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3D LUMPED COMPONENTS AND MINIATURIZED BANDPASS FILTER IN AN ULTRA-THIN M-LCP FOR SOP APPLICATIONS

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Abstract—In this work, a library of 3D lumped components completely embedded in the thinnest, multilayer liquid crystal polymer (M-LCP) stack-up with four metallization layers and 100 µm of total thickness, is reported for the first time. A vertically and horizontally interdigitated capacitor, realized in this stack-up, provides higher self resonant frequency as compared to a similarly sized conventional parallel plate capacitor. Based on the above mentioned library, a miniaturized bandpass filter is presented for the GPS application. It utilizes mutually coupled inductors and is the smallest reported in the literature with a size of $(0.035 \times 0.028 \times 0.00089)\lambda_g$. The M-LCP module presented in this work is inherently flexible and offers great potential for wearable and conformal applications.

1. INTRODUCTION

The wireless market continues to demand faster, cheaper, power efficient and smaller modules. Size reduction is especially important for hand-held devices, like smart phones. These devices have wide touch screens for convenient input and output, which relaxes the size requirement on the horizontal (x-y) dimensions. But the vertical (z-dimension) miniaturization is becoming important because of the high demand of slim modules. Size reduction is more challenging for frequencies below few GHz because distributed components are larger at these frequencies. To alleviate this problem, lumped components may be used instead of distributed components. For

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further compactness, these lumped components can be implemented through vertically integrated thin film conductors in a system-on-package (SoP) platform [1]. The main idea behind SoP is to add functionality to the package through these embedded passive components rather than use it as a mere holder for the integrated circuit (IC). This way, the system's horizontal printed circuit board (PCB) can be replaced with a 3D multi-layer package with embedded passives and interconnects. The SoP approach provides optimal solution for the size problem and offers efficient and reliable systems.

To realize SoP designs, a multi-layer technology, that provides 3D integration capabilities, has to be used. Low Temperature Co-fired Ceramic (LTCC) has been the choice for SoP designs in the recent years. Lumped components implemented in LTCC have demonstrated high quality factors and small form factors [2]. Even though LTCC is a mature technology, it is expensive, non flexible, and inorganic (not environmentally friendly). Other technologies are, therefore, being pursued for the SoP concept.

Liquid Crystal Polymer (LCP) has emerged as an organic material that exhibits good radio frequency (RF) and packaging characteristics in addition to its low cost and environmental friendly nature. In [3], an M-LCP based library of lumped components has been presented with good quality factors (Qs). This library, however is fabricated in a relatively thicker stack-up with lossy adhesive which is not desirable as detailed in Section 3.2. In our previous work [4], simulation results of lumped components in an adhesive-less (all LCP) technology, with an overall thickness of (400 μm), have been reported. We have also investigated in simulations a lumped-based quadrature coupler in an ultra-thin LCP process [5].

In this paper, we further investigate the effect of reducing the substrate thickness by demonstrating a complete library in an ultra-thin M-LCP stack-up (100 μm) for the first time. Based on this library, a miniaturized bandpass filter (BPF) is presented for the GPS band. To the best of the author's knowledge this filter is the smallest reported with a size of $((0.035 \times 0.028 \times 0.00089)\lambda_g)$, which is an order of magnitude smaller than all the previously reported designs. The ultra-thin LCP technology presented here offers considerable size reduction, as well as mechanical flexibility, which makes it ideal for ultra slim, and conformal applications.

2. THE HYBRID PCB-SOP CONCEPT

Typical electronic systems comprise a PCB with ICs and other discrete components mounted horizontally on its surface, as shown in Fig. 1(a).

