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CPW-Fed Body Worn Monopole Antenna on Magneto-Dielectric Substrate in C-Band

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Abstract—Body worn antennas generally face the problem of isolation when operated in close proximity to human body. Use of magneto-dielectric material as substrate for antenna makes the system compact and reduces the influence of body on performance of antenna. In addition, miniaturization of antenna size also takes place. 7 wt.% of nano-sized $Ni_{0.5}Zn_{0.5}Fe_2O_4$ is dispersed as magnetic filler in flexible linear low density polyethylene matrix. Beyond 7 wt.%, the sample stiffens and loses flexibility because of percolation limit of the polymer. Verification of the composite as a potential substrate for a body worn antenna is carried out by fabricating a coplanar waveguide fed simple rectangular monopole antenna, using transmission line model at 6 GHz. Antenna performance is studied by wearing the patch on human wrist. S_{11} of -21.78 dB at 5.32 GHz and -10 dB bandwidth of 49.62% is observed. For comparison, an antenna at the same resonant frequency is developed on linear low density polyethylene with magnetic inclusions. The antenna on magneto-dielectric substrate shows better performance than dielectric substrate. The magnetic and dielectric properties of the Nickel Zinc Ferrite-linear low density polyethylene composite magneto-dielectric substrate reduces the influence of the human body which makes the antenna system compact and robust as additional techniques are not required for shielding of human body influence on antenna performance.

1. INTRODUCTION

Performance of wearable antennas gets affected when they are in contact with or in close proximity to the wearer's body. It is desirable that the wearable antenna should be miniaturized, low profiled, flexible and should not be influenced by the wearer's body [1, 2]. The radiating element will perform effectively if it is isolated from human body. The influence of human body can be reduced by adopting different techniques for isolating antenna such as using backing ground plane [3–5], high impedance surface, adding cavity or shielding [6] and polymeric ferrite sheets [7]. Backing ground plane technique uses conducting ground plane on the back side of antenna for reducing the influence of body. Metalized ground planes of microstrip antennas reduce influence of the human body by directing most of the radiation into one hemisphere [7]. The metallic ground plane, however, lowers impedance bandwidth and limits flexibility of the antenna. High impedance surfaces, EBG structures [8] have been used for isolation of human body. These structures suppress electromagnetic wave reducing the back side radiation. High impedance surface employs electromagnetic band gap (EBG) structure as ground plane [8]. The EBG structure also decreases the back side radiation, but fabricating EBG structure is complex. Adding cavity or shielding plane behind the antenna makes it highly directional, thus, minimising influence of human body [9, 10]. However, addition of cavity or shielding plane behind the patch increases the thickness of the antenna and reduces the flexibility. Introduction of polymeric ferrite sheets partially shields the antenna from

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the body by suppressing radiation in the direction of the body thus reducing its influence [11]. Placing polymeric ferrite sheets on back side of the antenna reduces the influence of body on its performance due to its inherent magnetic loss [7]. Although polymeric ferrite sheets are flexible, the placement of such sheets on rear side of antenna will make the antenna system bulky. Magneto-dielectric shielding is an effective way of isolating radiating element from human body influence [4, 5]. Using flexible magnetic material as substrate will handle this problem.

Magnetic materials also provide miniaturization of the antenna and miniaturization factor $n = \sqrt{\varepsilon_r \mu_r}$, where ε_r and μ_r are real part of complex permittivity and permeability of the substrate material, respectively [12–17]. Bulk ferrites are rigid and have high magnetic loss at microwave frequencies which deteriorates the performance of the antenna [18–20]. Magneto-dielectric (MD) substrate material with nano ferrites inclusions in polymer matrix can be considered as an alternate substrate material [12, 13, 21–28]. Nano-sized ferrites are reported to have low saturation magnetization and low eddy current losses [29, 30]. The miniaturization factor can be further enhanced by increasing permeability by including large quantity of nano ferrite inclusions in the matrix, but the increase of inclusions is limited by percolation limit of the polymer [31].

Height of the substrate increases radiation loss in microstrip patch antennas (MPA). However, metallised layers (patch and ground plane) are susceptible to crumpling and cracking due to posture and body dynamics when the mounting plane is non-planar. Exclusion of metallic backing in coplanar waveguide (CPW) fed monopole antenna can offer more flexibility for wearable applications and provide ease of integration to other devices as no backside processing is required [32–35]. Using coplanar waveguide (CPW) feeding technique, the substrate height can be reduced, thus reducing radiation loss. In addition, exclusion of metallic backing in a CPW-fed monopole antenna makes it more flexible for body worn applications and gives ease of integration to other devices as no backside processing is required [36–41].

This work encompasses development of a wearable antenna which reduces body interferences and provides comfort to the wearer. Magneto-dielectric nano composite is integrated in the antenna system and used as substrate material. The use of a magneto-dielectric substrate also reduces the dimension of antenna. A CPW-fed simple rectangular monopole antenna in C-band is designed and fabricated on the substrate. Incorporating this feeding technique provides an option of reducing the thickness of the substrate material and increases flexibility. Using a flexible polymer matrix will further enhance the conformability of the antenna making it easy to mount on non-planar parts of the body.

