Design, Simulation, and Fabrication of Low-cost Inkjet Antennas

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Abstract— We present design, simulation, and fabrication of low-cost inkjet antennas that are produced by using silver toner in commercial printers. While they are easy to produce, fabrication of inkjet antennas with desired properties can be challenging due to diversity of printing and curing parameters that significantly effect the electrical properties of the final products. We show that, even when these parameters are optimized and fixed, antenna samples that are produced simultaneously may exhibit different impedance characteristics, requiring larger margins in design procedures. Despite these challenges, inkjet antennas are relatively inexpensive, flexible, and friendly to environment, and they are promising with such properties that are essential for future technologies. By fully exploiting the benefits of the developed setup, complicated patterns such as fractal structures, can easily be fabricated, as an important advantage of inkjet printing.

1. INTRODUCTION

Inkjet antennas that are fabricated by metal printing on paper or similar substrates have recently become popular as they are relatively inexpensive, flexible, and environmentally friendly [1]. In addition to special material printers designed for this purpose [2–5], one can use silver-based toners in standard inkjet printers to manufacture this type of antennas with reduced costs. Different types of inkjet antennas, including dipole antennas, meander antennas [1], bowtie antennas [3], Vivaldi antennas [4], and arrays [5] have been proposed, fabricated, and analyzed in the literature, while less attention has been paid to more detailed antenna structures [6], even though inkjet printers can offer quite high resolutions.

In this study, we present the design, simulation, and fabrication of low-cost inkjet antennas using silver toner in standard commercial printers. Before manufacturing, antennas are designed and simulated using an in-house fast solver based on the multilevel fast multipole algorithm (MLFMA) [7]. For a high-quality fabrication, many factors are considered and optimized, including the printer parameters and style, paper and toner types, curing duration and temperature, and post processing. We present the effects of these factors and discuss the properties of the fabricated antennas as well as the stability of their measurements. Finally, we present detailed structures, such as fractal antennas with Koch snowflake shapes, which are produced by fully exploiting the advantages of the inkjet printing technology.

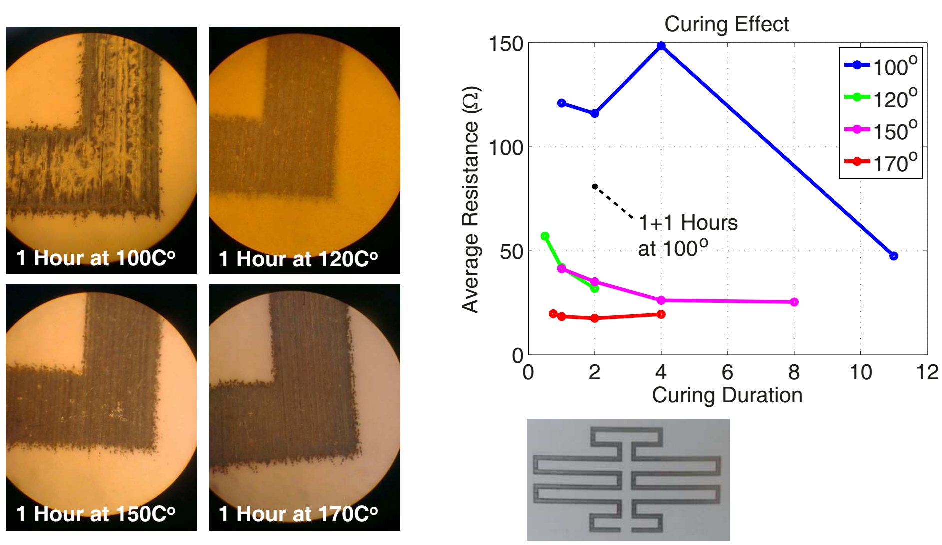

Figure 1: Cured samples of inkjet prints and the dependency of the resistance of a long conductive line to the curing duration and temperature.

2. SIMULATIONS OF INKJET ANTENNAS

In this work, inkjet antennas are investigated in a simulation environment based on MLFMA in frequency domain. Antenna surfaces are modeled in the three-dimensional space using the electric-field integral equation (EFIE). Discretization of EFIE using the Rao-Wilton-Glisson (RWG) functions on triangular domains lead to $N \times N$ matrix equations in the form of

$$\bar{\mathbf{Z}}^{\mathrm{EFIE}} \cdot \mathbf{a} = \mathbf{w}^{\mathrm{EFIE}}, \tag{1}$$

where the matrix elements and the elements of the right-hand-side vector are derived as