SoP approach, on the other hand, employs multilayer substrates which are vertically integrated through vias and can be used to realize 3D embedded passives with thin film conductors. The ICs, placed in custom cavities, can be connected to the passives through embedded interconnects. The complete system is miniaturized, low cost, and robust because of the 3D integration and the absence of the surface mount components, as shown in Fig. 1(b). However, going from a traditional PCB platform to a completely monolithic SoP requires a paradigm shift, which may take several years before its commercial acceptance. Meanwhile, hybrid solutions can enable integration of multi-layer SoP components (such as inductors, capacitors, filters, antennas, etc.) on standard PCBs, as shown in Fig. 1(c). Such multi-layer components are already commercially available, though mostly in LTCC technology. For hybrid solutions to work efficiently, the SoP substrates must be compatible with the existing PCBs. This is where LCP has major advantages over the competing LTCC technology because it is more compatible with the typical PCBs in terms of processing temperatures and thermal expansion.

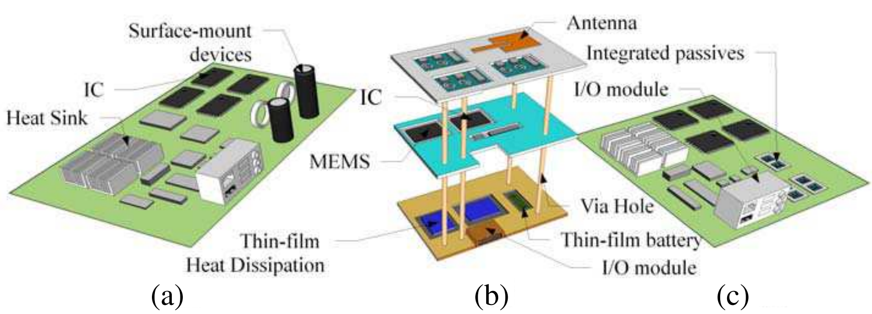


Figure 1. Concept of the SoP. (a) Typical PCB system with discrete components. (b) Monolithic SoP integration. (c) Hybrid solution (PCB with SoP components).

3. LCP CHARACTERISTICS AND PROCESS

3.1. LCP Characteristics

LCP has many electrical, and mechanical characteristics that make it an excellent candidate for wireless SoP [6]. Its dielectric constant is very stable across a wide frequency and temperature ranges. Moreover, its low dielectric constant and loss tangent of 2.9 and 0.0025 respectively, are very suitable for efficient RF and microwave designs. The coefficient of thermal expansion (CTE) of LCP can be engineered between 0 and 40 ppm/°C [6], which improves its thermal compatibility with wide range of materials including PCBs. The fabrication process of LCP does not involve temperatures above 280°C. This is very low as compared to $(850 \sim 950)$°C which is required for LTCC's fabrication [3]. This low temperature processing facilitates the integration of ICs and other components such as micro-electro mechanical systems.

LCP is not only an excellent substrate for RF applications but it is also a superior packaging material with high barriers against moisture and gas transmissions. The moisture absorption of LCP is 0.04% with coefficient of hygroscopic expansion of 4 ppm/%RH, making it a near hermetic material [7]. It has water vapour and oxygen transmission rates of 0.015 g-mil/100 in^2-day, and 0.04 cc-mil/100 in^2-day respectively [8], which indicate reliable packaging capabilities.

From the above characteristics, it is clear that LCP has better compatibility with the existing PCBs in terms of CTE as well as processing temperatures. Further, it is organic and environmentally friendly like typical PCBs. Finally, unlike LTCC where the ICs are post processed in the fired modules due to the high processing temperature, active components can be integrated in the LCP module before or during the LCP bonding process. Thus LCP is very suitable for hybrid systems which are the most practical implementations of SoPs at present.

