Laser Assisted Additive Manufacturing of CPW mm-Wave Interdigital Capacitors

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***Abstract*— A new fabrication approach for passive lumped interdigital capacitors is demonstrated for integration in microwave and mm-wave systems. Laser machining is combined with fused deposition modeling and micro-dispensing in order to enhance the performance of additively manufactured (AM) passive devices. Capacitances up to 0.3 pF and 0.5 pF are achieved at 5 GHz and 30 GHz, respectively. Measured and simulated data from different devices show maximum Q-factors and self-resonant frequencies of 750 and 120 GHz, respectively, representing a significant improvement when compared with previously demonstrated AM passive elements.**

***Index Terms*— Interdigital capacitors, additive manufacturing, laser machining, 3D-printing, lumped passive elements.**

I. Introduction

The performance of additively manufactured (AM) components continues to improve as the technology evolves; the systematic advances on the mechanical and electrical performance of 3D-printable materials, as well as the development of new fabrication techniques, are slowly taking AM from the prototyping stage to mass production. Among the most attractive promises of AM is the ability to enable complete 3D design freedom in order to fabricate conformal structural RF electronics, obtaining an expedited turnaround, minimum waste and reduced infrastructure.

However, along with minimum feature size limits that are characteristic of most standard AM techniques, fundamental challenges related to the electrical properties of AM materials still exist [1] (e.g., electrical conductivity, permittivity, and dielectric losses). These are challenges that need to be overcome in order to enhance the performance AM components and systems intended to operate in the mm-wave range. It has been proven that pulsed laser processing of AM layers can considerably improve the performance of additive manufactured microwave components, specifically coplanar waveguide (CPW) circuits, to levels comparable to that obtained by using traditional fabrication techniques at frequencies well into the mm-wave range [2]

Microwave lumped passive components are critical elements of wireless systems, which are typically used for matching or filtering purposes. In mobile RF front ends, lumped components are embedded into laminates or dies, or surface mounted. These often prevail over transmission line stubs due to their compact form factor. AM technologies such as aerosol jet printing (AJP) [3], inkjet printing [4], and micro-dispensing [5, 6] have been shown as a viable technology for the fabrication of microwave interconnects, capacitors, inductors, and resistors.

In this paper, the design, fabrication, and performance of an AM CPW-fed interdigital capacitor (IDC) is shown. This capacitor is fabricated by using FDM of acrylonitrile butadiene styrene (ABS), and micro-dispensing of DuPont CB028, combined with picosecond laser machining. Results show that capacitances in the range of 0.05 – 0.5 pF are achieved at 30 GHz, with Q factors up to 750 and self-resonant frequencies above 120 GHz.

II. Design and Fabrication

In this work, an interdigital lumped CPW capacitor is proposed as depicted in Fig. 1. Because it is a single conductor layer, this particular geometry allows not only for ease of integration with matching, filtering or biasing networks but also for ease of fabrication with regular AM techniques. The critical parameters that were design drivers included the overall size, self-resonant frequency, quality factor and effective series capacitance.

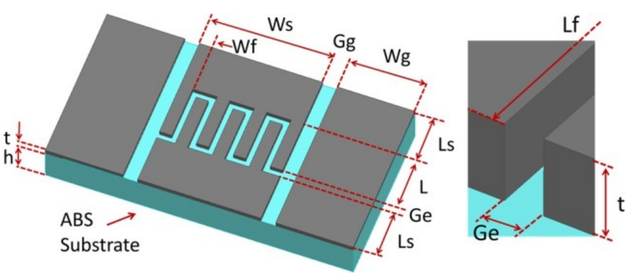

Fig. 1. Proposed CPW interdigital capacitor geometry.

