Magnetodielectric Nanocomposite Polymer-Based Dual-Band Flexible Antenna for Wearable Applications

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***Abstract*— One of the major challenges in wireless communication technologies is the antenna design. In this paper, a wideband flexible antenna made by covering a Kapton substrate with a flexible magnetodielectric polymer-based nanocomposite layer is proposed. This novel magnetodielectric polymer-based nanocomposite relies on carbon-coated cobalt (CCo) and is coated with a conjugated polymer, polyaniline (PANI). The nanocomposite (PANI/CCo) fabrication, whose morphology was studied via scanning electron microscopy, demonstrates a relative permeability, a dielectric permittivity, and a conductivity of 5.5, 4.3, and 7500 S/m, respectively. In this paper, two frequency bands are of interest [1.8–2.45 GHz (personal communication service and wireless local area network) and 5.15–5.825 GHz (wireless networks)]. The functioning of the antenna in free space and on body is numerically and experimentally investigated. The average specific absorption rate is also discussed. Thanks to its performance this magnetodielectric nanocomposite polymer (PANI/CCo) antenna has been found to be a good candidate for wearable applications where complex bending situations are encountered.**

***Index Terms*— Carbon-coated cobalt (CCo), magneto dielectric polymer, nanocomposite, polyaniline (PANI), wearable antenna.**

I. Introduction

THE need of smaller flexible electronic systems increases rapidly. Among the flexible electronic devices, printed planar antennas attract a great attention. Actually, the design of flexible antennas for wireless local area network (lower and upper WLANs) and body area network communication technology applications has drawn significant interest from the research community. Recently, in many papers, conductive polymers have been considered as potential materials for the antennas realization to participate in the improvement of the flexibility feature. For example, Chen *et al.* [1] and Hamouda *et al.* [2] designed and tested a polymer-based flexible ultra-wideband (UWB) antenna under different bending conditions.

There are several types of conductive polymers available on the market that can be used for printed antennas, such as polyaniline (PANI) [3], polypyrrole [4], [5], PANI charged with carbon nanotubes [6], [7], or conductive polymer poly 3, 4-ethylenedioxthiophene [8], [9]. These materials are widely used because they allow the improvement of the conductivity while maintaining chemical stability. Furthermore, conductive polymers can reduce the cost to approximately one-tenth of the price of plastic films; hence, the antenna cost is lowered [10].

PANI was selected because it is considered as a very promising material; it can be easily synthesized, it offers a relatively high conductivity, and its cost is pretty low compared to other conductive polymers. In addition, its intrinsic parameters can be modulated by chemical processes. The Co magnetic particle has attracted attention because of its unique properties such as compatibility with organic molecules, improved resistance to leaching [11] and the different applications that it allows in the fields of radio frequency systems, electromagnetic shielding, and magnetic sensors [12]–[16]. In fact, the magnetodielectric polymer-based nanocomposite relying on carbon-coated cobalt (CCo) dispersed in PANI combines both electrical properties of conductive polymers and magnetic properties thanks to the addition of magnetic particles. To improve the mechanical properties in terms of flexibility, polyurethane (PU) (Bayer, Desmopan 6065A) is added.

The proposed work emphasizes, at first, the development of magnetodielectric nanocomposite materials made of nanoparticles (CCo) and a conductive polymer matrix (PANI/PU). At second, the focus is put on the antenna design and fabrication. Finally, a comparison between the simulation study and the experimental investigation is made to evaluate the antenna performance (reflection coefficient, bandwidth, radiation patterns, and gain).

II. Material Development

A. Synthesis of CCo Nanoparticles and Polymer Nanocomposites

The preparation and characterization of magnetic nanocomposites based on PANI have been studied extensively [17]–[19]. To investigate the exploitation of magnetodielectric

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conductive polymers in the fabrication of flexible antennas, a printed flexible antenna based on PANI charged with CCo is reported in this paper. In fact, the PANI is mixed with PU to improve the mechanical characteristics of the system. The PANI-camphor sulfonic acid (PANI-CSA) and the PU are independently dissolved in a solvent dichloroacetic acid (DCAA). Different PANI-CSA and PU mixtures with different concentrations have been developed which allows determining the percolation threshold from the measurements of the static conductivity.

