2.4 GHz Band Pass Filter Architecture for Direct Print Additive Manufacturing

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***Abstract*—This paper presents the first capacitively-loaded cavity band pass filter (BPF) that is compatible with direct print additive manufacturing, a hybrid technique that combines fused deposition modeling and micro-dispensing. The single resonator achieves a measured unloaded quality factor of 160-320 over the frequency range from 2.4 to 6.8 GHz. The two pole filter is designed using a coupled-resonator approach to operate at 2.44 GHz with 1.9% fractional bandwidth. The simulated and measured insertion loss is 3.8 dB and 4.2 dB, respectively. Fused deposition modeling is used to deposit acrylonitrile butadiene styrene (ABS) to form the stand-alone resonator and filter structures (relative permittivity of 2.7 and loss tangent of 0.008) and silver paste (Dupont CB028) is used to form the conductive parts.**

***Index Terms*—Fused deposition modeling, 3D, quality factor, resonator, filter, evanescent-mode cavity.**

I. Introduction

Highly selective filters are key components to enable efficient usage of the crowded electromagnetic spectrum. Among the available filter architectures, evanescent mode capacitively-loaded approaches have received significant attention since they offer high quality factors, a large spurious-free region, compact volume, and can be made tunable. There are several papers that present the use of microelectromechanical systems (MEMS) to design evanescent mode cavity resonators and filters [1]-[4], but these approaches have the disadvantages of relatively high complexity and cost. Additive manufacturing (AM) has proven its capability in fabricating high performance, compact and light weight microwave circuits and antennas, as well as the ability to achieve designs that are complicated to fabricate using other manufacturing approaches [5]-[8]. Direct print additive manufacturing (DPAM) is an emerging AM process that combines the fused deposition modeling (FDM) of thermoplastics with micro-dispensing of conductive and insulating pastes. DPAM has the potential to jointly combine high performance and low manufacturing complexity, along with the possibility of real-time tuning.

In this paper, the first evanescent-mode capacitively-loaded filters that is compatible with the DPAM printing process is described. The design is fabricated using an nScrypt Tabletop 3Dn printer to provide a proof-of-principle for the high-Q resonator and filter that compromise between performance, cost, size, and complexity. As well, the design extends the performance limits of the previously demonstrated DPAM-based resonator described in [9]. The MEMS based topology used in [4] is considered as the basis to design the proposed two pole filter. With the presented design, no micromachining is required and the need for vias to connect the bottom and top walls of the cavity resonator is eliminated by coating the cavity side walls with silver paste. Finally, the proposed design succeeded in miniaturizing the volume by 35.8%, reduced the manufacturing complexity, and achieves performance on par with that in [4].

II. Design

A. Resonator Design

The cylindrical capacitively-loaded cavity structure is shown in Fig. 1(a), where the cavity height (*h*+*d*), cavity radius (*l*), post radius (*r*), and the gap (*g*) between the top of the post and the cavity top wall are the main parameters defining the resonator performance. Tunability can be enabled once the structure dimensions are set by changing the gap, where differences of a few microns can change the frequency by a GHz. Compared to the resonator design in [9], the quality factor is increased by up to 2X by reducing the opening by 64.3% near the feedlines (see Fig. 1(b)). This improvement in the quality factor is critical in achieving the low insertion loss and steep cut-off observed with the two-pole filter.

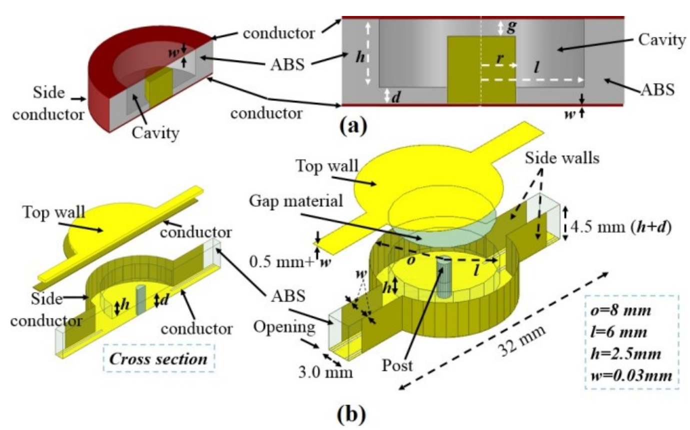


Fig. 1. Evanescent-mode cavity resonator. (a) Side-view of the cavity (gap filling material is not shown here) and (b) 3D view of a single resonator.

