Advanced System-on-Package (SOP) Multilayer Architectures for RF/Wireless Systems up to Millimeter-Wave Frequency Bands

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This paper reviews the development of advanced System-on-Package (SOP) architectures for the compact and low cost wireless RF wireless systems. A compact stacked patch antenna adopting soft-and-hard surface structures and cavity resonator filters using inter-resonance coupling mechanism for V-band applications are presented. A novel ultra-compact 3D integration technology is proposed and utilized for the implementation of a Ku-band VCO module. The high Q-factor inductors fabricated on the Liquid Crystal Polymer based multi-layer substrate demonstrate superior performance than conventional organic packages.

I. Introduction

Recently, the Multilayer System-On-Package (SOP) approach has demonstrated a unique capability of overcoming the limitations of conventional System-On-Chip approach [1]. It integrates passive components and functions, that would have otherwise been required in discrete form, and MMIC's in a single package, hence the term System-on-Package. In this paper, we present the development of advanced system-on-package architectures for compact, low cost wireless front-end systems to be used in RF and millimeter-wave frequency ranges. This demonstration is a strong indication that the system-on-package approach can emerge as the most effective solution for the flexible and reconfigurable systems required in high frequency applications such as secure personal communication networks and short-range broadband wireless local-area networks (WLAN). Various embedded functions are covered including compact stacked patch antennas using SHS structures, and cavity resonator filters with CPW I/O ports for V-band applications, as well as one Ku band VCO module using a novel ultra-compact 3D integration technology . In addition, the fabrication of very high Q-factor inductors in Liquid Crystal Polymer multilayer substrate demonstrates superior performance compared to any other multilayer organic packages.

II. High-Efficiency Integrated Microstrip Patch Antennas Using SHS

The limiting factor for most multilayer packages is the size of the antenna. In addition, especially for mm-wave applications, power efficiency and low cross polarization interference are very important, since the signal attenuation is faster than in lower frequencies. In order to reduce the undesired backside radiation, that is common in unidirectional antenna design, the use of a soft-and-hard surface (SHS) has been employed to compact microstrip patch antennas. The SHS can also suppress surface waves that propagate from the patch. Although a large ground plane as well as electronic bandgap structures (EBGs) has been used in the past to eliminate surface waves, the use of SHS can help maintain a more compact structure laterally [2]. The SHS is realized here by surrounding the patch with rings of metal vias (Fig. 1). The substrate material used is LTCC044 with a dielectric constant of 5.4 and a loss tangent of 0.0015. When applied to a frequency of 64.55 GHz, a reduced backside radiation of approximate 10 dB can be achieved with SHS in comparison to a similar design without SHS (Fig. 2). Also, an increased gain of 10 dB at broadside can be obtained with this structure. This antenna has an efficiency of greater than 85%.

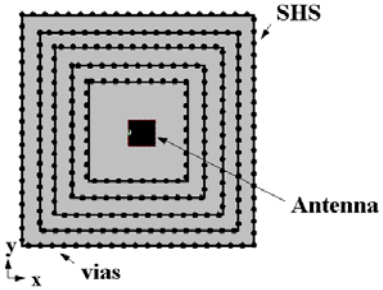


Fig. 1. Patch antenna surrounded by an SHS.

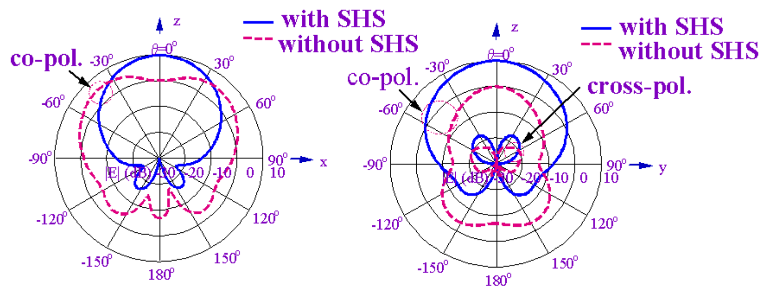


Fig. 2. Radiation patterns of patch antenna w/ and w/o. SHS.

