Advanced Carbon-Fiber Composite Materials for RFID Tag Antenna Applications

Aidin Mehdipour[1] , Iosif D. Rosca[2], Abdel-Razik Sebak[1] , Christopher W. Trueman[1], and Suong V. Hoa[2]

[1]Department of Electrical and Computer Engineering,
Concordia University, Montreal, Quebec, H3G 2W1, Canada
a_meh@ece.concordia.ca, abdo@ece.concordia.ca, trueman@ece.concordia.ca

[2]Department of Mechanical and Industrial Engineering,
Concordia University, Montreal, Quebec, H3G 2W1, Canada
rosca_iosif@yahoo.com, hoasuon@alcor.concordia.ca

Abstract— In this paper we explore the use of carbon fiber composites (CFC) in radio-frequency identification (RFID) antenna applications both numerically and experimentally. For this purpose, we use two kinds of CFC materials as the radiating element. We consider two types of RFID antennas: the T-match bowtie antenna, and the meander line antenna. The electromagnetic (EM) model of CFC antennas is developed using the Microwave Studio software for numerical analysis. By characterizing samples of CFC material an accurate model of the composite is obtained to be used in the antenna simulation. The composite RFID antenna performance is investigated and compared with a metal antenna. The performance of the antenna can be controlled using the anisotropic property of reinforced continuous carbon fiber composite material. The bandwidth, radiation resistance, and gain/read-range of the RFID antenna can be adjusted by changing the thickness, conductivity, and fiber orientation of the composite material. Because the CFC antenna has a much higher bandwidth, it can be more effective than a metal antenna in RFID.

Index Terms— Antenna, carbon-fiber composites (CFC), radiating element, radio-frequency identification (RFID).

I. INTRODUCTION

Radio-frequency identification (RFID) is extensively used in tracking and identifying objects in many applications [1-7]. The most-used RFID frequency bands are the UHF RFID band (902–928 MHz in North America, 866–869 MHz in Europe and 950–956 MHz in Japan) and the unlicensed wireless bands (2.4-2.484 GHz and 5.15-5.875 GHz). The main part of an RFID system is the antenna tag, which should be inexpensive, light, and easy to fabricate. An antenna with good corrosion resistance is desirable in some applications in harsh environments.

Metals such as copper or aluminum are commonly used for the radiating element of an RFID tag. However, cost, fabrication procedure, and weight are some of the important parameters which limit the use of metals. In harsh environments corrosion resistance and the adhesion between radiating element and substrate are major issues. Some recent studies have used various composite materials as replacements for metals [8-12]. In [8], a conducting-polymer patch antenna is proposed. A conductive textile coated with carbon nanotubes (CNTs) and gold is used to fabricate a patch antenna in [9]. Silver nanoparticle ink [10, 11] and the metallo-organic conductive ink [12] are used to prepare the high-conductive material as a replacement of metal for RFID tag antennas.

Advanced carbon-fiber composite (CFC) materials are being used widely in the aerospace industry as a good replacement for metal because of their higher strength, lower weight, and lower cost [13-21]. CFCs have lower electrical conductivity than metals, and so the shielding effectiveness is of concern when electromagnetic compatibility (EMC) must be maintained [15-19]. There are two types of highly-conductive CFCs, namely the reinforced continuous carbon fiber (RCCF) [16-18] and the CNT composites [19-24]. In one-layer unidirectional RCCF composites, the carbon fibers run in one direction only so that the conductivity is anisotropic, being high along the direction of the fibers, but low in the perpendicular direction. The effective anisotropic conductivity tensor of one-layer composite depends on the thickness of layer, the fiber diameter, the separation distance between fibers and the conductivity of the fibers [17]. CNT composites can be made using single-wall nanotubes (SWCNT) [24] or multi-wall carbon nanotubes (MWCNT) [21] to obtain conductivity. The electrical conductivity of CNT composites highly depends on the properties and loading of the CNTs, the aspect ratio of the CNTs, and the characteristics of the conductive network throughout the matrix. Unlike RCCF composites, the CNT composite material is an isotropic medium because the CNTs are randomly oriented throughout the material.

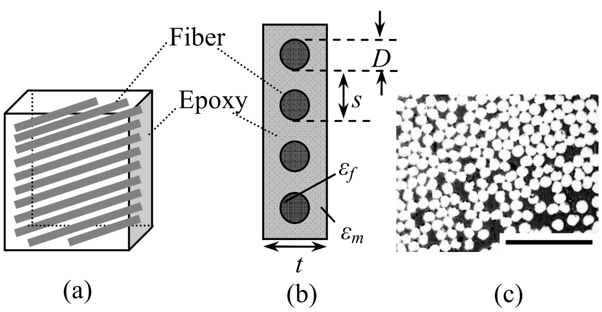


Fig. 1. (a) RCCF composite, (b) Cross-view, (c) Optical micrograph of RCCF Composite (scale bar 50 μm).

In [26], we used numerical modeling to investigate RCCF and braided-tissue carbon-fiber materials for the radiating element of an RFID antenna.

In this paper, we explore in detail using RCCF and SWCNT composites for RFID antenna applications. Two types of RFID antennas, namely the T-match bowtie [11] and the meander line [7], are considered for analysis. Both numerical and experimental results are provided. The organization of the paper is as follows. The composite materials properties and fabrication process are explained in Section II. The antenna performance using RCCF and SWCNT composites as the material of radiating element is carefully investigated in Section III. The fabrication of SWCNT antennas and the experimental results are presented in Section IV. Finally, Section V contains conclusions and ideas for future work.

II. CARBON-FIBER COMPOSITE MATERIALS

In this section, the structure of RCCF and SWCNT composite materials and the method of fabrication are explained. The composite samples are produced in Concordia Center for Composites (CONCOM) [27]. To develop a model of composite material for use in computer simulations of RFID antennas, we characterize the composite material over the frequency range of interest by using standard measurement setups, namely a coaxial fixture below 1.6 GHz, and waveguide setups at higher frequencies. Each measurement setup is modeled using Microwave Studio (MWS) [28, 29]. By minimizing the difference between the simulated and measured scattering parameters over a frequency range, the complex permittivity tensor can be extracted [21, 30].