Linear low density polyethylene (LLDPE) is chosen as a flexible substrate. LLDPE has good resistance to chemical, high thermal stability, good tensile properties, low water absorbance, non-toxic and is flexible [42, 43]. Magneto-dielectric nano composite is synthesized by dispersing nano-sized nickel zinc ferrite (NZF) into LLDPE polymer matrix as discussed by the authors in [44]. The performance of the CPW-fed simple rectangular monopole antenna fabricated on a magneto-dielectric substrate is compared with that of a pure LLDPE substrate as dielectric substrate, and they are studied in free space and proximity to human body.

2. DEVELOPMENT AND CHARACTERIZATION OF MAGNETO-DIELECTRIC SUBSTRATE

Nano-sized nickel zinc ferrite, $Ni_{0.5}Zn_{0.5}Fe_2O_4$ is synthesized using co-precipitation technique [45, 46]. Nickel ferrite has capability of handling high microwave powers and is chosen as primary series [47, 48]. Zn is included stoichiometrically in $NiFe_2O_4$ to reduce the magneto crystalline anisotropy and magnetic losses [14, 46, 49]. The formation of nano particles is confirmed from XRD and TEM analysis. The size of crystallites is found to be 31.84 nm. The detailed study is reported by the author in reference [44]. Earlier studies conducted by authors showed that linear low density polyethylene (LLDPE) is a good candidate as the substrate for flexible antennas in C-band [50]. Magneto-dielectric composite is prepared by dispersing the required quantity of nano ferrites into the polymer matrix. 7 wt.% of nano-sized nickel zinc ferrite-LLDPE (NZF-LLDPE) composite is synthesized and characterized for its tensile strength, water absorbance, and decomposition temperature. The properties of the NZF-LLDPE magneto-dielectric composite substrate are discussed by the authors in [44]. The percolation limit of LLDPE for NZF was found to be 7 wt.%. Complex permittivity, permeability and losses both magnetic and

Table 1. Characteristic parameters of LLDPE and NZF-LLDPE composite substrate.

Substrate material	ε'_r (at 6 GHz)	μ'_r (at 6 GHz)	$\tan\delta_e$ (dielectric) at 6 GHz	$\tan\delta_m$ (magnetic) at 6 GHz	Tensile strength (MPa)
NZF-LLDPE	2.38	1.45	0.056	0.101	50
LLDPE	2.20	1	0.003	—	18.8
Substrate material	Elongation at break (%)	Density (gm/cm^3)	Percentage of water absorbance (%)	Decomposition temperature (°C)	
NZF-LLDPE	40.55	0.97	0.01	446.84	
LLDPE	808	0.92	0.01	438.85	

dielectric in C-band are determined using the transmission/reflection method, with E8362C vector network analyzer (VNA). The characteristic parameters of the LLDPE and NZF-LLDPE composite substrate are tabulated in Table 1.

From Table 1 it is observed that NZF-LLDPE composite shows low dielectric and magnetic losses. The composite also has good tensile strength, negligible water absorbance and decomposition temperature (onset of inflection) up to ~ 446.84°C. Tensile strength of 50 MPa gives this composite sufficient flexibility and miniaturization of 1.85 ($n = \sqrt{\varepsilon_r \mu_r}$). The developed composite shows suitability to be used as substrates for body worn antennas.

3. DESIGN AND FABRICATION OF COPLANAR WAVEGUIDE FED RECTANGULAR MONOPOLE ANTENNA

A CPW-fed simple rectangular microstrip monopole antenna (MMA) is designed using transmission line model (TLM) technique on the NZF-LLDPE substrate at 6 GHz on 7 wt.% of $Ni_{0.50}Zn_{0.50}Fe_2O_4$-LLDPE composite and LLDPE substrate [51, 52]. The effective permeability for magneto-dielectric substrate is calculated using Pucel and Masse formulation [53]. The substrate height (h) is kept fixed at 1 mm. The design parameters are optimized using CST microwave studio for improvement in impedance matching. The schematic of CPW-fed rectangular MMA is shown in Figure 1, and the dimensions are given in Table 2. The fabricated antennas on the two substrates are shown in Figures 2(a), (b).

4. PERFORMANCE STUDY OF THE COPLANAR WAVEGUIDE FED MONOPOLE ANTENNA FOR FLAT PROFILE

S_{11} parameters of the MMA are determined using Agilent E8362C vector network analyzer (VNA), and E- and H-planes, co and cross polar radiation patterns are measured using an automated measurement setup with a PC controlled turn table, Agilent MXG-N5183A signal generator and Agilent U2000A USB power sensor. Figure 3 shows the S_{11} plots for MMA fabricated on NZF–LLDPE (magneto-dielectric) and LLDPE (dielectric) substrates. The radiation patterns at resonant frequency are plotted in Figure 4. The performance parameters are tabulated in Table 3.

