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Assessment of silver nanoparticle inkjet-printed microstrip lines for RF and microwave applications

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***Abstract*—The paper describes the fabrication process, the technology assessment and the experimental characterization of silver nanoparticle inkjet-printed microstrip structures on alumina substrates for RF and microwave applications. The present technology allows, through the adoption of innovative silver-based inks and a special piezoelectric-inkjet printer, the direct printing of microstrip prototypes on alumina substrates. The electrical characteristics of the manufactured strips have been modeled, starting from measured data, and several samples of line-stub impedance matching sections have been realized and measured to verify the repeatability of the line characteristic and printing alignment accuracy. More complex structures, including soldered components and ground wrap-around connection, have been realized and tested, showing good agreement between simulations and measurements.**

***Index Terms*—Microstrip filters, nanoparticles, prototypes, transmission line measurements, inkjet printing.**

I. Introduction

The increasing interest for inkjet printing technology in electronic applications is driven by the low cost, and fast production cycle of this fabrication process. At RF and microwave, direct printing of high resolution conductive lines is attractive for many applications, such as low-cost RFID tags on flexible substrates and planar antennas or, for fast circuit prototyping and small-scale production on conventional dielectric substrates, as a low-cost, high throughput and quick alternative to more conventional mechanical or laser-based techniques.

Although promising results have been obtained for DC and low frequency applications [1], the use of inkjet printing techniques for RF and microwave hybrid circuits still is almost unexplored [2], [3]. In fact, for high frequency applications, printed lines must comply with strict geometry constraints in terms of accuracy and repeatability. In a previous work [4], results of the characterization of inkjet printed microstrip and coplanar printed lines on alumina substrate have been presented, thus demonstrating that the metallic films obtained from sintered silver nanoparticles (NPs) exhibit parameters compatible with the realization of RF and microwave circuits.

In this paper, we describe the inkjet technology of silver NP films printed on alumina substrates, and the microstrip characterization and modelling approach. To assess the feasibility of complete RF/microwave circuits with this technology, test structures of increasing complexity are designed and characterized, starting from line-stub matching network samples, to analyze the accuracy and repeatability of the printing process, and finally investigating the behavior of more complete circuits, including soldered surface mounted components and ground wrap-around connections.

II. Inkjet technology

Direct printing of conductive patterned layers on alumina substrate poses some issues related to surface tension matching: the liquid ink must match the surface energy of alumina to realize defined edges and corners of the lines. Moreover, the sinterization process that acts on the NPs inducing electrical percolation, must be performed at relatively low temperatures in order not to promote oxygen diffusion from the substrate to the printed tracks. The raw materials exploited in this work are two kinds of commercial conductive inks, based on a colloidal dispersion of silver NPs in an aqueous medium, mixed, respectively, in a glycol/ethanol matrix (InkA-C10/40, Politronica Inkjet Printing) and in a UV-curable acrylic polymer (InkA-C100, Politronica Inkjet Printing). The solid loading of these inks ranges from 16 wt.% (InkA-C100) to 22 wt.% (InkA-C10). Both compositions are specifically formulated for piezoelectric inkjet printing to produce low resistivity and high resolution conductive traces on different kind of substrates. The distribution of NP diameters is multimodal and centered around 20 nm, in order to optimize particle packing and easily reach electrical percolation. Inkjet-printed Ag lines have been realized using a piezoelectric Jetlab® 4 printer from MicroFab Technologies Inc. equipped with a 60 μm nozzle diameter MJ-AT-01 dispenser. The print head has been heated at 40/60 °C and the substrate at 60/90 °C on a hotplate during the deposition process, looking for the best conditions for surface tension matching. The waveform used to eject the ink is a 35 V pulse lasting 18 μs, followed by a 13 V pulse lasting 36 μs as echo

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dwell, with rise/fall/final rise time 25/5/2 μs respectively. The step size has been set to 100 μm and four layers have been printed on top of each other. A vertical fiducial camera has been used to align the design and avoid mismatch as well as short circuits between the printed geometries and the metalized backplane, obtained by e-beam evaporation of Cr as adhesion promoter (20 nm) and Au (100 nm). The sintering process has been performed in a convection oven at 250 °C for 30 min.

