A Monolithic RF Lowpass Filter on Diamond via Additive Manufacturing

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***Abstract*—This paper demonstrates the design, fabrication, and RF testing of a monolithic lowpass filter (LPF) on single-crystalline diamond (SCD). This is the first time an RF filter has been fabricated on SCD. The LPF consists of grounded coplanar waveguide (GCPW) and microstrip (MS) transmission lines, via-less GCPW-to-MS transitions, and a bottom ground plane, all printed on a 5 mm × 5 mm × 0.15 mm SCD wafer with Aerosol Jet Printing technology using silver ink. The LPF is a stepped-impedance filter designed to have a cutoff frequency of 40 GHz and was measured from 10 MHz up to 67 GHz. Our results indicate that SCD is a good platform for the realization of high-frequency RF structures on a single substrate using additive manufacturing techniques.**

I. Introduction

Diamond constitutes an ideal semiconductor candidate in the manufacturing of RF electronics for wireless communications and high-frequency circuits for imaging, sensing, and radar applications. It exhibits the highest reported electric breakdown field among all semiconductors (10 MV/cm for diamond, comparing to 0.3 MV/cm for Si) owing to its ultra wide bandgap of 5.47 eV. It also has the highest thermal conductivity among all known materials (24 $W \cdot cm^{-1} \cdot K^{-1}$) and maintains a small loss tangent over a wide microwave and millimeter-wave (mm-wave) range ($< 10^{-5}$ at 140 GHz [1]). Diamond is therefore an excellent candidate for RF system packaging for both high-power and high-frequency applications.

Recently, the use of additive manufacturing (AM) technologies in microwave and mm-wave circuit fabrication has drawn the attention of the research community. AM technologies enable selective material deposition in three dimensions, utilizing conductive and non-conductive materials. Aerosol Jet Printing (AJP) could be a reliable alternative to conventional methods of packaging and integrating microwave and mm-wave electronics. Comparing to traditional photolithography, it could contribute to the reduction of manufacturing cost and fabrication time while exploiting the feasibility of 3D design, the ability to print structures on flexible and rough substrates, and the capability to resolve features less than 10 µm. Thus far, AJP has been used for the realization of microwave filters and mm-wave structures [2], [3], as well as transmission lines and power dividers on single-crystalline diamond (SCD) [1], [4]. In this work, for the first time to the best of our knowledge, an RF filter on SCD was fabricated via AJP using silver ink as the conductive material. The filter is a lowpass filter (LPF) and an SCD wafer was chosen as the substrate in order to demonstrate the capability of reliably realizing high-frequency RF structures on a single diamond wafer via AM.

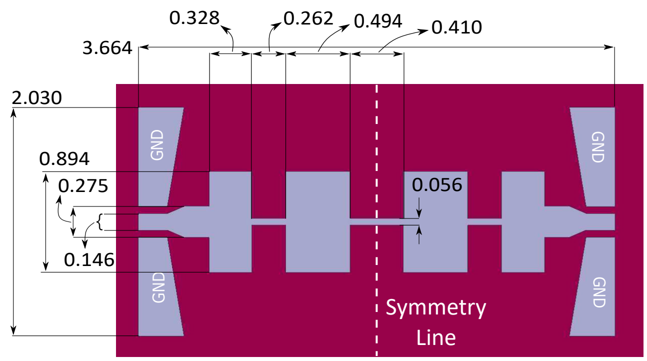


Fig. 1. Top view of the designed LPF (in units of mm, with bottom ground plane everywhere).

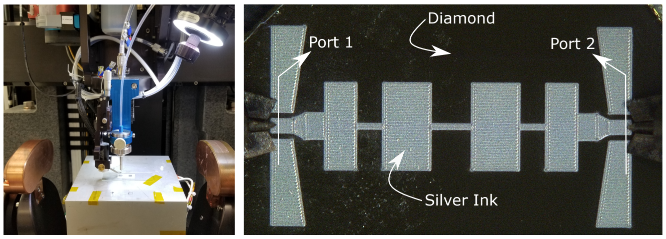
II. Design and Fabrication

A. LPF Design

The LPF follows the stepped-impedance prototype and was designed according to the methodology outlined in [5], with seven microstrip (MS) transmission line (TL) elements to provide a 0.5-dB equal ripple LPF response, a cutoff frequency of 40 GHz, a 30-dB insertion loss at 50 GHz, and an impedance of 50 Ω. Fig. 1 illustrates the design parameters of the stepped-impedance LPF. The lowest and highest element impedances were chosen to be 20 and 120 Ω, respectively. The structure is symmetric with respect to the middle 120-Ω element. The first and last 20-Ω elements, left and right, are terminated to 50-Ω MS TL parts, each of which lead to a 50-Ω grounded coplanar waveguide (GCPW) TL though a via-less GCPW-to-MS transition [6]. The design utilizes the GCPW parts to allow for probing and facilitate measurements. The entire structure was simulated and optimized in ANSYS HFSS©.

