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Fabrication and Characterization of Graphene Antenna for Low-Cost and Environmentally Friendly RFID tags

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***Abstract*— We present the fabrication and testing of graphene-based dipole antennas on cardboard which is a promising low-cost, recyclable, and flexible substrate for future wireless electronics. The article presents the details of the manufacturing, as well as results from the measurements and simulations. The measured sheet resistance of graphene antenna is 1.9 Ω/sq. Overall, a graphene-based planar dipole antenna with the length of 143 mm achieved the measured total efficiency of 40% and the realized gain of –2.18 dBi at 889 MHz. Moreover, a passive ultra-high-frequency radio-frequency tag based on a graphene dipole antenna on cardboard achieved the attainable read range of more than five meters at 950 MHz.**

***Index Terms*—Graphene-based antenna, radio frequency identification (RFID), doctor-blading technique.**

I. INTRODUCTION

Printable electronics are known as one of the emerging methods for fabrication of the electronic devices. It has wide applications in the radio frequency identification (RFID), environmental sensors and wearable electronics [1]. Printed techniques and their integration with carbon nanomaterials, specially graphene, open new horizon in the future electronic and telecommunication technology [2]. Graphene is a 2D nanomaterial with outstanding properties such as high charge mobility ($200000\ cm^2V^{-1}s^{-1}$), zero band gap, high thermal conduction ($5000\ Wm^{-1}K^{-1}$), high mechanical strength ($130\ GPa$), high surface area ($2630\ m^2\ g^{-1}$), and excellent biocompatibility [3], [4]. Due to these remarkable properties of graphene, it has great potential to provide high conductive inks, which can be integrated with the flexible and transparent substrates to produce chemically stable, mechanically flexible, and low cost RF products [1].

Recent works [1] and [5] demonstrate graphene based antennas for RFID application. In [1] good printable RFID antenna performance is achieved through rolling compression method. A binder-free graphene laminate is used but the fabrication process to achieve low resistivity requires multiple time compression which makes the manufacturing difficult on large scale. In [5] a graphene-based dipole antenna is presented for RFID application but maximum range for tag interrogation is 2.04 m.

In this article, we present a simple, fast and easy way to fabricate graphene-based antennas for RFID applications by doctor-blading method on the cardboard. First we fabricated graphene-based dipole antenna and measured its RF properties (S11, antenna realized gain, antenna efficiency, and radiation pattern). After verifying the performance of dipole antenna, we fabricated the tag antenna based on [6] design (the selected design has input impedance same as of used RFID IC input impedance). Moreover, we present the simulated and measured key property (theoretical read range) of the tag.

II. FABRICATION PROCESS

We used doctor-blading technique for antennas fabrication. Doctor-blading technique is a one-step and simple way to deposit graphene-based ink. In this method, a constant amount of ink is spread on the rigid or flexible substrates (see Fig. 1(a)). The wet layer thickness is mainly adjusted by the size of gap between the blade and the substrate and it depends on the printing speed and flow behavior. Furthermore, blade specifications such as shape, substance and edge profile play an important role on the fabrication process. The other effective operating parameters on the film formation are surface temperatures, surface energy of the substrate, surface tension and viscosity of the ink [7–9].

A high-viscosity graphene screen ink (Vor-ink^{TM} X103) was spread with a doctor blade across the mechanical mask on the substrate. The printing speed and gap width between a blade and the substrate were adjusted to 14 mm/s and zero, respectively. So, the final wet thickness is close to the mechanical mask's thickness. Manually doctor-bladed samples were dried for 4 minutes at 130 °C. The fabrication process is schematically shown in Fig. 1(a).

Fig. 1(b) and (c) shows the fabricated dipole antenna and RFID tag. The cardboard has relative permittivity, loss

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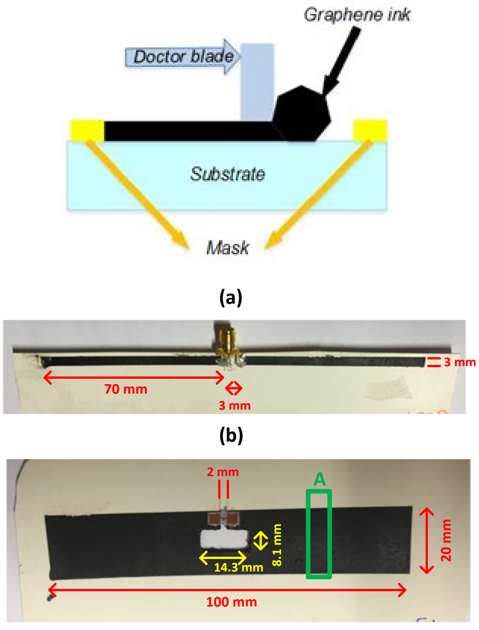