III. Microstrip characterization and modelling

Following the approach described in [5], the microstrip line propagation characteristics can be directly extracted from *raw* (uncalibrated) S-parameters measurements of a pair of samples with identical cross section, but different lengths (as in [4]). The characterization has been carried out with a Vector Network Analyzer (Agilent E8361A) with high dynamic range (120 dB) and a dedicated test-fixture (Anritsu 3680K) in the frequency range 0.01-26.5 GHz, and the measurements have been averaged 512 times to reduce measurement uncertainties [6]. Three microstrip line pairs, with lines lengths of 2 cm and 3 cm, having different line widths (320, 630, 950 μm corresponding to more than 50 Ω, almost 50 Ω and less than 50 Ω) have been used to extract the propagation parameters. This procedure, performed on lines printed with three different inks (InkA-C10, InkA-C40, InkA-C100) (18 total samples), has been carried out to asses line losses and effective refractive index VS frequency. A CAD microstrip model, indispensable for circuit design, has been then derived fitting LRM *calibrated* measurements, taking into account the printing process uncertainty. A very good agreement between the extracted and fitted propagation parameters derived with the two strategies has been obtained. This is an essential requisite for the CAD model accuracy required for the reliable designs of the microwave structures that will be described in the following sections. Since the best electrical behavior has been exhibited by the lines realized with InkA-C10, results relative to this ink will be considered in the rest of the paper. The substrate model parameters, as obtained with CAD fitting, are listed in Table I [4].

Parameter	Value	Unit
Metal Thickness	4.4	μm
Metal Conductivity	0.3×10^7	S
Metal Roughness	180	nm
Substrate ϵ_r	9.8	a.u.
Substrate Thickness	618	μm
tanδ	0.001	a.u.

Table I
Modeled electrical characteristics of the fabricated microstrips preinted with InkA-C10 ink.

A. Line-stub matching network

A line-stub matching network implementing a low-pass filter for a 50 Ω system (see Fig. 1) has been designed. Fig 2 presents a microscope picture of the stub open end border, showing the geometry definition of the manufactured lines. Three samples of the circuits have been fabricated in order to verify the repeatability of the stub alignment and its absolute position with respect to the transmission line. The measured scattering parameters of the structures, compared with simulated results, are shown in magnitude and phase, in the range 0.5-6 GHz, in Fig. 3 (S_{11}) and Fig. 4 (S_{21}). The agreement between measurements and simulations is good. Also the uniformity between the three fabricated samples results satisfactory.

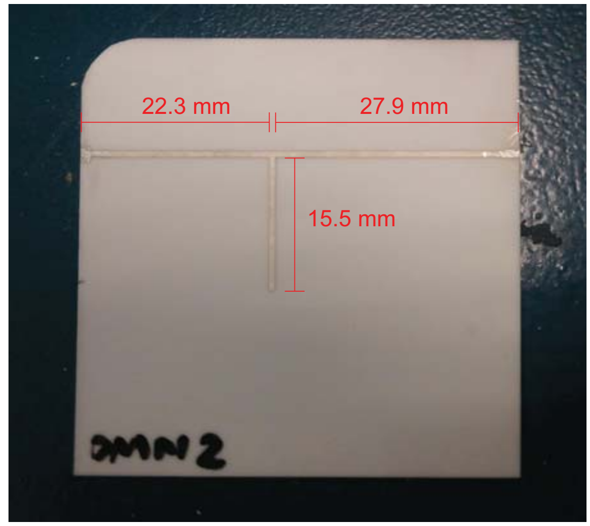

Fig. 1. Picture of one sample of the test structure I: a line-stub matching network, showing line lengths. The line width is 630 μm.

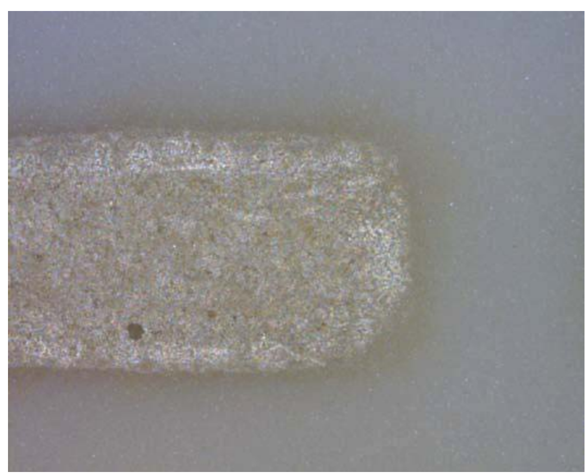

Fig. 2. Microscope picture of stub open-end of one sample of the line-stub matching network. The line width is 630 μm.

