

# A Fully Embedded LTCC Multilayer BPF for 3-D Integration of 40-GHz Radio

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**Abstract**—This paper demonstrates a low loss fully embedded multilayer bandpass filter (BPF) using low-temperature cofired ceramic (LTCC) technology for 3-D integration of 40-GHz multimedia wireless system (MWS) radio. The LTCC filter implemented in a stripline configuration occupies an area of only  $5.5 \times 2.3 \times 0.6$  mm including shielding structure and coplanar waveguide (CPW) transitions. The measured insertion loss was as small as 1.9 dB at a center frequency of 41.8 GHz, and the return loss was 12.2 dB including the loss associated with two CPW-to-stripline transitions. This six-layer BPF showed 3-dB bandwidth of 10.5% from 39.6 to 44.0 GHz at a center frequency of 41.8 GHz and suppressed the local oscillator (LO) signal to 20.2 dB at a local oscillator frequency of 38.8 GHz, making it suitable for the 40 GHz MWS applications.

**Index Terms**—Bandpass filter (BPF), embedded, low-temperature cofired ceramics (LTCC), multilayer, multimedia wireless systems (MWS).

## I. INTRODUCTION

THE INCREASING demands for real time and high-speed wireless data transmissions have accelerated realization of broadband wireless systems like wireless local area networks (WLANs) [1], wireless IEEE1394 [2], and multimedia wireless systems (MWS) [3], [4] using millimeter-wave frequency. One of the most important issues for implementation of the millimeter-wave wireless terminals is the system integration of the radio in a small size as well as an even greater functionality and lower manufacturing cost. The component, which covers

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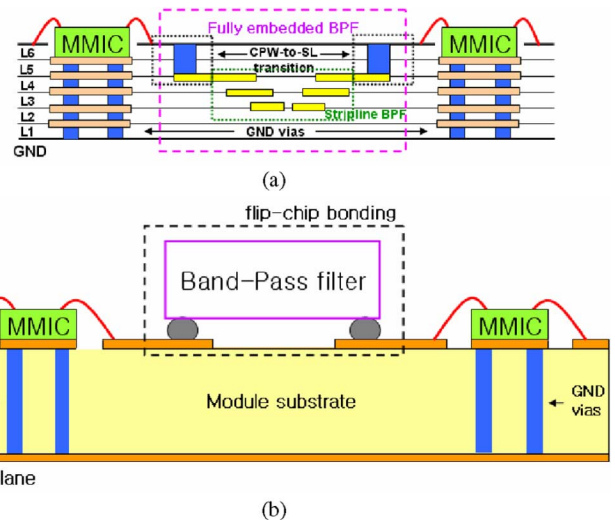


Fig. 1. (a) Proposed silicon on plastic structure with the fully embedded BPF and (b) traditional structure with an off-chip bonded BPF.

significant space and is required to be integrated 3-D with active circuitry, is the filter, especially, the bandpass filter (BPF), which cannot be integrated within the active circuit. Recently, there have been several reports on millimeter-wave filters [5]–[10]. However, they are developed as off-chip discrete components which need to be packaged on a separate printed circuit board [5], or be placed on top of the substrate [6]–[8], and so consume a large footprint in the radio. One of the most promising candidates offering low loss substrate for millimeter-wave multilayer circuits [9] as well as a high- $Q$  dielectric for filter is the low-temperature cofired ceramics (LTCC) technology [10]. With LTCC, the 3-D integration technology, filters can be fully embedded within the multilayer circuit, and then above them, other circuits such as amplifiers and mixers can be mounted space-efficiently. It has been reported recently that the embedded BPFs have been built just for Ku-Band transmitter module [11], for  $C$ -band radio-frequency (RF) front-end module [12], for Bluetooth RF transceiver module [13] and for millimeter-wave applications [14].

In this letter, we propose and implement a fully embedded LTCC multilayer BPF for 40-GHz MWS radio. The dielectric constant and loss tangent of the LTCC are 7.2 and 0.003 at 40 GHz and silver is used as conductor. This is the report on the fully embedded multilayer millimeter-wave BPF suitable for system-on-package applications.

