Fully Inkjet Printed 85GHz Band Pass Filter on Flexible Substrate

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***Abstract* — In this paper, a fully inkjet printed mm-wave band pass filter on a flexible substrate is presented. Firstly, a side-coupled ring resonator is designed to extract substrate's dielectric properties at mm-wave frequency band. Then, a parallel coupled microstrip transmission line filter is designed at 88 GHz frequency band with 10 GHz bandwidth. The filter has been fabricated by inkjet printing without making any vias. Very small feature sizes of ~20 µm have been reliably printed through new super inkjet printing technology. In addition, a Co-planar waveguide (CPW) transmission line and a CPW-to-microstrip transition have also been fabricated for comparison purpose. The filter's center frequency is 85.75 GHz with 20 GHz bandwidth, with potential applications fixed and mobile satellite communications. The insertion loss is ~5.8 dB, and overall return loss is below -10 dB. The rejection is lower than -20 dB.**

***Keywords* — mm-wave filter, fully inkjet printing, additive manufacturing, flexible filter.**

I. Introduction

Additive Manufacturing is a very attractive option for realizing electronics in a completely digital and low-cost fashion. No expensive masks are required and there is no material wastage like typical subtractive fabrication processes. Many electronic components have been realized through printing methods in recent years. Inkjet printing, for example, has a lot of advantages such as fast prototyping, drop-on demand printing, completely digital, minimum ink wastage, compatible with various substrates and materials, etc. But one major issue with inkjet printing technique is its resolution. Dimatix, from Fujifilm Inc., for example, gives single drop diameter from 50~80 µm. This means any design with minimum feature size below that would not be possible to fabricate reliably and in a repeated fashion.

For radio frequency (RF) designs, generally, the minimum feature sizes shrink with increasing operational frequencies. For example, there have been many filters demonstrated at lower RF frequencies through inkjet printing technique., Eyad et al. [1] fabricated a hair pin band pass filter by inkjet printing on PEN substrate which works at 6 GHz. D.Sette et al. [2] used silver nanoparticles-based ink to fabricate a 17 GHz filter. Hsuan et al. [3] used Liquid Crystal Polymer as substrate to inkjet print a filter that works at 25 GHz. K.Hettak et al. [4] designed a filter on PET substrate with silver ink that passes frequency band from 50 GHz onward. But this a high pass filter, and not a band pass filter. But it is very difficult to find any inkjet printed filters for mm-wave bands and the reason is the limitation of printing smaller feature sizes.

In this paper, we demonstrate the highest reported frequency band pass filter realized through inkjet printing. Very small feature sizes of ~20 µm have been reliably printed through new super inkjet printing technology. The filter has decent performance at mm-wave band, indicating the potential of super inkjet printing technology for future mm-wave fully printed components and systems.

II. Filter Design

Typically, the material properties (dielectric constant and loss tangent) for dielectrics, polymers, etc. are only provided at relatively low frequencies. In order to design the mm wave filter, the corresponding material properties at the frequency of interest must be determined. Here, ring resonators have been used to extract the dielectric properties. After that, microstrip to CPW transition can be simulated to evaluate the loss. Finally, the filter can be designed in simulation at the frequency of interest.

A. Material Properties Extraction

The permittivity has been extracted from two inkjet printed ring resonators on the 50 µm Polyimide substrate. The radius of the ring is calculated using the permittivity of the Polyimide dielectric at low frequency. Radius of 500 µm and 400 µm rings have been fabricated and measured, as shown in Fig. 1 and Fig. 2. It can be seen that resonance is at 82.75 GHz for 400 µm ring resonator and at 63.68 GHz for 500 µm ring resonator. After calculations, the dielectric constant is found to be around 2.9 at 63 GHz and 2.7 at 83 GHz. The average value (2.8) is the dielectric constant that will be used for ADS simulations.

B. CPW Line, Transition and Filter Design

In order to evaluate the loss, step by step, CPW line and transition are designed as well, as is shown in Fig. 3(a), (b). For filter design, single stage parallel coupled line band pass filter was chosen due to easier fabrication. Single stage is selected to minimize the loss. The filter layout is shown in Fig. 3(c). The dimensions are shown in Table 1.

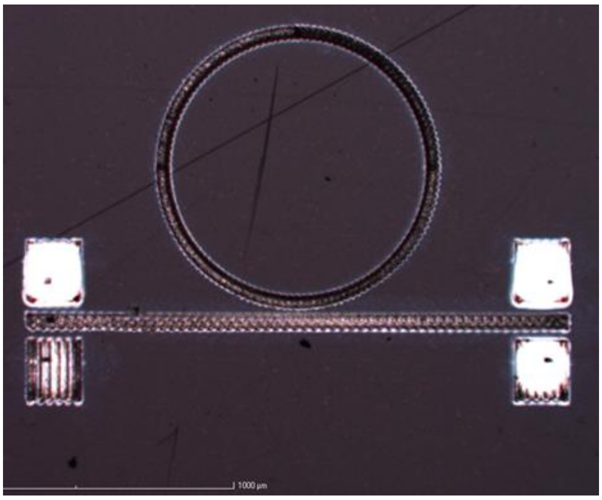

Fig. 1. Fabricated ring resonator. The scale bar is 1 mm.

