Low-Cost Antennas for mm-Wave Sensing Applications using Inkjet Printing of Silver Nano-particles on Liquid Crystal Polymers

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Introduction

For the first time, we demonstrate the possibility of realizing low-cost mm-Wave antennas using inkjet printing of silver nano-particles. It is widely spread that fabrication of mm-Wave antennas and microwave circuits using the typical (deposit/pattern/etch) scheme is a challenging and costly process, due to the strict limitations on permissible tolerances. Such fabrication technique becomes even more challenging when dealing with flexible substrate materials, such as liquid crystal polymers. On the other hand, inkjet printing of conductive inks managed to form an emerging fabrication technology that has gained lots of attention over the last few years. Such process allows the deposition of conductive particles directly at the desired location on a substrate of interest, without need for mask productions, alignments, or etching. This means the inkjet printing of conductive materials could present the future of environment-friendly low-cost rapid manufacturing of RF circuits and antennas.

Substrate Choice

Liquid Crystal Polymers have lately received considerable attention as a high frequency circuit substrate as well as a packaging material. This is mainly due to its impressive electrical characteristics; nearly constant relative permittivity at 3.2 and stable loss tangent below 0.005 up to 110GHz [1, 2]. Thermal expansion characteristics of LCPs are equally desirable since their controllable coefficient of thermal expansion (CTE) can be engineered to match various materials such as copper or silicon [2]. From an environment perspective, LCPs are recyclable, impervious to most chemicals, and can withstand relatively high temperatures (up to 350°C). Thus, Liquid crystal polymers are potentially useful in the conformal packaging of many antenna systems and circuits, particularly in the evolving mm-Wave indoor communication, sensing, and imaging applications at 60, 77, and 94 GHz, respectively.

Advancements and Challenges of Inkjet Printing

There are various existing printing technologies that are utilized in electronic/microwave circuit manufacturing, such as screen printing, gravure, flexography, lithography, nano-imprint, and inkjet printing. In this work, we chose the drop-on-demand direct-write inkjet printing. This is due to the fact that such technique is a deposition method that requires no physical contact with the substrate, in contrast to the other printing techniques, facilitating the printing on a variety of substrates. In fact, inkjet printing of electronic circuits on various substrates has already proven reliable. These substrates include FR4, glass, paper, polyester, polyimide, and silicon. A number of researchers studied inkjet printing for high frequency applications. However, most successful research was limited to UHF frequencies [3], with some recent work at the WLAN 2.4GHz band [4]. Extension to higher frequencies required more control on the tolerances of the printed structures, without sacrificing the RF conductivity. This is a challenging task that requires adequate control of various parameters, as illustrated next:

First of all, it is important to ensure jetting of an adequate drop formation. This is controlled through the jetting voltage and duty cycle. For example, an excessively high jetting voltage results in a large droplet velocity resulting in a drop splash into the substrate, which yields to poor quality. In contrast, if the jetting voltage is too low, proper ejection of droplets may be obstructed. Hence, it is important to properly control the jetting parameters such as jetting voltage, pulse width, and rise time in order to get a proper droplet formation.

Secondly, it is important to ensure jetting at the desired location. This is controlled by the relative distance between the jetting device and the substrate, and the printing speed. Additionally, it is important to be able to control the surface conditions of the substrate, particularly the substrate temperature, to ensure that the droplet remains in its desired location without excessive spreading.

978-1-4244-4968-2/10/$25.00 ©2010 IEEE

It is thus noticeable that proper inkjet printing is not a universal problem since the proper jetting parameters depend on the material properties and interactions between the material and the jetting device. Hence, a special study for each set of conductive ink and substrate material is required.