A. Single-Layer RCCF Composite and Method of Preparation

Fig. 1 shows a typical RCCF composite material. The carbon fibers are embedded in epoxy resin and are all oriented in a specific direction. The effective permittivity tensor of one layer of this composite depends on the thickness of layer (t), the diameter (D) of the fibers, the separation distance between fibers

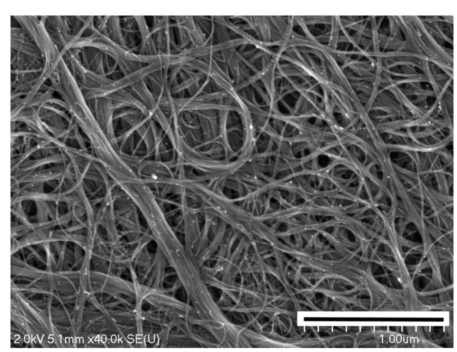


Fig. 2. SEM micrograph of bucky-paper made of SWCNTs (scale bar 1 μm).

(s) and the permittivity of the fibers of the fibers and the host medium (ε_f, ε_m). The effective tensor of homogenized model of RCCF is given by [17]

$$\varepsilon_{z'}^{-1} = (1-g)\varepsilon_m^{-1} + g\varepsilon_f^{-1} \quad (1)$$

$$\varepsilon_{x'} = \varepsilon_{y'} = (1-g)\varepsilon_m + g\varepsilon_f \quad (2)$$

where g is a coefficient which depends on the volume fraction of fibers inside host medium. Compared to metals, the conductivity of RCCF is anisotropic, being high along the direction of fibers, but low in the perpendicular direction. This is an important characteristic of RCCF composites which should be accounted for and can be taken advantage of in antenna design. We should extract the conductivity of composite sample for both directions. The proper measurement setup for this purpose is standard waveguide using the dominant TE_{10} mode, with the electric field oriented parallel to the short wall of the guide. We can obtain the conductivity tensor by using two sample orientations: with the fibers parallel to the electric field vector, and with the fibers perpendicular.

An RCCF sample is fabricated by co-author Rosca using the following procedure. The epoxy resin Epon 862 and the curing agent Epikure W are produced by Hexion Specialty Chemicals [31]. The unidirectional carbon cloth (T300) is purchased from MF Composites [32]. The mixture of resin and the curing agent (26.4 wt%) is degassed in a vacuum oven at 90 °C for 30 min. Next, one ply of unidirectional carbon cloth is impregnated with the mixture and placed between two aluminum plates coated with demolding agent. Finally, the plates are tightened together by bolt joints, and the composite is cured at 120°C for 6 hours.

Because the electrical properties of RCCF are not noticeably frequency-dependant [17, 18], the RCCF sample was characterized using a G-band waveguide setup and the conductivity values were used at the lower frequencies of the RFID bands. The RCCF composite conductivity is found to be 3500 S/m along fiber direction and 10 S/m perpendicular to the fibers.

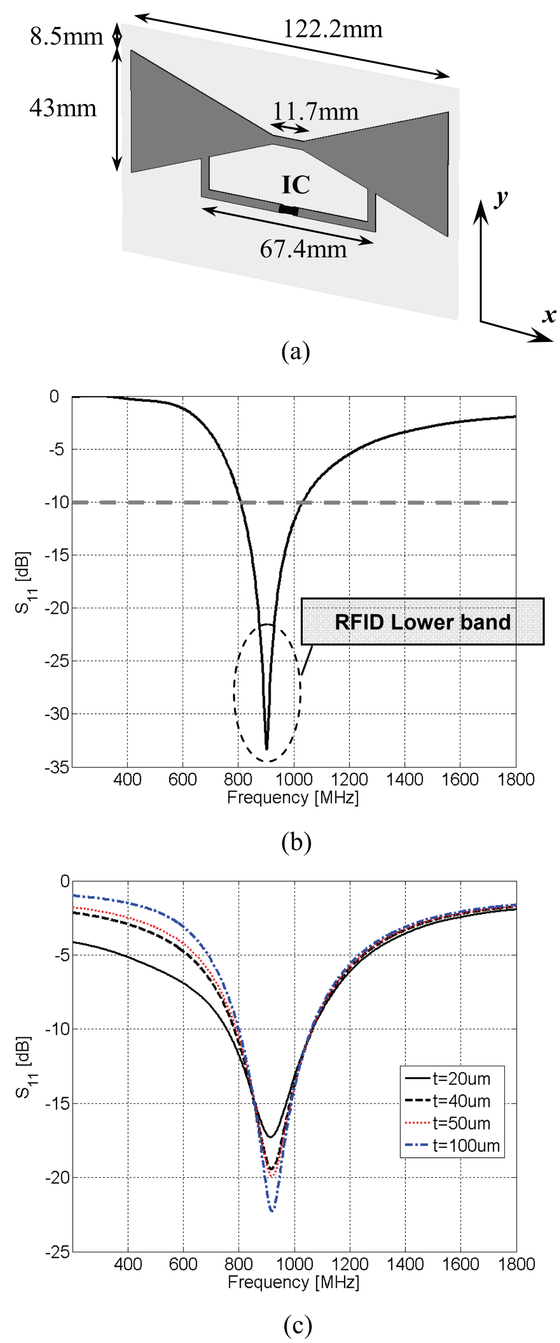


Fig. 3. (a) T-match folded bow-tie RFID antenna, (b) Return loss of the antenna with radiation element made of copper. (c) Return loss with radiation element made of SWCNT.

B. SWCNT Thin-Film Composite and Method of Preparation

A SWCNT thin-film composite is sometimes called a “bucky paper” and is shown in Fig. 2. Since the SWCNT composite has an isotropic conductivity, the standard coaxial cable fixture is used for sample characterization.

Thin film devices made of SWCNT exhibit high conductivity and sufficient mechanical strength that there is no need for a binder. For the standard coaxial setup, bucky papers were prepared by a filtration technique. First a given amount of SWCNTs (Nikkiso Co. [33]) is dispersed by sonication (Misonix 3000) in N, N-dimethyl formamide (DMF) for 30 minutes at 27W sonication power. Next, the SWCNT suspension is filtered on a polyamide membrane filter with diameter and pore-size of 90 mm and 45 μm respectively. The solvent is evaporated in a vacuum oven at 120 °C for 6 hours. The dried bucky paper of ~40 μm thickness is easily detached from the filter membrane and glued to an epoxy plate of 0.5 mm to ensure sufficient rigidity.