3.2. LCP Process

LCP has been used in single layers since 2004 [9]. Despite its excellent properties for RF circuits, not many designs have been reported until recently. This is mainly due to the difficulty in obtaining the necessary adhesion between LCP and metals. Traditionally, an adhesive layer (for example Titanium) has to be used between LCP and the metal [10]. This treatment is not desirable for the following reasons: (1) the roughness of the surface increases the resistance and hence decreases the quality factors of the components fabricated, (2) the inclusion of an adhesive layer increases the overall thickness of the substrate and so affects its flexibility, (3) the drilling and coating of via holes on such structures becomes difficult and less reliable, (4) the additional adhesive layer reduces the flatness of the surface, making the integration of LCP with ICs and PCBs less stable, and (5) adhesive materials and LCP usually have diverse CTEs, leading to thermal instability. To alleviate the above mentioned issues the use of adhesive-less LCPs is critical, especially for SoP and hybrid SoP applications where integration with ICs and PCBs is essential.

In this work, adhesive-less substrates from Rogers Corporation are used. These substrates come with 9 µm of copper layers on both sides. Patterns on either or both sides can be realized through etching. Multi-layers are then fabricated by utilizing two different types of LCP: ULTRALAM 3908 and 3850 as shown in Fig. 2. 3850 is the main substrate and 3908 is used as a bonding film between the two 3850s. The only difference between these substrates is that the melting temperature of the 3850 is 315°C, while 3908 melts at 280°C. Unlike the designs in [3], this design is completely adhesive-less. The stackup of the process used in this work is illustrated in Fig. 2.

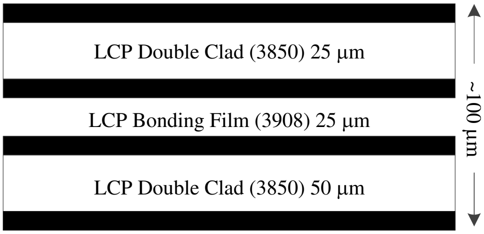


Figure 2. Multi-Layer configuration of the ultra-thin M-LCP process with overall thickness of 100 µm.

4. LUMPED COMPONENT LIBRARY IN ULTRA-THIN M-LCP

4.1. Spiral Inductors

Inductors are integral components of RF systems. They play a key role in circuits such as filters, matching networks and amplifiers. High Q inductors are required for bandpass filters and matching networks. Inductors fabricated in LTCC or M-LCP, can have very high Qs [2, 3].

Spiral inductors are very popular because they provide inductances in the order of several nHs [11], in compact sizes. Two types of spiral inductors, rectangular or circular as shown in Fig. 3, are generally used. Rectangular inductors are preferred in many silicon-based foundries. In M-LCP, however, both circular and rectangular inductors can be fabricated. To compare the performances, circular and rectangular inductors have been simulated using the full-wave simulator HFSS which uses a finite element method. Moreover, prototypes have been fabricated and measured. The inductors have the same outer perimeter, number of turns N, and parameters (W and s). The full wave simulation and the measurement of the inductors are shown in Fig. 4(a) and Fig. 4(b). Circular inductors demonstrate slightly better Qs and higher SRFs at the cost of lower effective inductances. This can be attributed to higher capacitance to the ground in the rectangular inductors especially at the corners. Also, the 90° bend in the current path increases the radiated power of the rectangular inductors.

The thickness of the substrate (H) has a great effect on the Q of the inductors. Increasing (H), increases L and Q considerably [4]. This poses a serious trade-off between the vertical size reduction, which is important for slim designs, and the Q of inductors, which is important for the efficient performance of the circuits. In our previous work [4], Qs as high as 150 (in simulations) have been demonstrated, but for a 4 times thicker M-LCP stack-up. This work investigates much thinner M-LCP stack-up (100 μm), and as a consequence, relatively lower Qs have been achieved.

