Additively Manufactured Multilayer High Performance RF Passive Components on Cellulose Substrates for Internet-of-Things Electronic Circuits

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***Abstract*—This paper demonstrates the feasibility to manufacture high performance radio-frequency passive components on cellulose substrates by exploiting two novel technologies: the vertically integrated inkjet printing and the copper laminate method. Both processes are substrate independent and thus suitable for fabricating circuits on paper as well; moreover, in a future perspective, they can be easily combined together in order to exploit their complementarity. Passive components such as capacitors and inductors, with Qs up to 22, never registered before on cellulose substrates, and Self-Resonant-Frequency (SRF) up to 4 GHz are described. The obtained values of the capacitance and inductance per unit area are 0.8 pF/mm^2 and 43 nH/mm^2, respectively.**

***Index Terms*—green electronics, Internet of Things, Passives, Inkjet Printing, Copper Laminate, Additive Manufacturing, Flexible Electronics**

I. Introduction

Passive components are fundamental elements for the design of several microwave circuits, such as filters, resonators, matching networks and so forth, The effective integration of such components in a way that eliminates the use of lumped elements, that typically increase the cost and the weight of the systems and reduce their mechanical flexibility and eco-compatibility, is of paramount importance when aiming at the development of electronic circuits for IoT market [1].

The aim of this work is to demonstrate that RF passive components on flexible cellulose-based substrates can be fabricated with low-cost, quick and environmentally friendly technologies, in particular the inkjet printing method and the copper laminate technique. The adoption of these processes is not only suitable for the reasons already explained, but also because they can be easily combined together and they are both compatible with Roll-to-Roll (R2R) industrial process for massive production of IoT hardware.

The structure of this paper consists of: a brief illustration of the two technologies, the description of inkjet printed RF inductors on paper substrates and then of preliminary prototypes of RF capacitors fabricated with the copper laminate method.

II. Technologies

In the last decade numerous novel technologies have been proposed as candidates to enable the industrial growth of IoT applications, being able to satisfy the requirements of: eco-compatibility, substrate independence, being cheaper and quicker than traditional manufacturing processes. These new technologies are, among the others, the gravure printing, the screen printing, the laser etching, the inkjet printing and the copper laminate: the last two are the ones adopted in this paper to fabricate the Metal-Insulator-Metal passives.

Inkjet printing has been already largely employed to fabricate planar circuits on paper substrates by depositing nano-particle silver inks [2]; recently, the development of dielectric inks, has allowed to use this technique for multi-layer structures (as for instance Metal-Insulator-Metal (MIM) inductors on LCP [3], capacitors on Kapton [4], and transformers on LCP [5]). A schematic example of the vertically integrated inkjet printing process is shown in Fig. 1, where for instance the steps to fabricate a MIM inductor are reported. Firstly, the silver ink (i.e. ANP) is printed to realize the first metal layer (film thickness equal to 0.5 μm per pass), then the sample is removed and baked into the oven up to 120°C. Afterwards, the selected dielectric ink (usually based on polymers such as PVP or SU8) is printed to make the insulation layer. The features of this layer are highly dependent on the type of ink used, as the curing procedure can be based on UV rays exposition (SU8) or just on high temperature baking (PVPh). Finally, the second metal layer can be printed and the complete structure is placed again into the oven for final curing. The

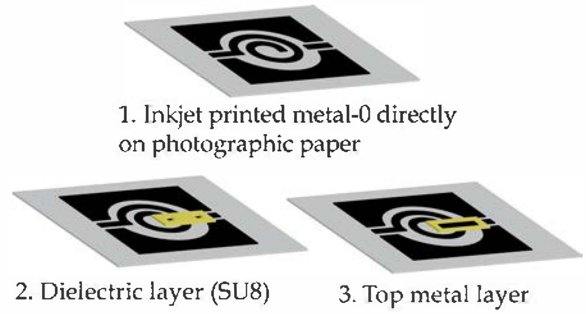

Fig. 1. Schematic example of multi-layer inkjet printing process.

copper laminate method has been proposed and characterized in [6] for frequencies up to 30 GHz, and several examples on cellulose substrates have been reported in literature [7], [8] for RF applications. This approach is based on the implementation of the lithography process to adhesive copper tape which can be easily glued on top of any substrates, either mechanically

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flexible or rigid, thin or thick. Figure 2 illustrates, step-by-step, an example of a MIM device fabrication with the copper laminate method.