III. V-band Cavity Resonator Filters

Another important function that can be easily integrated in multilayer modules is filtering, that needs to be realized using cavity resonators in mm-wave frequencies, due to compactness requirements and the significantly smaller size of the wavelegth. In this paper, two bandpass filters with CPW I/O ports have been designed and embedded in multilayer packages for V-band applications. The first bandpass filter, that is embedded in LCP (ε_r = 2.9, tan δ = 0.002), is composed of one cavity that utilizes cavity-to-CPW transformers to lead CPW I/O ports at the ends, as is shown in Fig. 3 [3]. The filter is stacked on the top layer of the LCP multilayer substrate, while its top and bottom are covered with ground planes. The length of CPW feed line (l_{feed}) is determined by 50Ω I/O impedance requirement and the length of the waveguide-to-CPW transformer (l_{ctc}) is the main controlling factor for this impedance matching. The effective length (L) and width (W) of the cavity, using TE_{101}, can be decided by the resonant frequency equation of the rectangular waveguide cavity [4]. The side walls of the rectangular cavity are replaced by a periodic lattice of via walls achieving the stop band rejection at desirable operating frequencies. Since the smaller spacing between vias is desirable to prevent leaky waves from the cavity, the minimum value (250μm) of vias center spacing of LCP design rule is used for the distance between them. Fig. 4 shows simulated center frequency of 69 GHz, a 3dB - bandwidth of 11.8 GHz and a minimum insertion loss of 3 dB, which can be attributed to dielectric and metal loss. Experimental results will be included in the final version of the paper.

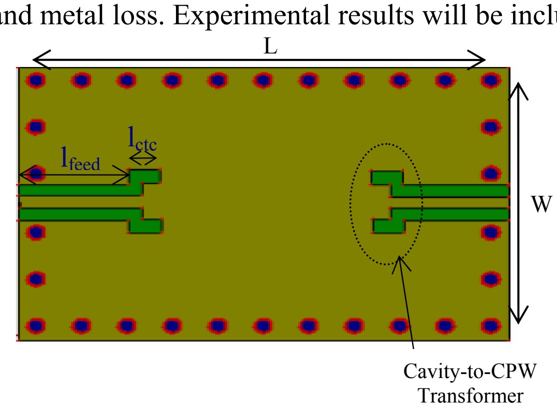


Fig. 3 Top view of V band one-cavity resonator BPF

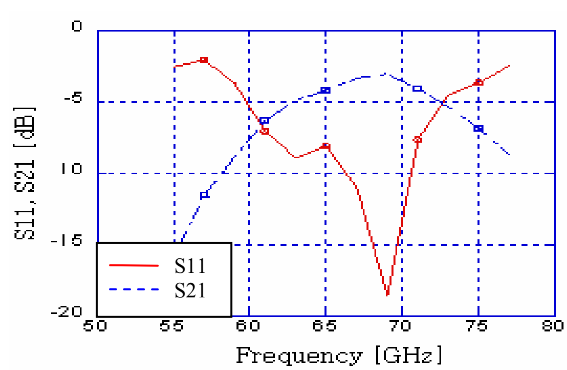


Fig. 4 Simulated insertion and return loss of one-cavity resonator filter

The second bandpass filter embedded in LTCC (ε_r = 5.6, tan δ = 0.0015) is composed of three harmonic cavity resonators that utilize cavity-to-CPW transformers to lead CPW I/O ports at the ends, as is shown in Fig. 5 [3]. With respect to the compactness of BPF consisting of the three cavities, LTCC is used instead of LCP since dielectric constant (ε_r = 5.6) of LTCC is larger than that (ε_r = 2.9) of LCP. The top and bottom of the filter are covered with ground planes. The operation of an harmonic resonant-line filter is derived from lumped-element prototype low-pass filter, such as Chebyshev bandpass filter, with impedance level transformation by means of impedance inverters [4].