CCo is a black material composed of carbon particles of a size less than 25 nm coated with a thin cobalt layer; it does not react with air and has outstanding magnetic properties. The CCo was selected as the magnetic phase because of its ferromagnetic nature, its high conductivity (17.2×10^4 S/cm), and the possibility of manufacturing it in the form of powder nanoparticles. The CCo particles are dispersed in the DCAA using an ultrasonic bath which can break the magnetic bond between the particles, and contributes to obtain a homogeneous solution. The dispersion time is about 15 min at room temperature.

The solution containing the particles of CCo is then added to the PANI-CSA–PU mixture. After that, the resulting solution is homogenized using a hot ultra sound at room temperature until obtaining a “homogeneous to the eye” solution. This nanocomposite, for the manufacture of an antenna, is then deposited on a Kapton substrate, and dried in a vacuum chamber for 6 h at 60 °C. The final average film thickness is on the order of 75 μm.

B. Characterization of PANI-CSA–PU–CCo Nanocomposite

The relative permeability and dielectric permittivity measurements of the composite (PANI/CCo) are performed by using two methods: the open-ended coaxial probe method in the frequency band (100 MHz–5 GHz) and Nicholson–Ross–Weir (NRW) technique in the X-band. The first method is based on a capacitive model, whereas in the second one, the permeability and permittivity are extracted from the measurement of the S-parameters (reflection/transmission coefficients) of a rectangular waveguide operating in the X-band. (The length of the sample filling the waveguide is 5 mm.) The NRW algorithm used is able to correctly perform the material characterization over the frequency range considered [18], [21]. The data obtained thanks to this characterization study have been integrated in HFSS library for the simulation analysis. The morphology of the nanocomposite and the particle sizes are obtained by means of a scanning electron microscope (SEM).

1) Scanning Electron Microscope (SEM) Images: Images of the surface of the films made using an SEM are given in Fig. 1. We note in Fig. 1(a) that the sensitive surface is homogeneous. The observation of SEM cuts at different magnitudes reveals the presence of nanoparticles in the matrix.

Fig. 1(b) shows that CCo/PANI nanoparticles are incorporated into the PU matrix in a random manner, thus promoting the flexibility of the proposed conductive polymer. The SEM image shows a smooth surface with no apparent defects.

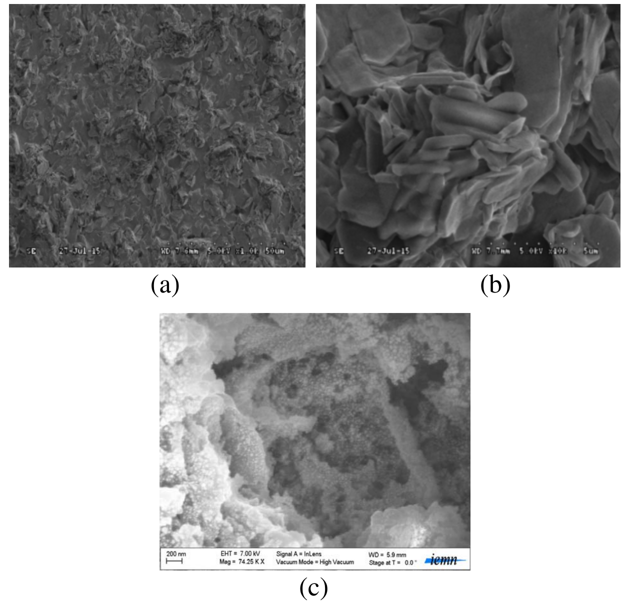


Fig. 1. SEM images of a layer of printed PANI/CCo polymer nanocomposite.

