

Magneto-dielectric Nanocomposite for Antenna Miniaturization and SAR reduction

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Abstract—A 900 MHz meander PIFA on a magneto-dielectric nanocomposite (MDNC) substrate for mobile communication is presented. Cobalt nanoparticles were synthesized with polymer matrix and its properties were measured up to 4GHz. Bandwidth, gain and radiation efficiency of antenna on different substrates (MDNC, High K material and FR4) were compared and it is demonstrated that MDNC is beneficial for antenna miniaturization with acceptable antenna performance. Head effects due to the antenna were studied and Specific Absorption Ratio (SAR) was calculated. The simulation results demonstrate that the MDNC reduces the head effects and the magnetic loss of MDNC helps to decrease SAR due to the antenna.

Index Terms—Magneto-dielectric, specific absorption rate, miniaturization, microstrip antenna, radiation pattern, nanocomposite.

I. INTRODUCTION

DUE to increasing demands for more functions within a compact size for mobile devices, antenna miniaturization becomes an important factor for mobile system development. This is because more components need to be integrated in a limited space. Since antenna performance is inversely proportional to its size, reducing antenna size is not easy. A few approaches for reducing antenna size is by changing the geometrical shape of the antenna (ex: meander) or by increasing the permittivity or/and permeability of the substrate containing the antenna. Using high permittivity material for antenna substrate, however, suffers from narrow bandwidth and low efficiency [1]. On the other hand, magneto-dielectric (MD) materials which have relative permittivity and permeability greater than unity have been applied to reduce the antenna size and has shown to provide performance advantages [2]-[4].

One approach for realizing MD material is through material synthesis where magnetic metal particles are mixed with dielectric material. To maximize the advantages of MD materials for antenna miniaturization, MD materials need to have high permeability with low magnetic loss at the operating frequency of antenna. However, this is challenging since increasing permeability usually leads to high magnetic loss

since it requires a larger density of metal particles dispersed in the dielectric material [5]. The high loss characteristics of MD materials, on the contrary, have been widely used for suppression of electromagnetic interference (EMI) in the GHz frequency range [6]. Since antennas in mobile devices are required to work close to the human body, energy absorbed by the human body is an important factor to consider for mobile systems. In the open literature, EBG structures beneath the antenna have been introduced [7] to decrease the energy absorption by the human body. The presence of the EBG structure improves antenna performance while decreasing back side radiation. An alternate approach is to synthesize MD materials that have appropriate properties which provide acceptable antenna performance while decreasing the back side radiation due to the inherent magnetic loss in the material. The latter approach has been used in this letter.

In this letter, Magneto-dielectric nanocomposite (MDNC) material has been synthesized and used as the substrate for the antenna. Metal nanoparticles are mixed with low loss polymer to reduce the magnetic loss. Meander planar inverted-F antenna (PIFA) has been designed, fabricated and measured on the MDNC substrate. Through simulations, the performances of the antenna on the MDNC substrate has been compared to other antennas on different substrates (High K and FR4) to demonstrate the advantages of MDNC substrate for antenna miniaturization. Finally, the energy absorbed by the human head due to these antennas is calculated and compared.

II. MAGNETO-DIELECTRIC NANOCOMPOSITE MATERIAL

In this letter, magneto-dielectric nanocomposite (MDNC) is synthesized by combining nanosized cobalt metal particle with fluoropolymer matrix. MDNC provides several advantages such as low eddy current and low domain wall losses due to nanoscale size metal particles along with higher frequency Ferro-Magnetic Resonance (FMR). However, they suffer from a few drawbacks such as suppressed permeability and higher losses over a broader frequency range [8]. The motivation of using cobalt nanoparticles in the composite arises from its superior effective field anisotropy and high saturation magnetization which directly relates to the increased FMR [9]. The cobalt nanoparticles, which are passivated with oxide, are milled with a dispersant in propylene glycol methyl ether acetate as the solvent medium and then milled with the fluoropolymer to make the nanocomposite slurry. The metal slurry was dried in a nitrogen oven to evaporate the excess

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solvent and the resultant dry powders were pressed into cubes as shown in Fig. 1 (a). The metal to polymer volume ratio is about 50:50 in this case. The particle size and shape were investigated through TEM image as shown in Fig. 1 (b) where the average crystallite size is 30nm.

