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Fully Embedded 2.4GHz Compact Band Pass Filter into Multi-Layered Organic Packaging Substrate

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Abstract: In this paper, fully embedded 2.4GHz WLAN band pass filter (BPF) was investigated into a multi-layered organic packaging substrate using high Q spiral stacked inductors and high Dk MIM capacitors for low cost RF System on Package (SOP) applications. The proposed 2.4GHz WLAN BPF was designed by modifying chebyshev second order filter circuit topology. It was comprised of two parallel LC resonators for obtaining two transmission zeros. It was designed by using 2D circuit and 3D EM simulators for finding out optimal geometries and verifying their applicability. It exhibited an insertion loss of max -1.7dB and return loss of min -17dB. The two transmission zeros were observed at 1.85 and 6.7GHz, respectively. In the low frequency band of 1.8GHz~1.9GHz, the stop band suppression of min -23dB was achieved. In the high frequency band of 4.1GHz~5.4GHz, the stop band suppression of min -18dB was obtained. It was the first embedded and the smallest one of the filters formed into the organic packaging substrate. It has a size of $2.2\times1.8\times0.77mm^3$.

Keywords: embedded passives, organic package, circular spiral inductor, MIM capacitor, BPF, high-Q, SOP (System on a Package)

1. Introduction

Many recent products have been implemented WLAN communication capabilities such as mobile hand held devices, personal laptop computers, and their peripherals. Their RF transceiver architectures revolve from conventional narrow-band operation into various multi-band forms such as two narrow-band RF transceivers combined in parallel[1-2]. Thus, these RF multi-band systems demanded advanced electronic module with small volume, low profile, light weight, low cost, and excellent performance[3].

These modules were composed of a lot of active and passive components. The passive components were surface-mounted on substrate as discrete form. They occupied a large area of packaging substrate and provided poor electrical performance and reliability due to their longer inter-connection lengths and more solder joints, respectively. Thus, System on Packaging (SOP) has drawn attractions, since it could reduce system cost, size, and time-to-market. The SOP is widely being developed to realize advanced electronic modules and systems[4-6]. In particular, Embedded Passive Device (EPD) is a very attractive one in RF SOP technologies. Among these passive devices, special interest is given to band-selection filters because of their important role in affecting the performance of RF transceivers. In particular, the RF band-selection BPF must bear new requirement of stringent stop-band suppression to reduce cross-band interference. This requirement becomes more difficult to be achieved when the operating frequencies of coexisted systems are close. Therefore, the BPF with multiple arbitrary trans-

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mission zeros is necessary for use in the growing multi-band RF transceivers. So far, Low temperature co-fired Ceramic (LTCC) has been widely studied for RF SOP applications, since LTCC materials have low loss tangent, which it allows to make high Q embedded passive components[7-8]. However, they are limited to mass production and low cost due to the shrinkage of the ceramic substrate occurred during the firing process. Therefore, organic substrate based embedded BPF has been studied for low cost RF SOP applications.[9-10]. However, these devices have poor performance characteristics and large sizes compared with the LTCC based ones.

In this paper, fully embedded 2.4GHz WLAN BPF was designed, fabricated, and characterized into a multi-layered organic package substrate by using high Q stacked spiral inductors and high Dk MIM capacitors. The proposed 2.4GHz WLAN BPF was designed by modifying chebyshev second order filter circuit topology in order to achieve better performance characteristics and reduce its size. It was comprised of two parallel LC resonators. Each resonator was comprised of one high Q stacked spiral inductor, two MIM capacitors, and short stub. The embedded spiral inductor was designed with circular and stacked geometry to improve its quality factor and packaging efficiency. The embedded MIM capacitors were realized with high dielectric and low loss tangent film at high frequency regime in order to reduce their sizes.

