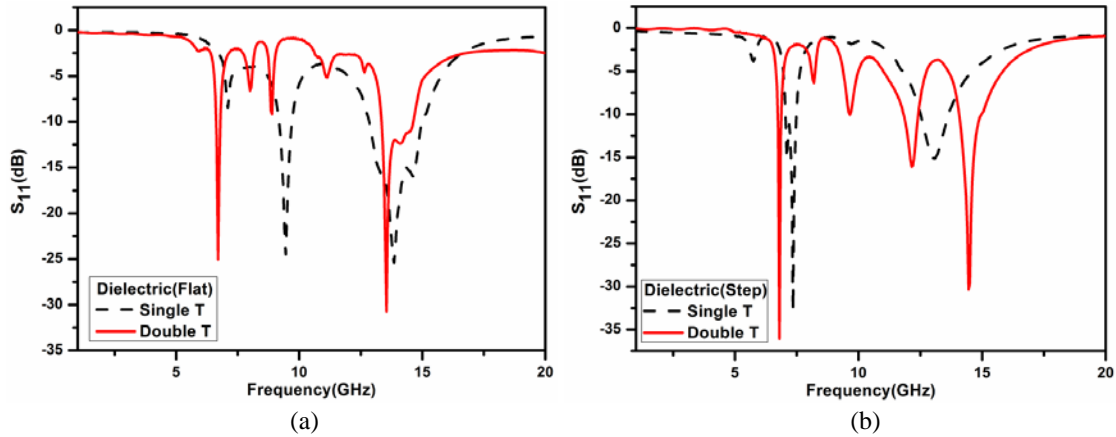


Figure 7. S_{11} plots for the T-slot configuration on (a) flat, (b) stepped dielectric substrate.

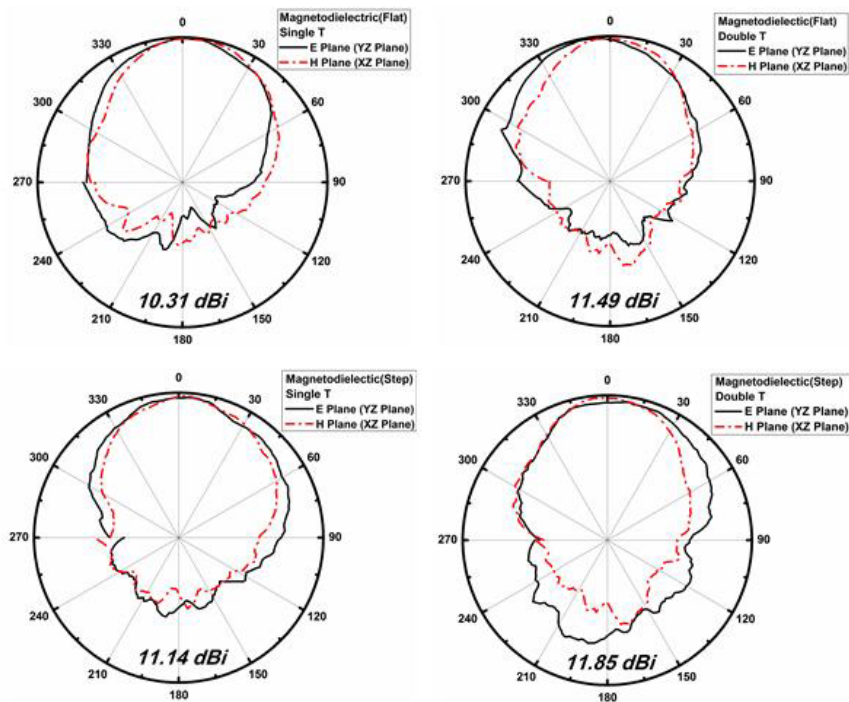


Figure 8. Radiation pattern (E -field & H -field) plots for magnetodielectric substrate (inset-directivities in dBi).

of the antenna compared to flat profile geometry. The stepped profile with double T configurations on magnetodielectric substrate shows the best performance with four frequency notches at 8.6 GHz, 10.31 GHz, 16.29 GHz and 17.86 GHz with S_{11} values, -21.2 dB, -18.34 dB, -28.43 dB, -25.42 dB, respectively. The impedance bandwidth also shows substantial increase to 22.4% for frequency of 16.29 GHz and 20.4% for frequency 17.86 GHz. An improvement of performance in stepped single T-profile is also observed.