The electrical lengths of harmonic resonators can be properly selected to cancel out the major spurious pass bands arising from harmonic resonance of individual resonators. In our case, electrical lengths (L_1 and L_3, respectively) of the 1st and 3rd resonators are nearly equal to $2\lambda_g/2$ and that (L_2) of the 2nd resonator, $3\lambda_g/2$ where λ_g is guide wavelength at midband. The inter-resonance coupling coefficient between two resonators in the filter can be adjusted by the spacing (d_{12} and d_{23}) of a pair of via holes to achieve the best performance of insertion loss and resonant frequency and the length (l_{ctc}) of the cavity-to-CPW transformers affects the external Q and bandwidth as well in the way that external Q decreases as L increases [3]. Fig 6 shows a simulated center frequency of 66 GHz, a bandwidth of 10 GHz and a minimum insertion loss of 3 dB.

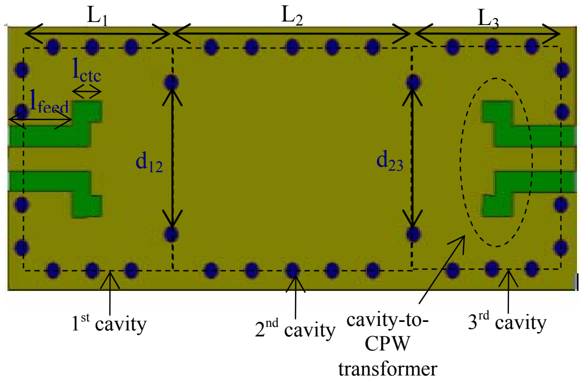


Fig.5. Top view of V band three-cavity resonator BPF

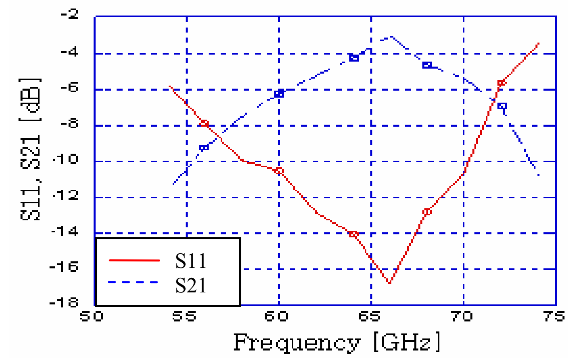
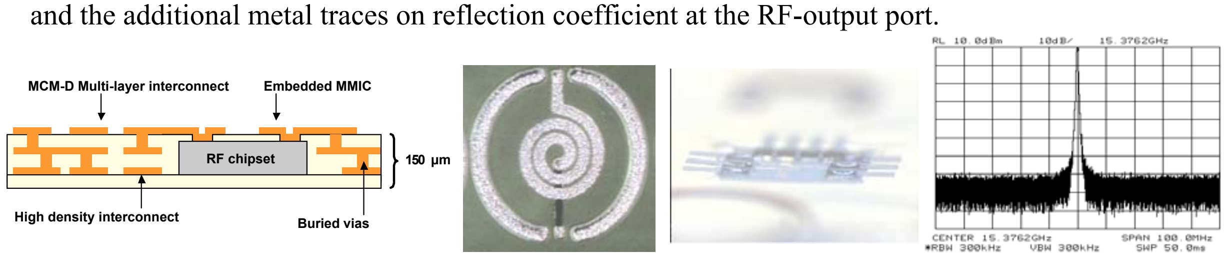