$$\begin{aligned} \bar{\mathbf{Z}}^{\mathrm{EFIE}}[m,n] &= i\omega\mu_0 \int_{S_m} d\mathbf{r}\mathbf{t}_m(\mathbf{r}) \cdot \int_{S_n} d\mathbf{r}'\mathbf{b}_n(\mathbf{r}')g_0(\mathbf{r},\mathbf{r}') \\ &\quad + \frac{1}{i\omega\epsilon_0} \int_{S_m} d\mathbf{r}\nabla \cdot \mathbf{t}_m(\mathbf{r}) \int_{S_n} d\mathbf{r}' g_0(\mathbf{r},\mathbf{r}')\nabla' \cdot \mathbf{b}_n(\mathbf{r}') \end{aligned} \tag{2}$$

and

$$\mathbf{w}^{\mathrm{EFIE}}[m] = -\int_{S_m} d\mathbf{r}\mathbf{t}_m(\mathbf{r}) \cdot \mathbf{E}^{\mathrm{inc}}(\mathbf{r}), \tag{3}$$

respectively. In the above, $\mathbf{E}^{\mathrm{inc}}$ is the incident electric field created by external sources, $k_0 = 2\pi/\lambda_0 = \omega\sqrt{\mu_0\epsilon_0}$ is the wavenumber, $i = \sqrt{-1}$, and

$$g_0(\mathbf{r},\mathbf{r}') = \frac{\exp(ik_0|\mathbf{r}-\mathbf{r}'|)}{4\pi|\mathbf{r}-\mathbf{r}'|} \tag{4}$$

is the free-space Green's function. In addition, $\mathbf{t}_m$ and $\mathbf{b}_n$ represent the testing and basis functions, respectively. Solutions of radiation problems are performed iteratively, where the matrix-vector multiplications are accelerated by MLFMA. As detailed in [7], MLFMA reduces the computational complexity of each multiplication to $\mathcal{O}(N \log N)$ by performing electromagnetic interactions via sequences of aggregation, translation, and disaggregation stages on multilevel tree structures.

In radiation modes, antennas are excited by using delta-gap sources. For a delta-gap source at the mth edge, we have

$$\mathbf{E}^{\mathrm{inc}}(\mathbf{r}) = I_m \lim_{d \to 0} \hat{\mathbf{u}}\delta_d(\mathbf{r},\mathbf{r}_m)/d, \tag{5}$$

where δ_d is the Dirac delta function, $\mathbf{r}_m$ represents any point at the edge, $\hat{\mathbf{u}}$ is the unit vector perpendicular to the edge in the plane of the triangles, I_m represents the strength of the feed, and d is the width of the theoretical gap. Using the RWG functions, one can obtain

$$\mathbf{w}^{\mathrm{EFIE}}[m] = \pm I_m l_m \delta_k[m] \tag{6}$$

as the right-hand side, where δ_k is the Kronecker delta function and l_m is the length of the mth edge. Then, the input impedance and the reflection coefficient can be calculated as

$$Z_{in} = \frac{I_m}{a_m l_m}, \qquad \Gamma = \frac{Z_{in} - Z_o^*}{Z_{in} + Z_o}, \tag{7}$$

where a_m is the mth current coefficient and Z_o is the impedance of the port/device matching to the antenna.

3. LOW-COST FABRICATION OF INKJET ANTENNAS

We print antennas on photograph papers using silver toner in standard commercial printers (Epson). Our observations on the low-cost fabrication of inkjet antennas can be listed as follows.

1. As it is well known in the literature [3], inkjet antennas need to be cured after printing, especially when standard printers are used. We use a simple one-tray oven to cure the antennas. However, the curing temperature and duration are very critical for producing high-quality prints with high conductivity all through the antenna. Fig. 1 depicts the results of some curing experiments involving long conductive lines. The average resistance values of the samples

are measured via a DC multimeter and plotted with respect to the curing duration. As shown in Fig. 1, temperatures over 100° lead to significant drops in the resistance while the duration becomes less effective when the temperature is high. (All temperatures in this paper are given in Celsius.) The effect of temperature on the prints is also visible in the zoomed photographs in Fig. 1. Since it is desirable to keep the temperature as low as possible due to adverse effects on the paper substrates, we usually prefer 1 hour curing at 150° for desired levels of conductivities.

2. Since heat curing is crucial when standard printers are used to produce antennas, the paper substates should be resistant to high temperatures. Our experiments show that heating up to 120°–150° is required for sufficient conductivity values required for high-quality antennas. Unfortunately, many photograph and transparent papers with high plasticity tend to bend above 100°, damaging the silver print. On the other hand, papers with very low plasticity can be very absorbent, leading to defective prints with small cracks. Hence, only a few commercial photograph paper types are suitable for antenna printing.