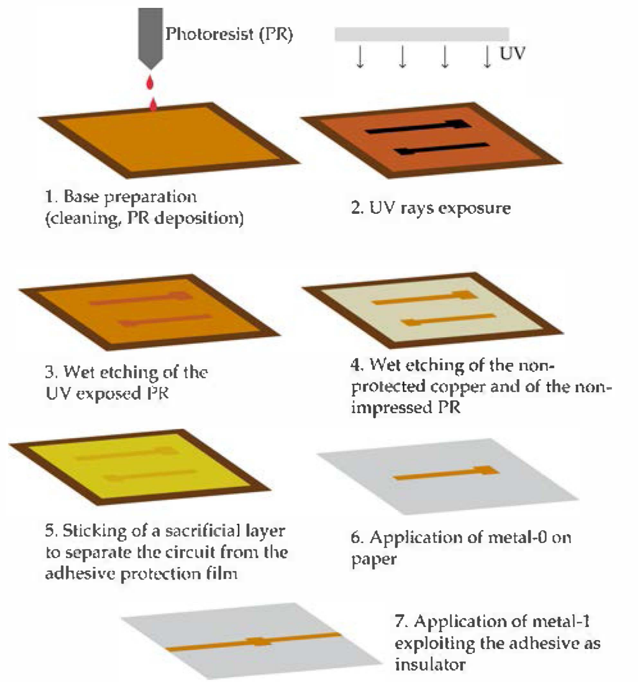

Fig. 2. Step-by-step illustration of the copper laminate method.

It is worth underlining that the substrate adopted for the components described in the following sections is a regular photographic paper from Mitsubishi, $230\,\mu$m thick, with a dielectric constant (ε_r) equal to 2.9 and a loss tangent (tanδ) of 0.06.

III. RF Inductors on Cellulose Substrates

In this section the first ever examples of MIM inductors on cellulose substrates, that are fabricated by means of vertically integrated inkjet printing method, are illustrated. Figure 3 shows the top view of the geometry (a-c) and the respective prototype photograph (b-d) of 1.5 turns and 2.5 turns inductors manufactured on the cellulose substrate. Both the gap and the line width (w in Fig. 3) are equal to $0.3\,\mu$m. The metal film is obtained by printing 5 layers of ANP silver ink resulting in a thickness of $2.5\,\mu$m while the insulator is printed with 4 passes of SU8 polymer based ink [9], [10], [4] with an overall thickness of $20\,\mu$m. Note that the insulation layer has a dielectric constant of 3 and a loss tangent equal to 0.04. The performance of these components has been evaluated by measuring the S-parameters and utilizing them to derive the curves of the inductance and quality factor versus frequency. The results are presented in Fig 4. The curves show the inductance (L) and the quality factor (Q) for five separate prototypes per each geometry, demonstrating the very high repeatability of the process. The 1.5 turns inductors exhibit an inductance value L of about 7 nH, while the achieved maximum Q is 11 with a Self Resonant Frequency (SRF) of 4.25 GHz. The 2.5 turns inductors feature an inductance equal to 18 nH, a maximum quality factor of 10 and a SRF of 2 GHz. It is worth noticing that a higher L and a lower SRF are expected for the larger inductors. A comparison with other

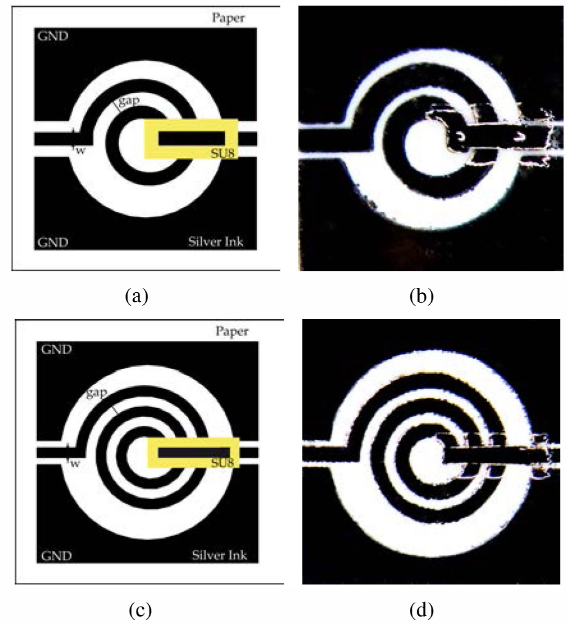

Fig. 3. Inkjet printed 1.5 turns and 2.5 turns MIM inductors: (a-c) design top view and (b-d) photographs of the respective prototypes.