Note that we have scanned several parts of the sample to check the deposition homogeneity. So, this SEM image points out on one hand smooth flexible nanocomposites well dispersed and on the other hand that the CCo particles are well embedded and that a strong bonding between the CCo and the PANI exists. From Fig. 1(c), it is very clear that the conductive polymer favors the dispersion of the nanoparticles (CCo), they are observed as bright spots well dispersed in the polymeric matrix. It can also be noticed that there is a remarkable change in the nanocomposite morphology, since more CCo nanoparticles are observed. The dispersion of PANI/CCo nanoparticles aggregates seems to be more regular. Brightly aggregations of mostly spherical nanoparticles having several tens of nanometer average sizes can clearly be observed.

2) Conductivity Measurement: Electrical conductivity is a very important parameter for antenna design. The most commonly encountered methods in the literature for measuring continuous conductivity are those of spikes [21], [22]. In this paper, the magnetodielectric nanocomposite polymer (PANI/CCo) has been modeled as a thin layer of finite impedance with a sheet resistance R_s estimated through the dc-conductivity σ by the following equation:

$$R_s = 1/(\sigma \times h) \tag{1}$$

where h is the thickness of the film.

The thickness is measured by means of an optical profilometer (Micromeasure TM^2 system, equipped with STIL-DUO). The measuring station makes it possible to carry out the 3-D microtopography as well as the analysis of the shapes and textures of the samples. It gives the possibility to measure the profiles and surfaces of samples. It is observed that the produced films are more homogeneous and well distributed over the substrate (Fig. 2). The main inconvenient of the films is the strong dispersion in terms of roughness that appears in the upper layer. Hence, the mean thickness of PANI/CCo film used as patch element coplanar waveguide (CPW) is 75 μm.

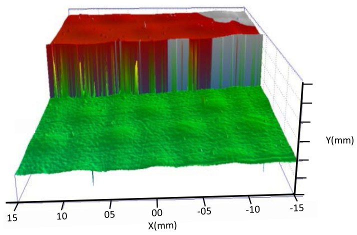
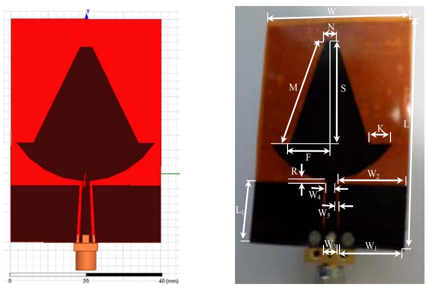


Fig. 2. Measurement of PANI/CCo film thicknesses.



(a) (b)

Fig. 3. PANI/CCo antenna (a) HFSS model. (b) Photograph of the PANI/CCo-antenna fabricated.

The conductivity of the samples was measured on pressed square shaped. To facilitate measurements, an automated measurement bench under computer control is used. The results are displayed on a graphical interface. The direct current conductivity measured has been found equal to 7500 S/m.