By characterizing the fabricated composite sample using the coaxial setup, the dielectric constant and conductivity in the RFID frequency band are obtained as $\varepsilon_r = 5$ and $\sigma = 25000$ S/m, respectively.

III. COMPOSITE RFID ANTENNA PERFORMANCE

In what follows, two well-known types of RFID antennas, namely the T-match bow-tie antenna and the meander line antenna (MLA), are considered. The return loss, radiation efficiency, gain, and bandwidth of each antenna are compared with the radiating element made of composite and of metal. The antennas are modeled with MWS, which uses the finite integration technique (FIT) to solve the discretized Maxwell equations. The details of FIT can be found in [29], [34-36]. The composite material is characterized using the permittivity and conductivity obtained above.

A. T-Match Bow-Tie Antenna

The T-match folded bow-tie RFID antenna is shown in Fig. 3 (a). The antenna is excited by a lumped port between arms of the T. The input impedance of the RFID microchip (TI RI-UHF-Strap-08 IC) [37] at the port is chosen as 380 Ω. The radiation element is placed on a 130 mm × 80 mm substrate with dielectric constant ε_r = 3.4 and thickness 0.26 mm. The return loss of the antenna with a copper radiation element is shown in Fig. 3 (b). The gain and radiation efficiency of the antenna are 2.4 dB and 97%, respectively.

1) SWCNT Composite Antenna

The radiation element was then changed to the SWCNT composite material, modeled using its equivalent permittivity and conductivity. The return loss of the RFID antenna for different thicknesses of composite material is shown in Fig. 3 (c). The resonant frequency of the RFID antenna with the composite radiation element is not much different from that with the metal element.

Due to the much lower conductivity of composites compared to metals, the ohmic loss (R_{Loss}) of an antenna with composite radiating element is higher. Therefore, the gain and radiation efficiency (η) of

Table 1: Radiation efficiency of the nanotube composite antenna (f = 921 MHz).

Thickness (μm)	σ = 10K (S/m)	σ = 15K (S/m)	σ = 20 K (S/m)	σ = 25 K (S/m)
20	37.83 %	46.94 %	54.25 %	59.35 %
40	55.78 %	62 %	68.57 %	72.34 %
50	59.4 %	67 %	74.3 %	76 %
100	72.42 %	79.15 %	82.8 %	85.2 %

Table 2: Maximum gain of the nanotube composite antenna.

Thickness (μm)	σ = 10 K (S/m)	σ = 15 K (S/m)	σ = 20 K (S/m)	σ = 25 K (S/m)
20	-1.94 dB	-0.61 dB	-0.01 dB	0.37 dB
40	0.005 dB	0.63 dB	0.97 dB	1.19 dB
50	0.37 dB	0.9 dB	0.92 dB	1.4 dB
100	1.2 dB	1.57 dB	1.76 dB	1.88 dB

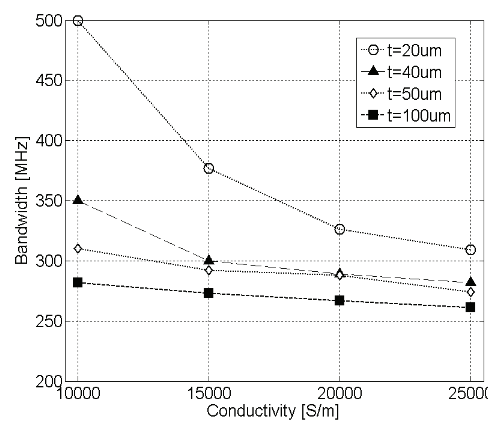


Fig. 4. The bandwidth of SWCNT antenna versus conductivity (f = 921 MHz).

composite antenna are lower than for a metal antenna. The ohmic loss of a conductive box with effective conductivity of σ_{eff} can be expressed as

$$R_{loss} = \frac{L}{\sigma_{eff} A_{eff}} \tag{3}$$

where A_{eff} is the effective area along a current path of length L. Since for a composite antenna the current flows inside the volume of radiating element, A_{eff} can be controlled by changing the thickness (t) of radiating element and skin depth of composite through the conductivity. Therefore, the gain of the composite antenna can be adjusted by changing both t and σ_{eff}. Tables 1 and 2 show the effect of the thickness and the conductivity on the composite antenna's performance, computed using the MWS model. The values can be compared with the copper antenna's gain of 2.4 dB and efficiency of 97%. Note that using the parameters of the sample described in Section II, t = 40 μm and σ = 25000 S/m, the radiation efficiency and gain are 72.34% and 1.19dB, respectively.

The tables show that as the conductivity and thickness of the composite increases, both the gain and the efficiency increase to approach the values for the metal antenna of 2.4 dB and 97%. However, as shown in Fig. 4, the bandwidth of the antenna for a return loss better than -10 dB is reduced by decreasing the antenna loss. In resonant circuits, as the ohmic loss decreases, the bandwidth decreases and the Q-factor increases, and the composite antenna shows this behavior. The -10dB bandwidth of the antenna with a metal radiating element is 822 to 1053 MHz, or 231 MHz, which is lower than the composite antenna. For example, the composite antenna with thicknesses of 20 μm and 40 μm is 310 MHz, and 270 MHz bandwidth, respectively. It is seen that more flexibility of design is attained by using composite material instead of metal.

The maximum read-range ($d_{\max}$) of an RFID antenna is obtained from [4]

$$d_{\max} = \frac{\lambda}{4\pi}\sqrt{\frac{G_{tag}.EIRP_t}{P_{chip}}} \tag{4}$$

where G_{tag}, $EIRP_t$ and P_{chip} are the gain of RFID tag, the effective isotropic radiated power of the reader and the sensitivity power level of RFID IC, respectively. With $EIRP_t$ = 0.5 W, the maximum allowed value, and P_{chip} = 1 mW [3], $d_{\max}$ of antenna with metal and fabricated-SWCNT radiating element are 76.52 cm and 66.54 cm, respectively.