2. Design and Fabrication

The proposed 2.4 GHz WLAN BPF was designed in the basis of conventional chebyshev second order filter circuit topology. Since the conventional chebyshev second order circuit has an inherent lower roll-off characteristics in comparison with higher order designs[11-12], it is optimally modified to overcome these drawbacks. Fig. 1 shows a reconstructed filter circuit to be embedded into an organic packaging substrate. It is comprised of two parallel LC resonators. The first resonator part is connected to

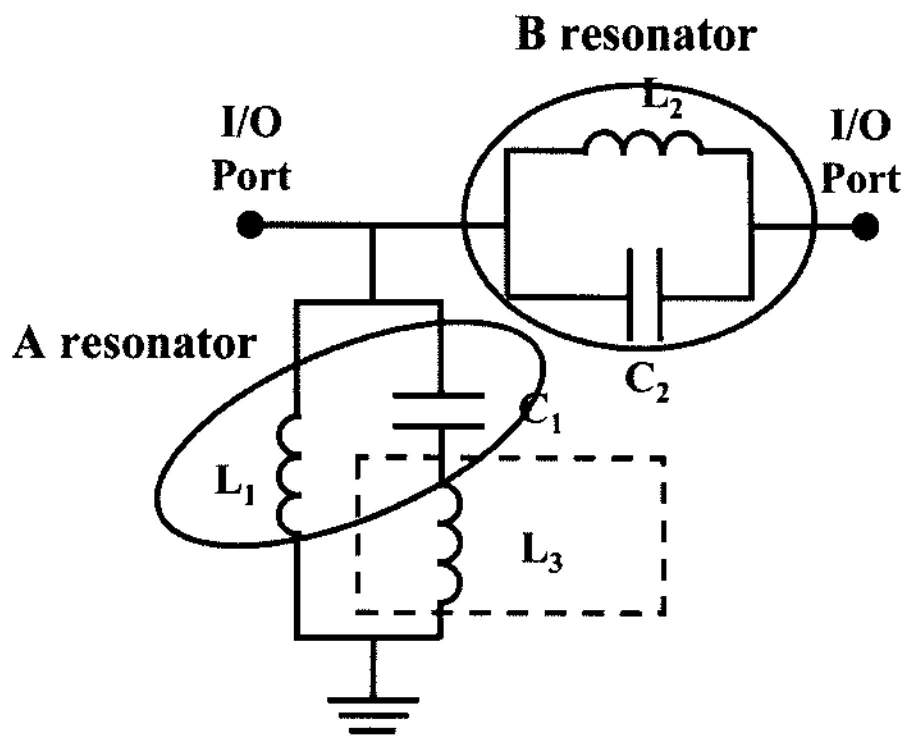

Fig. 1. An equivalent circuit model of proposed 2.4GHz WLAN BPF with modified chebyshev 2nd order filter topology.