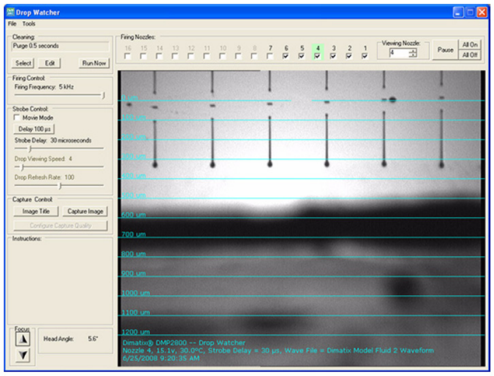
Settings for Proper Inkjet Printing of Conductive Silver particles on LCPs

In this work, we have used the Dimatix DMP-2800 bench-top inkjet printer [5]. The DMC-11601 cartridges were used throughout printing. Each cartridge has 16 nozzles capable of jetting 1pL drops. Thus, it is theoretically possible to realize printed feature sizes of 10 micrometers when all parameters are properly set. Such parameters were adjusted empirically throughout this work to optimize printing on LCP.

Prior to printing, LCP substrates were treated with an Ethyl-alcohol solution followed by heating up to 120 degrees Celsius in a digital oven for 10 minutes. This is to clean the material surface, and ensure proper surface properties.

Next, the printer cartridges are filled with conductive silver ink. Several vendors supply such ink including AnaPro, CimaNanoTech, InkTec, NanoMasTech, and SunJetTech. In this work, we use CCI-300 from Cabot Corporation. To avoid jetting of air bubbles instead of ink droplets, the cartridges are sonicated for 10 minutes after filling for degassing.

The cartridge properties are then adjusted. Best results were achieved when controlling the drop speeds at 7-9 meters/second with jetting at a rate of 13Kcycle/s with the cartridge temperature kept at 37 degree Celsius. The nozzles were placed at a distance of 0.5mm from the surface of LCP. Fig. 1 shows the typical drop formulation. It is important to ensure at a given drop velocity and elevation of the nozzle from the substrate that the droplet will hit the substrate without having a tail drop and without significant spreading. Proper drop placement was enhanced by keeping the LCP temperature at 60 degrees Celsius throughout printing. Several droplets of diameters 20-35micro-meters are illustrated in Fig. 2. Once printing is complete, the printed structure is thermally treated at 200 degrees for three hours. This is a crucial step to increase the conductivity as discussed next. For most RF applications, more layers are needed to increase the conductivity. To this end, multiple layers were printed with 10 minutes thermal treatment intervals in-between (up to eight layers were tested for maximum conductivity).



Cleaning: Purge 0.5 seconds

Firing Control: Firing Frequency: 5 kHz

Strobe Control: ☐ Movie Mode

Delay 100 µs

Strobe Delay: 30 microseconds

Drop Viewing Speed: 4

Drop Refresh Rate: 100

Viewing Nozzle: 4

Head Angle: 5.6°

Dimatix® DMP2800 -- Drop Watcher
Nozzle 4, 15.1v, 30.0°C, Strobe Delay = 30 µs, Wave File = Dimatix Model Fluid 2 Waveform
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Fig. 1. Velocity Adjustment of Droplets.

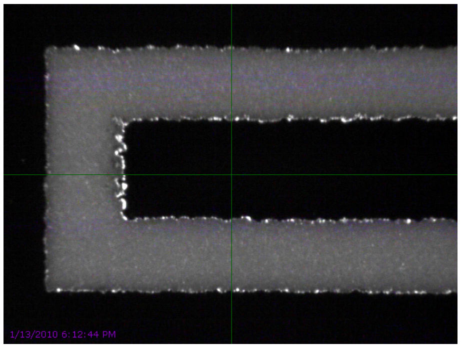

Fig. 3. Realized feature sizes of 50microns.

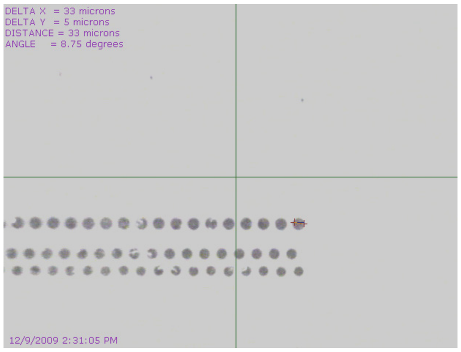

Fig. 2. Snapshot of printed droplets ranging from 20-30microns.