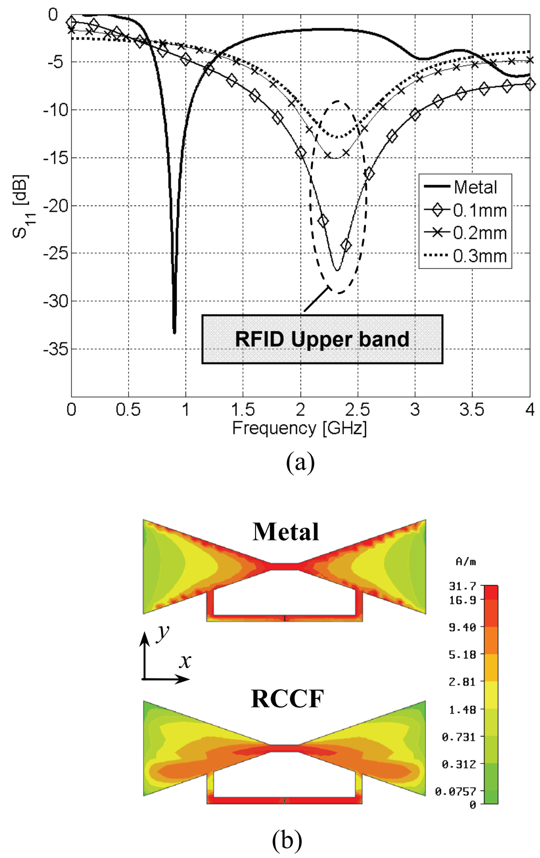
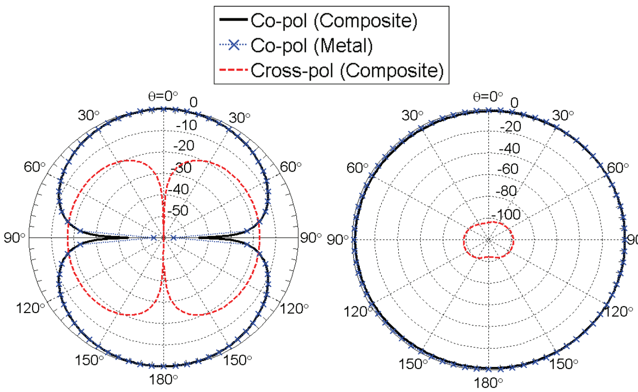


Fig. 5. (a) Return loss of RCCF antenna, (b) Current distribution on the radiation element at resonant frequency (f = 2330 MHz).

2) RCCF Composite Antenna

The second composite material we have chosen for study is RCCF composite. The direction of fibers determines the direction in which the anisotropic conductivity is large. MWS enables us to model anisotropic materials using the permittivity tensor. Using the tensor permittivity values for the fabricated RCCF sample, two antennas were modeled: one having the fibers oriented in the x direction of Fig. 3(a), and the other with the fibers in the y direction. It was observed that the current distribution on the antenna with the fibers oriented in the x direction flows from one arm to the other of bow-tie and then the antenna radiates effectively. The return loss of the RCCF antenna with x-directed fibers is shown in Fig. 5 (a) for different thicknesses of composite. Compared to the metal antenna, the resonant frequency is shifted upwards to about 2450 MHz in the RFID upper band. The reason for this shift can be explained by comparing the current flow on the composite radiating element in Fig. 5 (b) with that on the metal antenna. The current flow on the metal antenna resembles that on a dipole, using the full length of the antenna, corresponding to resonance in the lower RFID band. However, the current flow on the composite antenna is confined to the section of the antenna adjacent to the T-match, and the behavior is more like that of a short dipole antenna, with a correspondingly higher resonant frequency. The current flow at the ends of the T-match section is quite small.



(a) (b)

Fig. 6. Normalized radiation pattern of bow-tie antenna, (a) *E*-plane, (b) *H*-plane.

Table 3: Radiation efficiency and -10dB BW of the RCCF composite antenna.

Thickness (mm)	η (%)	BW (MHz)
0.1	35.17	1320
0.2	39.27	730
0.3	40.1	581

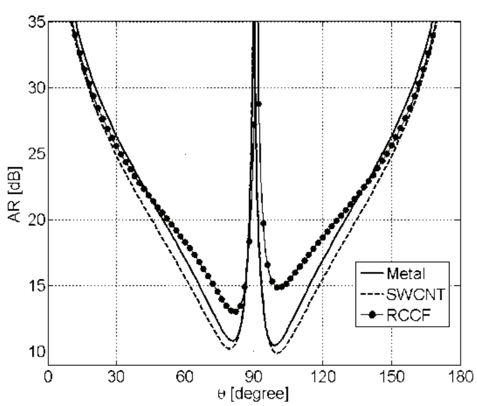


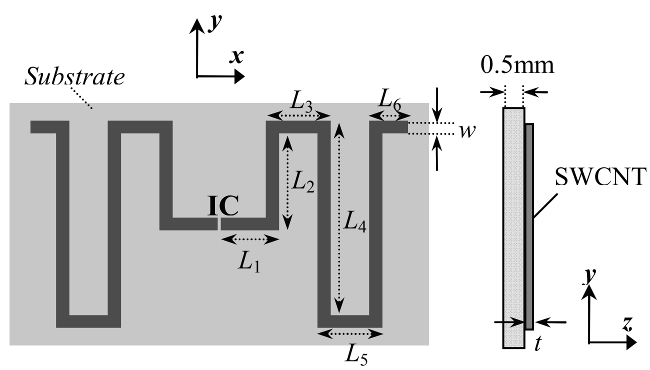
Fig. 7. *E*-plane axial ratio of bow-tie antenna with different radiating element.

The normalized radiation pattern in both *E*- and *H*-plane at the frequency of resonance, 2330 MHz, is shown in Fig. 6. It is observed that using RCCF composite instead of metal changes the radiation pattern very little. However, the polarization property of the RCCF antenna would be affected due to the anisotropic property of RCCF material. Fig. 7 shows the axial ratio (AR) of bow-tie antenna at *E*-plane. It is observed that the polarization purity of RCCF composite antenna is improved compared to the metal and SWCNT antennas.

