Magneto-Dielectric Nanocomposite for Antenna Miniaturization and SAR Reduction

Kyu Han, Madhavan Swaminathan, *Fellow, IEEE*, Raj Pulugurtha, *Member, IEEE*, Himani Sharma, Rao Tummala, *Fellow, IEEE*, Songnan Yang, and Vijay Nair, *Fellow, IEEE*

***Abstract*—A 900-MHz meander planar inverted-F antenna (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 4 GHz. 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 rate (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, microstrip antenna, miniaturization, nanocomposite, radiation pattern, specific absorption rate.**

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 are 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 that have relative permittivity and permeability greater than unity have been applied to reduce the antenna size and have 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, electromagnetic band-gap (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 backside radiation. An alternate approach is to synthesize MD materials that have appropriate properties that provide acceptable antenna performance while decreasing the backside 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, MDNC is synthesized by combining nano-sized 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 that 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

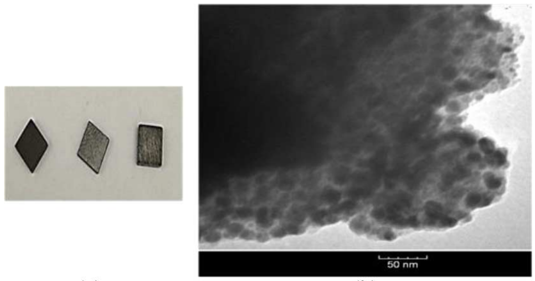
Manuscript received January 15, 2015; revised March 20, 2015; accepted May 02, 2015. Date of publication May 06, 2015; date of current version February 04, 2016.

K. Han, M. Swaminathan, R. Pulugurtha, H. Sharma, and R. Tummala are with the Georgia Institute of Technology, Atlanta, GA 30332 USA (e-mail: khan7@gatech.edu).

S. Yang and V. Nair are with Intel Corporation, Chandler, AZ 85226 USA.

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LAWP.2015.2430284



(a) (b)

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

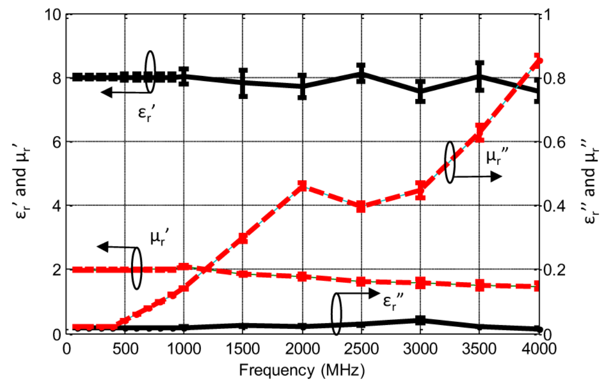


Fig. 2. Extracted relative permittivity and permeability of MDNC.

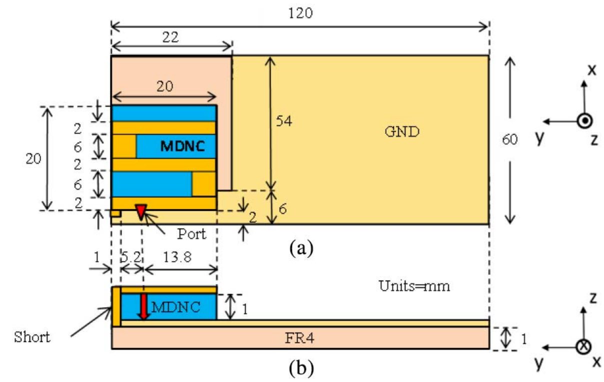
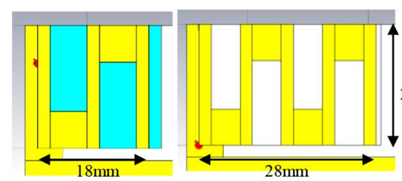


Fig. 3. Geometry of the proposed PIFA on MDNC: (a) top view and (b) side view.