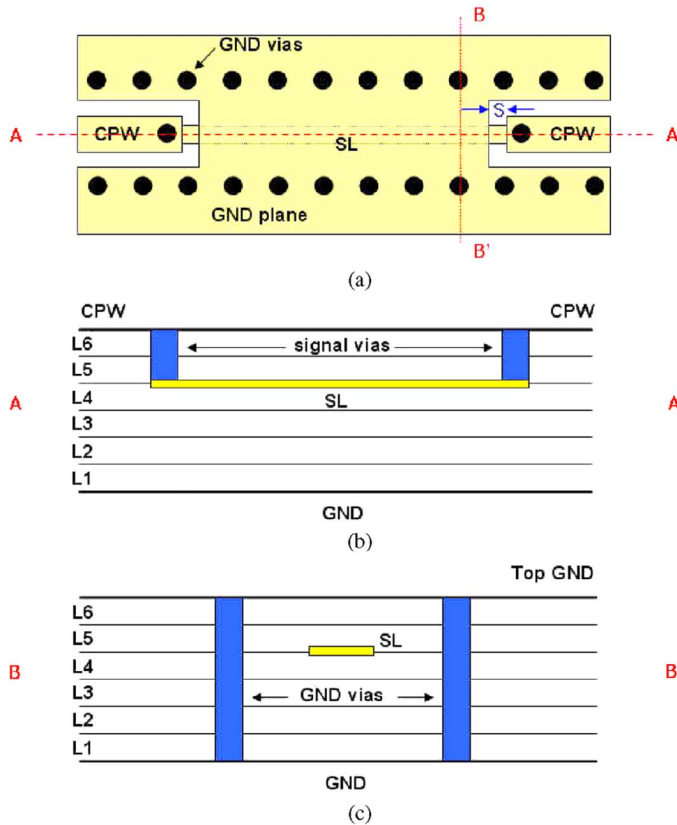


Fig. 2. Schematic description of the CPW-to-SL-to-CPW transition: (a) top view; (b) cross-sectional view across AA'; (c) cross-sectional view across BB'.

## II. EMBEDDED BPF

Fig. 1 shows the schematic description of the radio around BPF, where (a) describes the embedded BPF connected with next active monolithic microwave integrated circuits (MMICs) while (b) describes the traditional off-chip BPF requiring additional assemblies such as flip-chip or wire bonding. The stripline structure is selected to implement the millimeter-wave BPF because upper and lower ground planes make the even-mode and odd-mode phase velocities equal and also it has less radiation loss and dispersion compared to other transmission line structures [15]. The coplanar waveguide-to-stripline (CPW-to-SL) transitions allow the interconnection between the embedded SL BPF and active components such as a power amplifier and a mixer on top of the LTCC circuit. Also, the SL LTCC filter can be measured using microwave ground-signal-ground (GSG) probes.

## III. CPW-TO-STRIPLINE TRANSITIONS

Fig. 2 describes the test structure to evaluate the CPW-to-SL transitions. Both CPW and SL have been designed to have 50- $\Omega$  characteristic impedance. The CPW-to-SL transition structure has been optimized for minimum transition loss by controlling the space ( $S$ ) between CPW signal line and upper ground of the SL. The upper ground plane for both the CPW and SL has been connected to the bottom ground plane of the SL through multiple vias along the transmission lines to ensure same potential between the ground planes. Fig. 3 shows the simulated and measured  $S$ -parameter results for the CPW-to-SL transition of Fig. 2, which is composed of each two vias (input and output ports) in two layers (L5, L6), 4.6-mm-long SL and two 0.6-mm-

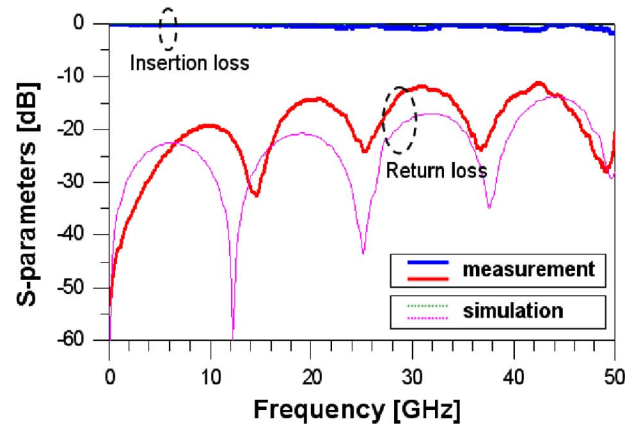


Fig. 3. Simulated ( . . . ) and measured (—) results of the CPW-to-SL transition.