In contrast to distributed passive elements, the dimensions of lumped components are much smaller when compared to the guided wavelength (i.e < λg /8). At mm-wave frequencies, such dimensions are smaller than what is achievable with regular micro-dispensing processes. Pico-second laser post-processing is thus implemented as a means to enhance the capacitor behavior at these frequencies with typical cuts achieving a 2:1 aspect ratio as shown in Fig. 1(right). This cut shape leads to improvements in the Q-factor over a thinner structure because a greater percentage of the electric field is confined to the air region between the two sides of the conductor, meaning less E-field in the lossy substrate.

The effective capacitance value of the IDC can be readily adjusted by varying the number of interdigital fingers and their respective length (*L*) achieving a range of capacitance from ~0.05 pF up to 0.5 pF at 30 GHz. The overall design dimensions are specified in Table I .

TABLE I
GENERAL DIMENSIONS

N° of Fingers	**3**	**7**	**9**	**11**	**13**
Wf (μm)	264.8	102	74.9	57.6	45.7

The following variables remain unchanged for all designs. Ws = 834.6 μm; Gg= 65 μm; Wg = 2 mm; Ls=520 μm; Ge ~ 15 μm; t= 30 μm; h= 300 μm.

The fabrication process is carried out with an nScrypt 3Dn tabletop system, a tool that combines the technologies of fused deposition modeling, micro-dispensing and laser machining, with 1 μm position repeatability and 5 μm accuracy. Acrylonitrile butadiene styrene (ABS), a thermoplastic with measured ε_r of 2.35 and tanδ of 0.0065 at 30 GHz [7], is used as the dielectric substrate. The ABS filament gets extruded through a 235°C heated 125 μm inner diameter nozzle and deposited layer by layer onto a metallic bed at 95°C. Subsequently the DuPont CB028 conductive traces are micro-dispensed on the dielectric surface with an approximate thickness of 30 μm. The paste is then oven dried at 90°C for 1 hour. A 1064 nm picosecond laser beam is then focused to a ~15 μm spot diameter at a repetition rate of 100 kHz and a P_{avg} of 2.4 W [2], patterning the capacitor geometry. Fig. 2 shows the fabricated interdigital capacitor prototypes with different finger lengths (a-d) and typical laser cuts in a 2:1 aspect ratio (e-f).

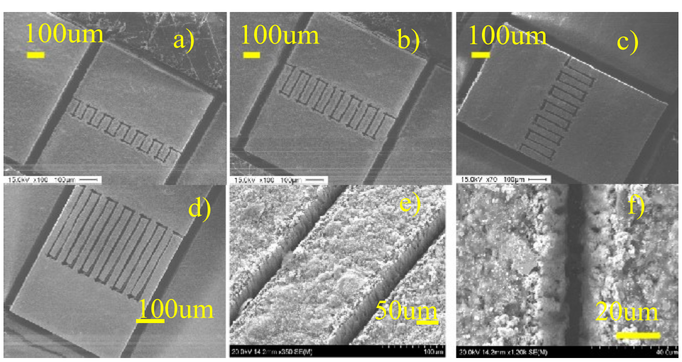

Fig. 2. a-d) SEM images of interdigital capacitor for different finger lengths e) SEM image of a laser cut with a ~ 2:1 AR; and f) Close-up SEM image of a typical laser cut on CB028 slot width ~15 μm and ink thickness ~30 μm.

III. SIMULATED AND MEASURED RESULTS

The simulations in this work were performed using HFSS 17.1 The measured data were obtained with an Agilent PNA-N5227A and GGB picoprobes. Fig. 3 shows the S-parameters up to 30 GHz for an interdigital capacitor with N° Fingers=13 and different finger lengths *L* ranging from 100 μm up to 600 μm. The plot shows good agreement between traces, indicating a high degree of simulation accuracy and repeatability in the fabrication process. For the same devices, Fig. 4 (top) shows the simulated and measured capacitance over frequency, where values from 0.05 pF for L=100 μm and 0.25 pF for L=600 μm are achieved. Close agreement with simulated data is also observed.