III. Antenna Design and Fabrication

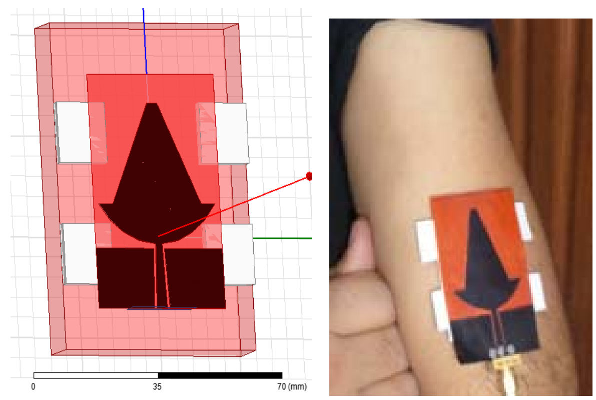
The selection of PANI/CCo was done with the promise that a successful antenna design based on this type of conductive polymers could lead to the development of some interesting flexible antennas. The geometry of the proposed antenna structure is depicted in Fig. 3. The antenna is made of three parts. The first part consists of a coplanar line which is the feeding line of the patch antenna. The second part is the circular form which gives the ultra large band property to the printed monopole antenna. And finally, the third part is the triangular form which is used to eliminate a specific frequency band. The dimensions of the antenna are separately optimized in a first step. Then, all dimensions of the antenna are optimized together. Thanks to the two radiators (circular and triangular forms), the dual-band dual-mode operation is achieved. The substrate is a 130 μm-thick Kapton (polyimide), which dielectric properties are $\varepsilon_r = 3.5$ and tan $(\delta) = 0.002$. A probe feed was implemented by using a coaxial cable. The feeding location of the PANI/CCo-patch antenna has been optimized to insure a good matching with a standard 50 Ω (CPW)-fed line also made by using a PANI/CCo film. The antenna is simulated using HFSS [Fig. 3(a)] by taking into account the characteristics measured for the nanocomposite considered (permittivity, permeability, conductivity, and thickness). Based on the simulation study, the antenna made of PANI/CCo nanocomposite has been realized. The photograph of the prototype is shown in Fig. 3(b).

TABLE I

Parameters of the Proposed Antenna

Substrate = Kapton (polyimide)											
Dimension (mm^2)			W×L= 58×40								
Patch material = PANI/CCo											
Conductivity (S/m)			7500								
Relative permittivity			4.3								
Relative permeability			5.5								
Dimension of the planar antenna											
W_1	W_2	W_3	W_4	W_5	L_1	R	K	N	M	S	F
18.3	17.5	3.3	2	0.7	1.8	2.3	4.5	3	27.8	25	28

All dimensions are in mm.



(a) (b)

Fig. 4. PANI/CCo-antenna on body. (a) HFSS model. (b) Photograph of the PANI/CCo-antenna on body.

The characteristic impedance of the organic CPW is designed to match 50 Ω. The optimized dimensions of the proposed organic antenna [Fig. 3(b)] are reported in Table I.

In order to investigate the performance of this organic antenna, when it is put on a human body, a phantom made of a single-homogeneous layer is used. This homogeneous phantom is mainly made of muscle tissue filled with tissue-emu-liquid (water, sugar, and salt) that has a dielectric constant of 56.7, a loss tangent of 0.24, and a conductivity of 1.71 S/m at 2.4 GHz. At the frequency of 5.4 GHz, these parameters shift to a dielectric constant of 47.23, a loss tangent of 0.27, and a conductivity of 4.7 S/m [15]. These properties of the homogeneous equivalent layer are added in HFSS material library. The overall size of this modeled phantom geometry is $60 \times 80 \times 25$ mm^3 with a density of 1040 Kg/m^3. The antenna is placed at 2 mm (air gap) above the phantom. To keep the gap between the human body and the antenna structure, pieces of adhesive based on Teflon are used. These “Teflon-based” adhesives (relative permittivity of 2.08 and loss tangent of 0.001) have practically no influence on the measurement. The proposed model [Fig. 4(a)] is simulated on HFSS.

To estimate the performance of the antenna, a comparison between simulation and measurement is led in two different situations: antenna in free space and antenna on body.