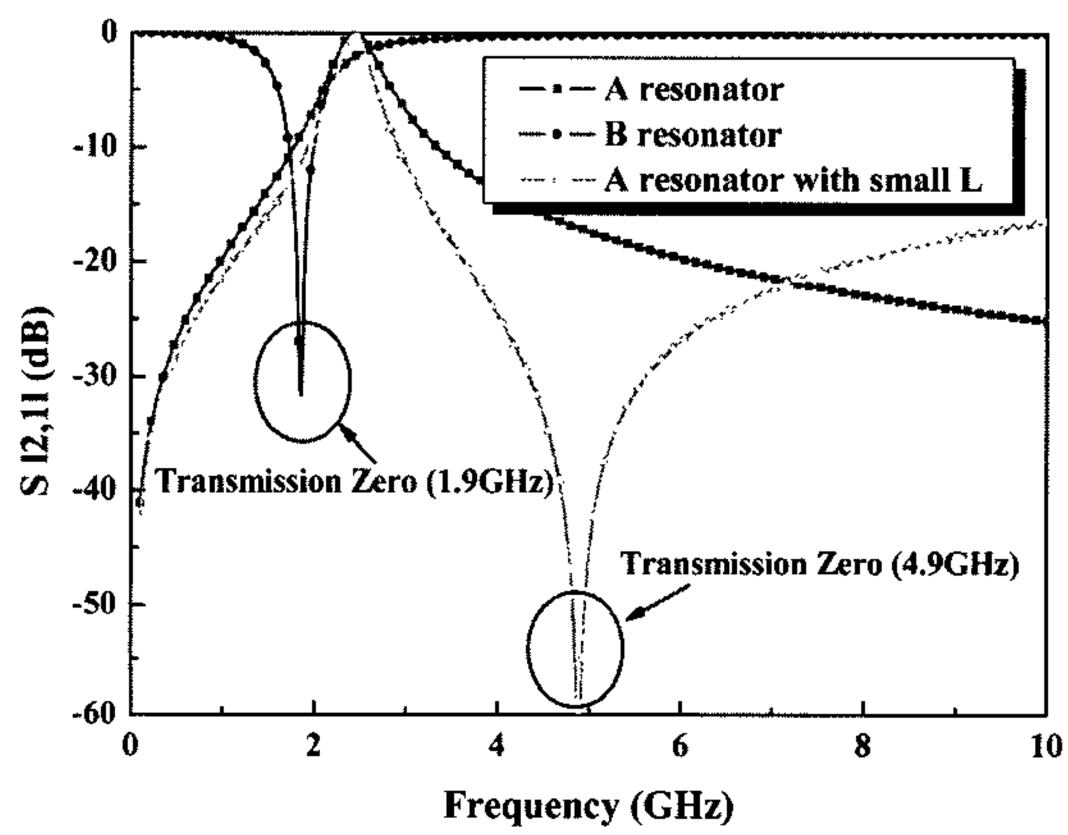

Fig. 2. 2D circuit simulated performance characteristics of two parallel LC resonators for obtaining transmission zeros.

the ground plane in parallel between the input and output ports. Its transmission characteristics act like band pass filter. The second resonator part is reconstructed by changing a conventional series LC resonator to a parallel LC resonator circuit. The parallel LC resonator is connected in series between the input and output ports. Its transmitted performance is represented by band stop behavior. The proposed BPF should have a pass-band bandwidth of nearly 100MHz centered at 2.45GHz and a high rejection at 1.8 / 1.9 GHz and at around 4.9GHz to suppress the DCS 1800 interference signal and the second harmonic of the operating frequency responses.

Lower band (1.8/1.9 GHz) transmission zero is obtained by resonant frequency of the series connected parallel LC resonator, since the series connected parallel LC resonator has band stop resonant point. Pass band center frequency obtained by calculating L1 and C1 of parallel LC resonator connected to the ground plane. In order to improve the upper band roll-off, a ground connected small inductance L3 is added by using laser via through 1st and 3rd layer. The upper band (4.9 GHz) transmission zero frequency is determined by the resonant frequency of C1 and L3. These designed parameters of L_1, L_2, L_3, C_1, and C_2 are 0.2552nH, 2.695nH, 0.095nH, 11.081 pF and 2.2775 pF, respectively.

The designed parallel LC resonators are comprised of high Q embedded stacked circular spiral inductors and high Dk MIM capacitors for improving their performance characteristics and packaging efficiencies. The embedded stacked circular geometry inductor is smaller than the embedded planar circular ones. Therefore the package size is easily reduced. And the stacked geometry is superior to obtain high quality factor and self resonance frequency[13-14]. The embedded stacked spiral inductors are designed on the 1st and 3rd layers. The utilized high dielectric composite material is comprised of barium titanate ($BaTiO_3$) powder and epoxy resin for reducing the size of the embedded capacitor by increasing the capacitance density. The MIM capacitor designed on the 2nd and 3rd layer has high dielectric film with thickness of 16μm.

Fig. 2 shows 2D simulated performance characteristics of two parallel LC resonators. Calculated and simulated resonant frequencies are well matched. Fig. 3 shows comparison of 2D circuit and 3D EM simulated performance characteristics of proposed 2.4GHz WLAN BPF. As shown in Fig. 3, 2D circuit and 3D EM simulated results demonstrate insertion losses of 1.7dB and 1.75dB, respectively. Two transmission zeros are observed at 1.85 and 5.25GHz, respectively. The 2D circuit and 3D EM simulated results are well agreed in overall frequency regime.

