

3D Integration: A Revolutionary Approach for SOP Millimeter-Wave Functions for High Data Rate Wireless Systems using Ceramic and Organic Technologies?

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Abstract

In this paper, the development of three-dimensional (3-D) millimeter-wave functions in multilayer low temperature cofired ceramic (LTCC) and liquid crystal polymer (LCP) technologies is presented for millimeter-wave compact and easy-to-design passive solutions for high data rate wireless systems. Both ceramic and organic technologies are candidates for the 3-D integration of system-on-package (SOP) miniaturized systems. LTCC has been widely used as a packaging material because of its process maturity/stability and its relatively high dielectric constant that enables a significant reduction in the module/function dimensions. As an alternative, LCP is an organic material that offers a unique combination of electrical, chemical, and mechanical properties, enabling high-frequency designs due to its ability to act as both the substrate and the package for flexible and conformal multilayer functions. A 3D LTCC patch resonator filter for two operating frequency bands (58-60GHz/38-40GHz) of RF communications and sensors for applications, such as wireless broadband internet or inter-satellite communications, and a band pass filter has been fabricated on LCP substrate for wideband millimeter waves applications, such as 60 GHz WLAN short-range gigabit wireless systems, demonstrate the capabilities of the 3D integration.

I. INTRODUCTION

Millimeter-wave (mmW) electronics for commercial applications, such as short-range broadband wireless communications and automotive collision avoidance radars, require low-manufacturing cost, excellent performance, and high level of integration. The multilayer LTCC System-On-Package (SOP) approach is very well suited for these requirements because it offers a great potential for passives' integration and enables microwave devices to be fabricated with high reliability, while maintaining the low cost [1]. The very mature multilayer fabrication capabilities of LTCC ($\epsilon_r=5.4$, $\tan\delta=0.0015$) up to 100+ GHz enable the replacement of broadside coupling by vertical coupling and make LTCC a competitive solution to meet millimeter wave design requirements. As an alternative, Liquid Crystal Polymer (LCP) is an organic material that offers a unique low-cost all-in-one solution for high frequency designs due to its ability to act as both a high-performance flexible substrate ($\epsilon_r=2.9-3.0$, $\tan\delta=0.002-0.004$) and a near-hermetic package for multilayer modules [2-4]. These characteristics make LCP very appealing for many applications and it can be viewed as a prime technology for enabling system-on-package RF and millimeter-wave (mmW) designs [2]. The choice of the most suitable technology depends on the application specifications such as environment, operation frequency, performance, volume and cost.

In this paper, we present the development of various advanced 3-D LTCC and LCP system-on-package passive components enabling a complete passive solution for compact, low cost wireless front-end systems to be used in RF and mmW frequency ranges. The design of single-mode slotted patch filter with a transverse cut on each side has been presented to achieve compactness and great compromise between size and power handling. This filter has been embedded in LTCC and designed for two operating frequencies (58-60GHz/38-40GHz) of mobile communication systems. The paper clearly demonstrates how the physical dimensions of the miniaturized filter are determined by showing the simulated filter response as a function of critical design parameters such as the length of transverse cuts and the overlap distance between feeding structure and patch resonator. Also, a band filter has been designed to enable a low cost, very easy to design filtering solution to be integrated into a wireless millimeter-wave gigabit link system. The ripple of modified stepped impedance Tchebysheff low pass filters has been exploited and combined with a rejection centered at 60GHz. Insertion loss as low as 1.5 dB has been measured, demonstrating the potential of LCP for millimeter-wave applications.

II. LTCC PATCH RESONATOR FILTER (60 GHz/39GHz)

Integrating filter on-package in LTCC multilayer technology is a very attractive option for RF front-ends up to mm-wave frequency range in terms of both miniaturization by vertical deployment of filter elements and reduction of the number of components and assembly cost by eliminating the demand for discrete filters. In mm-wave frequencies the band pass filters are commonly realized using slotted patch resonators due to their miniaturized size, their excellent compromise between size, power handling and easy-to-design layout [5]. In this section, the design of a single-pole slotted patch filter is presented for two operating frequency bands (38-40 GHz and 58-60GHz).