The radiation efficiency and gain of the antenna made of 0.2 mm-thick RCCF are computed at resonant frequency as 39.27% and -0.2 dB, respectively. Using (4), the maximum read-range of RCCF antenna is obtained as d_{max} = 21.3 cm. The radiation efficiency and -10dB bandwidth of the antenna for different thicknesses is reported in Table 3. Although the gain/read-range of the composite antenna is relatively low compared to the metal antenna, it should be noted that the antenna covers the microwave RFID frequency band centered at 2.45 GHz along with a wide bandwidth (BW = 1.32 GHz) due to the interesting properties of RCCF composite material.

B. Meander Line Antenna (MLA)

Figure 8 shows a meander-line antenna (MLA). Due to its small size and space-filling geometry, the MLA is one of the most desirable antennas for RFID applications [7], [38-40]. In the MLA design, a straight dipole is bent to take less length on the substrate, and this also lowers the resonant frequency. In addition, the radiation resistance is changed,



(a) (b)

Fig. 8. (a) MLA structure, (b) Cross-view.

which should be taken into account for matching-circuit design. The planar MLA of Fig. 8 with dimensions L_1 = 9mm, L_2 = 15.25 mm, L_3 = 10 mm, L_4 = 30.5 mm, L_5 = 10 mm, L_6 = 6 mm, and w = 2 mm resonates in the RFID lower frequency band around 950 MHz. The substrate is 0.5mm-thick epoxy with ε_r = 3 and loss tangent tanδ = 0.0013. The gain, radiation resistance and d_{max} of MLA with a copper radiating element are given in Table 4. The -10 dB bandwidth of maximum 24 MHz is achieved.

Table 5 gives the performance of the MLA when the radiating element is SWCNT composite, with a width of 2 mm, for various thicknesses of the SWCNT material. It is observed that the bandwidth for 30 μm thickness is much wider than the bandwidth of 24 MHz of the metal antenna. The bandwidth decreases with increasing thickness of the composite as the resistance per unit length of the arms of the antenna decreases. However, the gain is low compared to the metal antenna. The input impedance of the MLA is quite different from the RFID IC's impedance of 380 ohms, needing a matching circuit between antenna and IC. The 30 μm composite antenna has a resistance of 106 ohms, much closer to the IC's 380 ohms than the resistance of the metal antenna of 12 to 15 ohms, hence the matching circuit could be simplified. The input impedance can also be adjusted by using composites with different values of conductivity, to get closer to 380 ohms. Therefore composites provide more flexibility in the design. The center frequency of resonance for nanotube antenna can be adjusted by tuning the length of the MLA.

The ohmic loss of nanotube MLA can be controlled by varying the width of the line (w) and the conductivity (σ) of composite, as well as the thickness of line. The effect of w and σ on the gain and bandwidth of MLA is shown in Fig. 9. The gain could be improved considerably by using thicker and wider MLA. However, it can be seen that one may compromise between the gain and bandwidth.

IV. EXPERIMENTAL RESULTS

In order to investigate the composite antennas performance experimentally and to verify simulation results, we fabricated the monopole configuration of the SWCNT dipole bow-tie and MLA antennas as shown in Fig. 10. For SWCNT antenna fabrication, the same procedure explained in Section II-B is used.

Table 4: MLA performance with a copper radiating element (t =40 μm).

w (mm)	f_o (MHz)	η (%)	Gain (dB)	R_r (Ω)	d_{max} (cm)
1	873	96.71	1.84	12.51	75.57
2	914	97.94	1.86	14.82	72.35
3	959	98.22	1.87	15.3	69

Table 5: MLA performance with an SWCNT radiating element (w=2mm).

Thickness (μm)	f_0 (MHz)	η (%)	Gain (dB)	R_r (Ω)	BW (MHz)	d_{max} (cm)
30	966.5	15.24	-6.21	106	239	27
40	954.6	18.7	-5.32	81.5	162	30.3
50	950.4	22	-4.6	67.61	149.3	33
100	976.35	37.12	-2.35	43.58	93	42

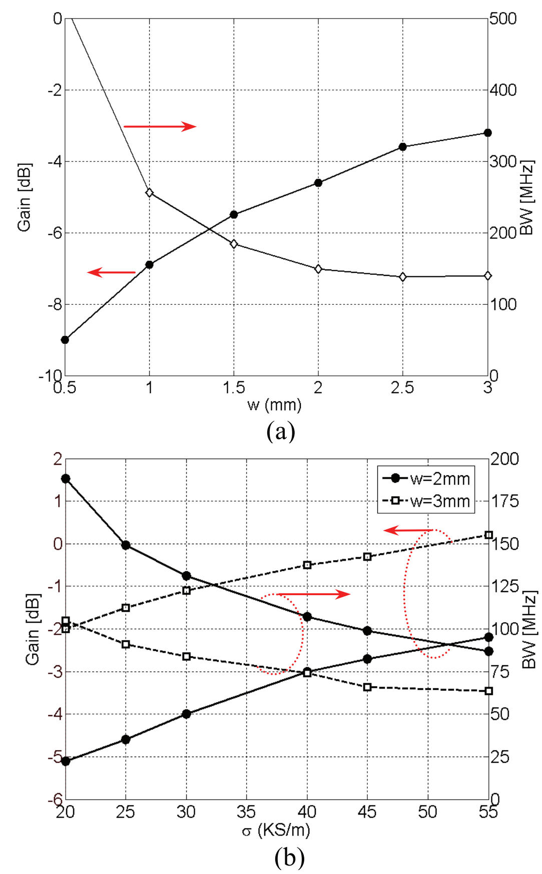
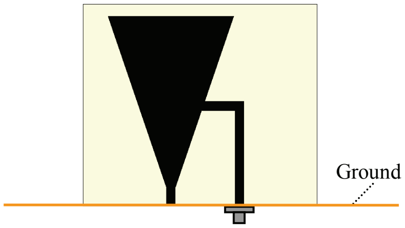
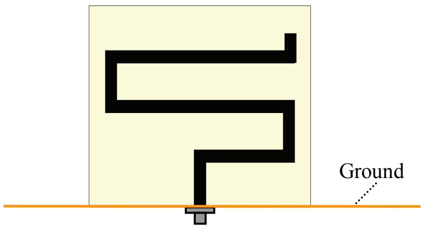


Fig. 9. Gain-bandwidth diagram of SWCNT MLA versus (a) w (σ = 25KS/m, t = 50µm, f = 950.4 MHz), (b) σ (t = 100µm, f = 976.35 MHz).