The frequency dependent dielectric and magnetic properties of the MDNC material were characterized to extract its complex relative permittivity, $\epsilon_r = \epsilon_r' - j\epsilon_r''$, and permeability, $\mu_r = \mu_r' - j\mu_r''$, with the results shown in Fig. 2. For measurements, Agilent 4291B impedance analyzer was used up to 1GHz and cavity perturbation technique (CPT) was used in the frequency range of 1-4GHz. CPT is a well-known method for extracting the electromagnetic properties of various materials. Substrate integrated waveguide (SIW) was used to implement the cavity for CPT measurement, as described in detail in [10]. The real part of the relative permittivity is approximately $\epsilon_r' \approx 8$, which is fairly constant over the frequency range up to 4GHz. The electric loss tangent ($\tan\delta_e = \epsilon_r''/\epsilon_r'$) shows maximum value of 0.0054 at 3GHz with a value around 0.0024 at ~1 GHz. The real part of the relative permeability is around $\mu_r' \approx 2$ at ~1 GHz and gradually decreases as the frequency increases. As the frequency increases, the magnetic loss tangent ($\tan\delta_m = \mu_r''/\mu_r'$) value increases. From the figure, $\tan\delta_m$ is below 0.1 up to 1.2 GHz, suggesting a possible use of this material around 1GHz [11]. The properties shown in Fig. 2 are the best reported in the open literature for metal-polymer nanocomposite materials in terms of the permeability achieved with the corresponding low loss characteristics in the 1GHz frequency range. In this letter, we use this material as the substrate for realizing the antenna around 1GHz.

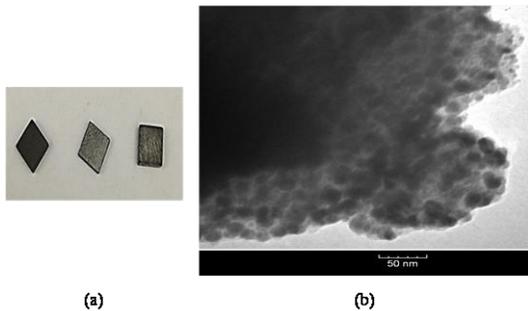


Fig. 1. (a) Photograph of synthesized MDNC materials and (b) TEM image of cobalt in fluoropolymer.

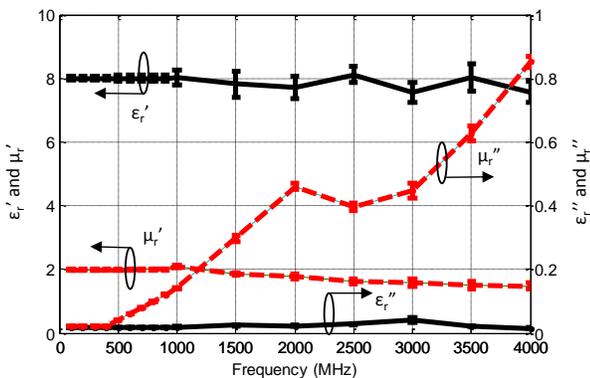


Fig. 2. Extracted relative permittivity and permeability of MDNC.

III. MEANDER PIFA ON MDNC MATERIAL

A meander PIFA working at 900MHz was designed on MDNC substrate as shown in Fig. 3. The relative permittivity and permeability of the MDNC material used for design were 8 and 2 at 900MHz respectively, based on the measured values from Fig. 2. $\tan\delta_e$ and $\tan\delta_m$ of the MDNC material used were 0.0024 and 0.068 at 900MHz respectively. Fig. 3 (a) shows the geometry of the proposed antenna on the MDNC substrate above an FR4 PCB with a relative permittivity of 4.3 and $\tan\delta_e$ of 0.02. The overall size of the FR4 PCB substrate is 60 mm x 120 mm x 1 mm. The size of the MDNC substrate is 20 mm x 20 mm x 1 mm where the meandered copper tape was patterned on top of the substrate. The meandered top plane was shorted to ground with 1mm width copper tape at the top left corner of the antenna.