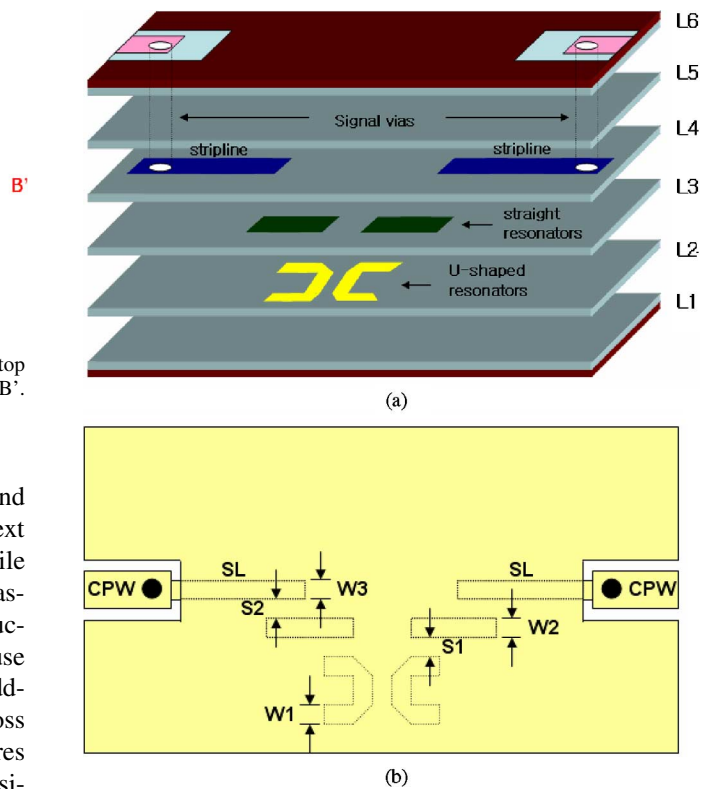


Fig. 4. (a) Schematic diagram and (b) top view of a fully embedded multilayer BPF.

long CPWs. The simulation and measurement were performed CST microwave studio and probe station, respectively. Even though there is a little ripple due to long cable length and a few calibration errors, the trend of the simulation and measurement results is generally similar. The total insertion loss including two transitions for measurement at the input/output (I/O) ports is measured as small as 1.9 dB at 40 GHz.

## IV. BPF DESIGN

The fully embedded multilayer BPF was designed to realize fourth-order Tchebyscheff prototype response having a 3-dB bandwidth of 10.5% from 39.6 to 44.0 GHz at a center frequency of 41.8 GHz with a 0.05 dB ripple. Fig. 4 shows a schematic diagram and a top view of the embedded multilayer BPF. This BPF is made up of four coupled line sections located on the second

TABLE I  
PHYSICAL DIMENSIONS OF THE MULTILAYER BPF

W1	W2	W3	S1	S2
120 $\mu\text{m}$	121 $\mu\text{m}$	100 $\mu\text{m}$	233 $\mu\text{m}$	35 $\mu\text{m}$

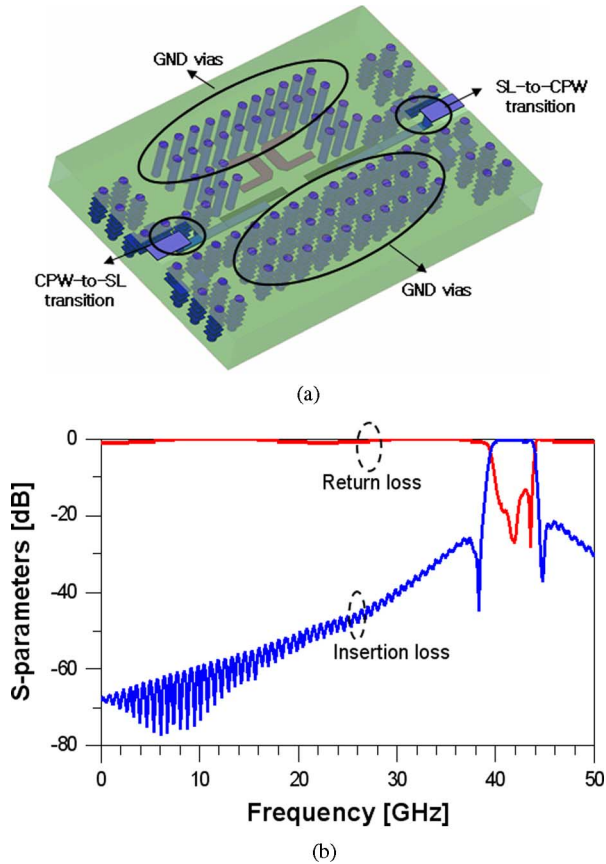


Fig. 5. (a) 3-D schematic view and (b) insertion loss and return loss of the designed multilayer BPF.