(a) (b)

Fig. 4. Antenna size comparison: (a) $\text{PIFA}_{\text{MDNC}}$ and (b) PIFA_{FR4}.

slurry. The metal slurry was dried in a nitrogen oven to evaporate the excess 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 30 nm.

The frequency-dependent dielectric and magnetic properties of the MDNC material were characterized to extract its complex relative permittivity, $\varepsilon_r = \varepsilon_r{}' - j\varepsilon_r{}''$, 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 1 GHz, and cavity perturbation technique (CPT) was used in the frequency range of 1–4 GHz. 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 $\varepsilon_r' \approx 8$, which is fairly constant over the frequency range up to 4 GHz. The electric loss tangent ($\tan\delta_e = \varepsilon_r''/\varepsilon_r'$) shows maximum value of 0.0054 at 3 GHz with a value around 0.0024 at $\sim$ 1 GHz. The real part of the relative permeability is around $\mu_r{}' \approx 2$ at $\sim$ 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 1 GHz [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 1-GHz frequency range. In this letter, we use this material as the substrate for realizing the antenna around 1 GHz.

III. Meander PIFA on MDNC Material

A meander PIFA working at 900 MHz 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 900 MHz, respectively, based on the measured values from Fig. 2. $\text{Tan}\delta_e$ and $\text{Tan}\delta_m$ of the MDNC material used were 0.0024 and 0.068 at 900 MHz, respectively. Fig. 3(a) shows the geometry of the proposed antenna on the MDNC substrate above an FR4 printed circuit board (PCB) with a relative permittivity of 4.3 and $\tan\delta_e$ of 0.02. The overall size of the FR4 PCB substrate is $60 \times 120 \times 1$ mm^3. The size of the MDNC substrate is $20 \times 20 \times 1$ mm^3, where the meandered copper tape was patterned on top of the substrate. The meandered top plane was shorted to ground with 1-mm-width copper tape at the top left corner of the antenna.

The PIFA on the MDNC substrate ($\text{PIFA}_{\text{MDNC}}$) 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 $\text{PIFA}_{\text{MDNC}}$ without having to change the dimension of the antenna. $\text{Tan}\delta_e$ of PIFA_{DH} was chosen as 0.0704, which is the sum of the electric and magnetic loss tangent of MDNC material at 900 MHz. $\text{Tan}\delta_e$ 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 represent 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.

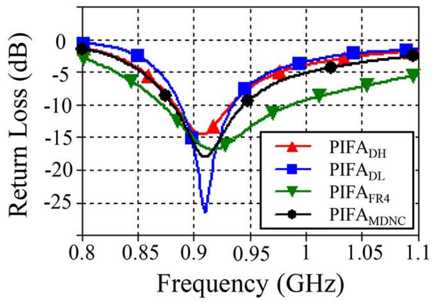


Fig. 5. Simulated return loss for the $\mathrm{PIFA_{DH}}$, $\mathrm{PIFA_{DL}}$, $\mathrm{PIFA_{FR4}}$, and $\mathrm{PIFA_{MDNC}}$.

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

Bandwidth, efficiency, gain, and size of the four antennas were compared and are listed in Table I. Antennas on high-dielectric material substrate, $\mathrm{PIFA_{DH}}$ and $\mathrm{PIFA_{DL}}$, showed narrower bandwidth than $\mathrm{PIFA_{MDNC}}$ as shown in Fig. 5. The bandwidth is proportional to material loss, but $\mathrm{PIFA_{MDNC}}$ showed wider bandwidth than $\mathrm{PIFA_{DH}}$ even though they have the same total loss. $\mathrm{PIFA_{MDNC}}$ also shows higher radiation efficiency and gain than $\mathrm{PIFA_{DH}}$. 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, $\mathrm{PIFA_{DL}}$ shows 15% higher radiation efficiency and 0.5 dBi larger gain than $\mathrm{PIFA_{MDNC}}$. $\mathrm{PIFA_{FR4}}$ 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 $\mathrm{PIFA_{MDNC}}$ still meets requirements for handheld devices such as smartphones since only 30% radiation efficiency is required [12]. The loss characteristic of MDNC material, however, can be beneficial for specific absorption rate (SAR) reduction, which is described in Section IV.