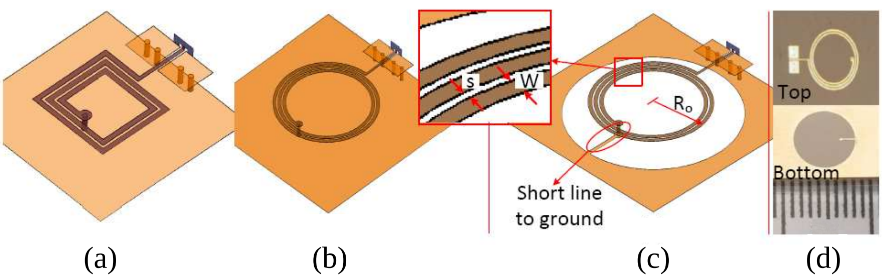


Figure 3. Spiral inductors. (a) Rectangular. (b) Circular with complete ground plane. (c) Circular with ground plane partially etched. (d) Photograph of the fabricated circular inductors with partially etched ground plane.

To analyse the negative effect of the ultra-thin substrate on the Q of inductors, a design with partially etched ground plane is proposed, as illustrated in Fig. 3 (b). A circular patch directly under the inductor is etched off the ground plane, and the inductor is connected to the ground plane by a short line (highlighted in the figure). Measured Qs of inductors with complete ground plane as well as partially etched ground planes are shown in Fig. 5. As expected, partial removal of the ground plane results in almost 100% increase in $Q_{\max}$. However, the self resonant frequency (SRF) is reduced slightly, which can be improved by reducing the number of turns.

Thirty different inductors have been fabricated and measured to completely characterize the inductors in ultra-thin M-LCP process.

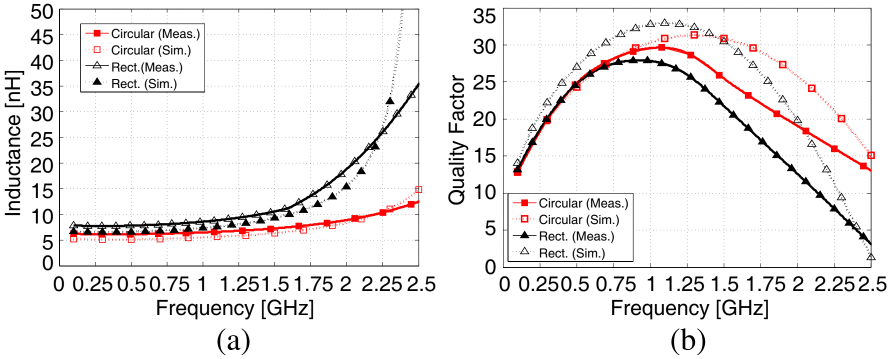


Figure 4. Comparison between circular and rectangular spiral inductors in terms of (a) Inductance, and (b) Q (smoothed using a standard MATLAB function which uses an average filter with local regression algorithm.).

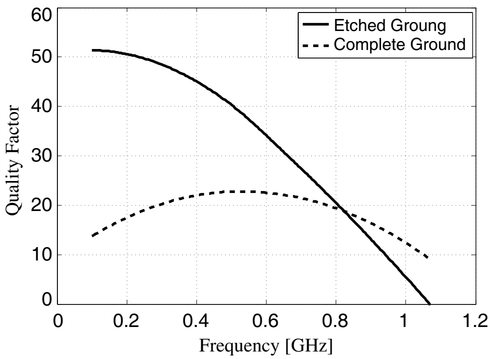


Figure 5. Measured Q (smoothed) of two different inductors (one with complete and the other with etched off ground as in Fig. 3). The inductor has $N = 2.5$, $R_o = 2500\,\mu\text{m}$, and $s/W = 0.5$.

The measured results for selected inductors are shown in Table 1. From the table, it can be seen that, even though the inductors in this library are fabricated on a $100\,\mu\text{m}$ thick substrate, Qs as high as 55 can be obtained.