Radiation pattern measurements are carried out using an automated system which includes a signal generator Agilent MXG-N5183A as source, Agilent U2000A USB power sensor, and a PC controlled turn table. The patterns are plotted at the frequency showing maximum S_{11} in X-band. Fig. 8 shows the patterns for all the configurations on the magnetodielectric substrate and Fig. 9, for the same configurations on the dielectric substrate.

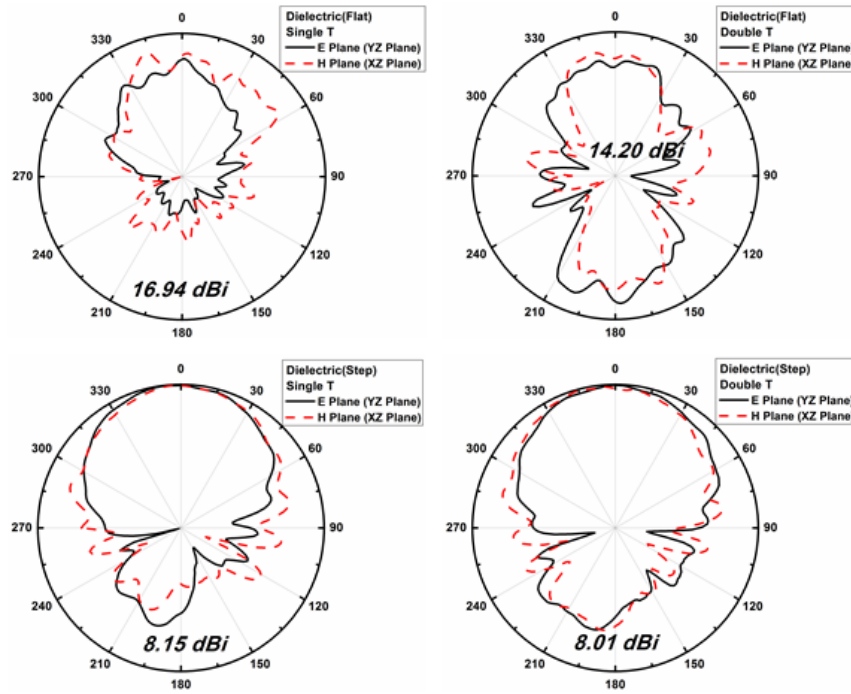


Figure 9. Radiation pattern (*E*-field & *H*-field) plots for dielectric FR4 substrate (inset-directivities in dBi).