3. The ratio of silver in toner is another crucial parameter for producing high-quality inkjet antennas. Obviously, low ratios (e.g., 15%) lead to low conductivity values that are not suitable for antennas. Interestingly, very high ratios (e.g., 35%) may also lead to low-quality antennas. Specifically, for these prints, we observe that silver is not well penetrated into the paper, resulting in defects after curing. This also indicates that the optimal silver ratio depends on the paper type and heating temperature/duration. For the selected photograph papers in this study, we use toners with 25% silver ratio, leading to the best conductivity properties when the prints are cured at 150°.

4. Producing antennas via standard printers need careful cleaning procedures between printing sessions. Despite all efforts, however, printheads easily wear out and the printing quality drops significantly. Fig. 2 presents a comparison of two identical antennas produced by new and worn-out printers. Measured input impedance and power reflection coefficient (when matching to an integrated circuit (IC) for radio-frequency identification(RFID) applications) values for a meander/loop antenna design are plotted with respect to frequency. In addition to a frequency shift, there is more than 3dB difference between the minimum power reflection values of the antennas. The defects (spikes) due to the worn-out printhead is visible in the inset of Fig. 2. Interestingly, the expiration duration of a printhead does not only depends on the number of prints but also on the usage period, indicating that the oxidization of silver residues is responsible for deteriorating performances of printheads.

5. Measurements of inkjet printers can be challenging, considering that standard soldering is not practical. Unfortunately, applying physical pressure between antenna terminals and coaxial cables leads to cracks due to soft substrates and produces poor results demonstrating underestimated antenna performances. The best option seems to be using conducting epoxy, which needs a second curing session for coaxial connections. We use the conductive epoxy

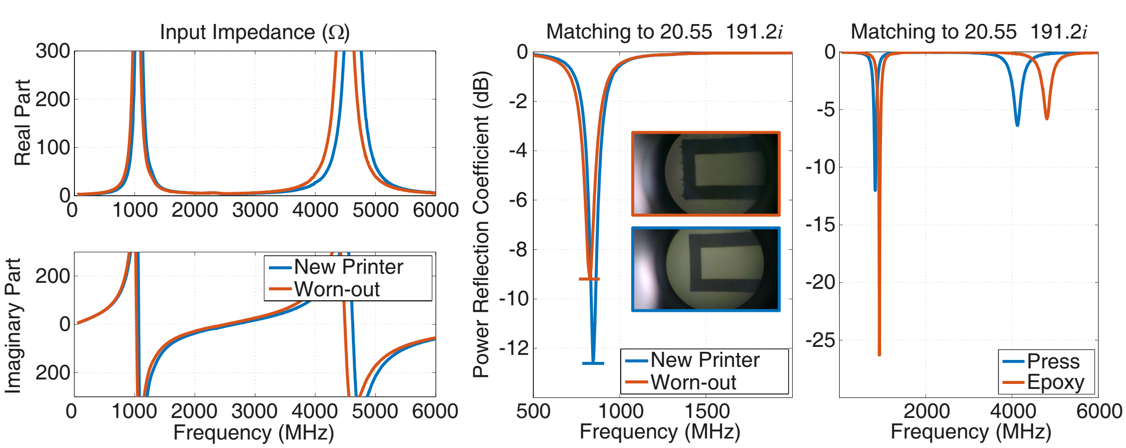

Figure 2: Effects of the printer age and measurement methods to the observed electrical parameters of a meander/loop antenna produced by inkjet printing.

also to connect RFID ICs to the antenna terminals. A comparison of physical press and epoxy connections for the measurement of a meander/loop antenna is depicted in Fig. 2, where significant discrepancies between the minimum power-reflection values and the corresponding frequencies are observed.

Even when all printing parameters are carefully optimized, selected, and fixed, performances of low-cost inkjet antennas may vary significantly. For example, electrical properties of the antennas that are produced together in the same setup can be different. A major reason is that inkjet printers are not designed for consistency (e.g., uniformity of the ink) but designed for readability of the output. Therefore, when designing inkjet antennas, sufficient margins need to be placed for required electrical properties. Fig. 3 presents a comparison of meander/loop antennas designed for RFID applications. The antenna is designed for matching to an IC with 20.55–191.2i input impedance at 865–868 MHz. Fig. 3 depicts the measured power reflection coefficient values with respect to frequency for 5 different samples that are produced at the same time. A zoomed plot is used to demonstrate different characteristics of the antenna samples at around the critical frequency. All samples satisfy -10 dB reflection values in the desired range, i.e., 865–868 MHz.