4.2. Vertical and Horizontal Interdigitated (VHID) Capacitors

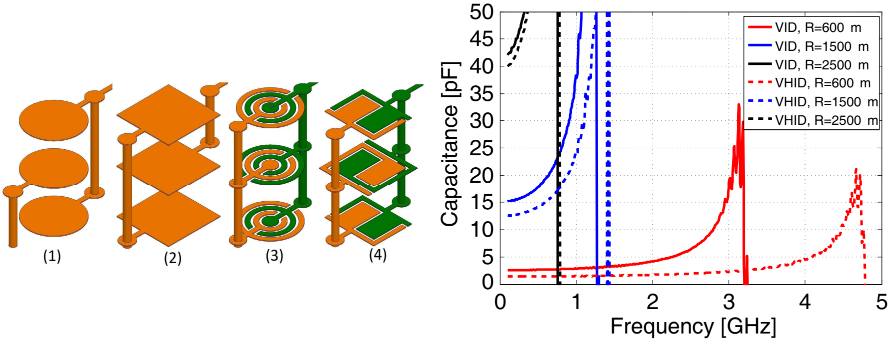
Capacitors are important building blocks of RF and microwave systems, as they are used in circuits such as matching networks, oscillator tanks, and DC blocks. Miniature capacitors can be designed

Table 1. Measured results of Selected Inductors (L_{eff} @1.5 GHz).

Type	N	R_0 [mm]	W [μm]	S [μm]	$Q_{\max}$ @f [GHz]	SRF [GHz]	L_{eff} [nH]
Circular	0.5	1.1	150	50	30@4.5	> 5	1.8
Circular	2.5	1.1	150	70	30@1	3.3	7
Circular	2.5	2.5	70	70	55@0.25	1.2	N/A
Rectangular	0.5	1.1	150	50	30@0.25	> 5	7
Rectangular	1	1.1	100	100	25@1	5	4

in M-LCP in the form of vertical interdigitated (VID) capacitors [4]. However, for ultra-thin M-LCP, the SRF of VID capacitors decrease rapidly because the plates of the capacitor are too close to each other. Since it is important to use ultra thin substrates for slim designs, increasing the SRF by increasing the thickness is not an option. However, in this work we resolve this issue by using VHID geometry, first introduced in [12] to increase the SRF for the same thickness. The VHID design combines the horizontal and the vertical interdigitated plates (Fig. 6(a)) and can be implemented for both rectangular and circular structures.

VID and VHID capacitors with identical sizes have been fabricated and the measured results are compared in Fig. 6(b). For the same



(a) (b)

Figure 6. (a) 3D structures of LCP capacitors: (1) Circular VID capacitor. (2) Rectangular VID capacitor. (3) Circular VHID capacitor. (4) Rectangular VHID capacitors. (b) Measured capacitance of circular VID and VHID capacitors for various radii.

size, the VHID capacitor shows higher SRFs as compared to the VID capacitor at the cost of slightly lower capacitance. This effect is particularly evident in smaller capacitors, while in larger capacitors, the SRFs of the two types of capacitors approach each other. This can be explained by considering the electric fields stored in the horizontal and vertical fingers. As the size of the plates increases with constant number of fingers, most of the electric field is stored between the vertical fingers rather than the horizontal fingers, and the VHID shape approaches that of the VID. Therefore, it could be deduced that, to maximize the improvement in the SRF of the VHID capacitors, maximum number of fingers should be used.

It is worth mentioning that the above analysis holds only for ultra-thin stackups. As the vertical distance between the capacitor plates is increased, the VHID capacitor starts to provide higher capacitance (smaller sizes) at the cost of lower SRFs. Therefore, it can be concluded that the VHID capacitor provides an additional degree of freedom for the designer to choose between capacitance density which is critical for thicker stackups, and higher SRFs which is critical for ultra-thin stackups.

5. BANDPASS FILTER DESIGN

5.1. Design and 3D Implementation

As a proof of concept, the library presented in the previous section, is used to design a miniaturized, 3D bandpass filter for a GPS receiver. It operates at a center frequency of 1.575 GHz (L_1 band) with a passband of 100 MHz. A second order Chebysheve topology employing an inductively coupled resonator structure is selected, as shown in Fig. 7(a). It has three transmission zeros to improve the performance in a compact size. The overall size has been reduced considerably due to the ultra-thin LCP medium. The filter is designed with the following ideal lumped values: $C_1 = 2.49\,\text{pF}$, $C_2 = 1.26\,\text{pF}$, $L_1 = 2.88\,\text{nH}$, $k = 0.18$, $C = 0.17\,\text{pF}$, and $L_L = 0.5\,\text{nH}$.