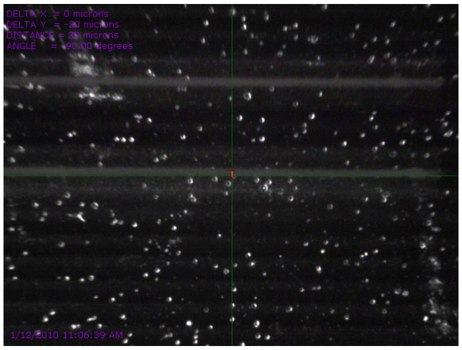

Fig. 4. Realized feature sizes of 20microns.

RF Characterization of the Ink-Jetted Silver particles

Figs. 3 and 4 demonstrate the capability of printing single layers with feature sizes as small as 20 microns and multiple layers (4 layers) with features of 50 microns. Wyko profilometer was used to measure the thickness of the structures. A nominal thickness of 3microns was measured with large variations around the edges. A four point probe was used to characterize the resistivity of the printed silver. The measured conductivity ranged from $3\times10^{6}\left[\mathrm{S/m}\right]$ to $7\times10^{6}\left[\mathrm{S/m}\right]$, which is around an order of magnitude less than bulk conductivity of silver. A number of coplanar waveguide lines were printed on 4mil LCP. The response of a 2.5mm line featuring a 300um center conductor and 150um gap is shown in Fig. 5. Note that the system reference impedance is changed to 90 Ohms instead of 50 Ohms to accommodate the chosen line dimensions since the ratio of the center conductor width to the gap separation of a 50 ohm CPW line is quite large. More details will be discussed at the presentation on the challenges of measurements and the extracted RF conductivity compared to the theoretical expected values and to traditional copper traces. Nevertheless, the results shown in Fig. 5 demonstrate acceptable losses paving the road for the realization of inkjet-printed mm-Wave antennas as discussed next.

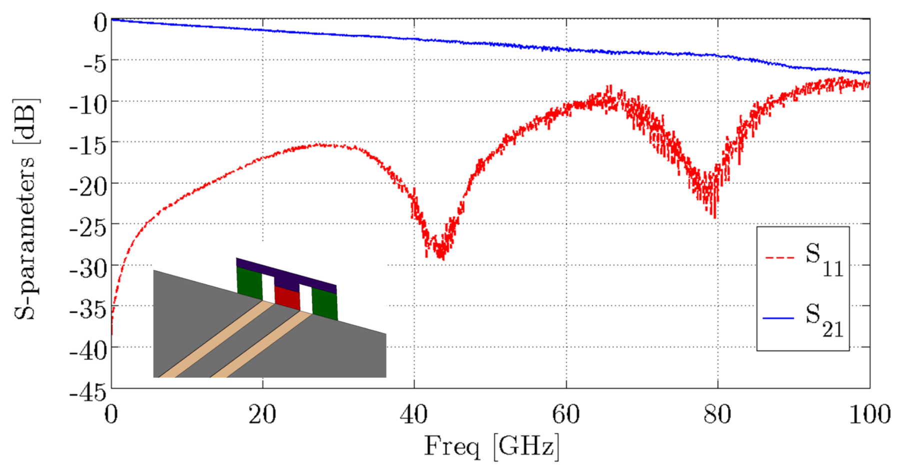

Fig. 5. S-parameters of a sample CPW line printing using silver ink.

mm-Wave Antennas using Ink-Jetted Silver particles

Here, we demonstrate -for the first time- an inkjet printed antenna on LCPs for mm-Wave applications. It is noteworthy to mention that several inkjet-printed antennas were demonstrated at low frequencies [3, 4]. However, the fabrication of such antennas was not quite challenging, due to their relaxed tolerances.