The PIFA on the MDNC substrate (PIFA_{MDNC}) was compared to similar antennas designed on high dielectric material substrates (PIFA_{DH} and PIFA_{DL}) and FR4 substrate (PIFA_{FR4}) to compare the effect of MDNC on antenna performance. The relative permittivity of both PIFA_{DH} and PIFA_{DL} was chosen as 15.1 to ensure that the antennas resonated at the same frequency as PIFA_{MDNC} without having to change the dimension of the antenna. $\tan\delta_e$ of PIFA_{DH} was chosen as 0.0704 which is the sum of the electric and magnetic loss tangent of MDNC material at 900MHz. $\tan\delta_e$ of 0.002 was used for PIFA_{DL} to determine the effect of high dielectric constant with low loss to antenna performance. DH and DL represents high dielectric materials with high and low loss respectively. The relative permittivity of PIFA_{FR4} used was 4.3 with a loss tangent of 0.02 and the antenna size was optimized to make the antenna resonate at 900 MHz as well. As shown in Fig. 4, the size of antenna on MDNC substrate is 39% smaller than the antenna on FR4 substrate.

Bandwidth, efficiency, gain and size of the four antennas were compared and are listed in Table I. Antennas on high

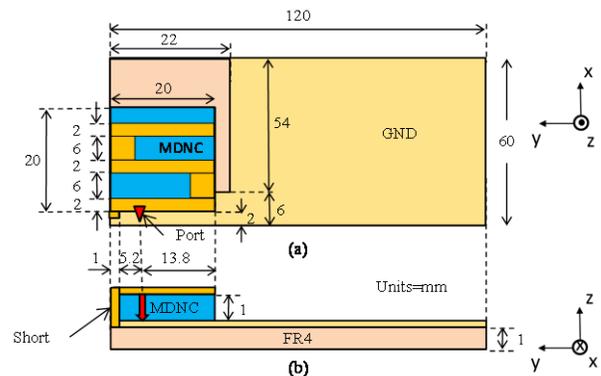


Fig. 3. Geometry of the proposed PIFA on MDNC (a) top view and (b) side view.

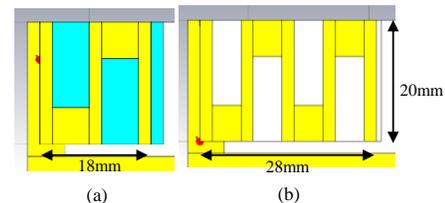


Fig. 4. Antenna size comparison (a) PIFA_{MDNC} and (b) PIFA_{FR4}.

dielectric material substrate, PIFA_{DH} and PIFA_{DL}, showed narrower bandwidth than PIFA_{MDNC} as shown in Fig. 5. The bandwidth is proportional to material loss, but PIFA_{MDNC} showed wider bandwidth than PIFA_{DH} even though they have the same total loss. PIFA_{MDNC} also shows higher radiation efficiency and gain than PIFA_{DH}. Increased stored energy in the high dielectric material reduces both radiation efficiency and gain. Therefore, antenna on MDNC substrate provides better antenna performance than antenna on high dielectric material substrate when they have the same total loss. On the other hand, PIFA_{DL} shows 15% higher radiation efficiency and 0.5 dBi larger gain than PIFA_{MDNC}. PIFA_{FR4} showed the widest bandwidth as well as the highest radiation efficiency and gain among all four antennas. This antenna performance can be attributed to low permittivity with moderate loss but with a larger antenna size. Although the measured magnetic loss tangent of 0.068 is high for the RF antenna applications, the performance of PIFA_{MDNC} still meets requirements for handheld device such as smart phones since only 30 % radiation efficiency is required [12]. The loss characteristic of MDNC material, however, can be beneficial for SAR reduction, which is described in following section.