After the topology is theoretically synthesized, the individual 3D components are optimized using EM simulations (Ansoft HFSS), and then the complete bandpass filter is assembled, as shown in Fig. 7(c). It should be noticed that L_L is obtained from the via holes without adding any more components.

5.2. Results

The filter has been fabricated by Metro Circuits, USA and the photograph of the prototype is shown in Fig. 8. The measurement

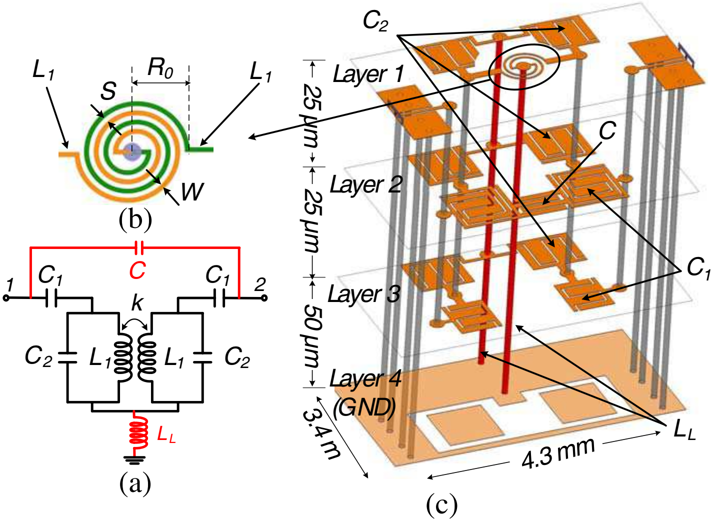


Figure 7. (a) Schematic of the BPF. (b) 3D structure of the mutually coupled inductors. (c) 3D structure of the bandpass filter.

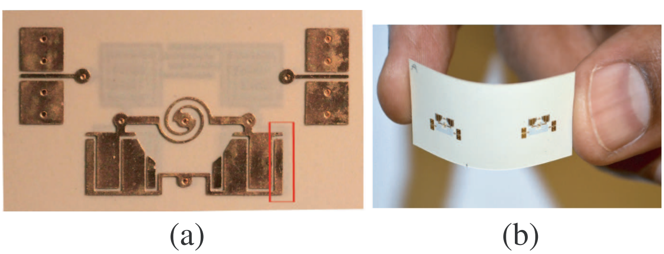


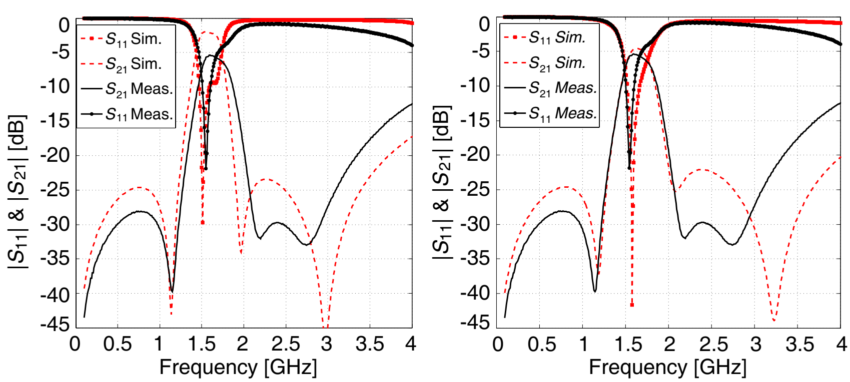
Figure 8. (a) A Photograph of the fabricated M-LCP bandpass filter. (b) Illustration of the flexibility of the LCP filter.