IV. SPECIFIC ABSORPTION RATE ANALYSIS

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 $\mathrm{PIFA_{MDNC}}$, $\mathrm{PIFA_{DH}}$, and $\mathrm{PIFA_{FR4}}$. 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 that 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.

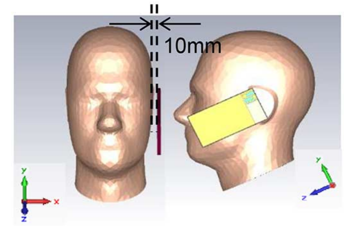


Fig. 6. Antenna setup with SAM phantom mannequin.

TABLE II
ANTENNA PERFORMANCE WITH HEAD PHANTOM

Specification	$\mathrm{PIFA_{MDNC}}$	$\mathrm{PIFA_{DL}}$	$\mathrm{PIFA_{FR4}}$
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

The antenna was placed around 10 mm 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 $\mathrm{PIFA_{MDNC}}$ due to the head was 72.77 MHz, which is 17 and 19 MHz less than that of the $\mathrm{PIFA_{DL}}$ and $\mathrm{PIFA_{FR4}}$, respectively. The reason for $\mathrm{PIFA_{MDNC}}$ showing the smallest resonance shift is due to the refractive index ($n = \sqrt{\varepsilon_r \mu_r}$) of MDNC, which is the closest to the refractive index of the head among the three materials. $\mathrm{PIFA_{MDNC}}$ showed the largest bandwidth with 2:1 VSWR among all three antennas. Though the peak efficiency and peak gain of $\mathrm{PIFA_{MDNC}}$ 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 $\mathrm{PIFA_{MDNC}}$ was 0.72 W/kg averaged over 1 g of tissue with a 100-mW input power. The other two antennas showed SAR of 0.85 W/kg, which is 0.13 W/kg larger than that of $\mathrm{PIFA_{MDNC}}$. Hence, MDNC material can reduce antenna size with acceptable performance for mobile devices, while its loss can help decrease the SAR of the antenna.

V. ANTENNA FABRICATION AND RESULTS

The proposed meandered PIFA on MDNC material was fabricated and measured. A 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 a vector network analyzer (VNA) with short, open, load, and thrus (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

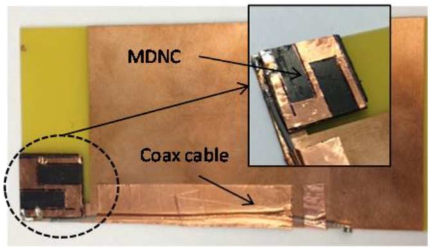


Fig. 7. Photograph of $\mathrm{PIFA}_{\mathrm{MDNC}}$.

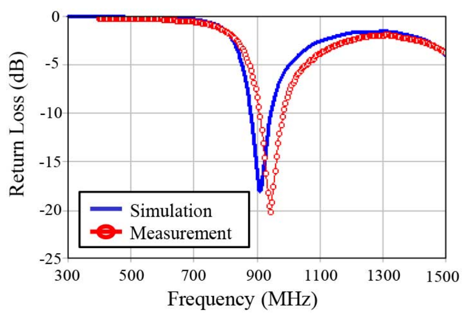


Fig. 8. Simulated and measured return loss of the $\mathrm{PIFA}_{\mathrm{MDNC}}$.

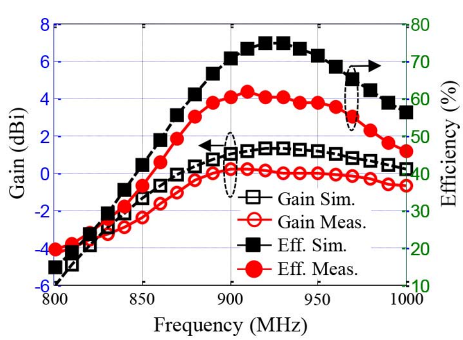


Fig. 9. Simulated and measured gain and radiation efficiency of $\mathrm{PIFA}_{\mathrm{MDNC}}$.