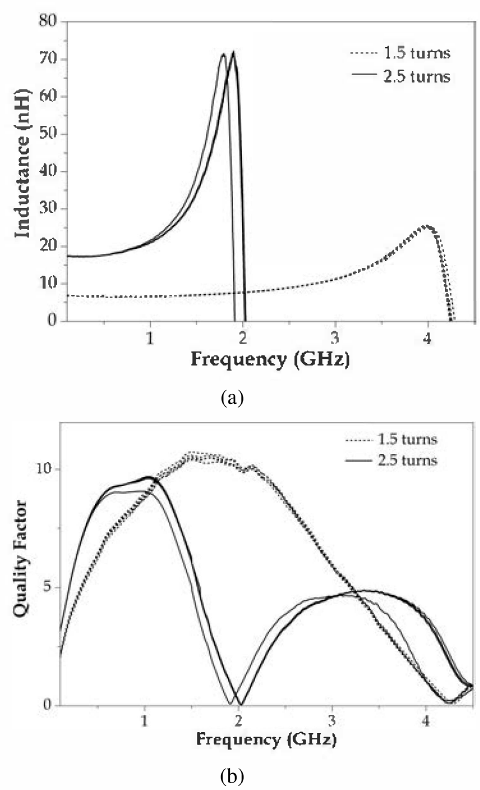

Fig. 4. Performance of the 1.5 turns (dashed lines) and 2.5 turns (solid lines) inkjet printed inductors deposited on photographic paper.

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state-of-the-art for inductors on paper substrates is reported in Tab. I. It is worth underlining that in terms of Q and

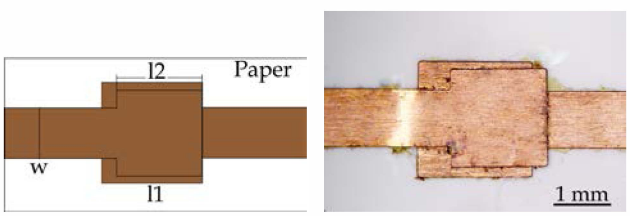
TABLE I
RF INDUCTORS ON PAPER: COMPARISON WITH THE STATE-OF-THE-ART.

Ref	geometry	process	L (nH/mm^2)
[11]	square	inkjet	0.04
[12]	circular	inkjet	0.002
this work	circular	inkjet	43

inductance per unit area, the obtained values are 2-3 times higher than what obtained with inkjet printing on other flexible substrates with similar geometries [13], [14], [15].

IV. RF Capacitors on Cellulose Substrates

This section illustrates the results obtained for RF MIM square capacitors on cellulose substrates, fabricated, for the first time, with the copper laminate method. Figure 5 shows the geometry top view and the micrography of the manufactured prototype. The lengths of the edges of the top plate and of the bottom plate are $l1 = 2\,\text{mm}$ and $l2 = 1.7\,\text{mm}$, respectively. Note that the top plate has been designed to be smaller than bottom top plate in order to facilitate the alignment and reduce the probability of short-circuit between the plates. In order



(a) (b)

Fig. 5. Copper laminate capacitors on cellulose substrates: (a) top view of the geometry and (b) micrography of the prototype.

to test the functionality of the device, the S-parameters have been measured and computed to determine the values of the capacitance (C) and quality factor (Q), exploiting the series model of capacitance between two ports. The frequency range for the measurement is between $0.05\,\text{GHz}$ and $1.5\,\text{GHz}$. The SRF is registered around $1\,\text{GHz}$, while the maximum Q is 22 and the capacitance is $2.5\,\text{pF}$. Note that the estimated value for the dielectric constant of the adhesive is about 2.5 (computed inverting the parallel plate capacitance equation), that is reasonable according to what can be found in literature for adhesives' electrical parameters [16]. A comparison with other state-of-the-art for capacitors on paper substrates is reported in Tab. II. Also for capacitors, a comparison with similar devices on other flexible substrates demonstrates that the component proposed in this work has a quality factor 2 times higher than what reported in literature [4].

V. Conclusion

In conclusion this work shows experimental results of passive components, with the best ever reported performance,

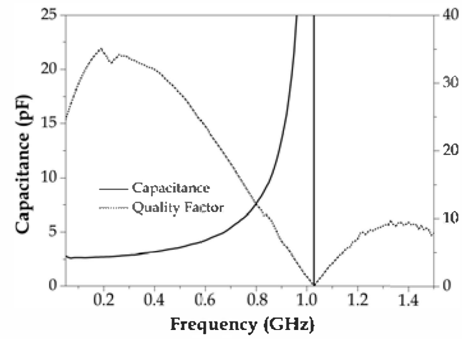


Fig. 6. Copper laminate capacitors on cellulose substrate: performance in terms of C and Q. The maximum Q is 22 and the SRF is 1 GHz.

TABLE II
RF CAPACITORS ON PAPER: COMPARISON WITH THE STATE-OF-THE-ART.

Ref	geometry	process	C (pF/mm^2)
[12]-1	square	inkjet	0.7
[12]-2	interdigit	inkjet	0.004
this work	square	copper lam.	0.8

fabricated on cellulose substrates by exploiting low cost, quick, R2R compatible and environmentally friendly, additive manufacturing technologies. The goal is not only to describe the superior performance, compared to the state of the art, of capacitors and inductors on photographic paper, but also to stimulate the possibility of integrating the copper laminate process with inkjet printing in order to fully exploit their complementarity. The intent is to include in the final presentation more results and possibly a first proof of concept of a fully integrated module on paper that can be fabricated with the proposed hybrid technology.

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