Inkjet-printed, Vertically-Integrated, High-Performance Inductors and Transformers on Flexible LCP Substrate

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***Abstract*— Vertically-integrated inkjet-printed inductors and transformers are demonstrated for the first time with high levels of performance and repeatability. The inductive components are fabricated using a well-characterized multi-layer inkjet printing process which is substrate independent and has been optimized for the fabrication of RF components. Printed spiral inductors with values of 10 nH and 25 nH are demonstrated with a maximum Q of over 20 at 1 GHz, which is the highest Q value reported to date for printed components, and a repeatability of within 5% between fabrication runs. Printed inductively coupled transformer-based baluns are also demonstrated which operate at 1.4 GHz with a maximum available gain of -1.7 dB.**

***Index Terms*— Inkjet Printing, Inductor, Transformer, Balun, Low-Cost Electronics**

I. INTRODUCTION

Inkjet printing is an additive fabrication technology which has attracted significant attention over the last decade as a method to rapidly process passive and active RF components in a low-cost, environmentally friendly manner. Historically, inkjet technology has been used to fabricate low-frequency single-layer components such as antennas, and lumped components for RFID applications. However, recent advancements in electronic ink development and inkjet processing have opened the door to producing efficient mulit-layer components at high frequency including parallel plate capacitors, multi-layer antennas, and complex RF sensors [1]–[3]. The ability to produce these 3-D components, coupled with the additive and non-contact nature of inkjet printing, is enabling the fabrication of complete RF modules which can be fabricated on nearly any substrate.

To date, there has been very little investigation into inkjet-printed lumped inductors and transformers, which are essential to building fully-printed modules. The best performing printed inductive component as of yet has been obtained by Menicanin et al. with a planar meander inductor printed on a flexible kapton substrate that has a maximum Q of 3 and an inductance of 2 nH [4]. More compact multi-layer designs have also been demonstrated by Kang et al. who have demonstrated a spiral inductor with an inductance of 200 nH for low frequency applications below 1 MHz [5], and Redinger et al. who have demonstrated a multi-layer spiral inductor with a Q of 0.5 and an inductance of 350 nH at 13.56 MHz [6].

However, to produce efficient fully-printed modules, printed inductors and transformers with high quality factors are required which can be repeatably fabricated utilizing multi-layer inkjet technology . In this work, high frequency multi-layer inductors and transformers with a high Q are demonstrated for the first time utilizing a repeatable multi-layer inkjet-printing process. The results demonstrate the current ability to rapidly and reliably fabricate high-performance multi-layer inductors and transformers utilizing a low-cost inkjet printing platform.

II. MULTI-LAYER INKJET FABRICATION

The multi-layer inkjet-deposition process, which has been optimized for high performance RF component fabrication, allows for the deposition of high conductivity metals, and variable thickness dielectrics which can range in thickness from 200 nm to over 200 um, in a layer-by-layer stackup which can currently produce structures with over 5 metal layers [1], [2], [7], [8]. The process is tuned for the Dimatix DMP-2800 printing platform.

The first step in the process involves printing a 6 um thick adhesion layer onto the host substrate to smooth the surface and tune the surface energy to allow for the printing of successive layers with good adhesion and surface wetting. This step is extremely important to allow for a substrate-independent process. Following the printing of the adhesion layer, Cabot CCI-300 silver nanoparticle ink is printed and cured at 180°C to pattern the first metal layer. Multiple deposition passes can be performed to increase the thickness of the metal layer at a rate of 500 nm per pass [7]. The conductivity of the metal layer is 1.1e7 S/m. To deposit the patterned insulating layer, an SU-8 polymer-based ink is printed and cured using a 90°C pre-bake for 5 minutes, a 365 nm UV exposure, and a 120°C post-bake for 5 minutes. The SU-8 polymer deposits at a rate of 6 um per pass and has a permittivity of 3 and loss tangent of 0.04 at 1 GHz [1]. To create vias, holes are left in the patterned dielectric when printed and the successive metal layer is printed into the hole which allows for low resistance contacts of less than 0.1Ω between layers. Successive metal and insulating layers are deposited using the same procedure as the first metal and dielectric layers.