5. PERFORMANCE STUDY OF THE COPLANAR WAVEGUIDE FED MONOPOLE ANTENNA WITH DIFFERENT BENDING RADIUS

The antenna performance is studied with bending axis parallel to the non-radiating edge, i.e., along the length of the patch (marked as AA' in Figure 1). Photographs of the bending antenna are shown in Figures 5(a) and (b). The antenna performance is tested with different bending radii, r, taken to

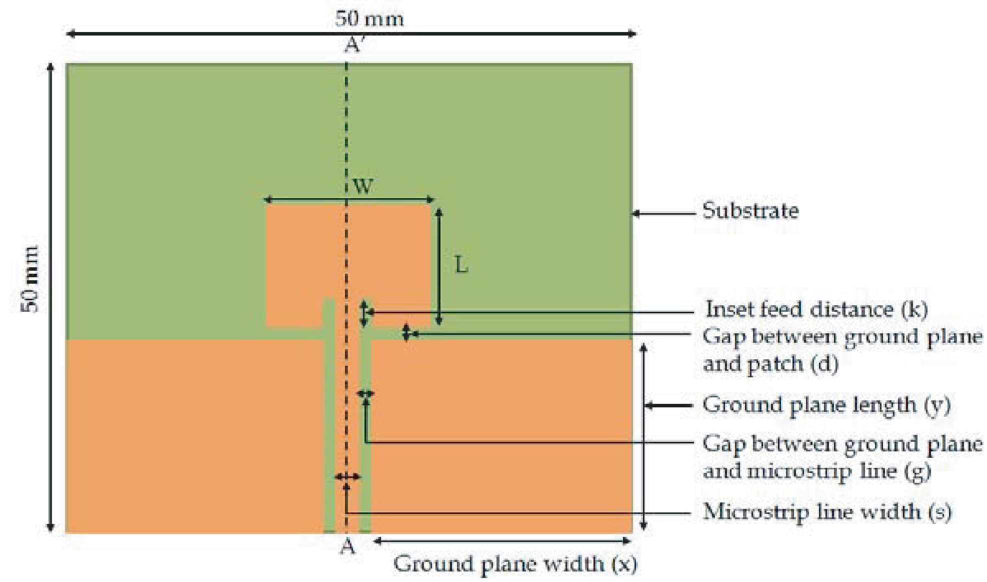
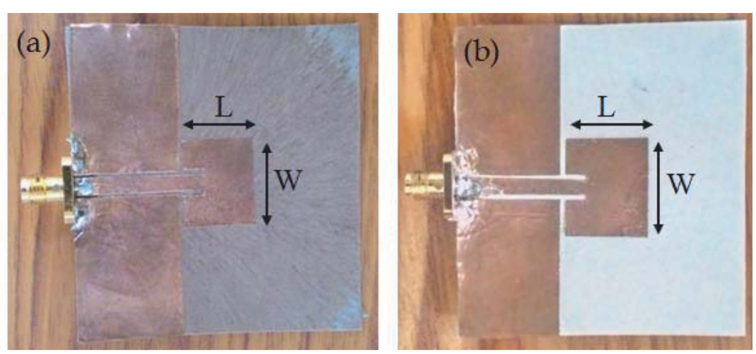


Figure 1. Schematic of CPW-fed rectangular MMA.



(a) (b)

Figure 2. Photographs of CPW-fed rectangular MMA fabricated on (a) NZF-LLDPE composite substrate and (b) LLDPE substrate.

be 10 mm, 20 mm, 30 mm, 40 mm and 50 mm as shown in Figure 6. The choice of radius r is made by taking the possibility that the MMA is to be worn on wrist and arm of the wearer.

S_{11} plots for different bending radii on NZF-LLDPE composite substrate and LLDPE substrate are shown in Figures 7(a) and (b), and respective E- and H-planes, co- and cross-polar radiation patterns at resonant frequencies are shown in Figures 8(a)–(f) and Figures 9(a)–(f). The performance parameters for different bending radii are tabulated in Table 4.

6. PERFORMANCE STUDY OF COPLANAR WAVEGUIDE FED MONOPOLE ANTENNA AT CLOSE PROXIMITY TO THE HUMAN BODY

The performance of antenna on the magneto-dielectric and dielectric substrate is conducted in close proximity to the human body. The antenna is placed on the wrist of the wearer with an approximate radius of 30 mm as shown in Figure 10.

Figure 11 shows the S_{11} plots for both the antennas in proximity to human body and in absence of human body for the same bending radius. The performance parameters for both the antennas are tabulated in Table 5.

Table 2. Design parameters for the MMA on NZF-LLDPE composite substrate and on LLDPE substrate.

CPW fed MPA on	Patch width (W) mm	Patch length (L) mm	Height of the substrate (h) mm	ε'_r	μ'_r	y (mm)	x (mm)
NZF-LLDPE substrate	16.70	14.07	1	2.38	1.45	20	28
LLDPE substrate	19.76	16.31	1	2.20	1	20	28
CPW fed MPA on	d (mm)	g (mm)	s (mm)	k (mm)	Miniaturization factor (n)	% of miniaturization	
NZF-LLDPE substrate	1	1	3	4	1.85	27.09	
LLDPE substrate	1	1	3.1	4.2	1.48	—	

Table 3. Performance parameters of the MMA on NZF-LLDPE composite substrate and on LLDPE substrate.