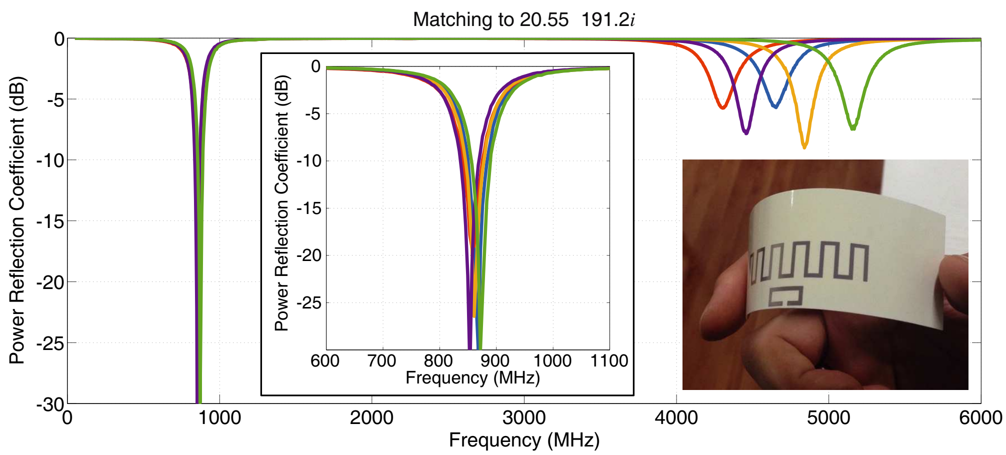

Figure 3: Power reflection coefficient values for meander/loop antenna samples that are produced under same conditions.

4. KOCH SNOWFLAKE ANTENNAS

Low-cost inkjet antennas have significant advantages, but also challenges in their productions. As discussed in Section 3, fabrication procedures involve many parameters that need to be optimized for high-quality results. In addition, electrical properties of the produced antennas can be sensitive and the antennas should be designed accordingly with possible margins on the target values. On the other hand, with well-designed combinations of fabrication procedures, low-cost (< 1 USD), flexible, and green antennas can be produced. As an another advantage, inkjet printing allows for very detailed prints that can be used to produce physically complicated structures. In fact, for a commercial inkjet printer, a large metallic patch is more challenging than a detailed thin pattern, as it is more difficult to maintain the uniformity in the former. Consequently, those antennas with

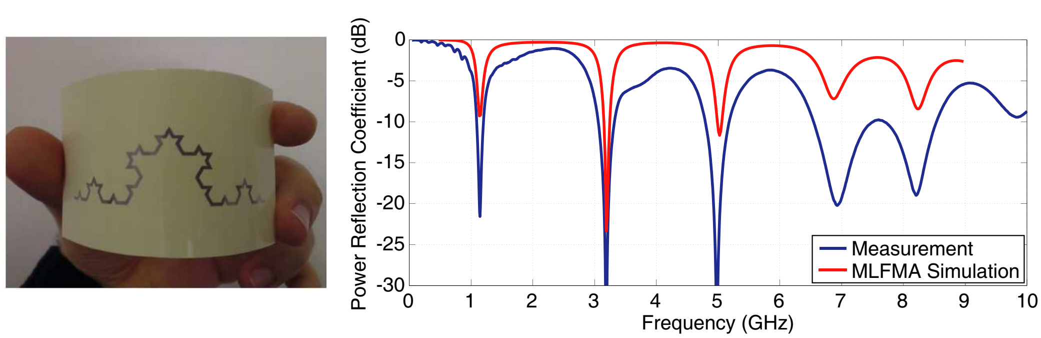

Figure 4: A Koch snowflake antenna produced by inkjet printing and power reflection coefficient values when the antenna is matched to 50 Ω.

tiny details that are difficult to produce otherwise benefit more from the advantages of the inkjet technology.

As an example, Fig. 4 presents a Koch snowflake antenna involving three iterations of triangular patterns. The measured and calculated power reflection coefficient values (when matching to $50\,\Omega$) are plotted with respect to frequency from 500 MHz to 9 GHz. Three major dips are observed at 1.14 GHz, 3.17 GHz, and 5.02 GHz, demonstrating the multiband characteristics of the antenna. Other dips at around 6.94 GHz and 8.22 GHz are caused by cross coupling of fractal iterations. Measured reflection values tend to be lower than the simulated reflection values at higher frequencies, mostly due increasing conductivity of the paper substrate that is not modeled in simulations.

5. CONCLUSION

Among alternatives, inkjet antennas are promising as they are relatively inexpensive, flexible, and environmentally friendly. In this study, we discuss the effects of fabrication parameters in low-cost inkjet antennas and demonstrate instabilities in their measurements. We show that, once the production line is optimized, one can fully benefit from the advantages of inkjet printing by considering antennas with complicated geometries, such as fractal antennas, which may not be trivial to fabricate in other setups.

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