B. Components soldering and ground wrap-around connection

RF and microwave hybrid matching networks usually require the embedding of lumped components, e.g. RF decoupling capacitors or resistors. Furthermore, in many circuits ground

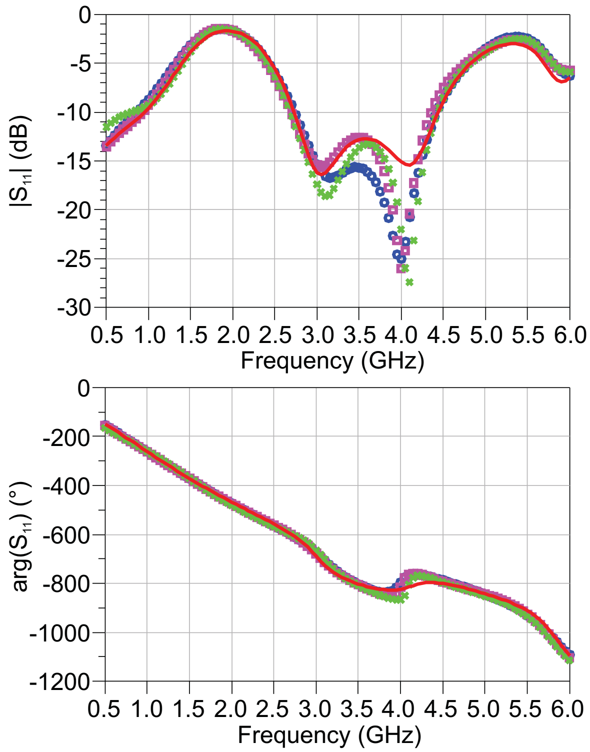

Fig. 3. Magnitude (upper figure) and phase (lower figure) of S_{11} of test structure I (Fig. 1). Simulation (red solid line) & measurements: sample 1 (blue circles), sample 2 (green squares) and sample 3 (purple crosses).

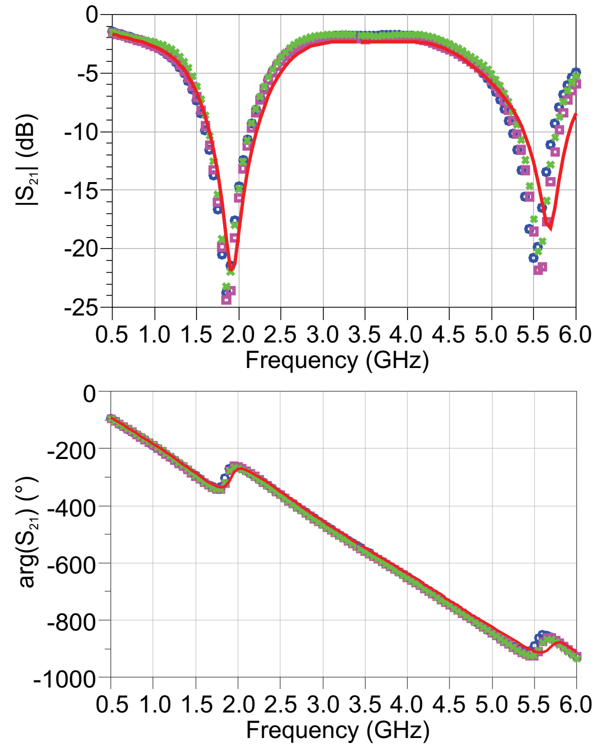

Fig. 4. Magnitude (upper figure) and phase (lower figure) of S_{21} of test structure I (Fig. 1). Simulation (red solid line) & measurements: sample 1 (blue circles), sample 2 (green squares) and sample 3 (purple crosses).

connection is necessary, for example for connecting by-pass capacitors in bias-tee networks or for RF shorted stubs. The feasibility of these two fundamental features of microwave circuits has been tested realizing the network of Fig. 5. It includes soldered surface mount components, i.e. a parallel R-C networks (e.g. for implementing the stabilization network of active devices), and a shunt resistor with ground connection through wrap-around. Different soldering methods have been tested to identify the best solution in terms of mechanical and electrical properties. In particular, three options have been exploited:

- lead solder paste (melting point $\sim$170°C);
- tin-aluminum-copper solder paste (melting point $\sim$210°C);
- indium wire (melting point $\sim$180$\circ$C).

The final choice has been the lead solder paste, mixed with flux with ratios 70/30 and 50/50, with warmup of the substrate at 130°C to avoid local cracks of the microstrip and hot air soldering at 230°C. Fig. 6 shows a microscope picture of a soldered resistor. Wraps-around, manually realized using conductive silver paste, have been chosen for ground connections since via-holes through alumina substrates are technologically demanding.

The fabricated network has been characterized in the 0.5-6 GHz frequency range. Fig. 7 and Fig. 8 show magnitude and phase of S_{11}, S_{21} respectively. Also in this case, the agreement between measurements and simulations is satisfactory.