CPW fed microstrip monopole antenna on	**Resonant frequency (GHz)**	**S_{11} (dB)**	**Directivity (dBi)**	**−10 dB bandwidth**	
				GHz	**%**
Magneto-dielectric substrate	5.40	−28.76	9.67	2.86	52.96
Dielectric substrate	5.30	−26.31	9.31	2.14	40.37

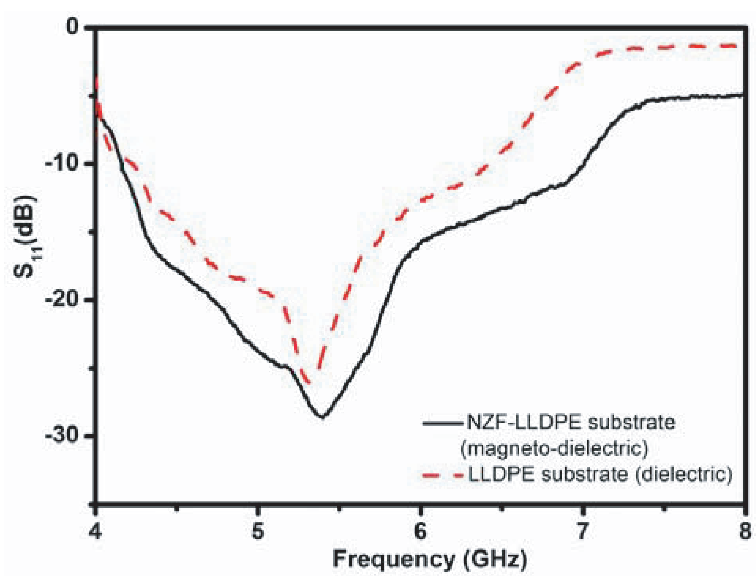
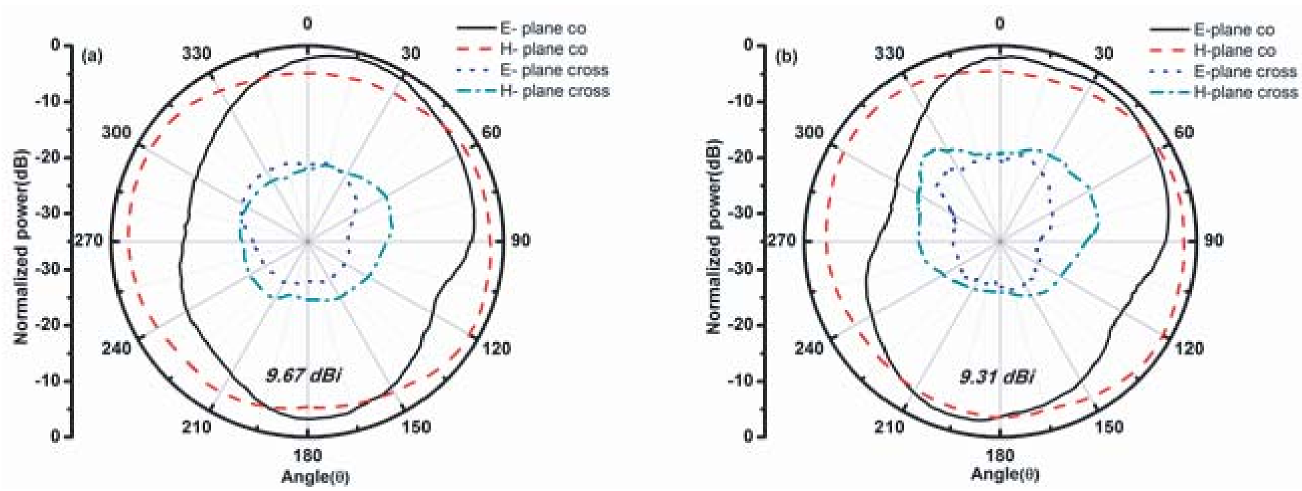
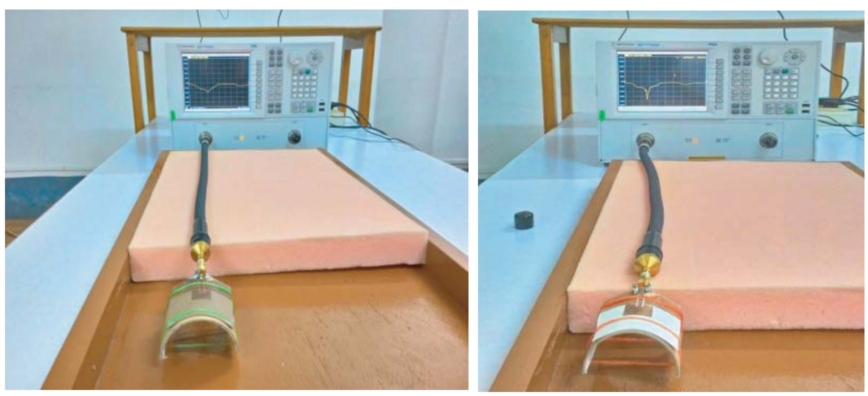


Figure 3. S_{11} plots for MMA on NZF-LLDPE composite substrate and on LLDPE substrate.



(a) (b)

Figure 4. E- and H-plane, co- and cross-polar radiation patterns at resonant frequencies for MMA on (a) NZF-LLDPE composite substrate at 5.40 GHz, (b) LLDPE substrate at 5.30 GHz.



(a) (b)

Figure 5. Photographs of performance study of MMA for bending along the non-radiating edge on (a) NZF-LLDPE composite substrate, (b) LLDPE substrate.