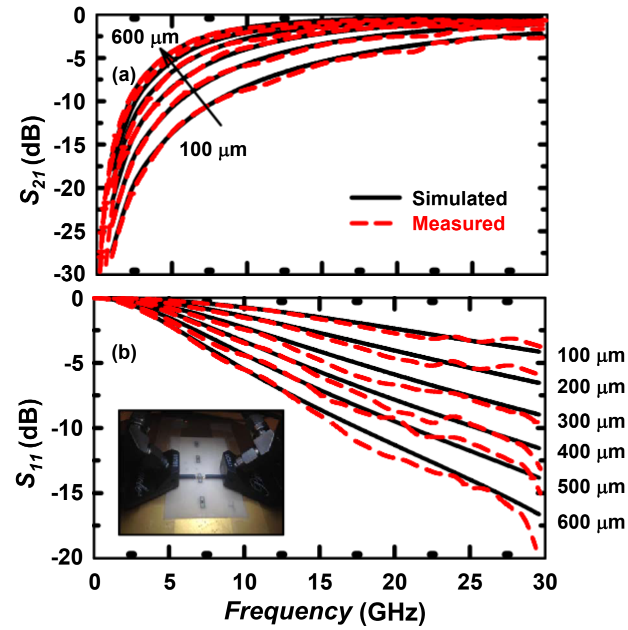

Fig. 3. Simulated and measured S-parameters for devices with N° Fingers:13 and variable L.

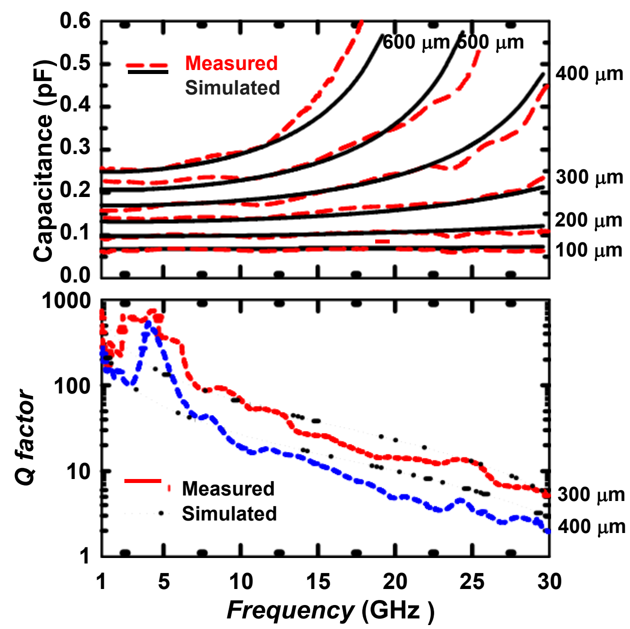

Fig. 4. Simulated and measured capacitance (top) and Q-factor (bottom) for devices with N°Fingers:13 and variable L.

Fig. 4 (bottom) shows the simulated and measured quality factor (Q), computed from (1); the measured Q values are extracted from the measured 2-port S-parameters, while simulated values are obtained from an equivalent RLC circuit model.

$$Q = \left|\frac{\mathrm{Im}\{-1/Y_{21}\}}{\mathrm{Re}\{-1/Y_{21}\}}\right| \quad (1)$$

Fig. 5 shows the predicted changes in effective capacitance at 5 GHz (a) and 30 GHz (b) for variations in the finger length *L*. Several prototypes with different numbers of were simulated, obtaining capacitance values ranging from 0.05 pF up to 0.3 pF at 5 GHz, and from 0.05 pF up to ~ 0.5 pF at 30 GHz. Additionally, the first self-resonant frequency (SRF) was studied via HFSS simulation since this parameter indicates the operational frequency range of the device. Figure 5(c) shows the location of the SRF for variations in the finger length for designs with different number of fingers (from 3 up to 13).