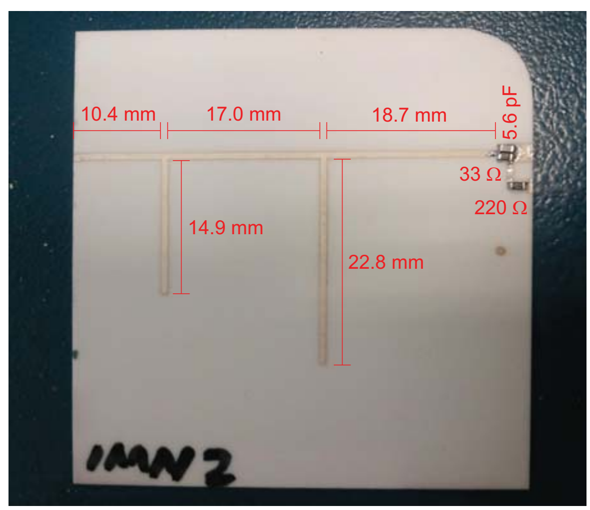

Fig. 5. Picture of the test structure II: a matching network with soldered components and ground wrap-around (right side of picture), showing line lengths. Line width is 630 μm.

IV. Conclusions

The fabrication of microstrip networks for RF and microwave applications through silver NP inkjet direct printing has been assessed. After optimization of the technological steps to ob-

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Fig. 6. Microscope picture of a resistor soldered with lead solder paste on the inkjet printed microstrip.

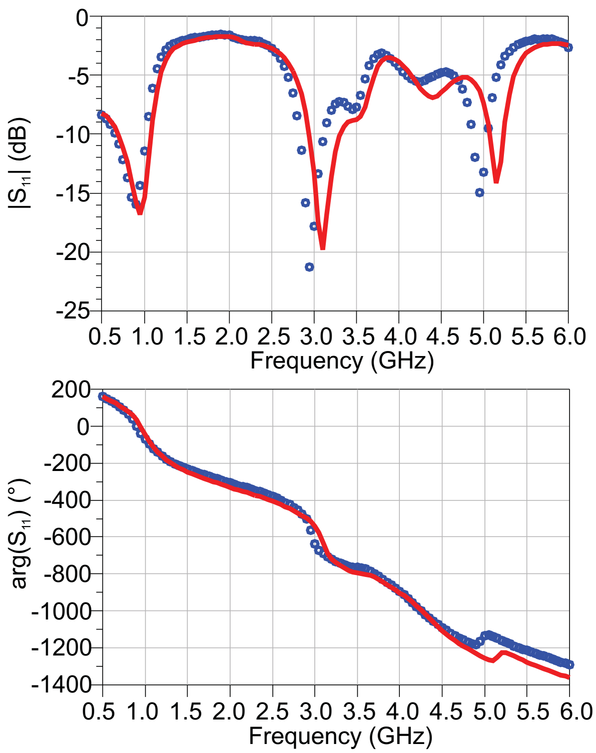

Fig. 7. Magnitude (upper figure) and phase (lower figure) of S_{11} of test structure II (Fig. 5). Simulation (red solid line) & measurements (blue circles).

tain a satisfactory mechanical robustness of the printed lines, characterization up to 6 GHz and modelling of microstrip line characteristics have been performed. Several samples of line-stub matching network have been fabricated and characterized, showing good repeatability and agreement with simulated results. The soldering of surface mount components has been exploited, together with wrap-around ground connections: also in this case the agreement between simulated and measured

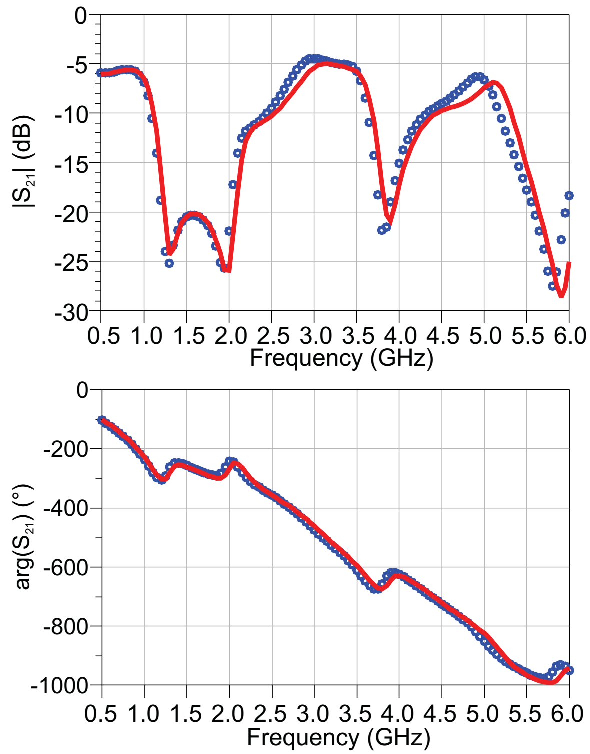

Fig. 8. Magnitude (upper figure) and phase (lower figure) of S_{21} of test structure II (Fig. 5). Simulation (red solid line) & measurements (blue circles).

results is satisfactory.

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