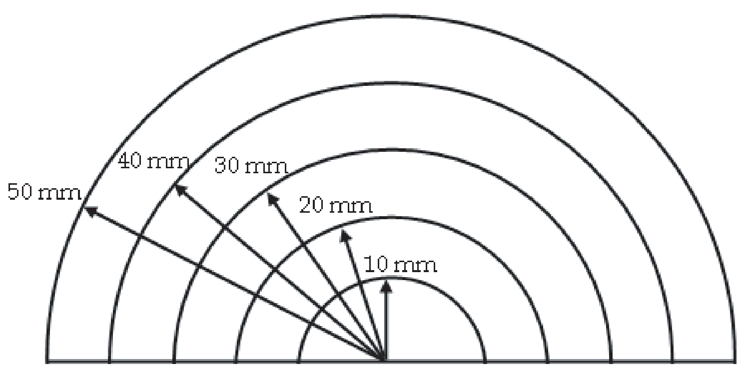
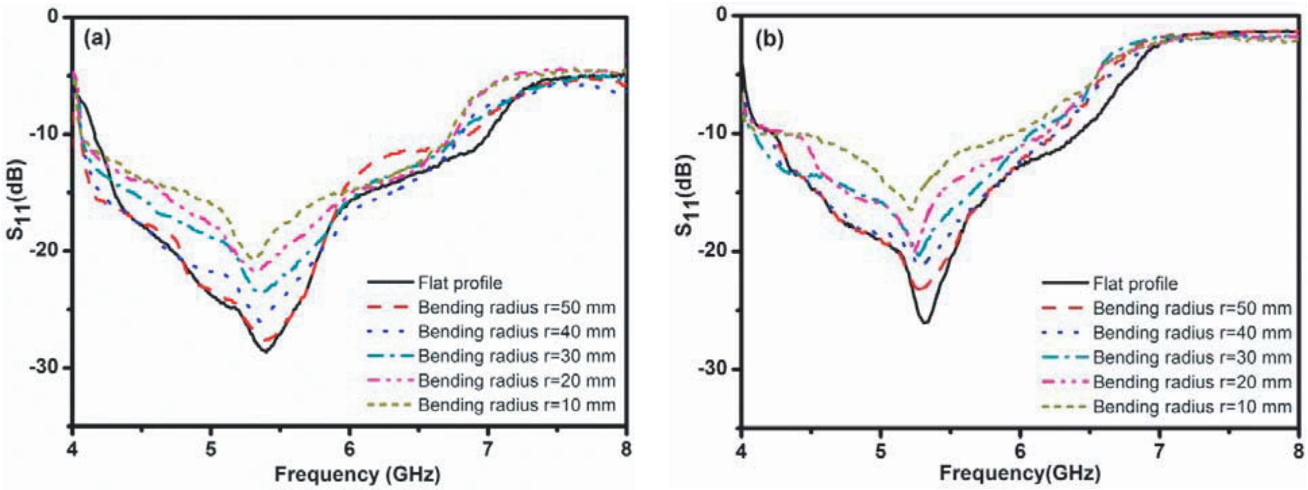


Figure 6. Schematic of the bending curvatures.



(a) (b)

Figure 7. S_{11} parameter of MMA with different bending radius r (a) on NZF-LLDPE composite substrate and (b) on LLDPE substrate.

Table 4. Performance parameters of the CPW fed MMA on NZF-LLDPE composite substrate and on LLDPE substrate for different bending radius r.

