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Compact Integrated Lumped Element LCP Filter

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Abstract—The filter presented in this paper is a novel, compact, 4-pole, UHF-band integrated lumped element filter with a 20% fractional bandwidth operating at centre frequency $f_0=500\text{MHz}$ with a 17dB passband return loss and a wide upper stopband with high rejection. The circuit was designed to minimise the overall footprint, as well as ensuring a wide, high attenuated stopband. This was achieved by building on previous work using LCP as a fabrication medium which implemented a block of shared vias; however by adding a new controlled coupling between two capacitors, the stopband performance was significantly improved. The final filter dimensions are $0.03\lambda_g \times 0.06\lambda_g$, and the out-of-band rejection is significantly larger than its predecessor at 50dB up to $3f_0$ and 40dB up to $5f_0$ with a stopband width extended to 7 times the centre frequency.

Index Terms— bandpass filter; lumped element filter; liquid crystal polymer, multilayer, wide stopband.

I. INTRODUCTION

AS the frequency spectrum become busier with time, the stopband performance of filters becomes significantly more important than it did in the past, and added functionality within products also means that there is a focus on size and weight reduction as well. An application that requires combining these two specifications is an IF filter within the receiver architecture in an Unmanned Aerial Vehicle (UAV). High frequency filters easily meet those requirements following distributed element design however at lower frequencies, such as those within the Very-High and Ultra-High Frequency (VHF/UHF) bands, distributed element filters become too large to be practical and integrated lumped element circuits, therefore become the more popular choice [1].

Lumped element filters can also be fabricated on Liquid Crystal Polymer (LCP) which means that individual components can be minimised at the outset of the project by employing the use of multilayered structures, an obvious benefit to using thin-film fabrication methods. LCP is preferable to other methods such as Low Temperature Co-fired Ceramics due to its compatibility with standard PCB technology and the lower fabrication temperature [2].

Traditionally the tubular filter design is used to design lumped element filters however it was noted that the

traditional layout of these filters is still reasonably large, and an elegant “folding” integrated technique would halve the overall footprint, of an already more compact design. This led to several unique design opportunities that are discussed later in the paper.

As mentioned above, as well as the selectivity and the physical footprint of the filter, the stopband performance, is equally important. Filters do already exist with good attenuation built using various different techniques [3-5]; however in the majority of papers the footprint is still rather large and the smaller designs do not have a particularly wide stopband. As a result, when designing a filter such as the one discussed, one specification is generally always sacrificed for the other. Although a miniature UHF-band filter has been developed recently [6], the upper stopband rejection is 30dB for a stopband width of 4.6 times the centre frequency.

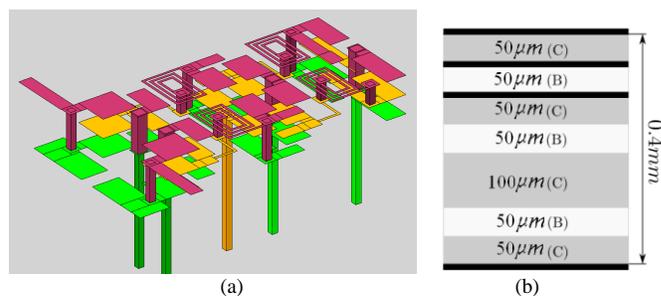


Fig. 1: (a) A 3D model of the proposed compact integrated lumped element filter and (b) a cross section of the layers used

As a result the focus of this paper was to present a novel implementation of miniature UHF filter as shown in Fig. 1 and to experimentally demonstrate, for the first time, its promising performance with a high level of rejection and a comparatively wide stopband.

II. INITIAL FILTER DESIGN

The filter circuit model chosen in this paper is a 4-pole tubular bandpass filter, however as mentioned previously, the design used a unique topology, displayed in Fig 1. The filter is to be centred on 500MHz with a fractional bandwidth (FBW) of 20%. The multitude of capacitors used in the impedance inverters were an easy target for miniaturisation using the multi-layered approach, rather than the traditional planar coupled method presented in design procedures [7, 8]. The LCP used has a dielectric constant of 3, and a loss tangent of 0.0025. The initial design equations used to obtain the component values are detailed in [9] and the capacitor values listed in Table 1 were calculated, after using the iterative work

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mentioned in [9] and deciding on a single inductor value of 20nH, due to ease of implementation. The circuit model shown in Fig. 2 was first simulated using AWR Microwave Office (MWO) design environment. The circuit model not only confirmed the intended response of the circuit, but facilitated the transition to a layered 3-D structure, by allowing the effects of each component to be analysed. It also meant that the properties of the vias and steps-in-width of the microstrip that were not included in the ideal circuit model could be countered quickly and effectively.