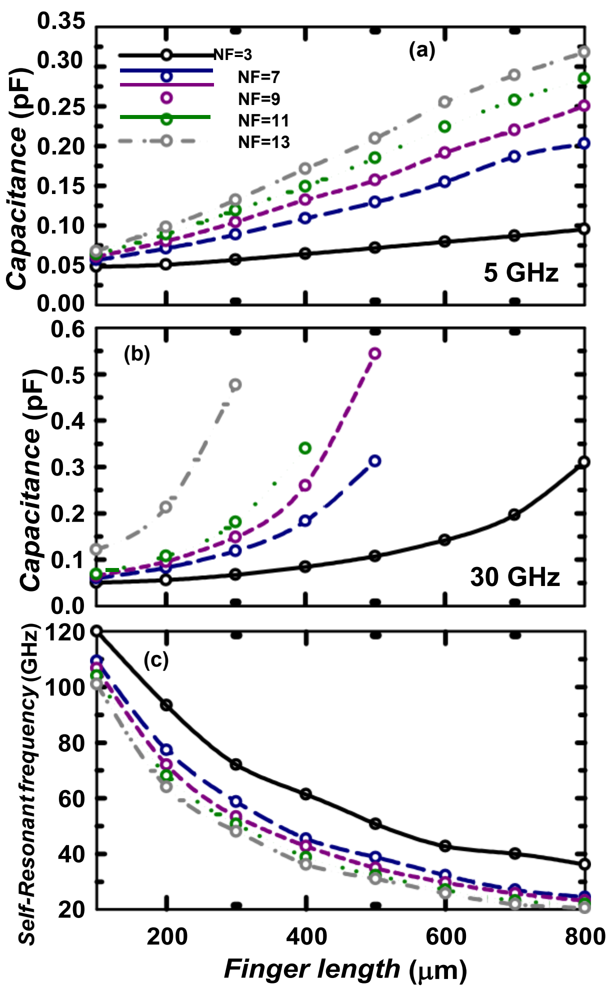

Fig. 5. Simulated capacitance at (a) 5 GHz and (b) 30 GHz. Simulated self-resonant frequency (c), for different finger length and different N°Fingers.

Table II shows a comparison of measured performance with previously published related work, including different geometries and fabrication methods. Note that AM capacitors tend to have lower Q, when compared to the ones obtained from GaAs dies. The main reasons for this are the lower conductivity of the inks, and the high *tanδ* of the printed dielectrics. In this work, higher Q values are achieved thanks to the use of laser machining, which increases the effective conductivity of the silver pastes [2]. Also it is important to note that the Q factor, capacitance, and resonance frequency are all related for a given technology. Typically, Q-factor and resonance frequency decrease for larger capacitance values.

TABLE II
COMPARISON WITH PREVIOUS WORK

Work	Geometry	Process	Q_{max}	*C* (pF)	SRF. (GHz)
*This work **	Interdigital	LEDPAM	750	0.14	47
Vanukuru [8]	Interd-mom	GaAs	400	0.02	>120
Mariotti-1 et al.[4]	Circular	Inkjet	15	6	2.5
Mariotti-2 et al. [4]	Square	Copper	35	5	1
Jung et al. [9]	MIM	GaAs	1000	1.05	11.5
McKerricher [10]	MIM	Inkjet	12.9	16.6	1.3

LE DPAM: laser enhanced direct printing additive manufacturing.* L=300μm

IV. CONCLUSION

A novel manufacturing process for lumped CPW interdigital capacitors is presented in this work. Pico-second laser post-processing is combined with standard fused deposition modeling and micro-dispensing in order to improve the performance of the IDCs up to mm-wave frequencies. S-parameter measurements of different prototypes were made up to 30 GHz demonstrating good agreement with simulated results. Capacitances up to 0.3 pF at 5 GHz and 0.5 at 30 GHz were achieved. A maximum measured Q-factor of 750 was obtained at 1 GHz showing an improvement of 715 when compared to the next highest AM device in the selected published works.

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