Abstract—This paper presents the modeling, design, fabrication, and characterization of an innovative and miniaturized thin-film bandpass filter with coupled spiral structures in ultrathin glass substrates (30–100 μm). This filter is demonstrated for two applications: 3-D integrated passive devices and embedded thin-film filters in RF modules. A compact filter design was achieved through an integrated resonant structure that effectively utilizes the inductive and capacitive coupling between metal layers on either side of an ultrathin glass substrate or organic build-up layer. The designed filters (layout area <1 mm² with 80–150 μm device thickness) were fabricated on a 30-μm-thin glass substrate using a panel-based low-cost approach with double-side thin-film wiring processes. The effect of process variations on the performance of the proposed structures was also studied. Furthermore, an improved WLAN filter is designed and demonstrated by employing specific structural modifications. The measured frequency response of the filters shows good model-to-hardware correlation, with very low insertion loss (0.6 dB) in the passband, and high adjacent-band rejection (>25 dB).

Index Terms—Bandpass filter (BPF), integrated passive device (IPD), ultrathin glass, WLAN.

I. INTRODUCTION

THE emerging need for ultraminiaturized and multifunctional mobile systems is driving high-density integration of active and passive components, with superior performance and at low cost. System-on-package [1] approach to system integration helps achieve heterogeneous integration and addresses the distinct substrate and design-rule requirements of digital, RF, and analog components. While system-on-chip approach on silicon substrates has miniaturized digital components over the years, the high electrical conductivity of silicon substrates combined with the high cost of wafer-based processes has limited the progress in high-quality RF miniaturization. Prior studies have shown that RF inductors and capacitors on active silicon chips or on passive silicon interposers have Q-factor limitations (Q < 40) [2]. Glass is an ideal material for RF integration of active and passive components due to its: 1) high electrical resistivity resulting in lower electrical loss and higher Q-factor; 2) smooth surface profile and good-dimensional stability that enable definition of small features (<10 μm) with precise alignment accuracy; and 3) potential for low-cost manufacturing, arising from large panel-based processing capability. Prior research studies have explored the benefits of glass for realizing passive components as integrated passive devices (IPDs) [3], [4]. However, due to challenges associated with through-via-hole formation and metallization in glass, such IPDs have been limited to single-side processing on relatively thick (> 200 μm) glass wafers that were only about 200 mm in diameter. Recent demonstration of small diameter through package vias (TPVs) in thin glass substrates, for the first time, enabled double-side RF integration on thin glass interposers [5]. Such TPVs in thin glass enable a new class of 3-D integrated passive and active component (IPAC) modules [6] with double-side passive and ultrathin embedded or nonembedded active components, where the passives and actives are separated vertically by only 30 μm (Fig. 1). The passives can be realized on the 3-D IPAC substrate using thin films, or prefabricated on a separate ultrathin double-sided glass substrate with through vias; termed as 3-D IPDs, to differentiate from traditional single-sided IPDs.

This paper presents a novel 3-D coupled spiral component design for a miniaturized lumped-element two-metal-layer bandpass filter (BPF) on polymer-laminated glass substrates. Traditionally, transmission line elements such as broadside-coupled stripline have been used to design filters [7], although they occupy a large area. A variety of lumped resonant structures has been employed to achieve low-loss filter performance occupying a small area. However, such modules either have high loss (>2 dB) or fairly large thickness (>200 μm) due to inherent substrate thickness and multilayer design approaches [8]–[10]. Lumped-element transformer-based resonators on thick single-side glass wafers have also been explored [4].

This paper differentiates from prior work in the following ways: 1) broadside-coupled spirals for maximum capacitance; 2) the use of glass substrates for lower loss and higher Q-factor; 3) a new type of spiral filter on glass as an alternative to traditional wireline filters; 4) an alternative packaging technology that enables higher Q-factor, lower insertion loss, and higher performance in thin glass substrates.
itive coupling; 2) compact arrangement of components for optimal area utilization; 3) panel-based double-side fabrication approach enabling low cost; and 4) first demonstration of double-side RF passives on ultrathin glass (30 μm) with through-vias.

This paper is divided into seven sections. Section I is the introduction. In Section II, the basic version of an innovative filter structure is proposed and analyzed using full-wave electromagnetic (EM) simulator; a circuit-level schematic is developed, and the simulation results are correlated with the measured response. Following this, studies on the parametric variations to the basic filter structure are presented in Section III. To improve the filter response, structural modifications to the basic filter structure are proposed and analyzed in Section IV. Furthermore, in Section V, the fabrication and characterization of the filter as a 3-D IPD component (as shown in Fig. 1) on ultrathin (30 μm) glass substrate is presented. In addition, the fabrication and characterization of the improved filter as an embedded thin-film passive (as shown in Fig. 1) on one side of a glass substrate of 100-μm thickness is presented in Section VI. Finally, the summary and references are contained in Sections VII.