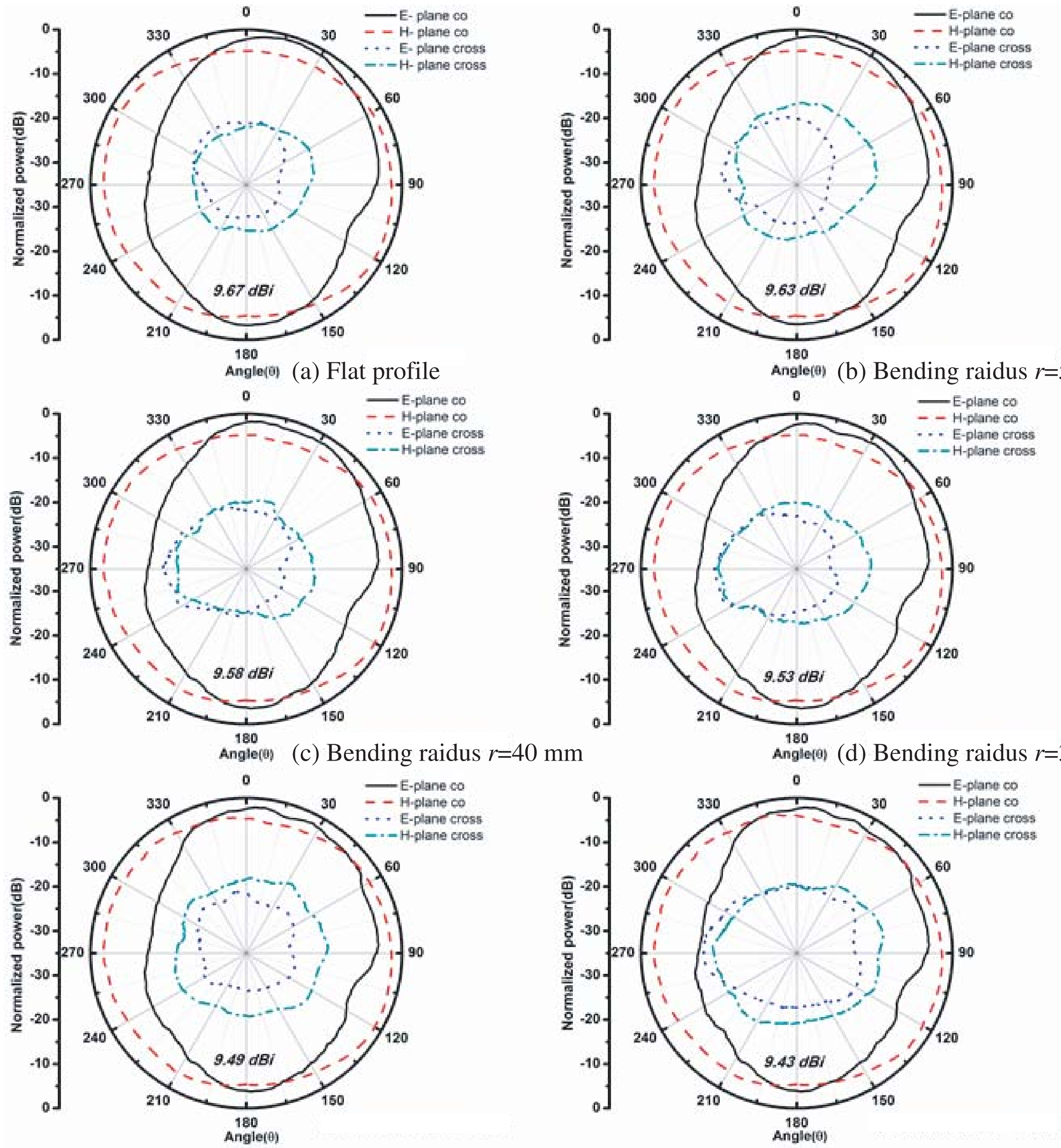
CPW fed microstrip momopole antenna on	**Bending radius (r) in mm**	**Resonant frequency (GHz)**	**S_{11} (dB)**	**Directivity (dBi)**	**−10 dB bandwidth**	
					GHz	**%**
Magneto-dielectric substrate	Flat profile	5.40	−28.76	9.67	2.86	52.96
	50	5.38	−27.34	9.63	2.81	52.23
	40	5.35	−25.79	9.58	2.74	51.21
	30	5.34	−23.31	9.53	2.72	50.93
	20	5.32	−21.33	9.49	2.70	50.75
	10	5.30	−20.72	9.43	2.65	50.0
	Flat profile	5.30	−26.31	9.31	2.14	40.37
	50	5.28	−23.14	9.27	2.04	38.63
Dielectric substrate	40	5.27	−21.49	9.22	2.07	39.27
	30	5.26	−20.31	9.18	1.99	37.83
	20	5.24	−20.16	9.13	1.86	35.49
	10	5.22	−16.40	9.07	1.87	35.82

7. ANALYSIS OF THE RESULTS

A slight shift in resonant frequency to lower side as compared to the design frequency is observed. The shift could be due to the coupling effect between the patch and coplanar ground plane [6, 20–22].

CPW-fed rectangular MMA on magneto-dielectric composite substrate shows improved −10 dB bandwidth as compared to the antenna on dielectric substrate as seen from Table 3. The characteristic impedance of a medium is given by $\eta = \eta_0\sqrt{\frac{\mu_r}{\varepsilon_r}}$. In the present study, characteristic impedance for magneto-dielectric substrate is 294.26 Ω, and for dielectric substrate it is 254.17 Ω. Thus, magneto-dielectric substrate allows a wider impedance matching bandwidth to free space value 377 Ω [23].

Further, Hansen and Burke [54] gave an expression of dependence of zero-order bandwidth on ε_r