The evanescent-mode resonator (Fig. 1(b)) consists of the FDM ABS substrate coated with Dupont CB028 silver paste. In this work the CB028 has been applied to the outer surfaces of the cavity bottom and side walls, the underside of the cavity top wall, and the feed section using a brush, although either the micro-dispensing or micro-spraying attachments available on the nScrypt printer could be used. The paste is dried at 90 °C for 60 minutes, achieving a bulk DC conductivity of 1.5×10^6 S/m. The shorted input and output coplanar waveguide (CPW) feedlines are laser machined using a 1064 nm pulsed picosecond laser, and a copper wire is used for the resonator post. Finally, the gap is filled with a low loss, liquid crystal polymer (LCP) material (ULTRALAM 3908 with relative permittivity of 2.9 and loss tangent of 0.0025). The measured thickness of the ULTRALAM gap material is 30 μm, although the vendor-provided value is 25 μm; the measured value is used in the design simulations. In the current process flow, the top piece of the cavity is made separately and coated with the CB028, the gap material is attached to the non-dried CB028, and the piece is then assembled to the lower portion of the cavity. The assembled unit is then dried as described above. The main challenge to making this a single, continuous printing process that does not require post-assembly is controlling the thickness of the gap material. Improvements in laser-thinning and micro-milling procedures should provide the required level of thickness control in the near future.

Fig. 2 shows the measured unloaded quality factor and resonance frequency versus the gap dimension, within the frequency range from 2.4 to 6.8 GHz. The gap varies between 30 μm at 2.4 GHz and 200 μm at 6.8 GHz and is controlled using a micro-positioner stage. Gap heights are extracted from a full-wave simulation by introducing an air gap between the post and ULTALAM layer, and matching the measurement data to the simulation results.

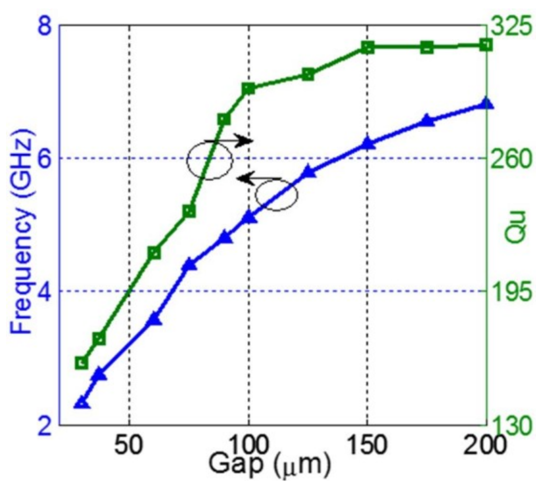


Fig. 2. Gap variation vs. resonance frequency and corresponding unloaded quality factor.

B. Filter Design

Using the developed resonator, a two-pole, 1.9% fractional bandwidth (Δ) Butterworth filter is synthesized at 2.44 GHz adopting the coupled-resonator design approach (Fig. 3). The filter response depends on both the external quality factor (Q_e) and the coupling coefficient between the two resonators (k).

The length (x) in Fig. 3(b) controls the external quality factor, and the opening (y) and spacing between the two posts (px) in Fig. 3(a) control the coupling between the resonators. These parameters can be found for a two-pole Butterworth filter (g_0=1, g_1=g_2=1.414) using [10]:

$$Q_e = \frac{g_0 g}{\otimes} = 75. \quad (1)$$

$$k = \frac{\otimes}{\sqrt{g_1 g_2}} = 0.01344. \quad (2)$$

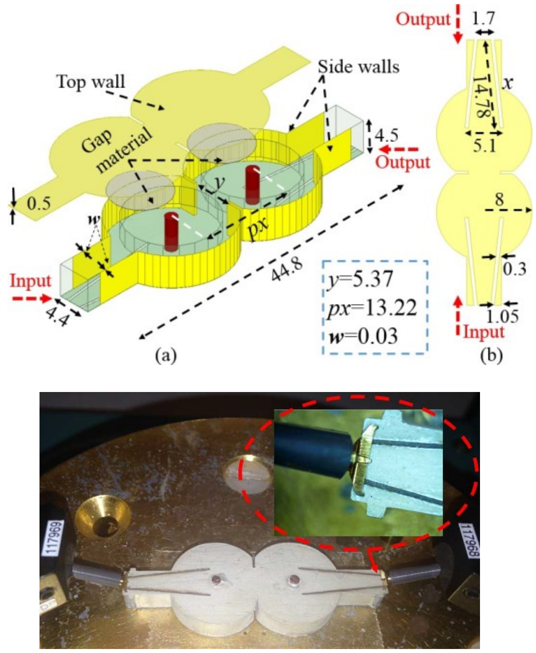
The post-to-post spacing and the feedline opening for a given internal coupling coefficient is plotted in Fig. 4. The coupling coefficient can be calculated using the general formulation from [10]:

$$k = \frac{f_{p2}^2 - f_{p1}^2}{f_{p2}^2 + f_{p1}^2}. \quad (3)$$

Where f_{p2} and f_{p1} refer to the resonance frequencies that result either from magnetic or electric coupling.

Tapered input and output shorted CPW laser-machined feed lines are used to provide the desired matching. ANSYS Electronics Desktop full-wave simulator is used to synthesize the filter design, and correct for the desired parameters. The filter fabrication process and assembly are shown in Fig. 5, where the first step is to print the filter structure using FDM process and ABS material as shown in Fig. 5(a). Then, the cavity side walls and bottom side are coated with the conductive material (i.e., silver paste) to create the cavities, and then dried as described previously at 90 C^o for 60 minutes. Fig. 5(b) illustrates the coated structure after having it dried and laser machined to define the input and output feedlines. The next step is to prepare the top wall along with the gap filling material (the ULTALAM layer), where the ULTRALAM is attached to the non-dried CB028 that being used to coat the top wall, and then dried in the oven using the same temperature as shown in Fig. 5(c). Finally, after installing the two posts, the top wall is attached to the filter structure, where a small amount of the silver paste is used to glue the top wall and the filter structure together before drying the whole structure.

The measurement is carried out using an Agilent Technologies PNA network analyzer N5227A and GGB 1850 micron-pitch microwave probes. The simulated and measured pass band insertion loss are 3.8 dB and 4.2 dB, and the simulated and measured return loss are 14 dB and 16 dB, respectively, as shown in Fig. 6. The discrepancies between the simulation and measurement data are due to the fabrication process tolerances, e.g., the silver paste thickness (~30±10μm) and structural dimensions (~±100 μm), and the surface roughness of 3-D printed structures [7].



(c)

Fig. 3. Evanescent-mode cavity filer (all dimensions are in mm) (a) filter structure (b) bottom wall and feedlines (c) fabricated filter on the probe station.

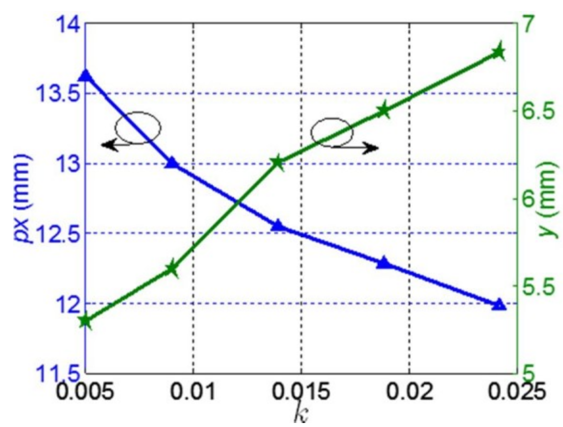


Fig. 4. Post-to-post spacing (*px*) and opening (*y*) vs. internal coupling (*k*).