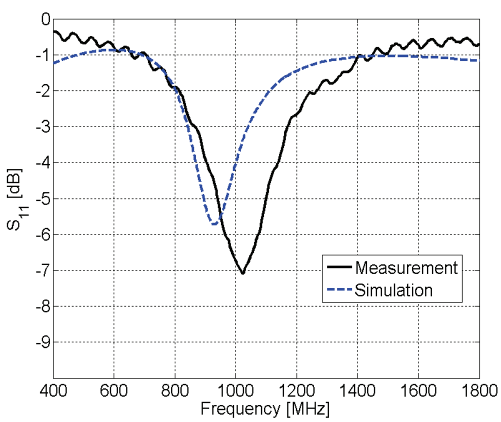


(a)

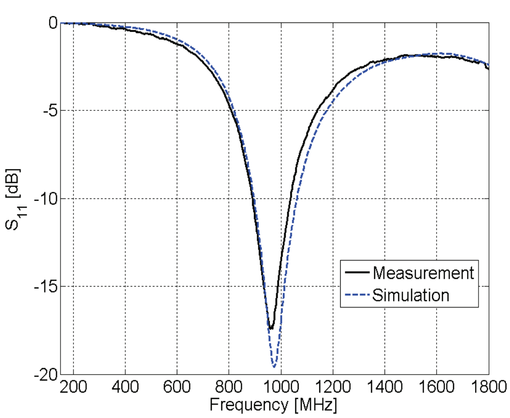


(b)

Fig. 10. Monopole configuration of SWCNT composite antennas, (a) T-match bow-tie, and (b) MLA.



(a)



(b)

Fig. 11. Return loss of SWCNT composite antenna, (a) T-match bow-tie, and (b) MLA.

Table 6: Simulation and measurement results for the SWCNT bow-tie antenna and MLA antenna.

Type of Antenna		f_o (MHz)	R_r (Ω)
Bow-tie	Simulation	930	157
	Measurement	1013	130.7
MLA	Simulation	963	40.2
	Measurement	965	54.3

However, in this case the filter membrane was covered by a mask of silicon rubber that allowed the nanotube to accumulate in the shape of the antenna. The monopole composite antenna mounted on a ground plane is fed through a 50-ohm SMA connector from the bottom. The size of ground plane for the bow-tie antenna is 120mm × 160mm, and for the MLA antenna is 100mm × 100mm. The composite material thickness is 40 μm. The dimensions of the bow-tie are as reported in Fig. 3(a). The MLA parameters are $L_1 = 8.5$ mm, $L_2 = 15$ mm, $L_3 = 10$ mm, $L_4 = 30.2$ mm, $L_5 = 10$ mm, and $L_6 = 3$ mm, and $w = 2$ mm.

Using HP8720 network analyzer, the return loss of composite antennas is measured as shown in Fig. 11. Satisfactory agreement is seen between the MWS simulation and the measurement. The small shift of measured resonance frequency can be explained by material and manufacturing tolerance. The resonant frequency and radiation resistance of both composite antennas are reported in Table VI.

V. CONCLUSION

The use of continuous carbon fiber composite and carbon nanotube composite is investigated numerically and experimentally for building antennas for RFID applications. The metal is replaced with CFC in a T-match bow-tie antenna and a meander-line antenna. In addition to low cost, low weight, ease of fabrication and good corrosion resistance, the composite antennas are shown to have promising characteristics compared to a metal antenna. Although the gain and the read-range of composite antennas are lower than those of metal antennas, the bandwidth is improved considerably for both the RCCF and the CNT antennas. Furthermore, the matching between input impedances of the RFID IC chip and the antenna can be controlled by using composite materials with different values of conductivity and thickness. It is observed that new antenna designs can be developed using the RCCF composites. One may also control the direction of current flow using the anisotropic conductivity of continuous carbon fiber composite, and this suggests many possibilities for new antenna configurations. Studying the composite antenna performance carefully, we show that CFCs can be efficiently used instead of metal as the material for fabricating the radiating element.

ACKNOWLEDGMENT

The authors would like to thank Natural Sciences and Engineering Research Council of Canada (NSERC), Bell Helicopter Textron Canada Ltd., Delastek Ltd. and Consortium for Research an Innovation in Aerospace in Quebec (CRIAQ) for supporting this work.

The SWCNT samples were generously offered by Nikkiso Co.

REFERENCES

[1] S.-L. Chen, and K.-H. Lin, "A slim RFID tag antenna design for metallic object applications," *IEEE Antennas and Wireless Propagat. Lett.*, vol. 7, pp. 729-732, 2008.

[2] G. Marrocco, "The art of UHF RFID antenna design: impedance-matching and size-reduction techniques," *IEEE Antennas and Propagat. Magazine,* vol. 50, pp. 66-79, 2008.

[3] K. Finkenzeller, *RFID Handbook*, 2nd ed. New York: Wiley, 2003.

[4] P. V. Nikitin, K. V. S. Rao, S. F. Lam, V. Pillai, R. Martinez, and H. Heinrich, "Power reflection coefficient analysis for complex impedances in RFID tag design," *IEEE Trans. Microw. Theory Tech.*, vol. 53, pp. 2721-2715, 2005.

[5] M. Hirvonen, K. Jaakkola, P. Pursula, and J. Säily, "Dual-band platform tolerant antennas for radio-frequency identification," *IEEE Trans. Antenna Propagat.* vol. 54, pp. 2632-2637, 2006.

[6] K. V. Seshagiri Rao, P. V. Nikitin, and S. F. Lam, "Antenna design for UHF RFID tags: a review and a practical application," *IEEE Trans. Antenna Propagat.* vol. 53, pp. 3870-3876, 2005.

