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Design, Simulation, and Fabrication of a Novel Type of Inkjet-Printed Pixel Antennas

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Abstract—We present a novel type of pixel antennas that are suitable for fabrication in low-cost setups based on commercial inkjet printers. The proposed antennas involve hexagonal cells that can be removed in accordance with rigorous optimizations via genetic algorithms that are supported by full-wave solutions with the multilevel fast multipole algorithm. Optimal pixel configurations are determined precisely for desired electrical characteristics, such as low power-reflection values at required frequencies. Measurements on fabricated samples demonstrate the effectiveness of the optimizations, as well as the favorable characteristics of the hexagonal-cell pixel antennas that fully benefit from the advantages of low-cost inkjet printing.

1. INTRODUCTION

Antennas that are produced by printing metal on paper or similar substrates using inkjet printers have recently become popular due to their important advantages [1–7]. These inkjet antennas are naturally flexible and environmentally friendly, and have low costs, especially when they are fabricated by using metal-based cartridges in standard commercial printers. While such a manufacturing setup involves several challenges, optimizations of fabrication procedures and parameters, such as paper type, toner ingredients, printer parameters, and temperature curing, enable high-quality antennas suitable for many areas, such as radio-frequency identification and sensing applications [2, 3, 8].

The literature has seen alternative types of inkjet antennas, such as meander antennas [1, 8], bow-tie antennas [4], Vivaldi antennas [5], and arrays [7], while less attention has been paid to more detailed structures [6]. In this work, we present a novel type of pixel antennas that fully benefit from the advantages of low-cost inkjet printing, while being less affected from its disadvantages. The proposed structures involve small hexagonal pixels that can be removed individually to optimize the electrical characteristics of the antennas. We emphasize the following properties of these antennas in the context of inkjet printing as follows.

- From the perspective of inkjet printing, filled (metallic) and empty spaces in planar antennas have the same manufacturing complexity, in contrast to standard fabrication procedures where metals are removed. Therefore, pixel antennas are naturally suitable for inkjet printing.
- The cell type used in the pixel antennas has of utmost importance, especially if the antennas are produced via low-cost inkjet printing. As opposed to other cell options, such as triangular or square, hexagonal cells do not lead to corner contacts. Such a contact, which may occur when two cells intersect at a single point, is computationally open circuit (unless special techniques are used), while they are short circuit in the fabricated samples, leading to deviations from the optimizations. It is also possible to make the optimization algorithm avoid such contact points, while this usually reduces the effectiveness of the optimizations.

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Consequently, the pixel antennas that are designed, simulated, and fabricated in this study are suitable for inkjet printing. Starting from a template antenna, we optimize pixels using genetic algorithms supported by the multilevel fast multipole algorithm (MLFMA). Antenna designs obtained via computationally intensive optimizations are produced by inkjet printing and tested in measurement setups. We show that the fabricated antennas produced by commercial printers demonstrate the desired electrical characteristics.

2. FULL-WAVE OPTIMIZATIONS OF PIXEL ANTENNAS

Figure 1 depicts a template antenna that is particularly considered in this paper. Two metallic patches of size 1.6 cm × 0.85 cm are connected via a feed line with 0.1 cm width and 1.4 cm length. Each patch consists of 198 hexagonal cells. The size of the cells (that have edge lengths of 0.5 mm) is selected by considering the tradeoff between the optimization quality and inkjet printing resolution. Specifically, when the cells are made smaller, the antennas can be optimized better, while the low-cost inkjet printing may not produce the desired details.

The pixels to be removed from the template antenna are found by optimizations via genetic algorithms. Antenna problems are formulated with the electric-field integral equation (EFIE), which is suitable for open metallic surfaces with zero thickness. Dielectric effects are included by using a dielectric host medium with an effective relative permittivity of the paper ($\epsilon_{eff} = 1.3 + 0.013i$, where $i = \sqrt{-1}$). Surfaces are discretized by using triangles, on which Rao-Wilton-Glisson functions are employed to expand the electric current density. The feed is modeled as a delta-gap voltage source. Solutions of the antenna problems required by the genetic algorithms are performed iteratively with MLFMA.