II. MODELING AND DESIGN OF THE PROPOSED FILTER

A. Substrate Stack-Up and Design Rules

The material stack-up for the initial analysis and demonstration of the filter structure is shown in Fig. 2. The stack-up comprises a 30-μm-thin, low-loss glass substrate laminated with a low-loss polymer on both sides. The glass has a dielectric constant (εr) of 6.7 and a loss-tangent (tan δ) of 0.006. The dry-film polymer (εr = 3, tan δ = 0.005) used in this paper is available in different thicknesses (3–17 μm). The polymer helps to improve handling and metallization of the thin glass substrate. The polymer thickness for this demonstration was selected at 17 μm to facilitate easier handling of the ultrathin glass. The minimum linewidth and spacing was 10 μm, and the TPV diameter was 30 μm.

B. Description of the Filter Structure

The proposed filter structure consists of two open-ended planar spirals separated by a thin dielectric, aligned with each other. In such a configuration, the passband response and transmission zeros are achieved through resonance due to the inductance of the spirals and the capacitance between them through the substrate. Additionally, a metal patch is added to the center of each spiral. These metal patches act as parallel-plate capacitors across the dielectric separation layer and help lower the resonant frequency. Such an integrated structure combining parallel spirals with metal patches maximizes volume utilization through: 1) compact lateral arrangement of spiral inductors and planar capacitors (metal patches), and 2) vertical coupling between these structures across the thin dielectric. The perspective view of the proposed structure is shown in Fig. 3.

C. EM Simulation and Modeling

The spirals and the parallel metal patches were isolated and simulated using full-wave EM solver (SONNET). The simulated Q-factor for the metal patch was 200, and for the inductor spiral was 50. The complete structure was then simulated for two polymer thicknesses: 5 and 17 μm. The simulated responses of the filter are shown in Fig. 4. It was observed that the passband center frequency for the 17 μm polymer was 3.5 GHz, while that for the 5 μm polymer was 2.5 GHz. This shift in the frequency response and the stopband roll-off can be attributed to changes in capacitance and mutual inductance arising from the variation in dielectric thickness. For both cases, the simulated passband insertion loss was 0.7 dB, with more than 20 dB return loss, and more than 35 dB attenuation at the transmission zero.

D. Equivalent Circuit Schematic

A circuit model for the filter structure was developed using spice simulator (Agilent ADS) based on individually simulated responses of the spiral and the metal patch elements. The schematic of such a structure is shown in Fig. 5, in which
“L1b” and “L2b” are the coupled inductor sections. The coupling factor “k” along with “L1b” and “L2b” controls the location of transmission zero and the passband. The coupling capacitor “C1” can be tuned to vary the location of the transmission zero alone. However, all these values are interdependent and are a function of the dielectric thickness, the linewidth, line spacing, and number of turns of the spirals. The frequency of the transmission zero is less sensitive to variations in the inductance of the uncoupled inductor sections “L1a” and “L2a.” Therefore, by varying “L1a” and “L2a,” the center frequency can be shifted without significantly modifying the location of the transmission zero. “C2” is the capacitance of the center patch. Varying “C2” can change the passband and the transmission zero. However, the passband is shifted more than the transmission zeros. Hence, adding the central capacitor (C2) provides higher flexibility to modify the structure to obtain the desired frequency response. The component values of the schematic are specified in Table I. The simulated response of this circuit schematic shows good correlation to the EM simulation response, as shown in Fig. 6.

As can be observed from the phase of insertion loss in Fig. 7, the negative slope at the passband indicates electric coupling to be the dominant mechanism.

Furthermore, from the plot of the group delay shown in Fig. 8, it can be observed that the passband delay of this filter is only about 0.2 ns, which is quite low, due to the low filter order.

III. PARAMETRIC ANALYSIS OF FILTER RESPONSE

The basic filter structure presented in Fig. 3 was modified to study the effect of process-variations on the filter performance. The modifications include changes in linewidth and spacing, polymer thickness, and X-Y alignment. The simulations were performed using EM simulations tools Sonnet EM Suite and HFSS. The results from these variations can directly contribute to the layout-level optimization—the ultimate step in the design process that yields the most accurate simulated response.