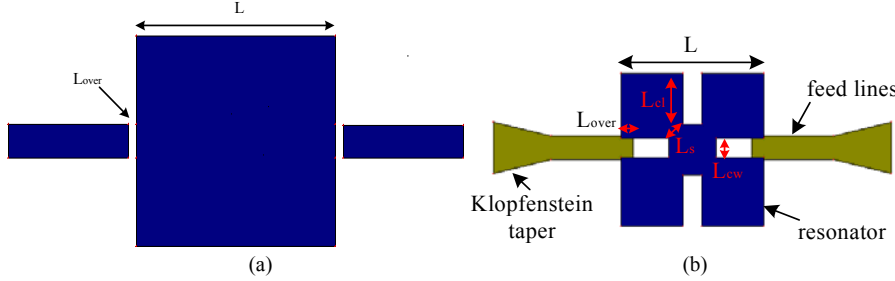


Fig. 1 Top view of (a) conventional $\lambda/2$ square patch (b) Miniaturized patch resonator.

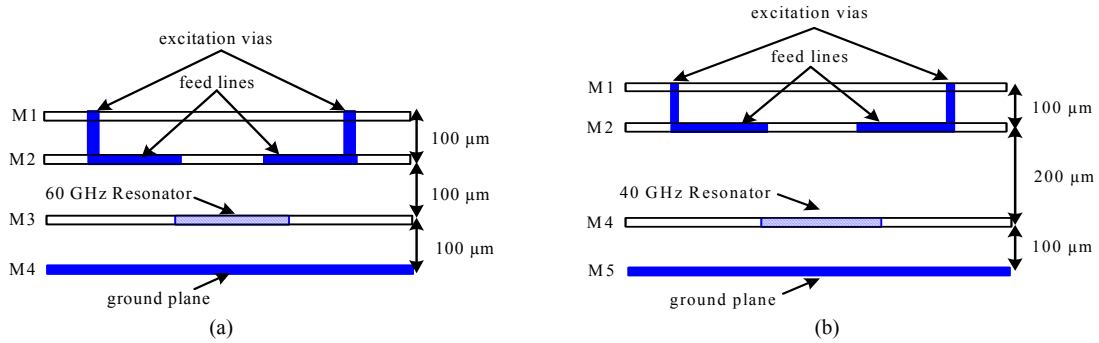


Fig. 2 Side view of (a) 60GHz slotted patch resonator (b) 39 GHz slotted patch resonator

Fig. 1 shows a top-view comparison between the basic half-wavelength square patch resonator ($L \times L = 0.996 \text{ mm} \times 0.996 \text{ mm}$) [5] (Fig. 1 (a)) and a novel configuration ($L \times L = 0.616 \text{ mm} \times 0.616 \text{ mm}$) capable to provide good miniaturization and power handling (Fig. 1 (b)), with a side view shown in Fig. 2 for two operating frequency bands. In the design of the $\lambda/2$ square patch, the planar single-mode patch and microstrip feedlines are both located at metal 3 (M3 in Fig. 2 (a)) and M4 in Fig.2(b)) and use the end-gap capacitive coupling between the feedlines and the resonator itself in order to achieve a 3% 3dB bandwidth and $<3\text{dB}$ insertion loss around the center frequency of 60 GHz. However, the required coupling capacitances to satisfy the design specifications cannot be achieved because of the LTCC design rules limitations. In order to maximize the coupling strength, while minimizing the effects of the fabrication, the proposed novel structure takes advantage of the vertical deployment of filter elements by placing the feed lines and the resonator into different vertical metal layers as shown as Fig. 2 (a). This transition also introduces a 7.6% frequency downshift because of the additional capacitive coupling effect compared to the basic $\lambda/2$ square patch resonator .

Transverse cuts have been added on each side of the patch in order to achieve a significant patch miniaturization by introducing an additional inductance. The fixed width of the cuts ($L_{\text{cw}}=L/8$ in Fig. 1 (b)) is determined by the fabrication tolerance. I3D simulations show that the operating frequency range shifts further downward about 33% as the length of the cuts (L_{cl} in Fig. 1 (b)) increases by approximately 379 μm . Further miniaturization is limited by the minimum distance (L_s in Fig. 1 (b)) between the corners of adjacent orthogonal cuts. Meanwhile, as the operating frequency decreases, the shunt conductance in the equivalent circuit of the single patch also decreases because its value is reciprocal to the exponential function of the operating frequency [6]. This fact additionally causes the reduction of the radiation loss

since it is proportionally related to the conductance in the absence of conductor loss [7]. Therefore, the insertion loss at resonance is improved from 2.27 dB to 1.06 dB by an increase of L_{cl} in Fig. 1 (b). The patch size is reduced significantly from 0.996 mm to 0.616 mm. The modification of the bandwidth due to the patch miniaturization can be compensated by adjusting the overlap distance (L_{over}). It is observed that 3-dB bandwidth increases as L_{over} increases due to a stronger coupling effect and then L_{over} is determined to be 18 μm corresponding to 1.85 GHz 3-dB bandwidth.