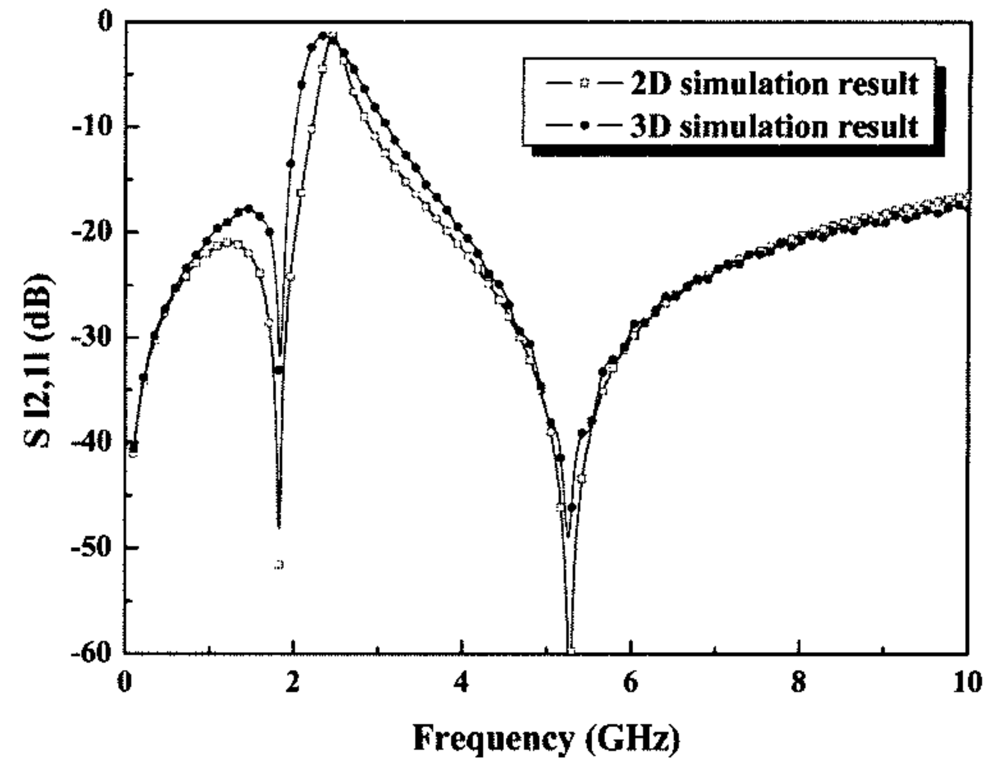

Fig. 3. Comparison of 2D circuit and 3D EM simulated performance characteristics of proposed 2.4GHz WLAN BPF

Fig. 4 shows a cross-sectional view of multi-layered organic packaging substrate to fabricate the proposed 2.4GHz WLAN BPF with high Q inductors and high Dk MIM capacitors. The multi-layered organic packaging substrate is eight metal layered structure using build up processing on a FR-4 laminate. The Copper Clad Laminate (CCL) as core substrate was 150um thick double sided with 1/2oz (17 μm) copper foil on each side. The CCL has relative dielectric constant of 4.4 and loss tangent of 0.03 at 1GHz. UV exposure was done on a mask and then copper etch was done in the 4th and 5th layer.