B. LPF Fabrication Process

The SCD wafer was fabricated via a high-pressure-high-temperature (HPHT) synthesis process and was commercially purchased. Lateral wafer dimensions are 5×5 mm^2, with (100) crystal oriented top and bottom surfaces. The wafer was cut



(a) (b)

Fig. 2. (a) The Optomec Aerosol Jet 5X System setup at Michigan State University, and (b) the fabricated LPF, with the two measurement ports indicated.

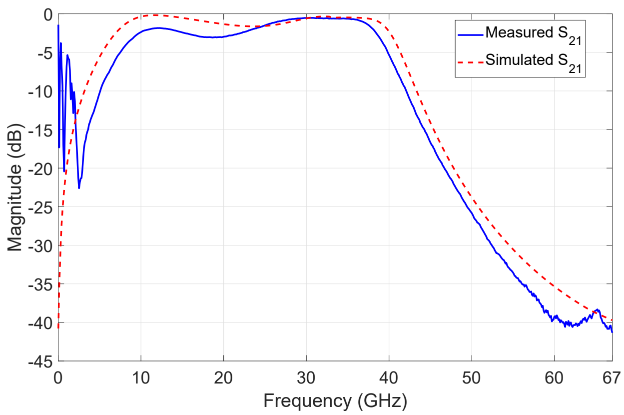


Fig. 3. Measured and simulated transmission ratio (S_{21}) of the fabricated LPF, with simulated results obtained for a diamond $\epsilon_r = 6.7$.

to a thickness of $\sim$ 0.2 mm using an infrared diamond-cutting laser, and then polished to the desired thickness of 0.15 mm on a cast iron polishing wheel seeded with diamond powder.

The TLs and bottom ground plane were fabricated via AJP technology using the Optomec Aerosol Jet 5X Printer, which deposits the material contained in a focused aerosol stream. The AJP manufacturing process enables the printing of silver ink with minimum printed feature sizes of 10 µm, with a single-layer path thickness of $\sim$ 1 µm. Overall, six layers were printed to achieve the designed silver thickness of 6 µm on top and bottom. First, the bottom ground plane was printed and cured, followed by the printing and curing of the LPF on top. The manufactured LPF is illustrated in Fig. 2b.

III. Results

All measurements were performed using two GGB Industries 67A-GSG-250-C Picoprobes, the MPI TS150-THZ Probe System, and the Keysight N5227 PNA. A short-open-load-thru (SOLT) calibration was performed to bring the reference planes to the tips of the probes. Figs. 3 and 4 show the measured and simulated results for transmission (S_{21}) and reflection ratios (S_{11} and S_{22}), respectively, in the frequency range from 10 MHz to 67 GHz, while the measured results at selected frequencies are summarized in Table I. The measured performance correlates well with the simulations. The cutoff frequency is close to the designed one at 40 GHz and the loss

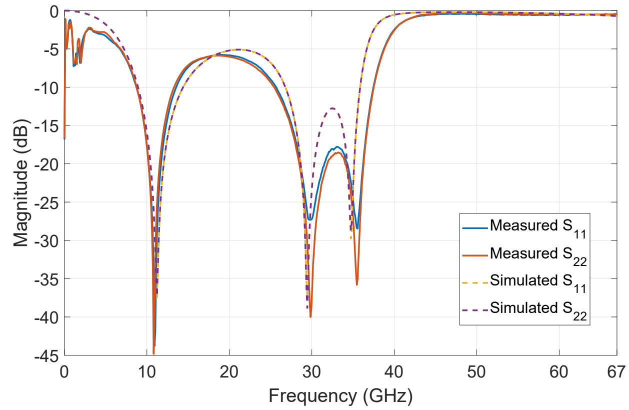


Fig. 4. Measured and simulated reflection ratios (S_{11} and S_{22}) of the fabricated LPF, with simulated results obtained for a diamond $\epsilon_r = 6.7$.

TABLE I
Measured LPF metrics at 10, 20, 30, 40, and 50 GHz.

Measured Metric	10 GHz	20 GHz	30 GHz	40 GHz	50 GHz
S_{21} (dB)	-2.4	-3	-0.5	-5.5	-25.8
S_{11} (dB)	-17.7	-5.8	-30	-2.5	-0.3
S_{22} (dB)	-18	-6	-37.3	-2.6	-0.5

achieved at 50 GHz is 25.8 dB, with the measured transmission rolloff closely following the simulated one. The maximum loss in the 10-40 GHz range is 5.5 dB. The high loss at low frequencies is due to the absence of vias in the GCPW-to-MS transition, which leaves no DC path. Moreover, increased noise is observed in the measurements at low frequencies, since little to no power is coupled from the ground pads to the ground plane. Similar behavior has been observed in [3]. Measured and simulated results show good agreement overall, exhibiting the desired LPF behavior from 10 to 67 GHz. These results reveal that the combination of SCD as a semiconductor material and AM as a fabrication technology shows great potential for the realization of high-frequency RF structures on a single wafer that can exploit the exceptional properties of diamond.

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