TABLE 1: CAPACITOR VALUES USED IN THE CIRCUIT MODEL IN FIG. 2.

Capacitor Name	Ideal Calculated Values (pF)	Values used in the EM Model (pF)
C01	15.9	15.43
Cp0	4.06	6.526
Cp1	4.15	4.73
C12	4.26	2.3
Cp2	7.42	7.769
C23	3.08	2.47
Cp3	7.91	9.083
P	N/A	0.07 nH

The next stage of the design was the electromagnetic (EM) simulation. This began by designing the individual components in Sonnet design environment using the value extraction method detailed in [10]; the components were drawn and simulated at the centre frequency of the filter, their values extracted and adjustments to dimension made as required. It should be noted that this type of quasi-lumped element behaves as an "ideal" lumped element up to 600 MHz, which was considered adequate for this particular design. Care was taken to also include the diameter reduction technique in the multilayer vias, in order to improve the contact to the connecting pad of the lower layers of the capacitors.

At this point a decision was made to use four metal layers, including the ground plane, as it was felt that this was an acceptable compromise between the complexity of the manufacture and the overall footprint of the circuit. Each component was designed specifically to keep the number of vias minimal, which led to the "shared via" design displayed in Fig. 1, where the through vias are shared between adjacent impedance inverters, and their parasitic effects modelled by the inductors labelled P in Fig 2.

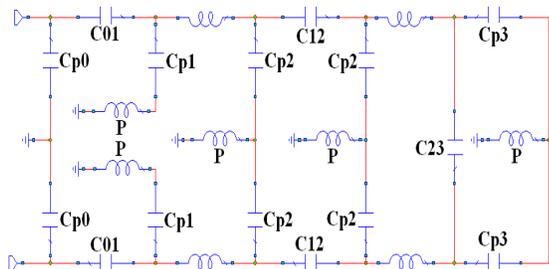


Fig. 2 Equivalent Lumped Element circuit model of the proposed compact integrated lumped element filter

The completed circuit was then assembled, and simulated, with the passband results shown in Fig 3. After the filter was completed a full EM simulation was run in Sonnet and compared to the MWO circuit model results. The tuning tool in MWO allowed the effects of capacitor values to be viewed,

allowing optimisation of the return loss to be conducted before work began on the stopband.

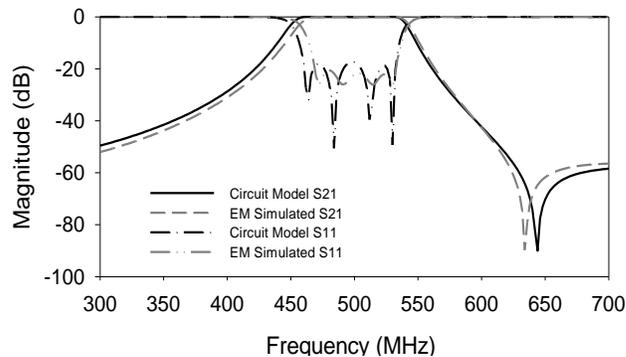


Fig. 3 Passband performance of the MWO circuit model, and the Sonnet layered structure (lossless case)

III. STOPBAND PERFORMANCE

Once the filter was completed, and the return loss was at an acceptable level a wider simulation was run to review the stopband capabilities. The gap between the two adjacent Cp0's afforded a unique opportunity, with a specific gap creating an additional transmission zero (TZ) within the stopband, as clearly demonstrated by the EM simulated response in Fig. 6. Several simulations were run to design the shape of this capacitor, looking at how the gap spacing, and the width of the coupled metal affected the results before settling on the design proposed. An earlier version had a slightly wider metal patch but the "rollback" from the second TZ caused the stopband to be lowered, and the immediate stopband securing the selectivity was not considered good enough.

During testing it was noted that this gap had a "critical point" where this level of attenuation would be at its highest, so it was suspected that fabrication tolerances would affect this result, but the lossy simulation conducted at this point showed that the filter had 37dB of attenuation with a stopband width of up to 7 times the centre frequency. The final layout designs are illustrated in Fig. 4

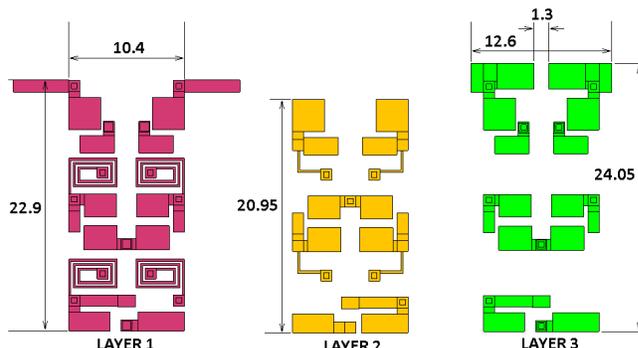


Fig. 4 Final layout designs of the proposed miniature filter (all sizes in mm)