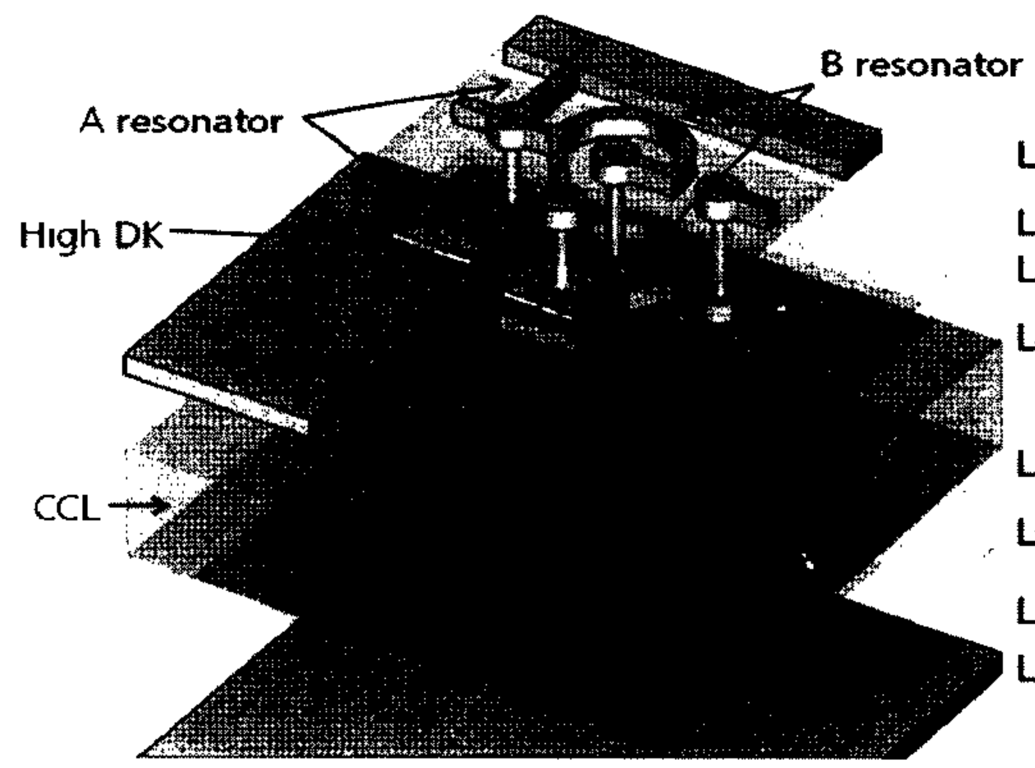

Fig. 4. A cross-sectional view of 8-layered organic package substrate to fabricate proposed 2.4GHz WLAN BPF.

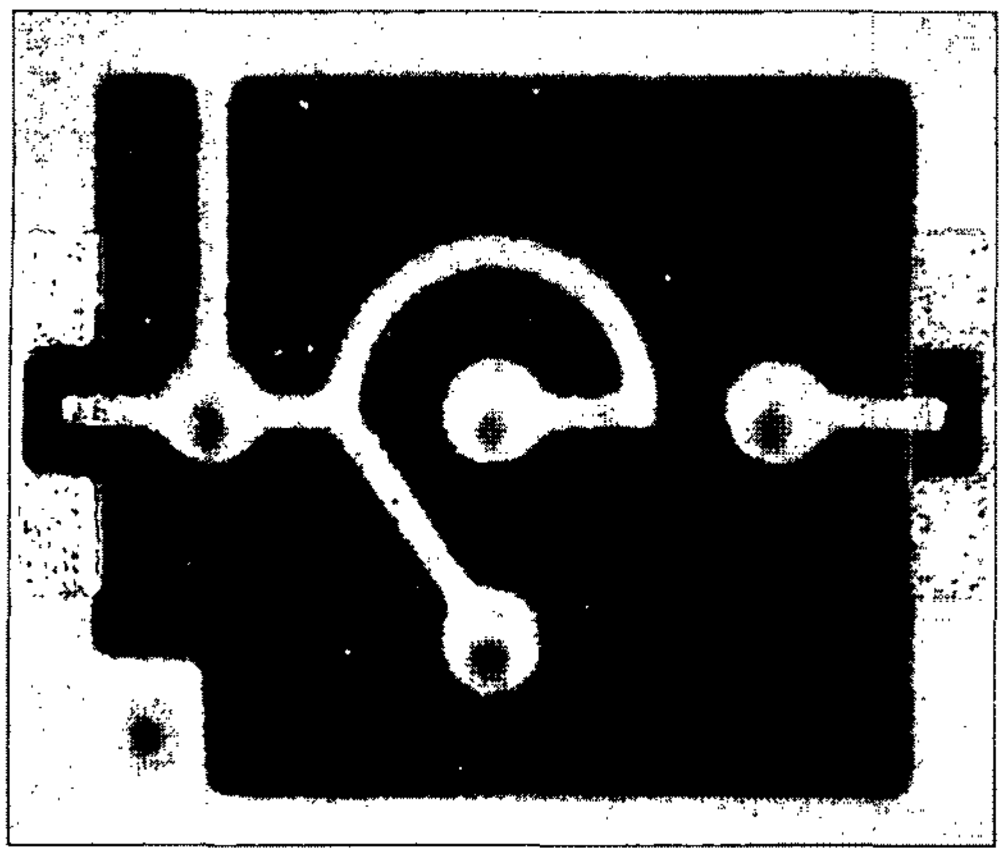

Fig. 5. A photomicrograph of 2.4GHz BPF embedded into 8-layered organic packaging substrate.