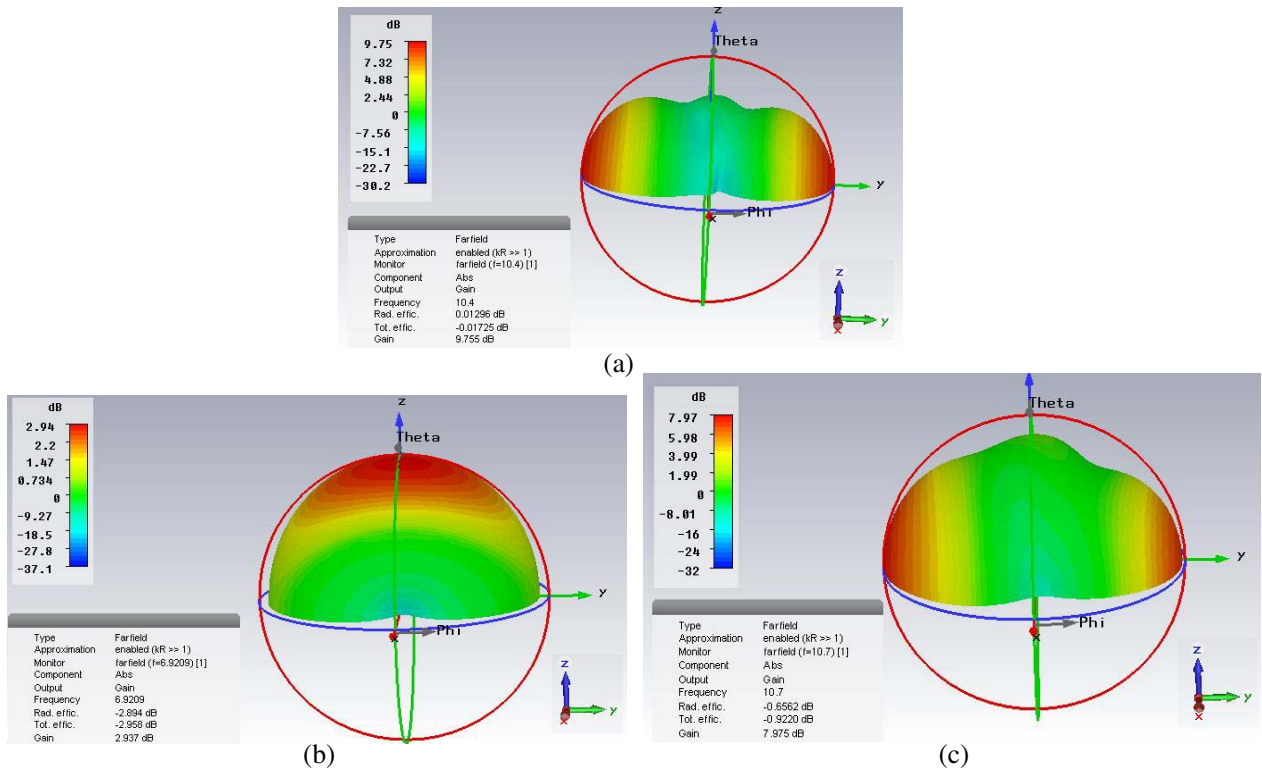


Figure 10. Simulated 3D plot for the gain of the double T slotted antenna on (a) the magnetodielectric substrate, (b) on the dielectric substrate, (c) standard ROGERS TMM 10 substrate.

The respective directivities are also mentioned in the inset of the plots. The stepped structure on magnetodielectric substrate shows an increase in directivity.

A simulation study using CST Microwave Studio is carried out for gain pattern analysis of the stepped profile double T configuration on the magnetodielectric substrate and on the dielectric substrate. The simulated patterns are shown in Figs. 10(a) and (b). A gain of 9.7 dB is observed for patch on the magnetodielectric substrate while patch on the dielectric substrate shows a gain of 2.9 dB.

Simulated study is also carried out for the same patch configuration on a standard laminated ROGERS TMM 10 substrate ($\epsilon' = 9.2$ and $\mu' = 1$) having approximately similar miniaturization factor as the magnetodielectric substrate. As shown in Fig. 10(c), a gain of 7.9 dB is observed.

5. CONCLUSION

A T-slotted patch is known to give multi-frequency resonance, but the performance is confined to the same band. Introducing step in the substrate profile reduces the surface wave of the antenna thus enhancing its performance. Encompassing T-slots and stepping geometry on the dielectric substrate shows multiband performance. Interestingly, double T stepped configuration on the dielectric substrate shows frequency notches in C-, X- and Ku-bands.

Incorporating the same T-slotted stepped structure on a magnetodielectric substrate shows multiple frequency notches in X- and Ku-bands. The miniaturization factor of the antenna on magnetodielectric substrate to that on the dielectric substrate is found to be 1.42. Bandwidth enhancement is also observed for antennas on magnetodielectric substrate. The double T slotted stepped profile antenna on magnetodielectric substrate proves to be better than other configurations in terms of the S_{11} and -10 dB impedance bandwidth. Removal of the substrate in vicinity of the patch reduces the overall volume and weight of the antenna. Simulated gain analyses show that the gain is higher for antenna on magnetodielectric substrate rather than on dielectric substrate having same miniaturization factor. Magnetodielectric substrate gives an interesting option of reducing the size, enhancing the impedance bandwidth and increasing the gain of the antenna. Compared to a flat geometry, the stepped configuration shows improved S_{11} characteristics. However, increase of magnetic inclusions and thereby the magnetic property of the substrate is limited by percolation limit of the polymer matrix. A polymer matrix with a higher percolation limit may solve this problem.

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