The proposed embedded microstrip line filters are excited through vias connecting the coplanar waveguide signal pads on the top metal layer (M1 in Fig. 2 (a)), reducing radiation loss compared to microstrip lines on the top (surface) layer. As shown in Fig. 1 (b), Klopfenstein impedance tapers are used to connect the 50 Ω feeding line and the via pad on the metal 2 (M2 in Fig. 1 (b)). The fabricated filter prototypes with coplanar waveguide (CPW) pads were fabricated in LTCC ($\epsilon_r=5.4$, $\tan\delta=0.0015$) with a dielectric layer thickness of 100 μm and metal thickness of 9 μm . The overall size is 4.018 mm \times 1.140 mm \times 0.3 mm including the CPW measurement pads. As shown in Fig. 3(a), the insertion loss is < 2.3 dB, the return loss > 25.3 dB over the pass band and the 3dB bandwidth is about 1 GHz. The center frequency shift from 59.85 GHz to 59.3 GHz can be attributed to the fabrication accuracy (vertical coupling overlap affected by the alignment between layers, layer thickness tolerance).

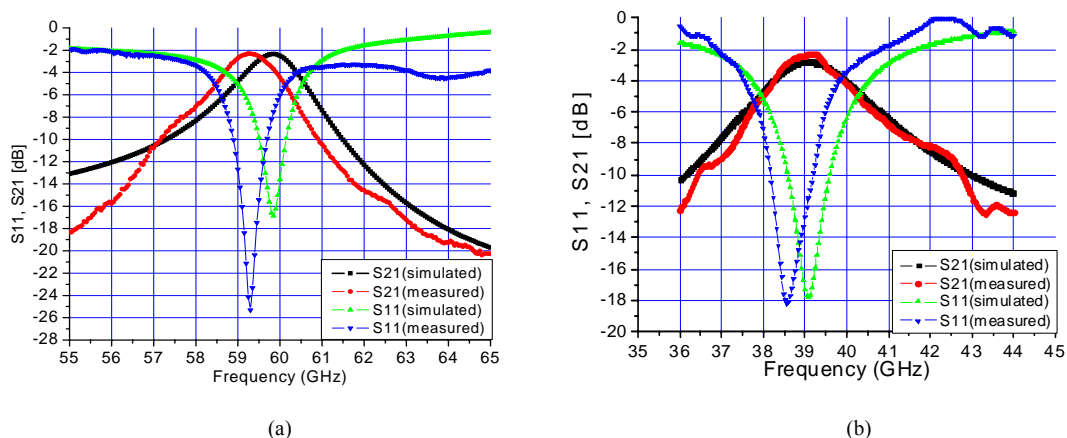


Fig. 3 Measured and simulated S-parameters of (a) 60 GHz slotted patch resonator (b) 39 GHz slotted patch resonator

The proposed slotted-patch filter architecture was also used in the design of mobile satellite communication systems around 39 GHz. The single-mode patch filter ($L \times L = 1.021 \text{ mm} \times 1.021 \text{ mm}$) was designed for 3.08% bandwidth and < 3dB insertion loss. The design procedure was similar to the 60GHz filter except from the fact that the resonator was placed on two layers (instead of one layer) beneath the feeding lines as shown in the side view of Fig. 2 (b). The overall size was 4.423 mm \times 1.140 mm \times 0.4 mm with CPW measurement pads. The fabricated filter exhibits a minimum insertion loss of 2.3 dB, a return loss of 18.2 dB, and a 3-dB bandwidth about 3%. (Fig. 3 (b)) The experimental error in the calculation of the center frequency can be attributed to the fabrication accuracy as mentioned in 60GHz case.

III. LCP MILLIMETER-WAVE BANDPASS FILTER

Liquid Crystal Polymer (LCP) has demonstrated excellent properties in terms of flexibility, thermal stability, hermeticity/packaging capability, while offering a low dielectric constant (around 3.15) [8]. In this paper we present a 60GHz band pass filter on LCP with excellent performance. The device manipulates the ripple near the cut off frequency a Tchebyscheff low pass filter to create a bandpass response. The initial low pass filter has been implemented by cascading two low impedance sections [9]. Two slots have been added in each of these low impedance sections to enhance the ripple amplitude. Then, an open stub creating a transmission zero at 36 GHz has been added to enhance the rejection up to -35 dB in the lower band (Fig. 4(a)). Capacitive feeding could be used to eliminate the low frequency pass band if it is required. This combination results in a pass-band response at 60 GHz center frequency and a relative 3-dB bandwidth of 15%. An insertion loss < 15 dB and a ripple of +/- 0.15 dB have been measured over a bandwidth of 6

GHz centered at 60 GHz. (Fig 4(b)). The design offers a very simple, low loss and low cost filtering solution for wideband mmW applications such as 60GHz WLAN gigabits wireless applications.