An improved genetic algorithm implementation with one-to-one crossover operations, success-based mutations, and family elitism is used for optimizations [9]. This implementation was originally developed to optimize antenna arrays, but it is modified to design pixel antennas. For this purpose, each pixel is represented by a binary number (0 or 1 for absent/present). Then, these numbers are combined as chromosomes of individuals in genetic algorithms. In a typical optimization presented in this paper, we use a pool of 40 individuals, leading to convergent optimizations in less than 200 generations. Therefore, a total of around 8000 MLFMA simulations are performed per optimization.

Each individual in genetic algorithms corresponds to an antenna design (pixel map). For a pixel map to be tested computationally, the RWG functions associated with the removed cells are deleted from the matrix equation and a new iterative solution is performed using MLFMA. Symmetry is enforced in all optimizations presented in this paper. While earlier solutions are used as initial guesses for new solutions, removal of a pixel often have drastic effects on the solutions, reducing the effectiveness of the initial-guess approach. On the other hand, setup contents of MLFMA, such as near-field interactions, translation operators, preconditioners, and tree structures, are performed only once per optimization. In addition, a lookup table is utilized to avoid multiple evaluations of the same configuration, especially towards the end of the optimizations where favorite designs dominate the pools.

Figure 2 presents the results of ten different optimizations, where the cost function (fitness of individuals) is selected as the transmission coefficient at 1.8 GHz. Specifically, we maximize $\tau = 2Z_o/(Z_{in} + Z_o)$, where Z_{in} is the input impedance of the antenna, while the reference impedance Z_o is selected as $50\,\Omega$. Hence the maximum achievable transmission value is 1.0; but all optimizations provide values above 0.9. Fig. 2 depicts the antenna layouts corresponding to the best individuals that provide the optimized transmission values.

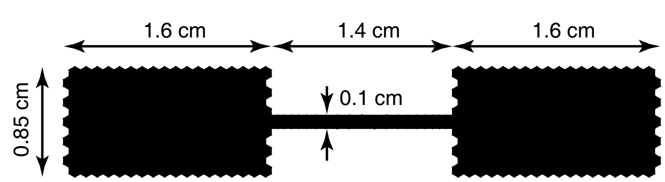

Figure 1. A template antenna involving hexagonal cells to be removed in accordance with optimizations.

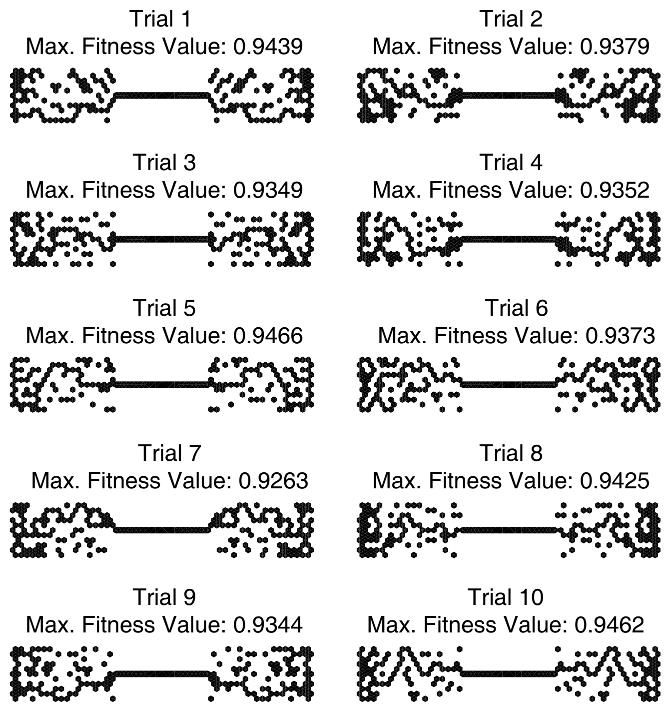

Figure 2. Results of ten different optimizations for maximizing the transmission coefficient at 1.8 GHz. Optimized antenna layouts (given the template in Fig. 1) are presented.