With the rapid demand on more bandwidth and more functionality, mm-Waves antennas have become a crucial element in realizing efficient sensor systems. To this end, we present a proof-of-concept simple dual band antenna design that could serve as a sensor in the 24/60/70GHz bands. The antenna is a variation of the planar monopole antenna. By controlling the size of the side ground plane as well as the length of the center conductor along with the width to gap ratio, one can optimize the antenna to cover the aforementioned bands. Here, optimization was conducted using a commercially available FEM solver (Ansoft HFSS). The antenna was modeled as a thin conductor 5 um thick, with 1um surface roughness and conductivity of $3\times10^{6}\left[\mathrm{S/m}\right]$. The antenna model was fed in a GSG probe-mimicking scheme as that shown in Fig. 5. Fig. 6 shows the simulated gain. Simulated efficiency is above 80% even for the low conductivity value. Probe-based measurements of such antenna were quite challenging. Several ripples were present in the measurements due to measurement uncertainties. Due to space limitations, we summarize the result as shown in Fig. 7. More discussions will be available at the presentation, including observations on repeatability and measurement reliabilities, along with the demonstration of a mm-Wave inkjet printed array.

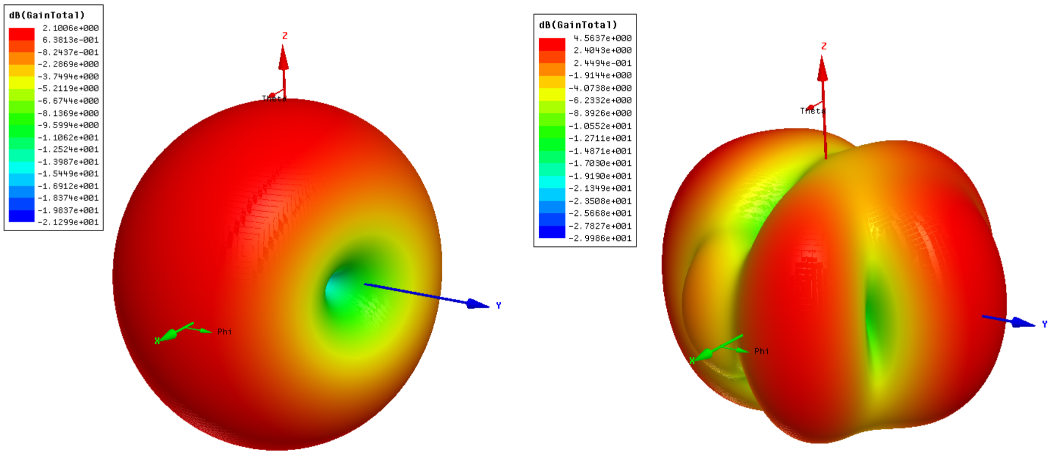

Fig. 6. Gain at 25GHz (left) and 70GHz (right).

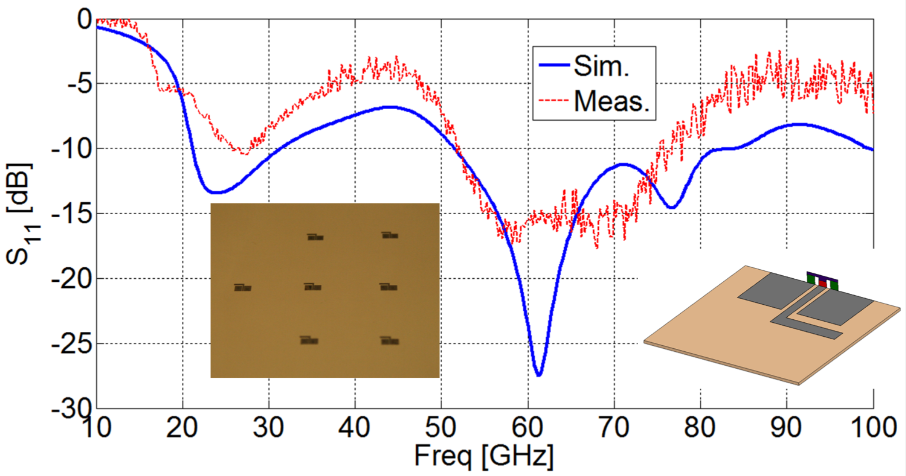

Fig. 7. Simulated vs. measured of an inkjet printed antenna on LCP.

Acknowledgment

This work was supported by NSERC Canada Graduate Scholarship, NSERC-RIM Industrial Research Chair Program and NSF ECS-0801798. Various EM simulations were made possible by university licenses of Ansoft HFSS, CST, and SEMCAD.

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