[7] G. Marrocco, "Gain-Optimized self-resonant meander line antennas for RFID applications," *IEEE Antennas and Wireless Propagat. Lett.*, vol. 2, pp. 302-305, 2003.

[8] H. Rmili, J.-L. Miane, H. Zangar, and T. Olinga, "Design of microstrip-fed proximity-coupled conducting polymer patch antenna," *Microw. Opt. Technol. Lett.*, vol. 48, pp. 655-660, 2006.

[9] Y. Bayram, Y. Zhou, J. L. Volakis, B.-S. Shim and N. A. Kotov, "Conductive textiles and polymer-ceramic composites for novel load bearing antennas," *Proc. of IEEE Antenna and Propagation Symposium*, July 2008.

[10] P. V. Nikitin, S. Lam, and K. V. S. Rao, "Low cost silver ink RFID tag antennas," in *Proc. IEEE Antennas Propag. Society Int. Symp.*, pp. 353-356, 2005.

[11] L. Yang, A. Rida, R. Vyas, and M. M. Tentzeris, "RFID tag and RF structures on a paper substrate using inkjet-printing technology," *IEEE Trans. Microw. Theory Tech.*, vol. 55, pp. 2894-2901, 2007.

[12] S. Ludmerer, "Conductive Inks for RFID Antenna: the low cost high speed route to RFID labels," Parelec. Inc. www.parelec.com.

[13] R. A. Tellakula, V. K. Varadan, T. C. Shamy, and G. N. Mathur, "Carbon fiber and nanotube based composites with polypyrrole fabric as electromagnetic absorbers," *Smart Mater. Struct.*, vol. 13, pp. 1040-1044, 2004.

[14] M. H. Choi, B. H. Jeon, and I. J. Chung, "The effect of coupling agent on electrical and mechanical properties of carbon fiber/phenolic resin composites," *Polymer*, vol. 41, pp. 3243-3252, 2000.

[15] M. De Rosa, F. Sarasini, M. S. Sarto, and A. Tamburrano, "EMC impact of advanced carbon fiber/carbon nanotube reinforced composites for next-generation aerospace applications," *IEEE Trans. Electromagn. Compat.*, vol. 50, pp. 556-563, 2008.

[16] C. Buccella, "Quasi-Stationary analysis of the electric field in anisotropic laminated composites," *IEEE Trans. Industry App.*, vol. 35, pp. 1296-1305, 1999.

[17] C. L. Holloway, M. S. Sarto, and M. Johansson, "Analyzing Carbon-Fiber Composite Materials with Equivalent-Layer Models," *IEEE Trans. on Electromagn. Compatibility*, vol. 47, no. 4, pp. 833-844, 2005.

[18] Mehdipour, C. W. Trueman, A. R. Sebak, I. D. Rosca, and S. V. Hoa, "Shielding effectiveness analysis of multilayer carbon-fiber composite materials," *Proc. of General Assembly of the International Union of Radio Science* (*URSI*), 2008.

[19] M. S. Sarto, and C. L. Holloway, "Effective boundary conditions for the time-domain analysis of the EMC performances of fiber composites",*Proc. of IEEE International Symposium on Electromagn. Compat.*, pp. 462-467, 1999.

[20] W. Bauhofer, and J. Z. Kovacs, "A review and analysis of electrical percolation in carbon nanotube polymer composites", *Compos. Sci. Technol*., 2008.

[21] R. K. Challa, D. Kajfez, V. Demir, J. R. Gladden, and A. Z. Elsherbeni, "Characterization of multiwalled carbon nanotube (MWCNT) composites in a waveguide of square cross section," *IEEE Microwave and Wireless Components Lett*., vol. 18, no. 3, pp. 161-163, 2008.

[22] F. H. Gojny, M. H. G. Wichmann, B. Fiedler, and K. Schulte, "Influence of different carbon nanotubes on the mechanical properties of epoxy matrix composites - A comparative study," *Compos. Sci. Technol*., vol. 65, pp. 2300-2313, 2005.

[23] B. Hornbostela, U. Leuteb, P. Potschkec, J. Kotza, D. Kornfelda, P.-W. Chiud, and S. Rotha, "Attenuation of electromagnetic waves by carbon nanotube composites," *Physica E*, vol. 40, pp. 2425-2429, 2008.

[24] Y. Huang, N. Li, Y. Ma, F. Du, F. Li, X. He, X. Lin, H. Gao, and Y. Chen, "The influence of single-walled carbon nanotube structure on the electromagnetic interference shielding efficiency of its epoxy composites," *Carbon*, vol. 45, pp.1614-1621, 2007.

[25] Z. Liu, G. Bai, Y. Huang, Y. Ma, F. Du, F. Li, T. Guo, and Y. Chen, "Reflection and absorption contributions to the electromagnetic interference shielding of single-walled carbon nanotube/polyurethane composites," *Carbon*, vol. 45, pp. 821-827, 2007.

[26] Mehdipour, A.-R. Sebak and C. W. Trueman, and S. V. Hoa "Carbon-Fiber composite T-match folded bow-tie antenna for RFID applications," to be presented *in IEEE Antenna and Propagation Symposium*, 2009.

[27] *Concordia Center for Composites* (*CONCOM*), Concordia University, QC, Canada, http://concom.encs.concordia.ca, 1979.

[28] *CST – Microwave Studio*, Computer Simulation Technology, 2009.

[29] CST of America, "Efficient, accurate, reliable EM simulation tool", *Microwave Journal*, Oct. 2008.

[30] R. K. Challa, D. Kajfez, J. R. Gladden, and A. Z. Elsherbeni, "Permittivity measurement with a non-standard waveguide by using TRL calibration and fractional linear data fitting," *Progress In Electromagnetics Research B,* vol. 2, pp. 1-13, 2008.

[31] Hexion Specially Chemicals Inc., Columbus, OH, 2006.

[32] Freeman Mfg. & Supply Co., Columbus, OH, 2001.

[33] *Composite Tech. Unit.*, Nikkiso Co., Ltd., Tokyo, Japan, 2000.