Fig. 6. Simulated insertion and return loss of three-cavity resonator filter

IV. Ultra-compact Ku-Band VCO Module

One of the major advantages of SOP is its capability to enable 3D integrated compact modules, making use of the vertical dimension and of laminated configurations. One demonstration of this type of proposed module concept for the Ku-band is illustrated in Fig.7a. A microwave multi-layer interconnect structure is built on a glass carrier using modified MCM-D technology and advanced photosensitive epoxy. Low loss interconnect is fabricated using build-up technology and 12μm thick electroplated copper. Micro-via technology with minimum diameter of 40 μm is used to connect the different metal layers. Thus high density interconnect network and integral passive components such as high performances embedded inductors, filters and antennas can be implemented within the multi-layer wiring structure RF commercial chipset are directly embedded into the MCM-D structure. Furthermore, glass carrier substrate used during the fabrication can be selectively etched and removed, leading to a final thickness of only 150 microns. Thus, we have fabricated high Q RF inductors (Fig. 7b) exhibiting inductance values ranging from 0.4 up to 2 nH, quality factor up to 80 and self-resonance frequency from 12 GHz to 37 GHz. A Ku-band VCO (Fig. 7c) has been implemented in a 0.125-μm GaAs pHEMT process and occupies an area of 0.62×0.55 mm^2. Fig.7d shows the output spectrum for the embedded VCO. A maximum output power of 10.67 dBm was measured and the measured oscillation frequency is 15.4 GHz. [5] An offset about 5 to 6 % from the bare die performances is attributed to the impact of the dielectric on the on-chip passives components and the additional metal traces on reflection coefficient at the RF-output port.



(a) (b) (c) (d)

Fig. 7. (a) Schematic configuration of INC module for Ku-band, (b) High Q RF inductor, (c) Embedded VCO , (d) Frequency spectrum at the output port.

V. High-QRF Passives using Liquid Crystal Polymer Based Multilayer Substrate

LCP (Liquid Crystal Polymer) is known for a very promising material as a high-performance and low cost multilayer package solution. It has a unique combination of properties that makes it ideally suited for high-density, high-speed digital and millimeter wave multi-layer substrate applications. These performances are better than any other organics based material currently used in PWB fabrication and can be quite comparable to ceramic based substrate widely used for RF and millimeter wave applications. A complete library of circular inductors was fabricated and measured using LCP (Fig. 8a). The fabricated inductors exhibit inductance values ranging from 1.1 up to 4 nH, quality factor up to 90 and self-resonance frequency from 8 GHz to 16 GHz (Fig. 8b). [6]

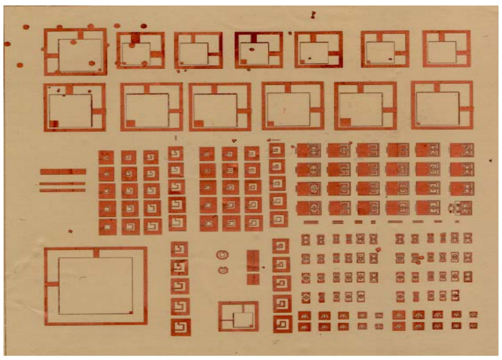


Fig. 8 (a) LCP test coupon

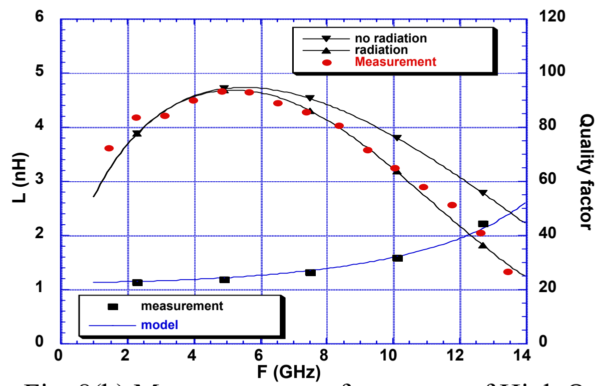


Fig. 8(b) Measurement performances of High Q RF inductors

VI. Conclusion

We have presented advanced System-on-Package (SOP) architectures for compact and low cost wireless RF wireless systems. The design of one- and three-cavity resonator filters using inter-resonant couplings and compact stacked patch antennas using SHS Structure for V-band applications has been reviewed. Multi-layer organic packaging developed for SOP is reported and the implementation of a Ku-band VCO module using a novel ultra-compact 3D integration technology has been proposed. In addition, the fabrication of very high Q-factor inductors in Liquid Crystal Polymer based multi-layer substrate demonstrates superior performances compared to any other multilayer organic packages.

ACKNOWLEGEMENTS

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