Table I
Simulated antenna performance for PIFAs

Material	MDNC	DH	DL	FR4
BW (%)	7.24	5.5	5.14	12.56
Radiation Eff. (%)	74.19	53.02	90.27	94.05
Gain (dBi)	1.26	-0.22	2.1	2.27
Area (mm ²)	360	360	360	584

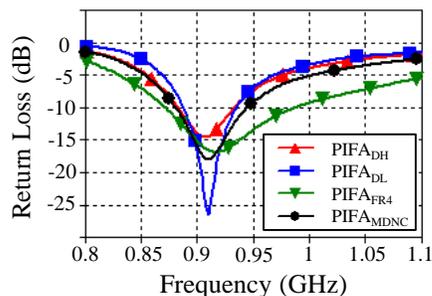


Fig. 5. Simulated return loss for the PIFA_{DH}, PIFA_{DL}, PIFA_{FR4} and PIFA_{MDNC}.

IV. SPECIFIC ABSORPTION RATE ANALYSIS

Specific absorption rate (SAR) is a measure of the rate at which energy is absorbed by the human body when exposed to RF electromagnetic field. In this letter, the effect of high loss characteristics of MDNC to reduce SAR is investigated by comparing simulated peak SAR of PIFA_{MDNC}, PIFA_{DH}, and PIFA_{FR4}. SAR of antennas is analyzed using an EN 50361 Specific Anthropomorphic Mannequin (SAM) phantom head, which is provided in CST microwave studio [13]. The phantom head consists of a shell filled with a liquid which represents the average material properties of the head. The relative

permittivity and loss tangent of shell and liquid are 5/0.05 and 42/0.53 respectively.

The antenna was placed around 10mm away from the left hand side of the head, as shown in Fig 6. The resonant frequency, bandwidth, peak efficiency, peak gain and maximum SAR of each antenna were calculated and are summarized in Table II. The resonant frequencies of the antennas shifted as they were placed close to the head. The resonance shift of the PIFA_{MDNC} due to the head was 72.77 MHz, which is 17MHz and 19 MHz less than that of the PIFA_{DL} and PIFA_{FR4} respectively. The reason for PIFA_{MDNC} showing the smallest resonance shift is due to the refractive index ($n = \sqrt{\epsilon_r \mu_r}$) of MDNC which is the closest to the refractive index of the head amongst the three materials. PIFA_{MDNC} showed the largest bandwidth with 2:1 VSWR among all three antennas. Though the peak efficiency and peak gain of PIFA_{MDNC} were the lowest among all three antennas, the deterioration of these values by the head phantom was the smallest. Therefore, human head effects on the antenna performance can be reduced by using MDNC as compared to using high dielectric material or FR4. The calculated SAR of PIFA_{MDNC} was 0.72 W/kg averaged over 1 gram of tissue with a 100mW input power. The other two antennas showed SAR of 0.85 W/kg, which is 0.13 W/kg larger than that of PIFA_{MDNC}. Hence MDNC material can reduce antenna size with acceptable performance for mobile devices while its loss can help decrease the SAR of the antenna.

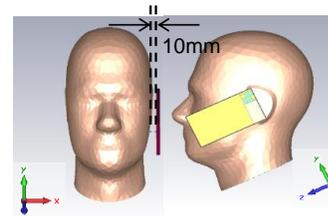


Fig. 6. Antenna setup with SAM phantom mannequin.

Table II
Antenna performance with head phantom

Specification	PIFA _{MDNC}	PIFA _{DL}	PIFA _{FR4}
Δf_r (MHz)	72.77	90	92.33
Bandwidth (%)	7.1	3.19	5.08
Efficiency (%)	18.17	19.54	20.49
Gain (dB)	-2.61	-2.33	-2.05
Max SAR (W/kg)	0.7224	0.8538	0.8547

V. ANTENNA FABRICATION AND RESULTS

The proposed meandered PIFA on MDNC material was fabricated and measured. Photograph of the fabricated antenna is shown in Fig. 7. Fig. 8 shows the simulated and measured return loss results. The fabricated antenna was measured using vector network analyzer (VNA) with short, open, load and thru (SOLT) calibration in an anechoic chamber. An operating frequency bandwidth of 2:1 VSWR was obtained from 911 to 981 MHz, which corresponds to a 7.4 % bandwidth.

