A Highly Integrated 3-D Millimeter-Wave Filter Using LTCC System-on-Package (SOP) Technology for V-band WLAN Gigabit Wireless Systems

J.-H.Lee(1), N. Kidera(2), S. Pinel(1), J.Papapolymerou(1), J. Laskar(1) and M.M.Tentzeris(1)

(1)School of ECE, Georgia Institute of Technology, Atlanta, GA 30332-250, U.S.A..
(2)Asahi Glass Co., Ltd. 1150 Hazawa-cho, Kanagawa-ku, Yokohama, Kanagawa 221-8755, Japan
e-mail: jonglee@ece.gatech.edu

Abstract- **In this paper, the development of highly integrated three-dimensional (3-D) filter solutions in multilayer low temperature cofired ceramic (LTCC) technologies is presented for millimeter-wave (mmW) compact, low-cost wireless front-end modules utilizing system-on-package (SOP) technology. These stacked-cavity embedded filters demonstrate an excellent performance (IL < 2.37 dB, 3-dB BW ~ 3.5 % at the center frequency of 57.3 GHz) and great potential for high level of 3-D integration potential. The slot-coupled cavity filters have been realized by vertically stacking three identical cavity resonators employing rows of vias as sidewalls, thus representing a new class of devices that enable the 3-D integration for V-band WLAN gigabit wireless systems.**

I. INTRODUCTION

The rapid growth of wireless communication, personal communication networks, and sensor applications has led to a dramatic increase in the regimes of RF/microwave/millimeter wave (mmW) systems [1]. Such emerging high-performance applications require miniaturization, low-manufacturing cost, excellent performance, and high-level of integration. The LTCC system-on-Package (SOP) approach has emerged as effective solution to meet these stringent needs because it offers not only great capability of integrating embedded functions, but also the real estate efficiency and cost-savings [2]. This paper focuses on the development of compact and advanced 3-D LTCC-based stacked-cavity filters enabling a complete passive solution for RF Front-end module of V-band WLAN gigabit wireless systems. The 60.25 GHz 3-D on-package 3-pole cavity filters have been demonstrated for the first time to provide easy and compact solution using rows of vias as sidewalls and the vertically stacked configuration [6] for 3-D module integration of antennas and active devices allocated into different layers. The performance of the proposed device is validated by the measurement data.

II. VERTICALLY STACKED 3-POLE CAVITY BAND PASS FILTER (BPF)

A vertically stacked cavity band pass filter (BPF) is designed to be easily integrated into a V-band multilayer module due to its compactness and its 3-D interconnect feature between the active devices on the top of the LTCC board and the antenna integrated on the back side. High-level of compactness can be achieved by vertically stacking three identical resonators with microstrip feedlines vertically coupled via a rectangular slot etched on the input and output resonators.

The 3-pole BPF is developed for 60.25 GHz center frequency, a 0.1 dB ripple, and a 4.15% fractional bandwidth based on a Chebyshev lowpass prototype. The cavity filter is embedded into the first five substrate layers (four metal layers) of the multilayer LTCC substrate and consists of three identical cavity resonators, two microstrip lines for input/output (I/O) feeding structures and four coupling slots (two external slots and two internal slots) etched in the ground planes of cavity resonators.

Figure 1 shows (a) the overview and (b) the side view of the proposed structure and the top view of (c) the feeding structure and (d) inter-resonator coupling structure. The effective length, width and height (L, W, H in Fig. 1 (a), respectively) of the cavity resonator, using TE_{101}, can be determined by the resonant frequency equation of the rectangular waveguide cavity [3]. A single substrate layer of 100 μm is utilized for each resonator. The single-mode (TE_{101}) cavity resonator is built using conducting planes as horizontal walls and via fences as vertical walls [4]. Since the smallest possible spacing (VD in Fig. 1 (c)) between vias is desirable to prevent leaky waves from the cavity, the minimum value (390 μm) of center-to-center vias spacing of LTCC design rule is used. With the aid of the full-wave simulator HFSS, we also find that two rows of vias separated by 390 μm are sufficient to block the field leakages from the via side walls.

