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A Study of Cost-Effective Conductive Ink for Inkjet-Printed RFID Application

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1. Introduction

The Radio Frequency Identification (RFID) is one of the emerging technologies that could replace the barcode technology for various applications such as access control, logistics, and security management [1]. The RFID system in ultra-high frequency (UHF) band has the advantages of its long operating distance for the communication between the RFID reader and the RFID tag and multiple RFID tags identification ability [2]. Hence, the UHF RFID system is widely applied for item-level identification which requires a large number of UHF RFID tags. As a result, the cost of the UHF RFID tag has become an important factor for the system deployment.

The printing technique is an effective solution for lowering UHF RFID tag fabrication cost comparing to the conventional etching technique. In the printing technique, the conductive ink is directly printed on the RFID tag substrate to form the shape of the RFID tag antenna where there is no conductor wasted as in the etching process. However, the efficiency of the conductive-ink printed RFID tag antenna is poorer than that of the bulk-conductor etched RFID tag antenna according to the low conductivity of the conductive ink [3]. Various research works examined the effect of the thickness of the conductive-ink layer on the efficiency of the UHF RFID tag antenna and the performance of the UHF RFID tag [4]-[6]. It was suggested that the performance can be improved by thickening the conductive-ink layer. Nonetheless, the cost of the UHF RFID tag increases for the larger amount of the conductive ink. Even though less amount of conductive ink is needed for higher conductivity conductive ink, the lower cost is not guaranteed since the costs of various conductive inks are diverse.

In this paper, we evaluate the cost performance of the commercially available conductive inks that have different electrical conductivity. The inkjet printing conductive inks are focused according to the thickness variability by re-printing or adjusting the printer properties. The minimum amount of the conductive inks required for achieving the maximum level of the antenna efficiency as the bulk-conductor etched antenna is obtained via the electromagnetic simulation. The simulation results illustrated that we can reduce the conductive ink consumption for the higher conductivity conductive ink. On the other hand, the total cost is not consistently decrease together with the total consumption of the conductive ink due to the variety of the cost of the conductive inks.

2. Conductive Ink

In the printed RFID application, the conductive ink composed of metal particle and solvent is generally used for printing the antenna of the RFID tag. There are various conductive inks for different printing techniques such as flexographic printing, gravure printing, screen printing, and inkjet printing, and different metal particles such as gold, copper, and silver. The differences of these conductive inks are their viscosity, conductivity, and curing process. The important property to be considered for choosing the conductive ink for RFID application is the electrical conductivity which is the ability of the ink to conduct an electrical current. The electrical conductivity of the commercially available conductive inks ranges from 10^6 S/m to higher than 10^7 S/m, while the electrical conductivity of a bulk copper is 5.8×10^7. The higher the conductivity, the greater radiation efficiency of the tag antenna can be achieved.

At the UHF band, the electric current mainly flows at the surface of the conductor, called skin effect. The skin depth (δ) or the depth below the conductor surface at which the current density decreases by factor 1/*e* is defined as $\delta = 1/\sqrt{\pi f \mu \sigma}$ where f is the operating frequency, μ is the magnetic permeability, and σ is the electrical conductivity of the conductor [7]. Accordingly, the thickness of the printed conductive ink should be thick enough, at least one skin depth, to obtain good antenna performance [4].

3. Performance Evaluation

In this paper, we focus on the conductive ink suitable for inkjet printing technique. We selected 7 commercially available conductive inks, named conductive inks A-G, which have different electrical conductivity. Fig. 2 indicated the electrical conductivity of these conductive inks. The minimum and maximum electrical conductivity of these conductive inks is 1.3×10^6 S/m and 2.3×10^7 S/m, respectively.

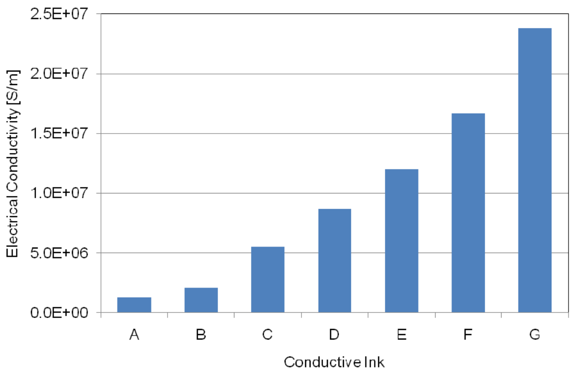

Fig. 2. Electrical conductivity of selected conductive inks.