IV. MEASURED RESULTS

The filter was fabricated in house and the fabricated prototype is displayed in Fig. 5. The final measured results shown in Fig 6 were obtained using an N5225A PNA Microwave Network Analyser. They show a relatively good match in the passband with the simulated results in Fig. 6,

despite fabrication tolerances that caused a 10dB discrepancy between the stopbands. This can be attributed to the sensitivity of the gap capacitance which was discussed in Section III. A typical etching error of 50 μm was found to cause discrepancies such as that seen in Fig. 6.

The circuit met the frequency specifications with a 20% FBW centered on 500MHz with a 17dB return loss. Physical implementation of the filter on copper coated LCP has created an insertion loss of 3.5dB due to conductor losses, which is acceptable for the intended application as an integrated IF filter where the absolute passband insertion loss is not a priority. The noted difference in the passband return loss between EM simulated results shown in Fig. 3 and Fig. 6 is because the result of Fig.3 is lossless, while the result of Fig.6 includes all losses. The first harmonic spur is present at 4.2GHz on the final measurement results, roughly 7 times the centre frequency, showing that a relatively wide stopband has been achieved, which is 33dB at its worst point.

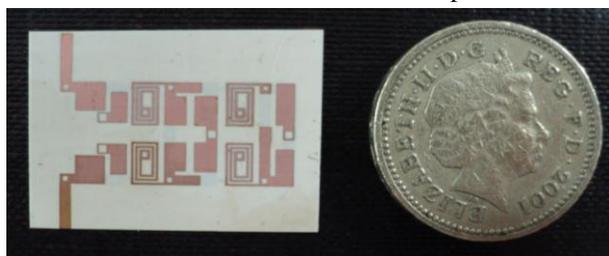


Fig. 5 Fabricated filter next to a British pound coin for size comparison

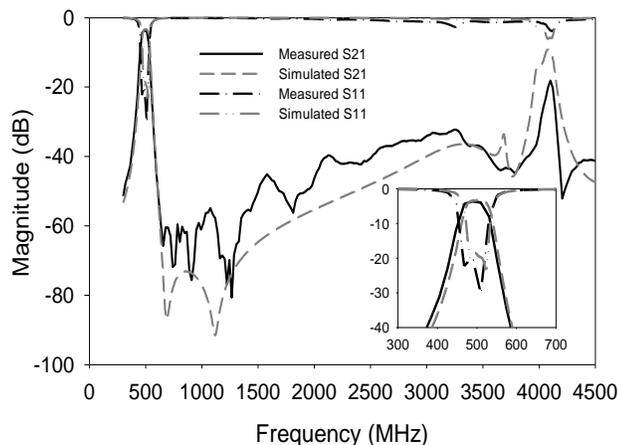


Fig. 6 Comparison between the lossy simulation results and the final measurement results with an inset close-up of the passband response

Table 2 shows this work's results in comparison with the referenced work discussed in Section I. It shows this filter achieved a significantly smaller size, operating at a lower centre frequency for a stopband-width and level of attenuation comparable with the best results seen.

TABLE 2: COMPARISONS WITH OTHER WORK

Filters	f_0 (GHz)	Footprint (λ_g)	Attenuation
[3]	0.96	0.03 x 0.13	30dB for 5 f_0
[4]	1.5	0.23 x 0.97	30dB for 5.4 f_0
[5]	2.5	0.37 x 2	30dB for 7 f_0
[6]	0.5	0.03 x 0.06	30dB for 4.6 f_0
This work	0.5	0.03 x 0.06	30dB for 7 f_0

V. CONCLUSION

In this letter a compact integrated lumped element bandpass filter whose centre frequency (f_0) lies in the UHF spectrum at 500MHz, with a 20% FBW was presented. The filter achieved the intended specifications with a return loss of 17dB when fabricated and the measured out-of-band rejection is larger than 50 dB up to 3 f_0 and 40 dB up to 5 f_0 with a stopband width extended to 7 times the centre frequency. The fabricated sample used 4 layers of metal, including the ground plane, and had a footprint of $0.03\lambda_g \times 0.06\lambda_g$, where λ_g is the guided wavelength at f_0 and weighs 0.44g without the connectors.

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