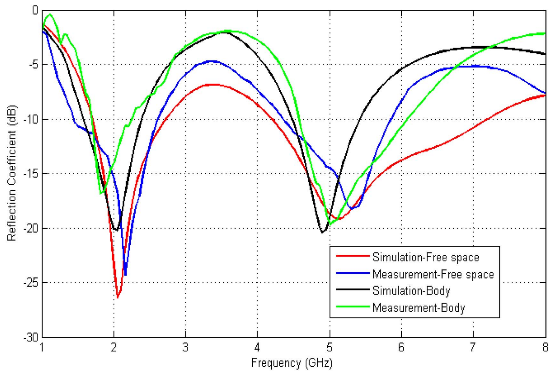
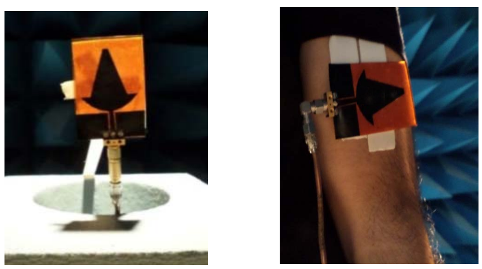
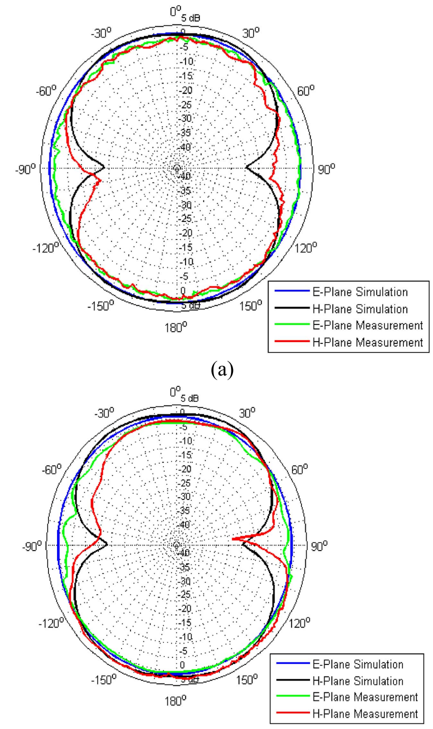


Fig. 5. Simulated and measured reflection coefficient of the UWB antenna in free space and on body.



(a) (b)

Fig. 6. Photograph of the realized organic antenna in the anechoic chamber. (a) Antenna in free space. (b) Antenna on body.



(a)

(b)

Fig. 7. Simulated and measured E- and H-plane radiation patterns of the antenna in free space at (a) 2.45 and (b) 5.4 GHz.

IV. Simulation and Measurement Results

Several simulations and measurements were done to determine the reflection coefficient, the radiation patterns, and the gain of the antenna in the cases of interest (free space and on body). The measurement results were then compared to the simulation data. For on-body measurements, a real human body has been used (weight of 72 kg and height of 1.7 m). The organic antenna is placed at approximately 2 mm above the arm of the test subject. To maintain this gap, we make use of a double sided 2 mm-thick adhesive tape to fix the antenna on the arm [see Fig. 6(b)].

A. Reflection Coefficient

The reflection coefficients of the proposed antenna in free space and on body are shown in Fig. 5. The antenna is tested using an Agilent PNA–X series N5242A network analyzer (10 MHz–26.5 GHz).

First, these results confirm the dual-band operation of the antenna proposed. Second, it can be observed that the agreement between the simulation and measurement data is relatively good. The discrepancy between the simulation and measurement results is attributed to several effects. A small part is due to the nonhomogeneous distribution of the CCo nanoparticles in the PU matrix, another one to the electromagnetic characteristics used for the body model, and finally to the properties of the composite material as a function of the frequency. One can also note that the experimental bandwidths at -10 dB are 1.4–2.6 and 4.3–5.90 GHz for free space and 1.7–2.3 and 4.6–6.1 GHz for the on-body situation. Finally, because of the body high-dielectric constant a small shift between the resonance frequencies is noticed. Generally speaking, one can conclude that the performance of the fabricated antenna based on PANI/CCo nanocomposite is relatively well predicted.