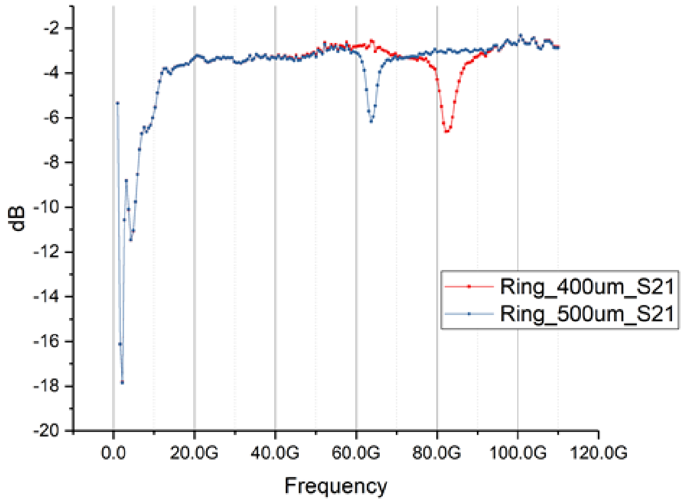

Fig. 2. Measured S_{21} of two ring resonators. Red curve indicates 400 µm radius ring resonator. Blue curve indicates 500 µm radius ring resonator.

Table 1. Design dimensions (unit: µm)

Item	L	G	W	L2	L3	W1	G1
Length	2000	40	120	1400	545	20	47

III. Fabrication Process

A 50 µm thick polyimide substrate has been used in our fabrication (purchased from UBE Ltd). Before printing, a spin coating cleaning procedure is followed. The spin coater was set to 4000 RPM (revolution per minute) and 60 sec. The polyimide sheet was sucked on the spin coater by vacuum. During the spinning, Acetone and IPA (Iso Propyl) was purged sequentially on the polyimide's surface. After spinning, the substrate was transferred in to a 200 °C oven and was kept there for 5 minutes in order to remove the water molecules from the surface. After this step, the substrate is ready to be printed.

The printing was conducted at room temperature. Since the polyimide sheet is very flexible and soft, the vacuum stage was used to ensure that the substrate is flat during printing.

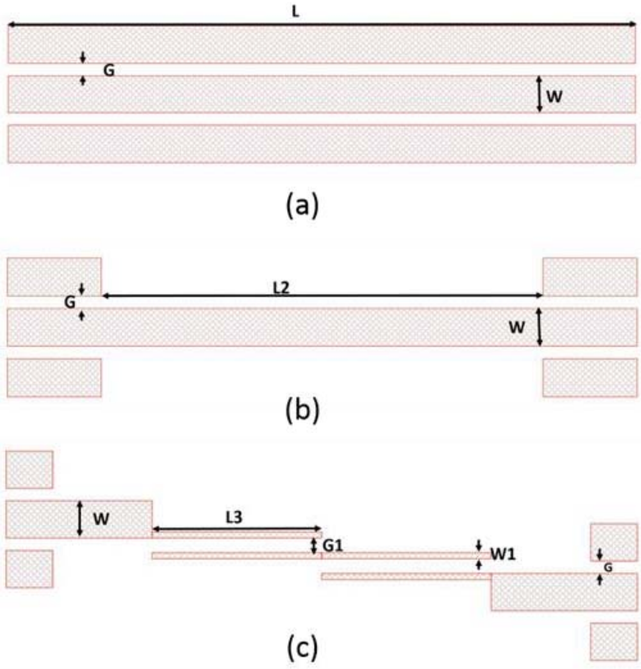

Fig. 3. (a) CPW line, (b) CPW transition line, (c) Filter.

The standard nozzle from SIJ Technology was used. High loading silver nanoparticle ink NPS-J from Harima Inc. was used, which has a silver content of ~65 % by weight and has a low range viscosity of 7~11 cp which makes the jetting much easier. To achieving the smallest possible single drop volume while still maintaining the nozzle to be reliably jetting, all the printing parameters are optimized. The jetting speed is fixed at 2 mm/s for printing lines, and 0.6 mm/s for printing circles. 75 % square wave was used as the jetting waveform. The jetting frequency is optimized to be 50 Hz. DC bias is set to 0 V and AC bias is set to 280 V~285 V. Spit bias is set to 1000 V.

A single layer provides around 35 nm thickness, so in order to achieve sufficient trace thickness, 20 layers have been used in the fabrication. This will provide thickness 2 times more than the skin depth at 80 GHz. Once the printing is done, the sample is transferred into an oven where it is baked at 200 °C for 60 min to convert the ink into conductive layer. The measured conductivity of 20 layers trace is $3E^7$ S/m.

IV. Measurements and Discussions

All the measurements were conducted on a cascade RF probestation. Anritsu ME7828A was used as Vector Network Analyzer to 110 GHz. Wincal was used to do on chip calibration. High frequency probes i110-A-GSG-125 were used for measurement. The measuring frequency was calibrated from 1 GHz to 110 GHz.