[34] Munteanu, and T. Weiland, *RF & microwave simulation with the finite integration technique – from component to system design*, Springer Berlin Heidelberg, 2007.

[35] M. Clemens and T. Weiland, "Discrete electromagnetism with the finite integration technique," *Progress In Electromagnetics Research, PIER* 32, pp. 65-87, 2001.

[36] R. Potthast, and L. Kuhn, "On the convergence of the finite integration technique for the anisotropic boundary value problem of magnetic tomography," *Mathematical Methods in the Applied Sciences*, vol. 26, pp. 739-757, 2003.

[37] *UHF Frequency ICs*, Texas Instrument Inc., Dallas, TX, http://focus.ti.com/docs/prod/ folders/ print/ri-uhf-strap-08.html, 2006.

[38] C. T. Rodenbeck, "Planar miniature RFID antennas suitable for integration with batteries," *IEEE Trans. Antenna Propagat.* vol. 54, pp. 302-305, 2006.

[39] J. Rashed, and C. T. Tai, "A new class of resonant antennas," *IEEE Trans. on Antennas and Propagat.* , vol. 39, pp. 1428-1430, 1991.

[40] T. J. Warnagiris and T. J. Minardo, "Performance of a meandered line as an electrically small transmitting antenna," *IEEE Trans. on Antennas and Propagat.* , vol. 46, pp. 1797-1801, 1998.

Aidin Mehdipour received the B.S. degree from Amirkabir University of Technology, Tehran, Iran, in 2003 and the M.S. degree from University of Tehran, in 2006, both in electrical engineering. He is currently working toward the Ph.D. degree at Concordia University, Montreal, Canada. His main research interests include advanced carbon fiber composites electromagnetic analysis, novel material development for shielding and antenna applications, small antenna design, RFID and wideband/ultrawideband antennas. In 2006, he was a senior research engineer of the Iran Telecommunication Research Center (ITRC) in a project on ultra-wideband antenna design. He serves as a reviewer for the *IEEE Transactions on Electromagnetic Compatibility*. He has authored and co-authored over more than 20 papers in referred journals and conference proceedings. Mr. Mehdipour is the recipient of the David J. Azrieli Graduate Fellowship, as the highest ranking Concordia University fellowship award, and the France and André Desmarais Graduate Fellowship for the 2009-2010 academic years.

Iosif Daniel Rosca received his engineer diploma in Polymer Science and Technology from Polytechnic University of Bucharest, Romania. He earned his Ph.D. in Chemistry with Prof. J.M. Vergnaud at Jean Monnet University, Saint-Etienne, France. He is associated professor of Polymer Science and Technology at the Polytechnic University of Bucharest, Romania. Rosca spent 2 years as JSPS Postdoctoral Fellow at Hokkaido University, Japan. He is currently a Research Associate with Prof. S. V. Hoa at Concordia University, Canada. His present research focuses on fabrication and application of polymer composites based on carbon nanomaterials.

Abdel-Razik Sebak received the B.Sc. degree (with honors) in Electrical Engineering from Cairo University, Egypt, in 1976 and the B.Sc. degree in Applied Mathematics from Ein Shams University, Egypt, in 1978. He received the M.Eng. and Ph.D. degrees from the University of Manitoba, Winnipeg, MB, Canada, in 1982 and 1984, respectively, both in electrical engineering. From 1984 to 1986, he was with the Canadian Marconi Company, Kanata, Ontario, working on the design of microstrip phased array antennas. From 1987 to 2002, he was a Professor in the Electrical and Computer Engineering Department, University of Manitoba, Winnipeg. He is currently a Professor of Electrical and Computer Engineering, Concordia University, Montreal. His current research interests include phased array antennas, computational electromagnetics, integrated antennas, electromagnetic theory, interaction of EM waves with new materials and bio-electromagnetics. Dr. Sebak received the 2007-2008 Faculty of Engineering, Concordia University double Merit Award for outstanding Teaching and Research. He has also received the 2000 and 1992 University of Manitoba Merit Award for outstanding Teaching and Research, the 1994 Rh Award for Outstanding Contributions to Scholarship and Research in the Applied Sciences category, and the 1996 Faculty of Engineering Superior Academic Performance. Dr. Sebak has served as Chair for the IEEE Canada Awards and Recognition Committee (2002-2004) and IEEE Canada CONAC (1999-2001). He has also served as Chair of the IEEE Winnipeg Section (1996-97). He was the Technical Program Co-Chair (2006) and served as the Treasurer (1992, 1996, and 2000) and Publicity Chair (1994) for the Symposium on Antenna Technology and Applied Electromagnetics (ANTEM). Dr. Sebak has also served as Chair (1991-92) of the joint IEEE AP/MTT/VT Winnipeg Chapter. He received, as the Chapter Chair, the 1992 IEEE Antennas and Propagation Society Best Chapter

Award. He is a Senior Member of the IEEE, and a member of the International Union of Radio Science Commission B.

Christopher W. Trueman received his Ph.D. from McGill University in 1979. He has applied the methods of computational electromag-netics to problems such as aircraft antenna performance, antenna-to-antenna coupling and EMC on aircraft, aircraft and ship radar cross-section at HF frequencies, suppression of scattering of the signal of a commercial radio station from power lines, dielectric resonators, unconditionally-stable formulations for the finite-difference time-domain method, and the fields of portable radios such as cellular phones held against the head. Recently, his research has investigated the radar cross-section of ships at VHF frequencies, composite materials for aircraft, indoor propagation, and EMC issues between portable radios and medical equipment. Dr. Trueman is currently the Associate Dean for Academic Affairs in the Faculty of Engineering and Computer Science at Concordia University.

Dr. Suong Van Hoa is a professor in the Department of Mechanical and Industrial Engineering at Concordia University, Montreal, Quebec, Canada. He is also Director of Concordia Center for Composites. He has been working on composites materials and structures since 1979 and on polymer nanocomposites since 2000. He has worked on the incorporation of nanoparticles such as nanoclays, carbon nanotubes into composites materials. He has also developed self healing composite materials using microcapsules. He has published more than 500 articles in scientific journals and conferences, and many patents. Dr. Hoa is the recipient of the NanoAcademia prize from Nanoquebec in 2008.