Two external slots (Fig. 1 (b)) on metal layer 2 and 5 are dedicated to magnetically couple the energy from the I/O microstrip lines into the 1st and 3rd cavity resonators,

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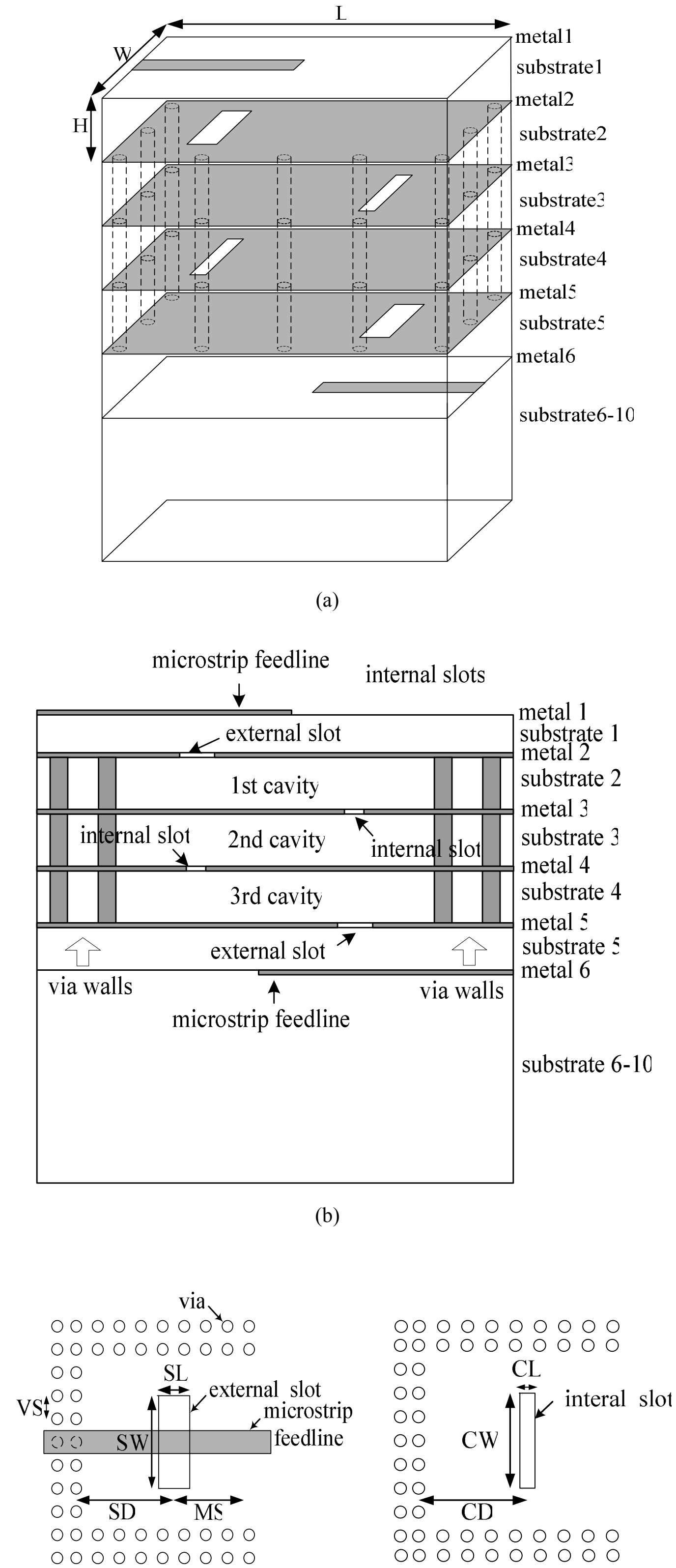

(a)

(b)

(c) (d)

Fig.1 (a) The overview (b) The Sideview of the vertically stacked 3-pole cavity band pass filter. (c) The top view of the feeding structure (d) The top view of the inter-resonator coupling structure.

respectively. To maximize magnetic coupling by maximizing the current, the microstrip lines are terminated with a short at the center of each slot implemented with a quarter wavelength open stubs (MS in Fig. 1 (c)) [4]. The latter internal slots (Fig. 1 (b)) are employed to couple energy from the 1st and 3rd cavity resonators into the 2nd resonator.