A. Linewidth and Spacing Variations

The linewidth and spacing of the filter design were 30 μm. Keeping the pitch between two lines of the spiral at 60 μm, the linewidth was varied from 20 to 45 μm. The resulting variation in the filter response was studied. The variation in the passband center frequency and insertion loss is shown in Fig. 9. As the linewidth increased from 20 to 45 μm, the center frequency increased, whereas the insertion loss decreased. When the linewidth is increased, although the capacitance between the spirals increases, the inductance of the spirals reduces. Since the resonant frequency depends on both inductance and capacitance, it can be deduced that the increase...
in capacitance is not as much as the reduction in inductance, resulting in increase of the resonant frequency. Furthermore, since the primary passband mechanism is electric-field coupling, the insertion loss decreases with higher capacitance.

The variation in the transmission zero insertion loss of the filter for different line widths is shown in Fig. 10. As the linewidth increases, the frequency of the transmission zero decrease, until 30 μm. After that, the frequency of the transmission zero increases. It can also be observed that the attenuation reduces with increasing linewidth.

**B. Variation in Polymer Thickness**

The center frequency of the passband is plotted in Fig. 11 for different polymer thicknesses from 3 to 17 μm. It was observed that as the polymer thickness is increased, the resonant frequency increases linearly. This is attributed to the reduction in the capacitance between the two metal layers and also to the smaller coupling between the inductors.

**C. Variation in X-Y Alignment**

When fabricating multilayer substrates, misalignment between successive layers is a common issue that arises from lithography processes and is attributed to tool limitations, material shrinkage (in organics), and positional tolerance of vias. Hence, it is useful to study the effect of such misalignment on the performance of the proposed filter. It can be seen from Fig. 12 for X-Y misalignment of up to 30 μm, the filter passband does not shift, whereas the transmission zero shifts by 300 MHz.

**IV. MODIFICATIONS TO IMPROVE THE FILTER PERFORMANCE**

Typical filtering for WLAN applications requires high rejection over a specific range of frequencies. An example of the target specification, adapted from a commercial WLAN diplexer datasheet [11], is shown in Table II. To be useful for WLAN applications, it is necessary to improve the performance of the basic filter structure so as to match these target specifications. For this, structural modifications were

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Freq. (GHz)</th>
<th>Spec (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insertion loss</td>
<td>2.4-2.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Attenuation</td>
<td>4.8-6</td>
<td>25</td>
</tr>
<tr>
<td>Return Loss</td>
<td>7.2-7.5</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>2.4-2.5</td>
<td>10</td>
</tr>
</tbody>
</table>
performed on the basic filter structure presented in Fig. 3. The following modifications were analyzed: 1) secondary spirals; 2) grounded spirals; and 3) ground capacitors.

A. Addition of Secondary Spirals

Secondary spirals were added to the spirals on each layer, at a particular “point of tap,” as shown in Fig. 13. The addition of such spirals increased the capacitance and the inductance in the primary spirals, thereby lowering the passband frequency and the transmission zero. From Fig. 14, it can be observed that the frequency of the transmission zero is shifted more than that of the passband. Small variations in the location of the “point of tap” or the size of the secondary spirals will result in a small change to the passband but a larger shift in the transmission zero.

B. Addition of Grounded Spirals

To increase the attenuation characteristics of the filter, grounded spirals were introduced between the spirals, as shown in Fig. 15. The grounded spirals attenuate a wider range of frequencies compared to having just a single transmission zero for attenuation. The other advantage of such ground spirals is that they do not increase the area of the filter.
significant. The frequency response of a 2.4-GHz filter with and without ground spirals is shown in Fig. 16.

C. Effect of Adding Ground Capacitors
Similar to the addition of grounded spirals, the introduction of capacitors to ground improves the attenuation in the upper stopband. The top view of the filter layout with the ground capacitor is shown in Fig. 17. The corresponding simulated frequency response with and without the ground capacitor is shown in Fig. 18.

V. FABRICATION AND CHARACTERIZATION OF 3-D IPD FILTERS

A. Fabrication Process for Glass Substrates
A pictorial representation of the key process steps in fabricating a two-metal-layer glass substrate with TPVs is shown in Fig. 19. Borosilicate glass panels having a thickness of 30–100 μm were used as the RF module substrate. First, the glass surface was cleaned using organic solvents [acetone, methanol, and isopropyl alcohol (IPA)], to remove residue and impurities from the surface. Following this, thin dry-film polymer with a thickness of 17 μm was laminated on both sides of the glass substrate using a hot-press lamination process. TPVs were formed in the polymer-laminated glass substrate using UV-laser ablation. Electro-less copper deposition process was used to achieve a conformal seed layer. Lithography was performed on the seeded samples, and a semiadditive plating process was used to further metallize the TPVs and to achieve the redistribution layer patterns on both sides.