The simulated and measured peak gain and efficiency of the antenna are shown in Fig. 9. The measured radiation efficiency was 51-61.7 % over the frequency band while the simulated radiation efficiency was 60-76 % over the same band. The

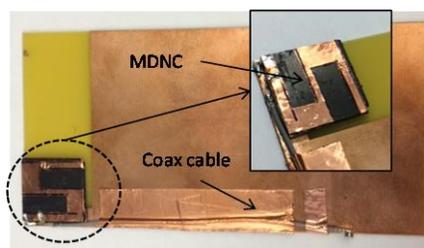


Fig. 7. Photograph of PIFA_{MDNDC}.

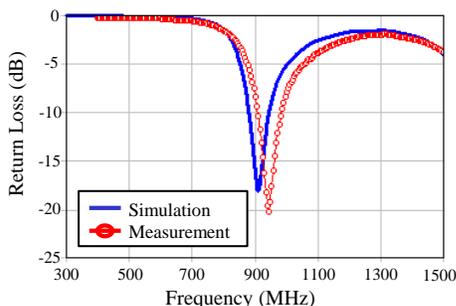


Fig. 8. Simulated and measured return loss of the PIFA_{MDNDC}.

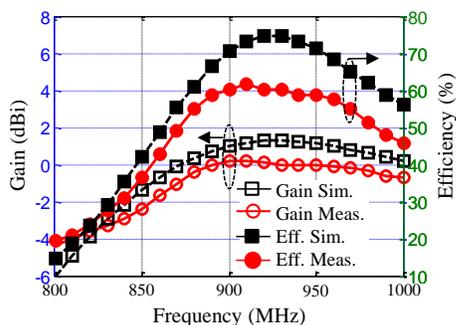


Fig. 9. Simulated and measured gain and radiation efficiency of PIFA_{MDNDC}.

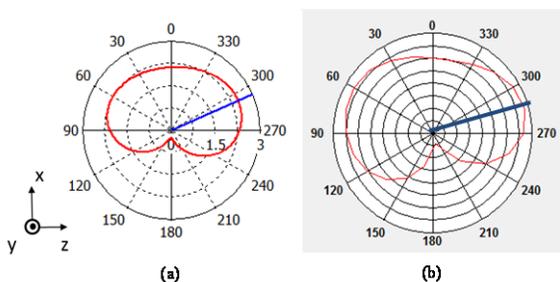


Fig. 10. Simulated and measured xz-plane radiation pattern of PIFA_{MDNDC}.

measured antenna gain was about -0.3-0.2 dBi over the band which compares to the simulated gain of 0.61-1.29 dBi over the same frequency band. Simulation and measurement showed some difference which can be attributed to size difference during the fabrication process, frequency dependent properties of the MDNC material, and the effect of the coaxial cable used for measurements. The measured gain and efficiency of the proposed antenna, however, meet the requirements for a practical handheld device since only 30 % radiation efficiency is required for this operating band for most applications [13]. Fig. 10 shows the simulated and measured xz-plane radiation

patterns. Good agreement is obtained with a main lobe at 293° (simulation) and 285° (measurement). Based on the measured results and the advantages possible for SAR reduction, the proposed meander PIFA on MDNC substrate offers a good solution for hand held applications.

VI. CONCLUSION

Magneto-dielectric nanocomposite material was synthesized by mixing cobalt metal particles and fluoropolymer dielectric material. The permittivity and permeability of the material was extracted up to 4GHz. A meander PIFA on MDNC substrate was designed and its radiation pattern, bandwidth and efficiency were measured. The proposed antenna was compared to antennas on high dielectric and FR4 substrates. The antenna on MDNC substrate showed acceptable performance for hand held mobile applications in a small size. Though the MDNC antenna showed lower radiation efficiency than other antennas due to the high magnetic loss, the efficiency achieved met requirements while the higher magnetic loss reduced the SAR due to the antenna.

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