B. Radiation Patterns and Gain

In order to complete the performance study, the radiation patterns and the gain of the proposed organic antenna are measured in free space [Fig. 6(a)] and on body [Fig. 6(b)]. The radiation patterns (E- and H-planes) are measured in the IEMN anechoic chamber. All measurements are obtained by using a standard horn antenna (SAS–200/571) and an Agilent 8735ES vector network analyzer (30 kHz–6 GHz). The frequencies selected for the measurements are 2.45 and 5.4 GHz. The test subject for these investigations is the one considered for the previous tests.

Fig. 7 shows the radiation patterns in both E- and H-planes at 2.45 and 5.4 GHz in free-space conditions. A quite good agreement is observed between simulation and measured results. It can be observed that the E-plane patterns are omnidirectional while the H-plane patterns are bidirectional. It is also noticed that the organic antenna offers a stable radiation performance for the two frequencies tested. These diagrams also exhibit small ripples in the case of the measurement results, due probably to the addition of different contributions. Among them one can found the some small irregularities of the PANI/CCo/PU sheet (roughness), the nonhomogenous

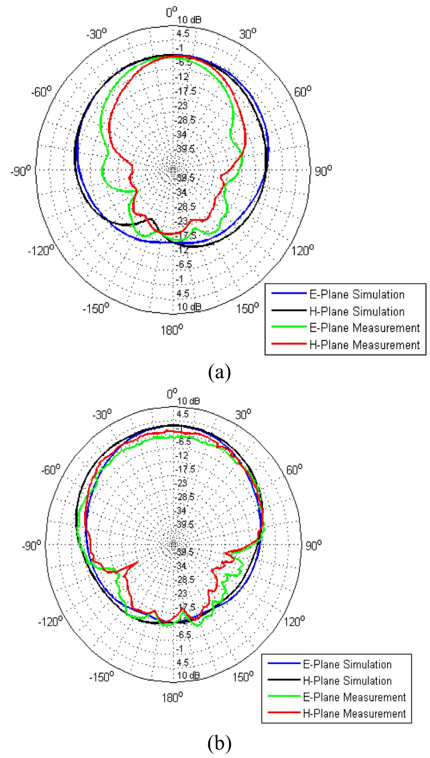


Fig. 8. Simulated and measured E- and H-plane radiation patterns for on-body antenna at (a) 2.45 and (b) 5.4 GHz.

distribution of the nanoparticles in the PU matrix, the coaxial cable radiation, and the most important factor which is the vibration of the antenna during the measurement. However, the fabricated organic antenna prototype reveals a satisfactory behavior in the two operating bands.

The simulated and measured radiation patterns for on-body antenna in the E- and H-planes at the resonant frequencies, 2.45 and 5.4 GHz, are given in Fig. 8(a) and (b).

The conclusions of these tests are first that the radiation patterns are clearly affected by the presence of the human body. This is due to the dielectric properties of the human body tissues compared to the antenna substrate which shields most of the backward radiation [23], [24]. In addition, the radiation patterns of the proposed antenna on human body becomes more directive in the E- and H-planes and some fluctuations in radiation patterns in the opposite side of the antenna are observed in both simulation and measurement. Overall, a relatively good agreement between the simulation and the measured data can be observed in Fig. 8(a) and (b) in spite of the differences between the human body model and the real human body characteristics. The radiation patterns in lower frequency [Fig. 8(a)] are more directives due to the strong dielectric properties of human body at low frequency.

The simulation and measurement antenna gains are summarized in Table II for free-space and on-body cases.