In order to determine physical dimensions of these coupling slots, two important design parameters such as the external quality factors (Q_{ext}) and the inter-resoantor coupling coefficients ($k_{i,i+1}$) are considered. All desired values of the design parameters are obtained using element values of Chebyshev lowpass prototype. First, Q_{ext}, which include loading effects, is utilized to control the coupling between the feeding network and the 1st and 3rd resonators of the filter. The optimum Q_{ext} is determined to be 24.86. The length (SL in Fig. 1 (c)) of the external slots is varied along with the constant slot width ($SW \approx \lambda_g/4$ in Fig. 1 (c)) and optimized to achieve the desired Q_{ext} using HFSS simulator. In addition, the desired inter-resonator coupling coefficients ($k_{12}=k_{23}=0.0381$) are obtained against the variation of the slot length (CL in Fig. 1 (d)) for a fixed Q_{ext} at I/O ports. Full-wave simulations are also employed to find the two characteristic frequencies (f_{p1}, f_{p2}) that are the resonant frequencies of the coupled structure when an electrical wall or a magnetic wall, respectively, is inserted in the symmetrical plane of a coupled structure, such a cavity [5]. These characteristic frequencies are associated to the inter-resonator coupling between cavity resonators as following: $k = (f_{p2}^2 - f_{p1}^2)/(f_{p2}^2 + f_{p1}^2)$ [5]. All the layout dimensions are summarized in Table I.

TABLE I
3-POLE CAVITY BPF DIMENSIONS

Design Parameters	**Dimensions (mm)**
cavity length (L)	1.95
cavity width (W)	1.284
cavity height (H)	0.1
external slot width (SW)	0.548
external slot length (SL)	0.320
external slot position(SD)	0.4175
internal slot width (CW)	0.538
internal slot length (CL)	0.138
internal slot position(CD)	0.4175
open stub length (MS)	0.571

Figure 2 shows the comparison between the simulated and the measured S-parameters of the 3-pole vertically stacked BPF. The simulation is performed with consideration of dielectric constant variation at the high frequency and the parasitic effects from the I/O open pads are de-embedded from the measurements with the support of "WinCal3.0" software. The filter exhibits an insertion loss <2.37 dB, which is higher than the simulated (1.37 dB). The main source of this discrepancy might be caused by the

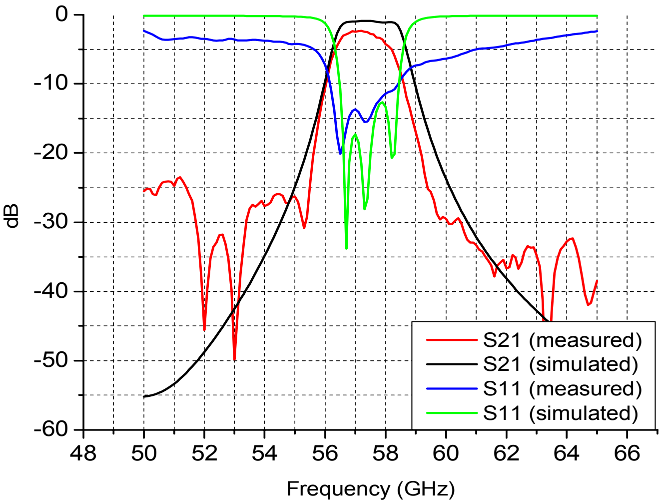

Fig. 2. Measured and simulated S-parameters of 3-pole cavity BPF.

radiation loss from the "thru" line that could not be de-embedded because of the nature of SOLT calibration. The center frequency shift from 57.5 GHz to 57.3 GHz might be attributed to the fabrication accuracy (slot positioning affected by the alignment between layers, XY shrinkage). Also, the filter exhibits a 3 dB bandwidth about 3.5% (≈ 2 GHz) comparable to the simulated 3.8 %

III. CONCLUSION

We have presented the development of highly integrated millimeter-wave stacked-cavity LTCC filters enabling a compact passive solution for SOP-based compact wireless front-end modules to be used in V-band WLAN gigabit wireless systems. This type of filters has demonstrated an excellent performance and the potential for high level of 3-D integration. The slot-coupled cavity filter geometry has been realized by vertically stacking three identical cavity resonators employing rows of vias as sidewalls, thus offering an easy-to-fabricate multilayer filtering solution.

IV. ACKNOWLEGEMENTS

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