(a)

(b)

(c)

Fig. 1. (a) Schematic image of the doctor-blade technique, (b) Dipole antenna, and (c) RFID tag.

tangent, and thickness of 1.8, 0.015, and 560 µm, respectively [10]. A dipole antenna is designed with 70 mm length of one arm with 3 mm width. Gap between the arms is 3 mm. We followed the RFID tag antenna dimensions as explained in [6].

In Table I, thickness (t), sheet resistance (R_t), conductivity (σ), and resistivity (ρ) of fabricated samples are mentioned. The 4-point sheet resistance was measured by Thales software and Zennium device equipped with a special head of four probes. According to the head, there is a limitation to measure sheet resistance of narrow patterns like dipole antenna. As a result, we are able to measure sheet resistance of RFID tag antenna only. But manufacturing of both dipole and RFID tag antennas is same, so we can say that dipole antenna has also the same sheet resistance as of RFID tag antenna.

The thickness of the printed samples was measured by Alicona optical profilometer (a highly flexible optical 3D measurement system). According to Fig. 2(a) the thickness of the coated graphene for RFID tag varies mostly between 30 to 60 µm, although some peaks with 120 µm thickness can be seen in Fig. 2(a), which is as a result of ink agglomeration. The average thickness is 38 µm for RFID tag antenna, and 42 µm for dipole antenna and RFID tag antenna. Furthermore, the printed surface has uneven structure which is probably as a result of the porous surface of cardboard (see Fig. 2(b)). According to the rough and relatively porous nature of cardboard, the ink penetrated approximately 30 µm into the cardboard (see Fig. 2(c)).

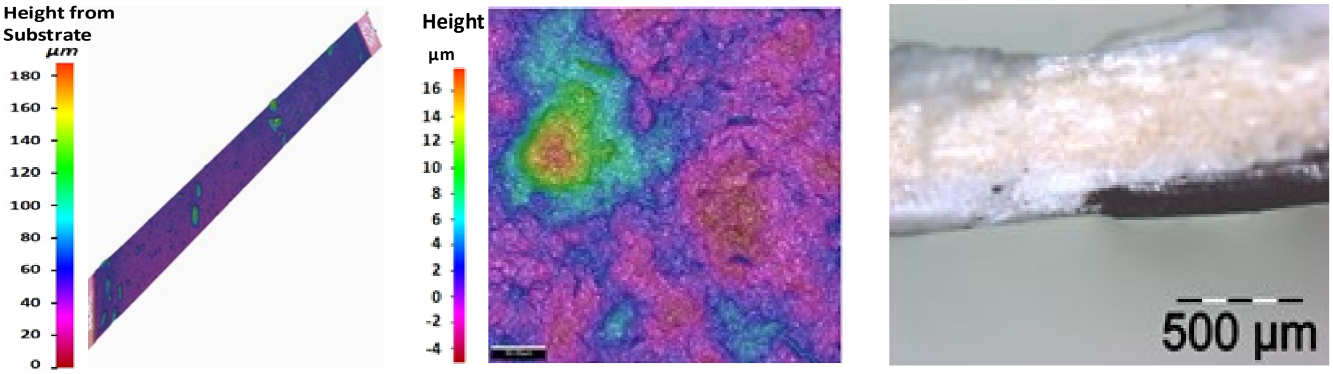
TABLE I
FABRICATED SAMPLES PROPERTIES

Antenna Pattern	t (µm)	R_t(Ω/sq)	ρ (Ω.m)	σ (S/m)
Dipole	42	1.9±0.1	7.9×10^{-5}	1.25×10^{4}
RFID tag	38	1.9±0.1	7.2×10^{-5}	1.39×10^{4}

III. RF MEASUREMENTS OF FABRICATED SAMPLES

After fabrication, we measured the fabricated dipole and RFID tag antennas. For dipole antenna, we measured the S11, radiation pattern, realized gain and efficiency. To check the RFID antenna performance we attached the NXP UCODE G2iL series RFID IC with conductive epoxy.