(a) Flat profile (b) Bending raidus r=50 mm

(c) Bending raidus r=40 mm (d) Bending raidus r=30 mm

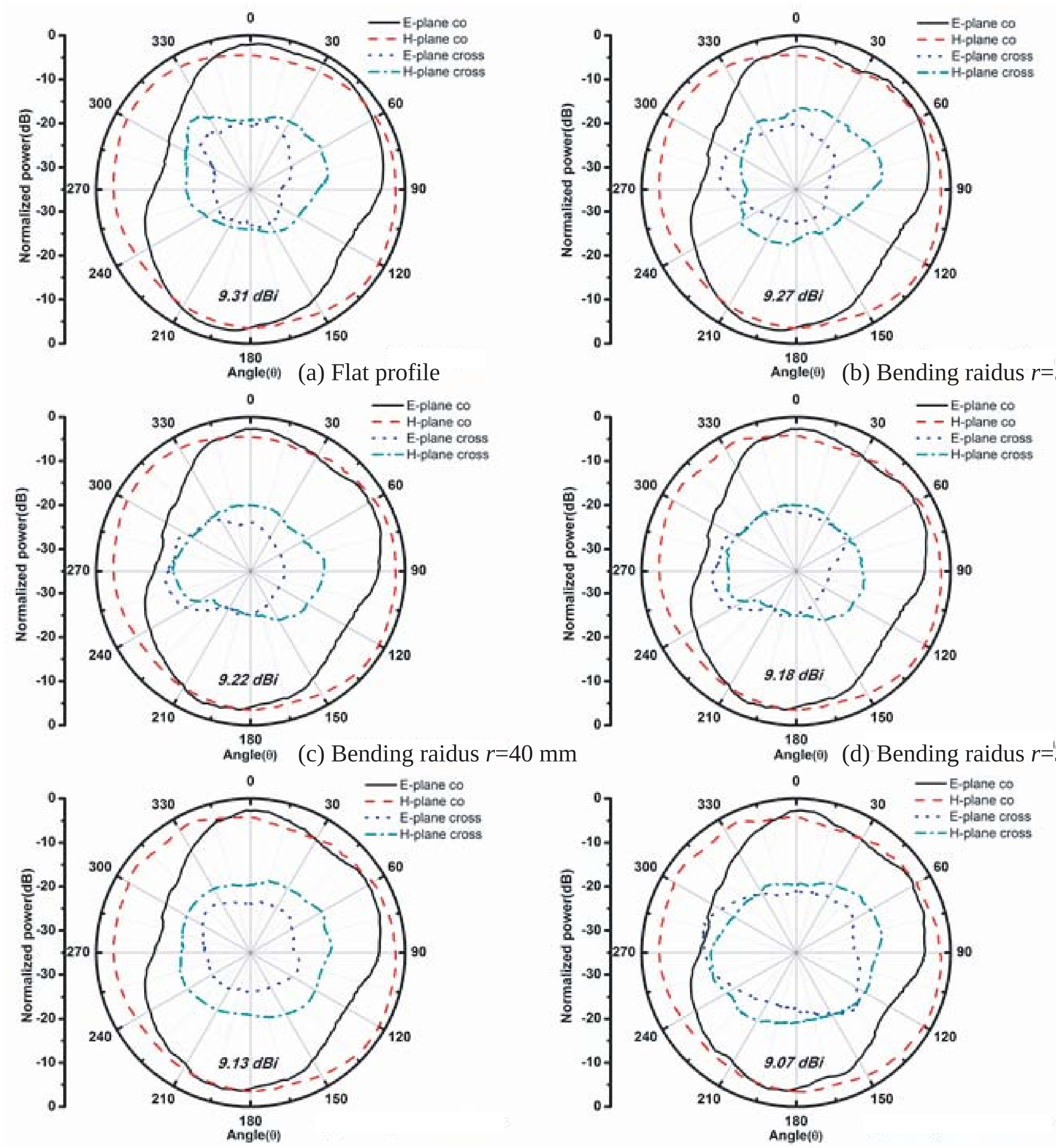
(e) Bending raidus r=20 mm (f) Bending raidus r=10 mm

Figure 8. E- and H-plane, co- and cross-polar radiation patterns at resonant frequencies for MMA on NZF-LLDPE composite substrate. (a) Flat profile at 5.40 GHz and bending along non-radiating edge with bending radius r = (b) 50 mm at 5.38 GHz, (c) 40 mm at 5.35 GHz, (d) 30 mm at 5.34 GHz, (e) 20 mm at 5.32 GHz, (f) 10 mm at 5.30 GHz.

and μ_r of the magneto-dielectric substrate material for an antenna

$$BW = \frac{96\sqrt{\frac{\mu_r}{\varepsilon_r}}\frac{t}{\lambda_0}}{\sqrt{2}\left[4 + 17\sqrt{\mu_r \varepsilon_r}\right]}$$

where t is THE thickness of the substrate, and λ_0 is THE wavelength of free space. The antenna on the magneto-dielectric (NZF-LLDPE) substrate shows higher bandwidth than that on dielectric substrate



(a) Flat profile (b) Bending raidus r=50 mm

(c) Bending raidus r=40 mm (d) Bending raidus r=30 mm

(e) Bending raidus r=20 mm (f) Bending raidus r=10 mm

Figure 9. E- and H-plane, co- and cross-polar radiation patterns at resonant frequencies for MMA on LLDPE substrate. (a) Flat profile at 5.30 GHz and bending along non-radiating edge with bending radius r = (b) 50 mm at 5.28 GHz, (c) 40 mm at 5.27 GHz, (d) 30 mm at 5.26 GHz, (e) 20 mm at 5.24 GHz, (f) 10 mm at 5.22 GHz.

(only LLDPE) of same thickness.

The resonance frequency shifts slightly towards the lower frequency side with decrease in bending radius as seen from Table 4. The S_{11} degrades with bending which may be due to reduction in current distribution at the edge of the patch [25, 26]. Bending changes the effective length of the antenna, which may be the reason for marginal shift in resonance frequency [27–29]. -10 dB bandwidth and directivity of the antenna does not show significant variation with bending.