and third layers (L2, L3) and they have a length of  $\lambda/4$  each at the center frequency. In order to reduce the size of the filter, the two hairpin resonators are used in the filter [16]. The number of used layers is 6, and thus the total thickness is 0.6 mm. The 50- $\Omega$  input and output CPWs are connected with SLs located on the fourth layer (L4) through the signal vias. The straight resonators located on the third layer (L3) couple to a set of bent U-shaped resonators located on the second layer (L2), which are magnetically coupled.

The BPF was designed using the formulas of the general single-layer parallel coupled BPF. The even-mode and odd-mode impedance values for each segment were obtained by using the admittance inverter corresponding to a single section, and the physical dimensions of the coupled stripline by using the nomodiagrams [17]. The physical dimensions are obtained through being adjusted to the desired response. The resonator length was corrected to consider the fringing capacitance from the end of each SL. Each physical dimension of the multilayer BPF shown in Fig. 4(b) is summarized in Table I. Fig. 5(a) shows a 3-D schematic view of the designed multilayer BPF. In a designed BPF, there are discontinuities at

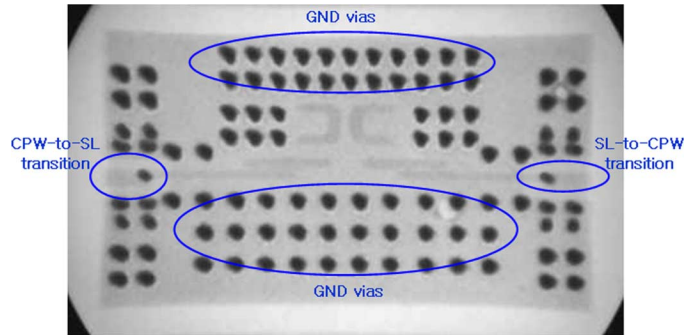


Fig. 6. X-ray photograph of the fabricated BPF.

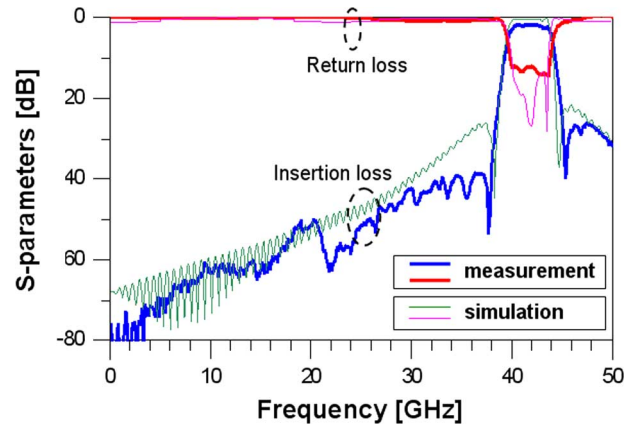


Fig. 7. Simulated and measured insertion and return loss of the embedded multilayer BPF.

the angled bends of the hairpin resonators. In order to reduce the effects of discontinuity due to angled bends of the hairpin resonators, the hairpin resonator bends must be chamfered [16]. The discontinuity reactance causes a reduction in length compared to that measured along the centerlines of the stripline [18]. The simulated optimum length of the bend is 70  $\mu\text{m}$ . And in order to equalize the electric potential between the upper and lower ground planes of the SL structure, ground vias are placed around the filter.

Fig. 5(b) shows the results designed by an electromagnetic (EM) simulator, CST microwave studio. The insertion loss and return loss of the filter are 1.2 and 13.2 dB, respectively. The 3-dB bandwidth ratio is controlled to 10.5% from 39.6 to 44.0 GHz, and the local oscillator (LO) rejection at a local oscillator frequency of 38.8 GHz is as much as 21 dB. We understand the variation of the return loss as a parasitic resonance according to the space made by the ground via surrounding the U-shaped resonators.