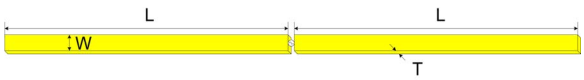

Fig. 3. Dipole antenna configuration.

The performance evaluation of these conductive inks is performed using basic dipole antenna. The configuration of the dipole antenna is as shown in Fig. 2, which has the length L = 92 mm, the width W = 2 mm, and the thickness T. The length L and width W are the optimal sizes that yield the best impedance matching with the NXP G2XL IC chip and the best radiation efficiency [8]. The thickness T is the thickness of conductive ink layer. The volume V is defined as the total amount of conductive ink required for obtaining the dipole antenna in Fig. 3, where V = 2WLT. The radiation efficiency of the antenna is simulated using the Advanced Design System (ADS) momentum analysis software based on the method of moments (MoM) at the operating center frequency of 922 MHz. Polyester (PET) with the thickness 51 µm, the dielectric constant 3.5, and the loss tangent 0.002, is employed as the antenna substrate.

Fig. 4 illustrates the radiation efficiency of dipole antenna printed using various conductive inks and various conductive ink volumes. The radiation efficiency of the copper dipole antenna with the electrical conductivity 5.8×10^7 is used as the reference value. The conductive ink A which has the minimum electrical conductivity results in the lowest radiation efficiency. The larger electrical conductivity brings the higher radiation efficiency. The radiation efficiency is also improving together with the increase of the conductive ink volume. The radiation efficiency of the conductive ink A reach the maximum radiation efficiency of copper dipole antenna by increasing the conductive ink volume to approximately 8 mm^3. The conductive ink G which has the maximum electrical conductivity requires only about 0.5 mm^3 of conductive ink to achieve the greatest radiation efficiency. Fig. 5 indicates the minimum volume and thickness of the conductive inks that yield the maximum radiation efficiency. The thickness of the conductive ink G can be as low as 1.4 µm, which is printable by inkjet. The larger conductive ink volume and thickness can be achieved by adjusting drop size, adjusting drop spacing, or reprinting.

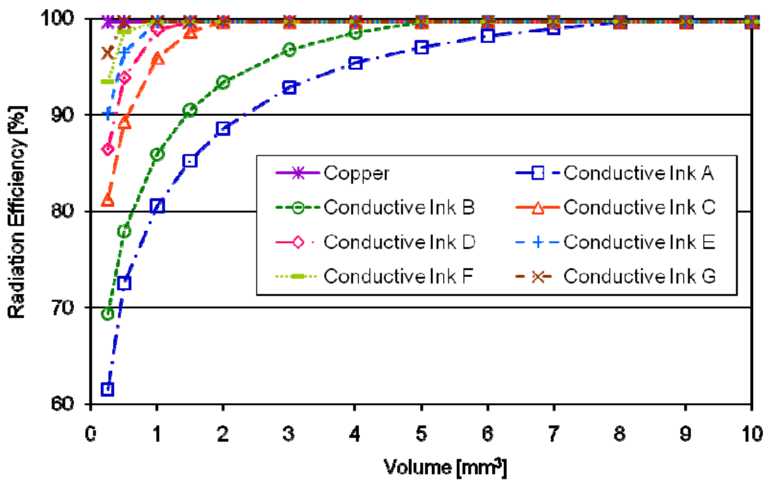

Fig. 4. Radiation efficiency of the conductive ink printed using various ink volume.