of the filter has been done using a vector network analyser (Anritsu ME7828) and 150 μm pitch probes. Measured and simulated results are compared in Fig. 9(a). The filter exhibits an out of band rejection of −25 dBs @ 100 MHz from the pass band for both sides. Also, due to the third TZ, the out of band rejection stays below −25 dBs up to 3 GHz. The measured insertion loss is, however, around 3 dBs larger than the simulated one. Investigation into this unexpected loss revealed that it is mainly due to the PCB finish layer that were not part of the original simulation. The finishing layer used is electroless Nickel immersion Gold (ENIG), which consists of a layer of Nickel

($\sim 9\,\mu\text{m}$), and a thin layer of Gold ($\sim 0.1\,\mu\text{m}$) on top of the original Copper metallization. The conductivities of Nickel and Gold are $1.43 \times 10^{-5}\,\text{S/m}$ and $5.8 \times 10^{-5}\,\text{S/m}$, respectively. The skin depth at 1.5 GHz for Nickel and Gold are ($\sim 0.34\,\mu\text{m}$) and ($\sim 2\,\mu\text{m}$) respectively. Therefore, most of the current flows in the Nickel layer rather than the Copper and the Gold, and thus increases the resistivity by almost 6 times, leading to increased insertion loss. Also, since Nickel has a relative permeability of about 600, it decreases the fundamental frequency of the resonators because it acts as a magnetic core for the inductors. However, this frequency shift is reduced by another upper frequency shift caused by a miss alignment of about $100\,\mu\text{m}$ between the first two layers.

To verify these two imperfections, post-measurement simulations have been performed, as shown in Fig. 9(b). As can be seen, the new simulations now closely match the measurements, which proves the hypothesis that the increased loss in measurements is due to the unplanned finishing layers and can be removed by avoiding these layers. Therefore, for the sake of comparison, the simulated insertion loss of 2.3 dB can be trusted.

In Table 2, a comparison between LCP-based bandpass filters reported in the literature for low GHz bands, and the bandpass filter proposed in this work is presented. It is clear that the filter presented in this work is the thinnest despite being four layers thick, and an order of magnitude smaller than the reported ones. Moreover, because of the extremely thin layers, the modules are flexible in nature and can be bent in either directions (Fig. 8).



(a) (b)

Figure 9. Measurement and simulation results of the bandpass filter. (a) Measurement and original simulation. (b) Measurement and corrected simulation.

Table 2. Comparison between the bandpass filters presented in this work and the literature.

Ref.	**Tech.** (ϵ_r)	f_c (GHz)	**Size (mm)**
[13]	LCP (2.9)	2.5	$23 \times 41 \times 0.1$
[9]	LCP (2.9)	2.45	$12\,\text{mm}^3$
[14]	M-LCP (3.1)	9.9	$10.9 \times 2.9 \times 0.2$
[15]	M-LCP (2.95)	2.9	$3.9 \times 4.1 \times 1.85$
This Work	M-LCP (2.9)	1.575	$4.3 \times 3.4 \times 0.1$
Ref.	**Vol.** ($\lambda_0^3 \times 10^{-5}$)	**IL (dB)**	**Flex.**
[13]	5.45	1	No
[9]	0.65	2	Yes
[14]	23.4	2.3	No
[15]	2.7	1	N.R.
This work	0.02	2.3*	Yes

* This is the corrected insertion loss.

6. CONCLUSION

In this work, inductors and capacitors fabricated in an ultra-thin M-LCP substrate are presented. A miniaturized bandpass filter for GPS is designed and measured. The measured and simulated results of the filter show good agreement. The capabilities of LCP in building ultra-thin components and devices for SoP has been investigated and found to have good potential. Also, the designs presented in this work show high degree of mechanical flexibility which can be investigated in future work.

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