## V. MEASUREMENT RESULTS

Fig. 6 shows an X-ray photograph of the fabricated BPF, and Fig. 7 reveals the measured insertion loss and return loss of the filter for a frequency range from 0 to 50 GHz and for a magnified window from 36 to 46 GHz. The measured values include the loss associated with two SL-to-CPW transitions, each of which is composed of a two-layer via. The total insertion loss of the filter including transition losses is as small as 1.9 dB at a center frequency of 41.8 GHz. The 3-dB bandwidth ratio is controlled

TABLE II  
SUMMARY OF THE MEASURED RESULT COMPARED TO THE SIMULATED

Parameters	Simulated Data	Measured Data
Center Frequency(GHz)	41.8	41.8
3 dB bandwidth (%)	10.5	10.5
Insertion Loss (dB)	1.1	1.9
Return Loss (dB)	13.2	12.2
LO rejection (dB) at 38.8 GHz	21	20.2

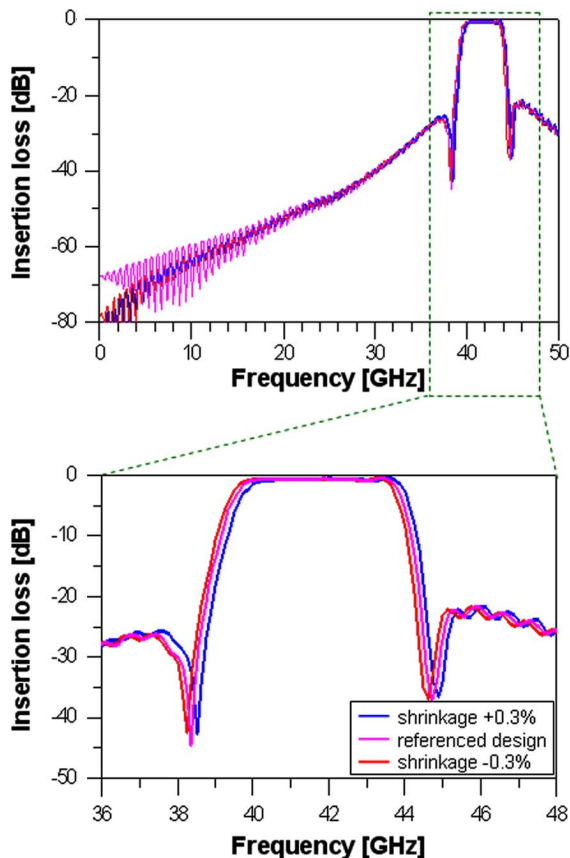


Fig. 8. Simulation results of the proposed BPF according to the variation of LTCC process.

to 10.5% from 39.6 to 44.0 GHz, and the LO rejection at a local oscillator frequency of 38.8 GHz is as much as 20.2 dB. The measurement equipment consists of 2 GSG probes with 500  $\mu\text{m}$  pitch, probe station and network analyzer (8510C), which can be measured from direct current (dc) to 50 GHz.

Table II outlines the measured performance compared to the simulated performance. The measured insertion loss at the center frequency is 0.8 dB larger than that of the simulated result, and the difference might include the cable and probe losses for measurement and lossy metal effect. However, a good agreement was observed for the frequency behavior between simulated and measured values.

The most important parameter in the LTCC fabrication process is the variation of the shrinkage rate. In the worst case of our LTCC process, the variation of the shrinkage rate is  $\pm 0.3\%$ . As shown in Fig. 8, when the variation of the shrinkage rate has the value of  $+0.3\%$ , it means that the length of the line

shrinks more than expected. Even though the center frequency shifts to upward, the bandwidth of the BPF can be maintained to 40.5–43.5 GHz and the LO signal can be suppressed under 20 dB. However, when the variation of the shrinkage rate has the value of  $-0.3\%$ , it means that the length of the line shrinks less than expected. So, the center frequency shifts to downward and then the variation of the center frequency is as small as around 0.4%.

## VI. CONCLUSION

We have presented a fully embedded multilayer LTCC BPF for 40 GHz MWS applications with optimized coplanar waveguide-to-stripline (CPW-to-SL) transitions and fourth-order Tchebyscheff structure of SL resonators. This proposed filter allows 3-D integration of millimeter-wave radio that can result in significant size reduction and low-loss connection to the next circuits. The measured insertion loss is as small as 1.9 dB, and the return loss is 12.2 dB including the loss associated with two CPW-to-SL transitions. The 3-dB bandwidth is 10.5% at a center frequency of 41.8 GHz. The overall size is  $5.5 \times 2.3 \times 0.6$  mm including the ground vias and CPW pads.

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