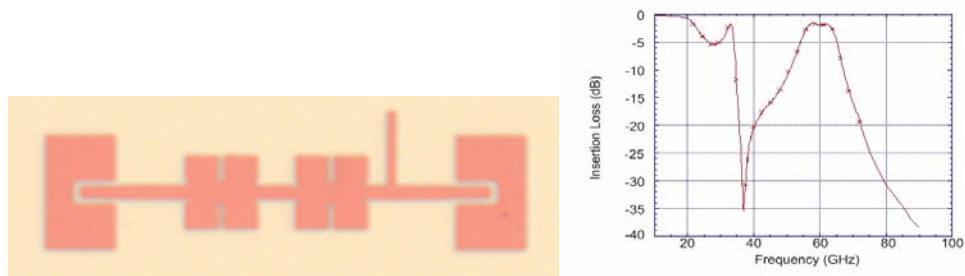


Fig. 4 mmW LCP band pass filter with two resonators and a rejection stub (A) prototype, (B) Measured insertion loss

IV. CONCLUSIONS

We have presented the development of highly integrated millimeter-wave SOP passive functions enabling a complete passive solution for compact, low cost wireless front-end systems in both multilayer LTCC and LCP technologies. The LTCC patch resonator filter that uses vertical coupling, overlap and transverse cuts as design parameters achieves a high level of miniaturization and a great compromise between size and power handling. Excellent performance is verified for two operating frequencies (58-60GHz/38-40GHz) of mobile communication systems through the measured insertion loss (< 2.3 dB/2.3dB) and return loss (> 25.3 dB/18.2dB) over the pass-band, and a bandwidth (1.67%/3%) centered at (59.3 GHz/39GHz). Also, a bandpass filter exploiting the ripple of modified stepped impedance Tchebyscheff low pass filter combined with a rejection stub has been designed on LCP to enable a low cost, very easy to design filtering solution to be integrated. Insertion loss as low as 1.5 dB and a ripple of ± 0.15 dB have been measured over a bandwidth of 6 GHz centered at 60GHz. The design offers a very simple, low loss and cost-saving filtering solution, ready to be integrated in wideband millimeter-wave applications such as 60GHz WLAN gigabits wireless systems. In the next step, we will demonstrate additional compact and easy-to-design passive functions, such as filters and antennas with excellent performance, compact size and high integration potential for applications like mixing and multiplexing.

Acknowledgments

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References

1. K.Lim et al., "RF-System-On-Package (SOP) for Wireless Communications," *IEEE Microwave Magazine*, Vol.3, No.1, pp.88-99, March 2002.
2. S. Pinel et al., "High Q passives on Liquid Crystal Polymer substrates and BGA technology for 3D integrated RF Front-End Module", *IEICE Tran.Electronics*. Vol.E86-C, No.8, pp 1584-1592, August 2003.
3. M.F. Davis et al, "Integrated RF Function Architectures in Fully-Organic SOP Technology", *Procs. EPEP2001*, pp. 93-96, Cambridge, MA, Oct. 2001.
4. K.Brownlee et al., "Liquid Crystal Polymer for High Performance SOP Applications", *8th International Symposium on Advanced Packaging Materials*, pp 249-253, IEEE 2002.
5. V.Kondratyev et al., "On the design of LTCC filter for millimeter-waves," *IEEE MTT-S Int .Microwave Sym. Dig.*, pp. 1771-1773, Philadelphia, PA, June 2003.
6. David M. Pozar et al., *Microstrip Antennas*, IEEE press (New York, 1995).
7. Robert E. Collin, *Foundations for Microwave Engineering*, McGraw Hill (New York, 1992).
8. M.M.Tentzer et al., "3D Integrated RF and Millimeter-Wave Functions and Modules Using Liquid Crystal Polymer (LCP) System-on-Package Technology", *IEEE Transactions on Advanced Packaging*, Vol.27 No.2, pp.332-340, May 2004.
9. G.L.Matthaei et al., *Microwave filters, impedance-matching networks, and coupling structures*, Bookmart Press, (Nort Bergen, 1985).