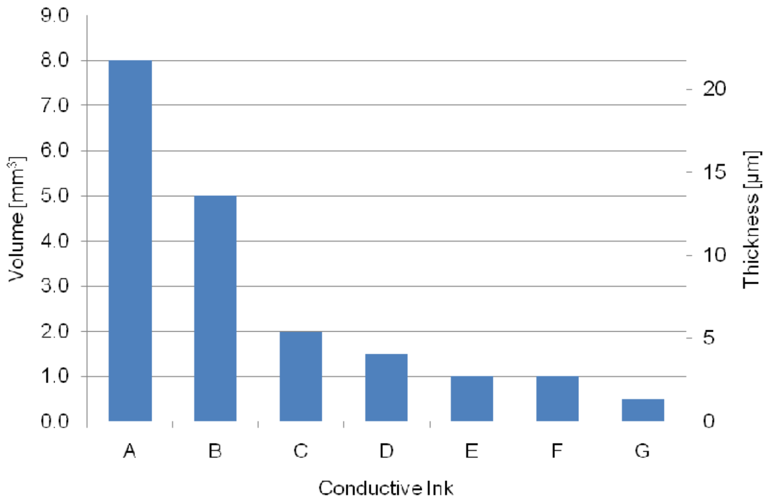

Fig. 5. Minimum volume and thickness of conductive inks required to achieve maximum radiation efficiency.

4. Cost Evaluation

The previous section indicated that the conductive ink with larger electrical conductivity gives the antenna with the higher radiation efficiency and requires lower amount of conductive ink. However, the lower amount of conductive ink does not mean the lower cost. The cost of the conductive ink generally depends on the ink properties such as viscosity, electrical conductivity, and curing temperature. The normalized cost of the conductive ink A-G per 1 mm^3 is as shown in Fig. 6. It is noted that the cost of these inks are quoted for the minimum volume of 50-100 ml exclude freight charge.

Fig. 7 illustrates the cost of conductive ink requires to achieve the maximum radiation efficiency. The conductive ink A requires 8 mm^3 of ink which results in the maximum cost, while the conductive ink G requires only 0.5 mm^3 of ink which costs less than 10% of the conductive ink A. Even though the cost per 1 mm^3 of the conductive ink G is higher than that of the conductive ink A, the antenna printed using the conductive ink G can save more than 90% of the cost in order to achieve the maximum efficiency. The conductive ink C and F also give the excellent cost reduction.

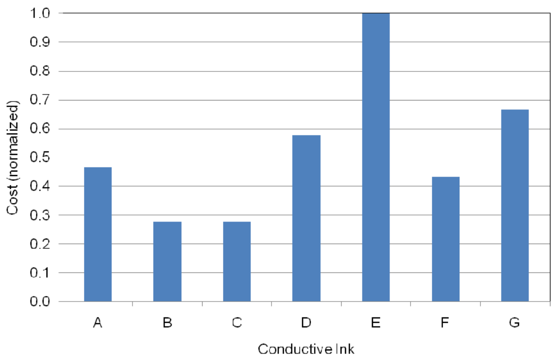

Fig. 6. Cost of 1 mm^3 conductive inks.

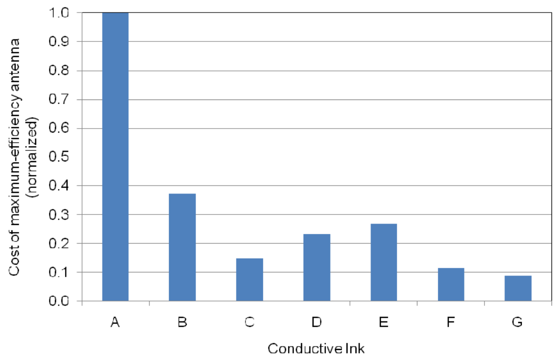

Fig. 7. Cost of maximum-efficiency antenna printed using various conductive inks.

5. Conclusion

In this paper, the cost performance of the commercially available inkjet printing conductive inks is evaluated for the UHF RFID tag application. For the same printing technique, the cost mainly depends on 2 factors; the cost of the conductive ink and the printed ink volume. The simulation results indicated that lower ink volume is required for the greater conductivity conductive ink in order to achieve the same level of the antenna efficiency. However, the cost is not consistently reduced together with the volume. The smart selection of the conductive ink with the proper cost and electrical conductivity can save more than 90% for the inkjet-printed UHF RFID tag antenna fabrication.

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