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 handheld applications.

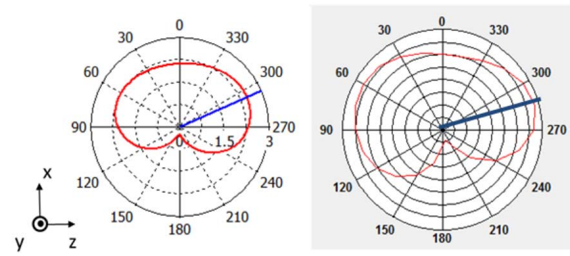


Fig. 10. Simulated and measured xz-plane radiation pattern of $\mathrm{PIFA}_{\mathrm{MDNC}}$.

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 4 GHz. 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 handheld 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.

References

[1] J. S. Colburn and Y. Rahmat-Samii, “Patch antennas on externally perforated high dielectric constant substrates,” *IEEE Trans. Antennas Propag.*, vol. 47, no. 12, pp. 1785–1784, Dec. 1999.

[2] P. Ikonen, K. N. Rozanov, A. V. Osipov, P. Alitalo, and S. Tretyakov, “Magnetodielectric substrates in antenna miniaturization: Potential and limitations,” *IEEE Trans. Antennas Propag.*, vol. 54, no. 11, pp. 3391–3399, Nov. 2006.

[3] H. Mosallaei and K. Sarabandi, “Magneto-dielectrics in electromagnetics: Concept and applications,” *IEEE Trans. Antennas Propag.*, vol. 52, no. 6, pp. 1558–1567, Jun. 2004.

[4] K. Han *et al.*, “Magneto-dielectric material characterization and antenna design for RF applications,” in *Proc. 8th EuCAP*, 2014, pp. 381–384.

[5] A. N. Lagarkov and K. N. Rozanov, “High-frequency behavior of magnetic composites,” *J. Magn. Magn. Mater.*, vol. 321, pp. 2082–2092, 2009.

[6] B. Lu *et al.*, “Microwave absorption properties of the core/shell-type iron and nickel nanoparticles,” *J. Magn. Magn. Mater.*, vol. 320, pp. 1106–1111, 2008.

[7] S. Zhu and R. Langley, “Dual-band wearable textile antenna on an EBG substrate,” *IEEE Trans. Antennas Propag.*, vol. 57, no. 4, pp. 926–935, Apr. 2009.

[8] P. M. Raj *et al.*, “Tunable and miniaturized RF components with nanocomposite and nanolayered dielectrics,” in *Proc. IEEE NANO*, 2014, pp. 27–31.

[9] P. M. Raj *et al.*, “Magnetic losses in metal nanoparticle-insulator nanocomposites,” *J. Mater. Sci.: Mater. Electron.*, vol. 24, no. 9, pp. 3448–3455, 2013.

[10] K. Han *et al.*, “Magneto-dielectric material characterization and antenna design for RF applications,” in *Proc. IEEE ECTC*, May 2014, pp. 782–788.

[11] J. Lee, J. Heo, J. Lee, and Y. Han, “Design of small antennas for mobile handsets using magneto-dielectric material,” *IEEE Trans. Antennas Propag.*, vol. 60, no. 4, pp. 2080–2084, Apr. 2012.

[12] CST Microwave Studio Computer Simulation Technology, Framingham, MA, USA [Online]. Available: http://www.cst.com/Products/CSTMWS

[13] Y. L. Ban, J. H. Chen, S. Yang, J. L. W. Li, and Y. J. Wu, “Low-profile printed octa-band LTE/WWAN mobile phone antenna using embedded parallel resonant structure,” *IEEE Trans. Antennas Propag.*, vol. 61, no. 7, pp. 3889–3894, Jul. 2013.