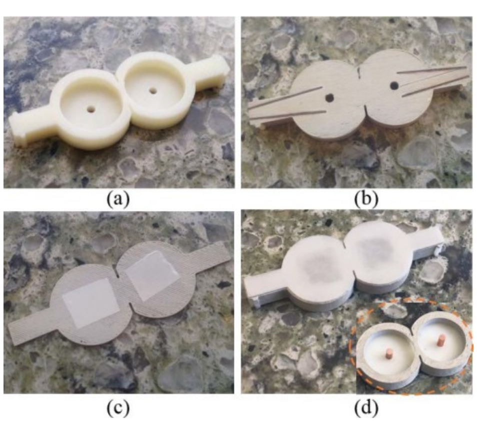


Fig. 5. Filter fabrication and assembly steps.

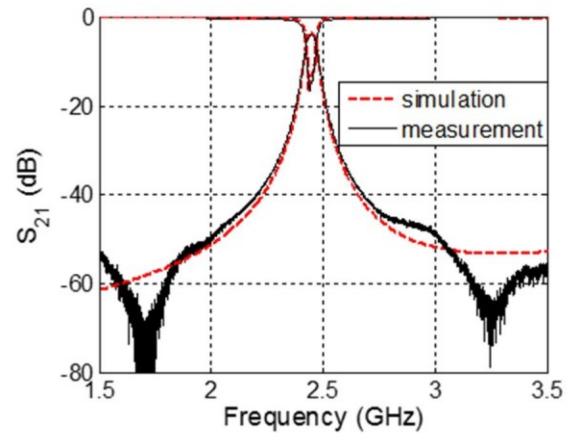


Fig. 6. Simulated and measured S-parameters of the filter.

The proposed filter can be tuned by changing the gap (g) for both coupled resonators to maintain the required coupling coefficient. Two measured examples are shown in Fig. 7; the first one has 2% fractional bandwidth at 2.7 GHz with 3.85 dB IL, and the second one has 2.4% fractional bandwidth at 3.8 GHz with 3.55 dB IL. The gap has been controlled using a micro-positioner stage to illustrate the filter tuning capability.

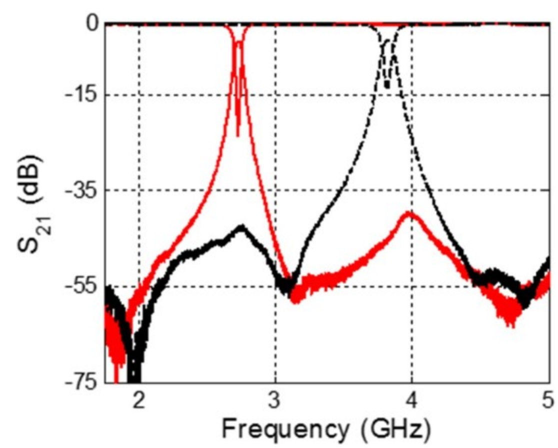


Fig. 7. S-parameters of the 2% (red line), and 2.4% (black line) filter.

III. Conclusion

This paper presents a 3D printed evanescent-mode cavity filter that is compatible with DPAM. The supporting ABS substrate is fabricated using fused deposition modeling (FDM), and silver paste (Dupont CB028) is used to metallize the top wall, side walls and the input and output shorted CPW feedlines. For the prototype purposes, manual brushing is used to form the conductive parts versus micro-dispensing. New models of the nScrypt Tabletop 3Dn printers have the capability for conductive paste spraying, which fits the proposed design procedure. A DPAM-based post can replace the copper wire by controlling the surface roughness and the fabrication tolerance, as currently the post offers a smoother surface and better dimensional control. The presented design approach simplifies the evanescent-mode filter fabrication, eliminating the need for micromachining and vias, and achieving a total weight of 1.97 g. The high degree of similarity between the simulation and measurement validates both the fabrication process and design procedure, and provides a proof-of-principle for high performance DPAM filter technology. At higher frequencies, the Q-factor improvement due to increased electrical size dominates over increasing skin effect loss, making the proposed structure a good candidate for higher microwave frequency designs as well.

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