The Pre Preg (PP) as FR-4 laminate was laminated with 90 μm thick single sided with 1/3oz (12 μm) copper foil and comprised of 3rd and 6th layer, The PP has relative dielectric constant 4.1 and loss tangent of 0.016 at 1GHz. And the PP was laminated with 60 μm thick single sided with 1/3oz (12 μm) copper foil and comprised of the 7th layer. To use the MIM capacitor, the high Dk Resin Coated Copper (RCC) was laminated with 16ìm thick single sided with 1/3oz (12 μm) copper foil and then copper etch was done in the 2nd layer. To make inductor pattern, high Dk RCC rejection was implemented by using laser and then copper etch was partially done in the 3rd layer. The used high Dk RCC is comprised of barium titanate (BaTiO3) powder and epoxy resin. It has relative dielectric constant of 30 and loss tangent of 0.03 at 1GHz. The PP was laminated with 90 μm thick single sided with 1/3oz (12 μm) copper foil and comprised of the 1st and 8th layer. Plated through hole (PTH) with the diameter of 300ìm were mechanically drilled for connecting the top and bottom ground planes of the circuits. Laser via holes with the diameter of 150 μm were made for connecting between 1st to 2nd / 3rd and 8th to 7th / 6th layer. The electroless and electrolytic copper plating was implemented for hole wall metallization. Consequently, the thickness of the 1st / 8th layer and the 3rd / 6th layer was 28 μm and 22 μm, respectively because of electrolytic copper plating for PTH and laser via filling. After fabrication of these embedded passive circuits, the Photo-imageable Solder Resist (PSR) was coated and patterned to protect the devices and open the test pads. The opened copper metal pads are coated with nickel and gold cladding layer and their thickness is 3 μm and 0.6 μm, respectively.

Fig. 5 shows a photomicrograph of 2.4GHz WLAN BPF embedded into 8-layered organic package substrate for low cost RF SOP applications. The fabricated 2.4GHz WLAN BPF is the smallest one of the filters formed into the organic package substrate. It has a size of 2.2 mm×1.8 mm×0.77 mm.

3. Experimental Results and Analysis

The embedded 2.4GHz WLAN BPF were measured and characterized by using an HP 8510B network analyzer and PICOPROBE coplanar GSG probe with 250 μm in pitch size. And a short-open-load-through (SOLT) was adopted to calibrate before measuring them.

Fig. 6. shows comparison of measured and 3D EM simulated performance characteristics of embedded 2.4GHz WLAN BPF. The fabricated 2.4GHz WLAN BPF showed insertion loss of max. -1.7dB and return loss of min. -17dB at the frequencies ranged from 2.4GHz to 2.5GHz, respectively. Two transmission zeros were measured at 1.85 and 6.7 GHz, respectively. The measured higher transmission zero frequency was slightly shifted up. When the proposed filter was embedded into the organic packaging substrate, the interconnection via through the 1st to 3rd layers gave an effect on the higher transmission zero frequency. Since the measured interconnection via inductance was smaller than the expected one, the stop band rejection was somewhat deteriorated. In the low frequency band of 1.8GHz~1.9GHz and 0.8GHz~1 GHz, the stop band suppressions were -25dB~23dB and -21dB~23dB, respectively. In the high frequency band of 4.1GHz~5.8GHz, the stop band and second