B. Fabrication of the 3-D IPD Filters

The basic filter structure was fabricated on ultrathin glass substrate (D263—from SCHOTT glass) having a thickness of 30 μm, using a panel-based double-side thin-film wiring process. The use of thin polymer layers on glass interposers have been shown to facilitate handling and plating metallization [13]. A thin dry-film polymer was laminated on both sides of the thin glass. The final surface copper thickness was 8 μm. The top view image of the fabricated structure and the characterization setup is shown in Fig. 20.

C. Characterization of the Filters
The frequency response of the fabricated structure was obtained through S-parameter characterization using a vector network analyzer. A short-open-load-thru calibration was performed prior to the measurements. As shown in Fig. 21, very
Fig. 21. Simulation–measurement performance correlation of the filter.

Fig. 22. Modified substrate stack-up and design rules for 4 ML diplexer fabrication.

Fig. 23. 3-D view of the revised low-band filter design.

good correlation between the measurements and simulations was observed for the passband insertion loss and return loss.

VI. DESIGN AND DEMONSTRATION OF EMBEDDED THINFILM FILTERS FOR WLAN MODULES

A. Substrate Stack-Up and Design Rules

The substrate stack-up and design rules as depicted in Fig. 22 were employed in the design and fabrication of the improved WLAN filter. The substrate core was glass of thickness 100 μm, laminated with a 20.5-μm-thick polymer. The buildup consisted of a polymer layer having a thickness of 17.5 μm. The diameter of the TPVs was 100 μm, and that of the blind vias was 45 μm. The minimum linewidth and spacing was 20 μm, while the metal thicknesses on each layer were 8 μm.

B. Revised WLAN Filter Design

An improved WLAN filter, with slightly larger dimensions, was designed with both ground capacitors and grounded spirals. The layout is shown in Fig. 23, and the simulated response with the target frequency bands is shown in Fig. 24. The insertion loss was 0.9 dB with more than 25-dB high-band rejection up to 8 GHz.

C. Fabrication and Characterization

The revised low-band design was fabricated using two-metal layers (M1–M2) on one side of a glass substrate, and the measured responses of the filter are shown in Fig. 25. It can be seen that the insertion loss was 0.6 dB, which is close to the target specification of 0.5 dB. The high-band rejection was more than 25 dB from 5.5 up to 9.5 GHz. Overall, the frequency response was shifted from the design target by about 200 MHz in the passband and 500 MHz in the rejection band. This is a result of process variations and can be rectified through subsequent optimization of the design to account for process variations.

VII. SUMMARY

Next-generation RF systems require miniaturized ultrathin passives that can be embedded in the module substrate or assembled on the surface as standalone passive devices. In lieu of these requirements, the modeling, design, fabrication, and characterization of an innovative WLAN filter...
was presented in this paper. A novel layout schematic for a BPF was proposed based on coupled spiral structures, and a lumped-element circuit schematic was developed. The equivalent circuit was verified with full-wave EM simulations. Furthermore, the mechanism of coupling in the structure was determined to be electric coupling, and the simulated passband group-delay was found to be extremely low, at 0.2 ns. The effect of process variations on the performance of the filter was studied through parametric variations to the layout of the filter. These included variations in the linewidth, polymer thickness, and $X$-$Y$ alignment. In addition, the filter structure was modified to study the subsequent effect in performance. The different modifications studied consisted of the addition of secondary spirals, grounded spirals, and ground capacitors. The basic filter structure was fabricated as a 3-D IPD on ultrathin glass substrate of thickness 30 $\mu$m, and measured to obtain the S-parameter response. The measurement showed good correlation to the simulated performance. Through modifications to the basic filter layout, an improved embedded WLAN filter was then designed, fabricated, and characterized on a glass substrate consisting of a 100-$\mu$m-thick glass core. This WLAN filter design with dimensions $1 \times 0.5$ mm$^2$ was fabricated on one side of a four-metal-layer glass substrate with a polymer of thickness 17.5 $\mu$m between the spirals. The measured insertion loss was 0.6 dB, and high-band rejection was more than 25 dB. This revised design matched the target specifications reasonably well. Thus, the capability of the proposed filter design to help miniaturize RF passives was demonstrated on ultrathin glass substrates, toward miniaturized 3-D IPD components and embedded WLAN modules.

REFERENCES


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