CPW-fed monopole antenna on the magneto-dielectric substrate in close proximity to human body (placing on the wrist) shows a shift in resonant frequency of 20 MHz as compared to same antenna in

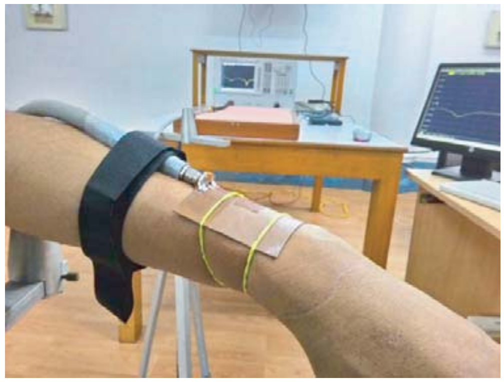
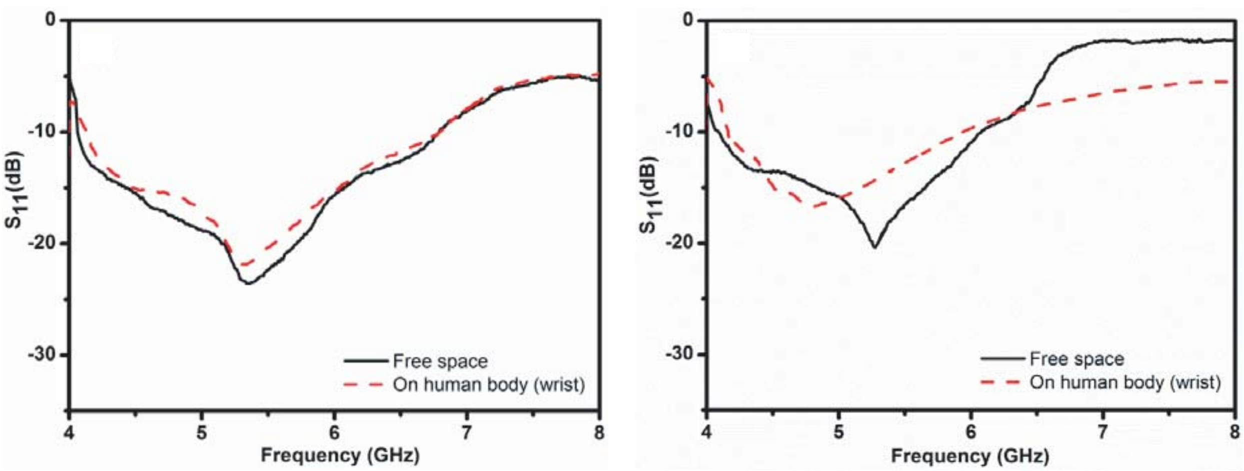


Figure 10. Photograph of antenna placed on human body (wrist).



(a) (b)

Figure 11. S_{11} plots for CPW fed MMA in proximity to the human body on (a) NZF-LLDPE substrate (magneto-dielectric) and (b) LLDPE substrate (dielectric) for $r = 30$ mm.

Table 5. Performance parameters of the CPW fed MMA in proximity to human body with bending radius 30 mm.

<table>
<tr><th colspan="2" rowspan="2">CPW fed microstrip monopole antenna on</th><th rowspan="2">Resonant frequency (GHz)</th><th rowspan="2">S₁₁ (dB)</th><th colspan="2">−10 dB Bandwidth</th></tr>
<tr><th>GHz</th><th>%</th></tr>
<tr><td rowspan="2">Magneto-dielectric substrate</td><td>Free space</td><td>5.34</td><td>−23.31</td><td>2.72</td><td>50.93</td></tr>
<tr><td>On human body (wrist)</td><td>5.32</td><td>−21.78</td><td>2.64</td><td>49.62</td></tr>
<tr><td rowspan="2">Dielectric substrate</td><td>Free space</td><td>5.26</td><td>−20.31</td><td>1.99</td><td>37.83</td></tr>
<tr><td>On human body (wrist)</td><td>4.80</td><td>−16.84</td><td>1.74</td><td>36.25</td></tr>
</table>

free space, and S_{11} changes by -1.53 dB, while the antenna on the dielectric substrate shows a shift of 460 MHz with S_{11} changing by -3.47 dB for same bending radius of 30 mm as seen from Table 5.

The near field of the antenna tends to focus on the human body and changes the impedance matching of antenna because of its large dielectric constant resulting in shift of resonance frequency. The shift is less in the case of magneto-dielectric substrate because it reduces the field concentration on human body to some extent due to its dielectric and magnetic properties [4, 5].

8. CONCLUSION

Nano-sized nickel zinc ferrite in LLDPE matrix is developed as magneto-dielectric substrate, and its performance is compared with LLDPE as dielectric substrate for a simple rectangular monopole antenna designed at 6 GHz for application as a wearable antenna. CPW feeding technique enhances performance of rectangular monopole antenna on magneto-dielectric substrate. The antenna shows a S_{11} of -28.76 dB, -10 dB bandwidth of 52.96% and directivity of 9.67 dBi at 5.40 GHz. No backing ground plane in CPW feeding technique makes it easy to mount the antenna and enhance flexibility. The magnetic and dielectric property of the magneto-dielectric substrate reduces the influence of the human body to some extent. This makes the antenna system compact and robust as additional techniques are not required for shielding as in the other design methods used to reduce the influence of human body on antenna performances as mentioned in the beginning of Section 1. The performance of antenna is better on magneto-dielectric substrate than the antenna on dielectric substrate, when being tested in close proximity to the human body (placing on wrist). Thus, antenna on the magneto-dielectric substrate is more suitable for the use in wearable applications in the C-band.

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