The measured gain of the antenna in free space presents a reasonably high value that increases with frequency from 0.54 dBi at 2.45 GHz to 2.75 dBi at 5.4 GHz. For the on-body case, we can notice that the measured gain performance of the proposed antenna is as expected considerably affected by the presence of the body, it varies from −2.3 dBi at 2.45 GHz

TABLE II
SIMULATED AND MEASURED GAINS

Frequency GHz	Gain (dBi) free space		Gain (dBi) On-body	
	Simulation	Measurement	Simulation	Measurement
2.45	1.05	0.54	-2.10	-2.3
5.4	3.12	2.75	1.53	1.22

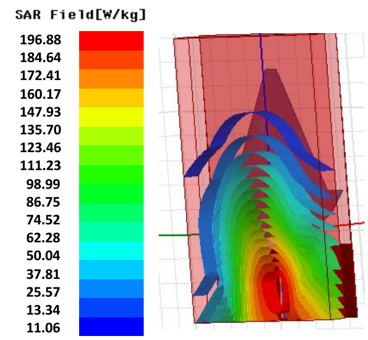


Fig. 9. Simulated SAR at 2.45 GHz of the proposed body antenna for 10 g of tissue.

to 1.22 dBi at 5.4 GHz. Compared to the free-space case, for on-body simulation and measurement results, it is observed a significant reduction of the gain due to the body high dielectric constant which disturbs the induced current on the antenna as it is located in the near-field region of antenna. In fact, the body behaves both as a dielectric absorber (because of its high permittivity) and as a dielectric reflector (because of the huge difference between skin and air refractive index) which results in two significant mechanisms (energy reflection/absorption) which contribute to the gain reduction.

One has also to mention that the simulated efficiency has been found to be 82% at 2.45 GHz and 91% at 5.4 GHz. All together this paper demonstrates that the antenna proposed is a good candidate for on-body wearable communication systems.

C. Specific Absorption Rate

To ensure carriers safety, the maximal incident power of wireless systems has to be limited [25], [26]. The specific absorption rate (SAR), which is the power absorbed by the human body, has to be lowered.

The simulated average SAR over 10 g of a single-homogeneous layer of tissue modeled in HFSS (density of 1040 Kg/m^3) is presented in Fig. 9. The volume of the proposed antenna is 390 mm^3.

In Fig. 9, the maximum value of the simulated average SAR at 2.45 GHz is approximately 196 W/kg (for 10 g of tissue) in the case where the input power is 1 W. The amplitude of the near E-field should be designed for the first mode and to achieve the impedance matching of the second mode. When the weight of the homogeneous phantom model decreases from 10 to 1 g, the simulations show that the average SAR decreases from 196 to 126 W/kg for the same conditions. These results are better than those found in [27]–[29]. So, to satisfy the IEEE Std C95.1-2005 standards, the maximum input power has to be kept lower than approximately 12 mW. The simulation conducted at 5.4 GHz shows comparable results. Hence, all together the results obtained demonstrate that the proposed organic antenna based on a magnetodielectric nanocomposite (PANI/CCo) printed on a flexible substrate (Kapton substrate) offers a good solution for wearable wireless communication applications.

V. Conclusion

A nanocomposite material was synthesized by mixing CCo nanoparticles and a conductive polymer (PANI) material in a PU matrix. This nanocomposite which conductivity is 7500 S/m was exploited to realize a monopole dual-band antenna for WiFi frequencies and various wireless networks applications. The proposed antenna properties, reflection coefficient, radiation patterns, and gain have been simulated and measured in free space and on body. The highest on-body measured gain is 1.22 dB. Finally, the evaluation of the radiation performance and SAR shows that the proposed antenna is a good candidate for body-centric applications.

Thus, in addition to features such as low cost, low weight, ease of fabrication, and good corrosion resistance, the composite antenna proposed demonstrates good electrical characteristics. Actually, the antenna performance makes it suitable for practical applications where the flexibility is a feature of interest. The ongoing research work is mainly focused on the improvement of the nanocomposite conductivity.

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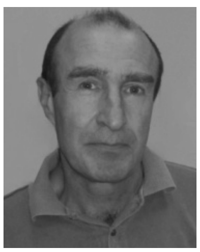

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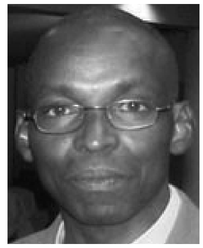

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