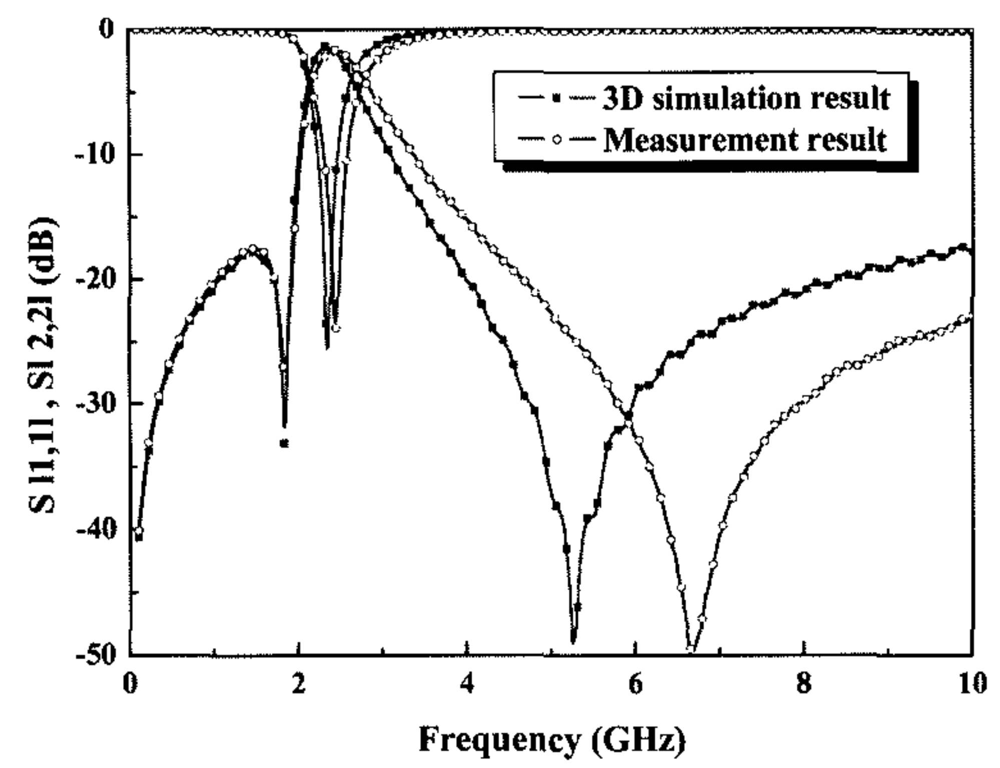

Fig. 6. Comparison of simulated and measured results of 2.4GHz WLAN band pass filter embedded into 8-layered organic package substrate.

order harmonic band suppression of -18dB~32dB were obtained. As shown in Table 1, the fabricated filter is smaller than the LTCC based devices and has compatible performance characteristics. Thus, it can be directly used for advanced wireless LAN systems with low cost, low profile, small size and volume.

4. Conclusion

Fully embedded 2.4GHz WLAN BPF into 8-layered organic packaging substrate have been designed, fabricated, and characterized for low cost RF SOP applications by using 3D EM simulator and PCB standard fabrication process. The PCB embedded 2.4GHz WLAN BPF has been designed by modifying chebyshev 2nd order filter topology and realized by using high Q stacked circular spiral inductors and high Dk MIM capacitors. As the measured performance characteristics of the fabricated filter were well matched with the 3D EM simulated ones. Its performance characteristics were similar to LTCC devices, but its size and volume were smaller. Thus, these embedded filters and passives are promising for advanced organic based SOP products with various functionalities, low cost, small size and volume.

Acknowledgements

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Table 1. Comparison of the Embedded 2.4ghz Wlan Bpf and Previous Works.

Reference	Substrate	Insertion loss @ pass band	Return loss @ pass band	Stop band rejection		Component size (mm^3)
				@ 1.8~1.9 GHz	@ 4.1~5.4 GHz	
Ref [6]	PCB	Max -2.46 dB	Min -16.8 dB	Min -50 dB	Min -10 dB	5×5×0.18
Ref [7]	LTCC	Max -1.93 dB	Min -15 dB	Min -27 dB	Min -30 dB	2.5×2.0×0.8
Ref [8]	LTCC	Max -1.5 dB	Min -15dB	Min -48 dB	Min -31 dB	5.4×3.9×0.765
This work	PCB	Max -1.7 dB	Min -17dB	Min -23dB	Min -18 dB	2.2×1.8×0.77

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