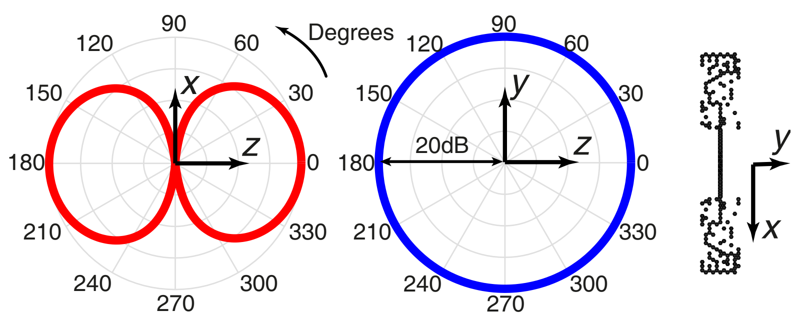

Figure 3. Far-zone radiation pattern of an optimised antenna simulated with MLFMA.

Among the antennas in Fig. 2, Trial 5 with 0.9466 fitness value is selected for fabrication. The computed far-zone radiation pattern of the antenna is depicted in Fig. 3, where we check the isotropic radiation of the antenna at 1.8 GHz. While the radiation characteristics could also be included in the optimization, the input impedance that is more critical for this size of antennas is particularly focused in this study.

3. FABRICATION AND MEASUREMENTS

The optimized and selected antenna is produced by using low-cost commercial (Epson) printers loaded with silver-based (25% ratio) cartridges. Temperature curing is applied for increasing the conductivity. A standard photograph paper is used as substrate. Some production challenges, printing parameters, and measurement techniques are detailed for other types of antennas in [8]. In a single fabrication cycle, we print multiple samples simultaneously for measurements.

Figure 4 presents a fabricated antenna produced by low-cost inkjet printing. For measurements,

Figure 4. A fabricated pixel antenna for measurements. The antenna is produced via low-cost inkjet printing using standard printers.

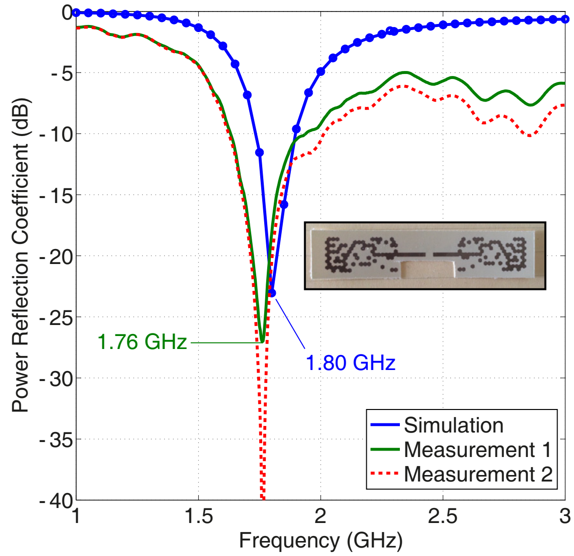

Figure 5. Measured and simulated power-reflection values for the antenna in Fig. 4.

the antenna is connected to a coaxial end using physical press. Fig. 5 presents power reflection values for two different samples, when the antennas are matched to 50 Ω. Our observations are as follows.

- The measured reflection values make dips at around 1.76 GHz, which is close to the optimization frequency of 1.8 GHz. This kind of shifts are typical in low-cost inkjet printing, depending on the quality (especially conductivity) of the prints. The fabricated antennas also demonstrate low reflection values at 1.8 GHz, while better matches may be obtained via scaling if it is critically required.
- Due to metal losses that are not modeled in the simulations, the measured power-reflection values are generally shifted down. As shown in these results, predicting the metal losses is usually not critical to optimize the operating frequency. In fact, even the measurements of theoretically identical antennas deviate from each other due to printing effects. On the other hand, minimization of losses (e.g., by minimizing the overall length of the main line) may be included in the cost function of the optimization.

To sum up, Fig. 5 clearly demonstrates that the fabricated samples of the designed antenna geometry have the desired properties with low power-reflection values at around 1.8 GHz.

4. CONCLUSIONS

We present a type of pixel antennas that are suitable for fabrication in low-cost inkjet printing setups. The antennas are designed by using an optimization environment that consists of genetic algorithms and MLFMA. Success of the optimizations is further verified experimentally on samples produced by using commercial printers. The designed and measured samples present promising properties of the proposed antenna type that make it suitable for various applications, such as radio-frequency identification.

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