Fig. 3 shows the S11 measured values for dipole antenna. S11 has minimum values of -15.5 dB at 876 MHz. The antenna shows a broadband behavior. Antenna has 165 MHz (800 MHz – 965 MHz) of -10 dB bandwidth. Fig. 4 shows the measured total efficiency and realized gain of the dipole antenna. The antenna has a maximum 40% total efficiency and -2.18 dBi realized gain at 889 MHz. Lower value of total efficiencies for antennas is due to lower radiation efficiency (as matching efficiency of antennas is reasonably good) because of low conductivity of graphene material. Fig. 5 shows the measured E-Plane and H-Plane realized gain radiation patterns. Based on S11 plot, radiation patterns are measured at 876 MHz. Both plane radiation patterns are close to ideal dipole antenna radiation patterns.



(a)

(b)

(c)

Fig. 2. (a) 3D profile of section 'A' as mentioned in Fig. 1(c), which shows the height of printed graphene from the cardboard (b) 2D surface image, shows the thickness variation from the average thickness (zero represents the average thickness) and (c) Cross section of doctor-bladed graphene ink on the cardboard.

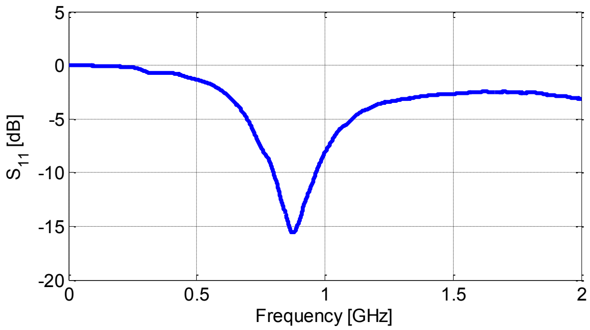


Fig. 3. Measured S11 [dB] of dipole antenna.

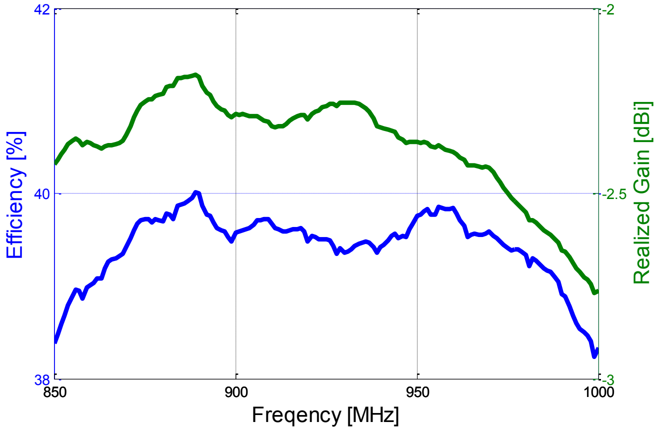


Fig. 4. Measured total antenna efficiency [%] and realized gain of dipole antenna.

After attaching the RFID IC with tag antenna, we measured the theoretical read range of RFID tag in the UHF frequency range of 800 – 1000 MHz. Theoretical read range is the maximum distance between the reader antenna and tag in free space (without any reflection from external environment) through which tag IC can be activated. We used RFID measurement system of [11], in which *query* command response from tag in ISO 18000-6C communication standard is monitored. System is calibrated through provided reference tag from the manufacturer. We swept the transmission power and the transmission frequency of the carrier. After measuring the threshold power to make the tag response valid, we calculated the theoretical read range [12].

$$Theoretical\ Read\ Range\ (m) = \frac{\lambda}{4\pi}\sqrt{\frac{EIRP}{P_{TS}L_{fwd}}} \qquad (1)$$

where λ is wavelength of transmitted carrier, $EIRP$ is equivalent maximum isotropic radiated power. We have followed European RFID emission regulation: $EIRP$ = 3.28 W. P_{TS} is measured threshold power, which is the minimum transmitted power from transmitting antenna required to activate the tag, and L_{fwd} is forward loss which can be described as wireless link loss between carrier generator's output port and input port of isotropic antenna when placed at measured tag's location. The forward loss is calculated during calibration of measurement equipment using reference tag before the measurement of actual tag.