III. MULTI-LAYER INKJET-PRINTED SPIRAL INDUCTORS

Utilizing the characterized process described in Section II, 0.5, and 1.5 turn coplanar waveguide (CPW) spiral inductors are fabricated as shown in Fig. 1. The inductor design is first optimized in the CST full-wave time domain solver. The host substrate is 100 um LCP, which has a permittivity of 2.9 and a loss tangent of 0.003 at 1 GHz. Metal 1 contains the 500 um pitch CPW probe feed and planar spiral. Dielectric 1 is

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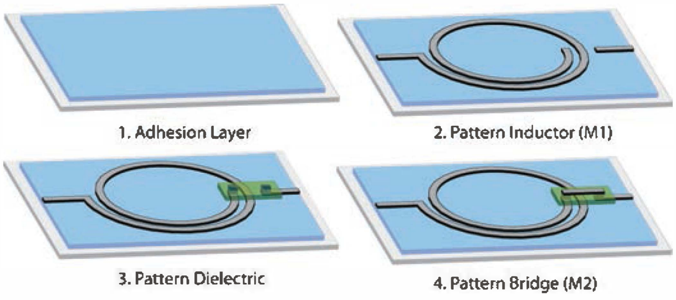
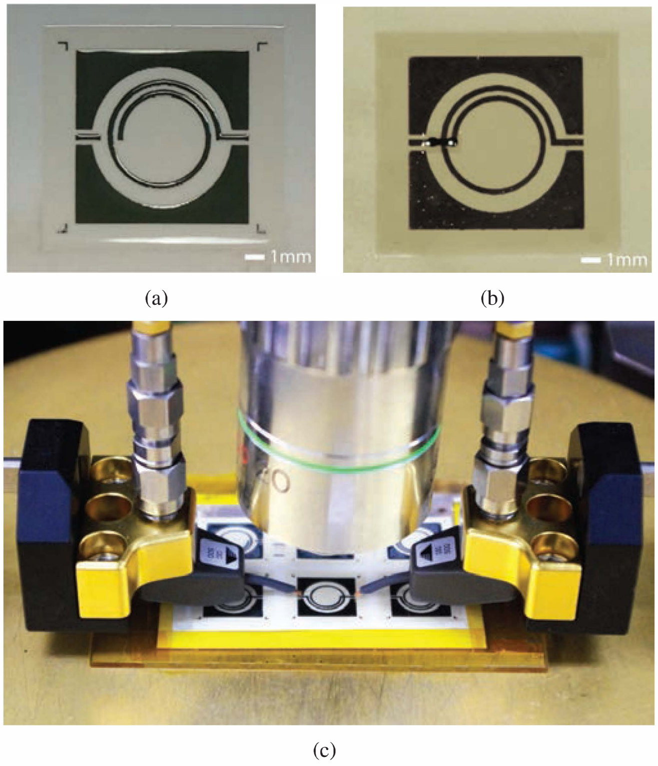


Fig. 1. Fabrication process for vertically integrated spiral inductors

then patterned with a thickness of 24 um with two via holes to allow for the connection of the inside and outside of the spiral on Metal 2 while keeping the crossover capacitance low. To determine process repeatability, and the effects of printed metal thickness versus inductor Q, 3, 4, 5, and 10 passes of silver are deposited for the metal layers on the 0.5 turn inductors, and 3, 4, and 5 passes are deposited for the 1.5 turn inductors for a total of seven separate fabrication runs.