The measured result for CPW and CPW transition is shown in Fig. 4. Only S_{11} and S_{21} will be shown as they are the same to S_{22} and S_{12}, respectively. As can be seen from the figure, the insertion loss of CPW is around -1 dB. But the insertion loss of CPW transition is about -3.3 dB at 80 GHz. This is because, in CPW transition the microstrip experiences more loss from the Polyimide substrate as the field is denser in the Polyimide substrate as compared to the CPW case. This -3.3 dB loss can be improved by using low loss substrate.

Fig. 5 shows the measured and simulated S-parameter of the filter. The filter shows band pass from 75.67 GHz to 95.83 GHz. This band pass filter centering at 85.75 GHz with band width of 20.25 GHz. The insertion loss is -5.8 dB at 85 GHz. The return loss is lower than -10 dB in the pass band. The filter showed good rejection with below -20 dB at 63 GHz and 105 GHz. As can been seen, there are some discrepancies between simulated and measured results. In the simulation, the surface roughness of the conductor layer are not considered. Despite some difference, the overall trends of the two traces are similar. The fabricated filter is shown in Fig. 6.

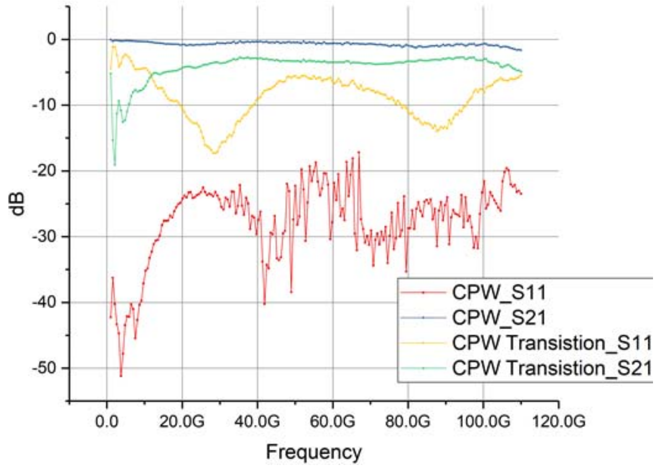

Fig. 4. Measured S_{11} and S_{21} of CPW and CPW Transition.

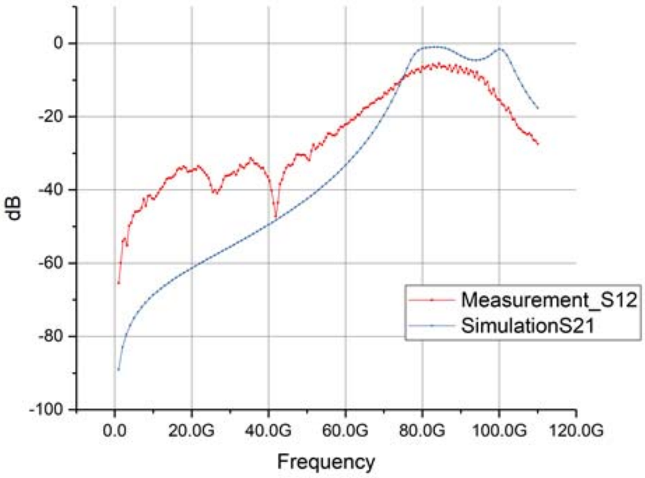

Fig. 5. Measured and Simulated filter. Only Transmission is shown here.

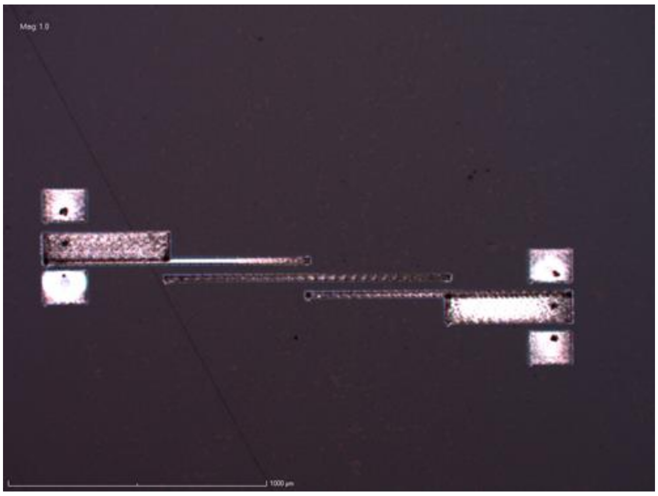

Fig. 6. Fully Inkjet Printed mm-wave band pass filter.

V. CONCLUSION

In this work, the filter's performance is investigated and compared with the simulated result. Here only Polyimide substrate has been tried. The overall performance is possible for further improvement by using other low loss substrate, such as glass or LCP materials. Also by improving the surface roughness of the printed line, the performance can be better. Finally, the possibility of using super inkjet printer to print very fine pattern is shown in the paper.

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