Fig. 6 shows the simulated and measured theoretical read range [m] of the RFID tag. Simulation is done based on measured parameters (sheet resistance and thickness) in Table I. We did the simulation ANSYS HFSS v15 by assigning conductivity value to conductor as presented in Table I. The tag IC is modeled by using a resistor (2.85 kΩ) and a capacitor (0.19 pF) in parallel configuration which result in an impedance of 12-j185 Ω at 940 MHz [13]. Fig. 7 shows the measured E-Plane and H-Plane realized gain radiation patterns of RFID tag antenna at 950 MHz. Measured radiation patterns are calculated from [13]

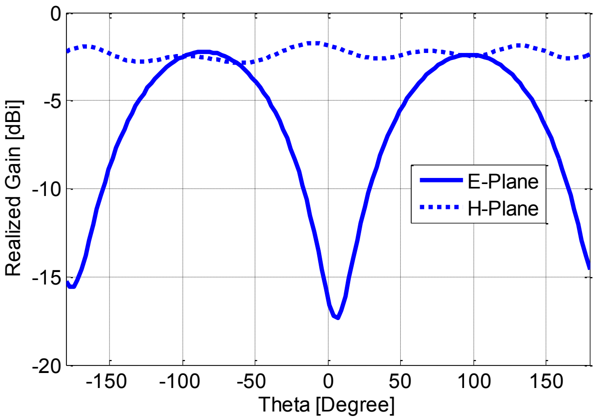


Fig. 5. Measured E-Plane and H-Plane realized gain radiation pattern at 876 MHz of dipole antenna.

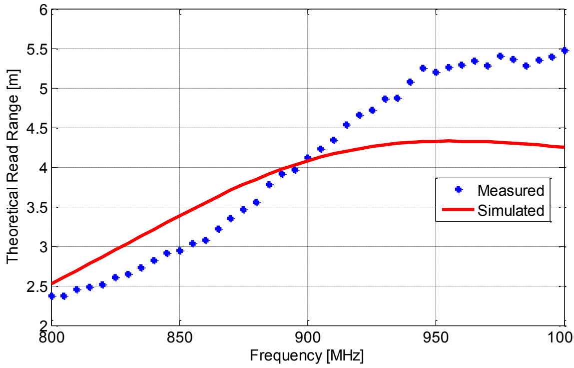


Fig. 6. Measured and simulated theoretical read range [m] of RFID tag.

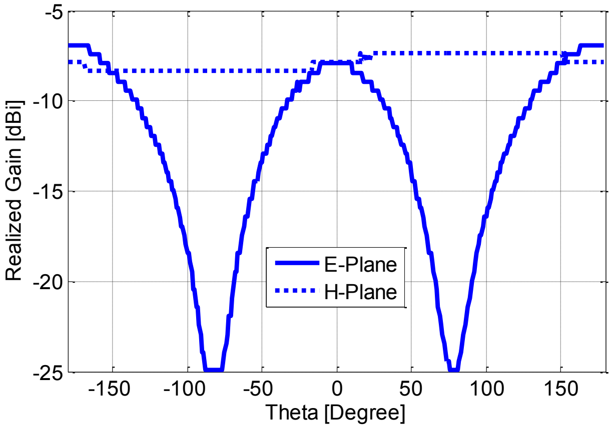


Fig. 7. Measured E-Plane and H-Plane realized gain radiation pattern at 950 MHz of RFID tag antenna.

$$Antenna\ Realized\ Gain\ = \frac{P_{ic,o}}{P_{TS}L_{fwd}}$$

where $P_{ic,o}$ is minimum power required for IC to activate, which is -18 dBm. Simulated theoretical read range is calculated based on [14]. Tag has more than 5 m of measured theoretical read range and tag antenna has more than -7 dBi of realized gain. Tag dimensions are originally designed for 940 MHz [6] on stretchable silver coated fabric. According to measurement plot (Fig. 6), tag has constant read range after 940 MHz which may due to reason that this design is made for different substrate (causes different matching behavior). By tuning the feeding gap of the tag antenna, maximum theoretical read range value and frequency can be tuned.

IV. CONCLUSION

The proposed graphene tag on cardboard is a cost-effective and eco-friendly with excellent processability. It has strong potential to implement for small range tracking such as in postal parcel transportation. The fabricated RFID tag has theoretical read range greater than 5 m. The fabricated dipole antenna has measured -2.18 dBi realized gain and 40% total efficiency. The performance of RFID can be further improved by tuning tag antenna parameters like input feed gap, length and width of tag antenna. Our future step is to optimize the tag antenna parameters for better RFID tag performance over the whole UHF RFID band.

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