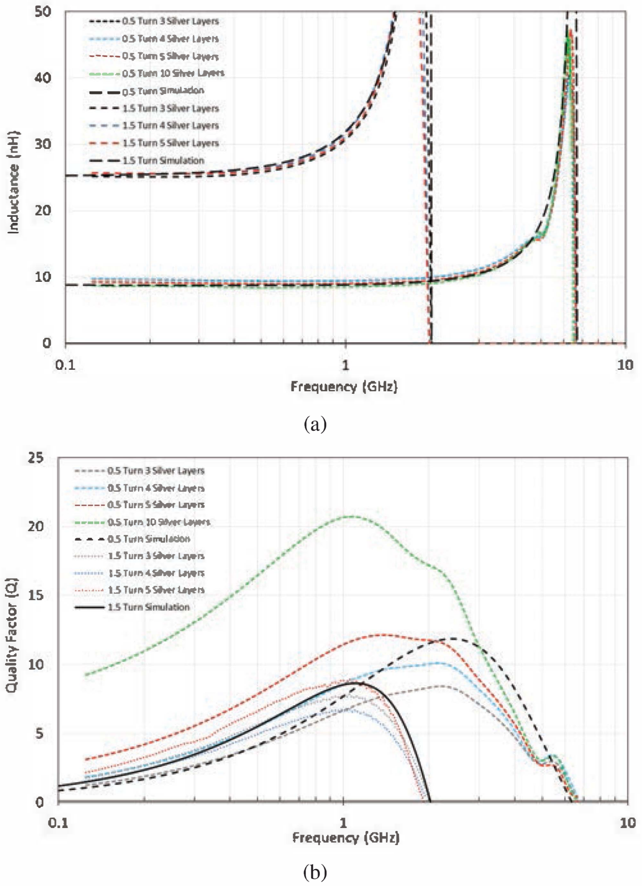
The fabricated inductors are shown in Fig. 2. The inductors are placed on a 1.5 mm thick glass slide for measurement. The measurement is performed using an Anritsu 37369A VNA with Cascade ACP 500 um pitch GSG probes.



(a) (b)

(c)

Fig. 2. (a) 1.5 turn inductor after M1 deposition, (b) 1.5 turn inductor after M2 depositon, and (c) measurement setup



(a)

(b)

Fig. 3. Measurement and simulation of (a) inductance, and (b) Q-value

For the 0.5 turn inductors, the measured inductance, which is shown in Fig. 3(a), is 10 nH with a self resonant frequency (SRF) of 6.5 GHz. The inductance value and SRF are nearly identical between fabrication runs, and the results agree well with full-wave simulation results performed in CST. Simulation results are for the 5 silver pass inductor iteration. The Q of the half turn inductors varies from 8.5 for three passes of silver to 21 for ten passes of silver at 1 GHz. The demonstrated Q is nearly an order of magnitude higher than previously reported values in the literature for a much higher inductance value [4], [6]. For the 1.5 turn inductors, the measured inductance is 25 nH with a SRF of 2 GHz, again having a very repeatable inductance and SRF between fabrication runs and good agreement with simulation. The Q for the 1.5 turn inductors varies from 6.5 for three passes of silver to 8.75 for five passes of silver.

IV. MULTI-LAYER INKJET-PRINTED TRANSFORMERS

Extending past inductors, transformers are a crucial component to fully printed modules for impedance matching circuits, and RF baluns to connect single ended circuits to balanced antennas. Transformers were previously unable to be realized utilizing inkjet-technology due to their complex multi-layer topology and the lack of a well-characterized, reliable multi-layer process. However, the recent advances in processing technology enable the fabrication of such complex components.

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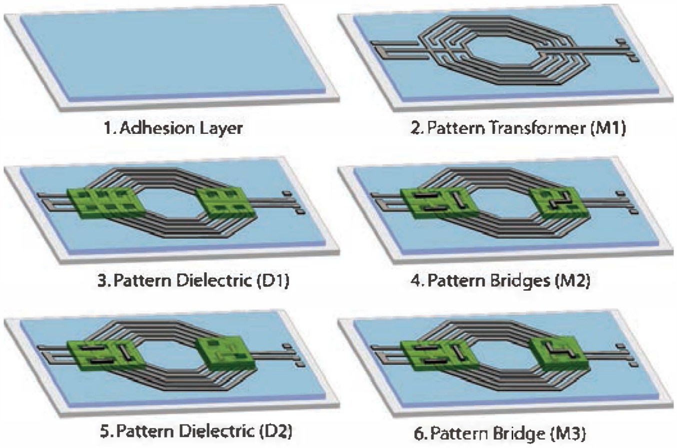


Fig. 4. Fabrication process for vertically integrated transformer

The design of the transformer, which is shown in Fig. 4, is based on the procedure developed in [9]. The proposed balun is a center-tapped 1:2 transformer connected as shown in Fig. 5: differential (Port 1) to single-ended (Port 2, with terminal 2B grounded) converter. The center tap (Port 3) is grounded providing a 180° phase difference between terminals 1A and 1B. The primary coil (differential side) is composed of three turns in parallel while the secondary coil (single-ended side) is a two-turn inductor, which gives a turns ratio of 1:2. The transformer features 150 um lines, 200 um spacings, and has an outside diameter of 5.6 mm. In order to fabricate the transformer, the same process is utilized as that of the inductors which is described in Section II. The process for the transformers is shown in Fig. 4. Again, the host substrate is 100 um thick LCP. The primary and the secondary coils, and the probe pads are on Metal 1. Dielectric 1 is patterned with a thickness of 24 um with via holes for the bridges needed to connect the turns of the secondary coil by means of Metal 2. Dielectric 2 is patterned with a thickness of 24 um with via holes used to connect the turns of the primary coil through Metal 3. The fabricated transformer is displayed in Fig. 6.

Table I includes the resultant primary coil inductance (L_{pri}), secondary coil inductance (L_{sec}), coupling factor (k-factor) and Maximum Available Gain (MAG) of the printed transformer. The MAG is the gain of the structure when both the input and the output ports are matched, and as reported, the MAG of the balun is -1.7 dB at the working frequency of 1.4GHz, meaning that, under matching conditions, 67% of the input power is transferred to the output.

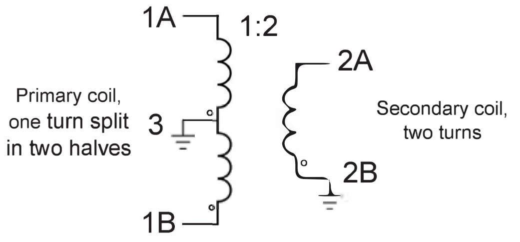
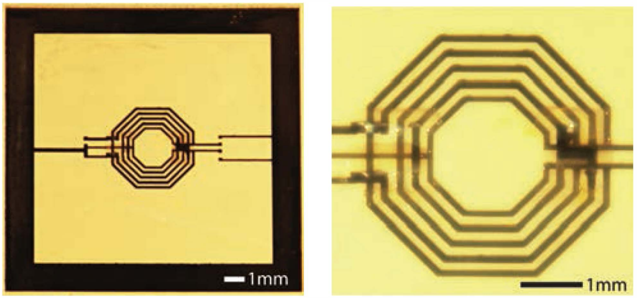


Fig. 5. Schematic of the fabricated transformer



(a) (b)

Fig. 6. Optical micrographs of (a) total transformer structure, and (b) inner coil of fabricated transformer

TABLE I

PERFORMANCE OF THE PROPOSED BALUN

Frequency	L_{pri}	L_{sec}	k-factor	MAG
1.4 GHz	6.1 nH	14.2 nH	0.49	-1.7 dB

V. CONCLUSION

Utilizing a finely tuned multi-layer inkjet-printing process, high performance inductors and transformer-based baluns are demonstrated for the first time with Q-values of over 20, which is over seven times higher than that of previously reported printed components in the literature. The resulting high performance and repeatability of within 5% for the inductance and SRF of the printed inductors between fabrication runs shows great promise for integrating printed inductive components into fully printed modules. While the printed inductive components are demonstrated on a common LCP packaging substrate, the substrate-independent nature of the process will easily lend itself to the fabrication of printed inductors and transformers directly onto CMOS circuits and conformal packages to greatly decrease the cost and chip area requirements for inductive component integration.

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