

Design of On-Chip Ultra-Miniaturized Low-Loss Dual-Band Bandpass Filter in LTCC for 5G Applications

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Abstract— In this paper, a novel on-chip ultra-miniaturized dual-band bandpass filter (D-BPF) using the low-temperature cofired ceramic (LTCC) technology is proposed. To realize the ultra-miniaturization of the proposed D-BPF, the vertical configuration for the lower and upper bands is implemented. The low insertion loss and wide passbands can be obtained by using direct coupling between resonators. Furthermore, the simplified LC model of the proposed layout is given and analyzed. For verification, the proposed DBPF is designed, simulated, fabricated and measured, respectively. Finally, the D-BPF used in the sub-6 GHz band with the core size of 3.3 mm × 2.8 mm can cover from 3.01 to 3.79 GHz and from 4.77 to 5.33 GHz within the condition of $|S_{11}| < -15$ dB.

Index Terms— Dual-band bandpass filter (D-BPF), low-temperature cofired ceramic (LTCC) technology, low insertion loss, wide passband, ultra-miniaturization, sub-6 GHz.

I. INTRODUCTION

With the increasing development of the fifth-generation (5G) communication technology, dual-band or multi-band RF devices have become the research hotspot. As a key passive device widely used in communication base stations or personal terminals, filters need to develop towards the multi-band, miniaturization, wideband, low insertion loss (IL), and low cost. Fortunately, the low temperature co-fired ceramic (LTCC) technology can meet these requirements due to its low dielectric constant substrate, low-loss conductors and flexible multi-layer configurations [1]-[2].

At present, many designs of LTCC dual-band bandpass filter (D-BPF) operating in the sub-6 GHz show that smaller circuit sizes can be obtained by using lumped elements or hybrid elements including LC and distributed components such as the embedded microstrips and coupled lines (CLs) [3]-[8]. It is difficult to obtain the large bandwidth (BW) to meet the needs of the 5G communication such as the n78 band (3.3-3.8 GHz) based on the design presented in [3]-[5]. In [6], the poor matching degree in both the lower band (LB) and higher band (HB) results to the high IL. The design of the D-BPF in [7] lacks the flexible and controllable central frequency (CF) for the LB and HB. In [8], the CF in the HB can change, but the too large size needs to be improved.

Therefore, in order to overcome the mentioned shortcomings in the design of the D-BPFs, an on-chip D-BPF using the LTCC technology for 5G applications is presented in this paper. Specifically, the advantages of the proposed D-BPF can be summarized as: (1) the ultra-miniaturization suitable for the system-on-chip, (2) the wide BW in both the LB and the HB, (3) the

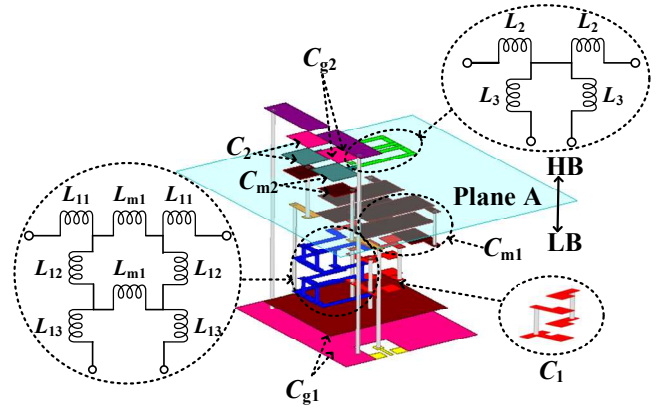


Fig. 1. The 3-D layout of the proposed D-BPF. (The virtual plane A is inserted to show the HB and LB, and the lumped model of the inductor is given.)

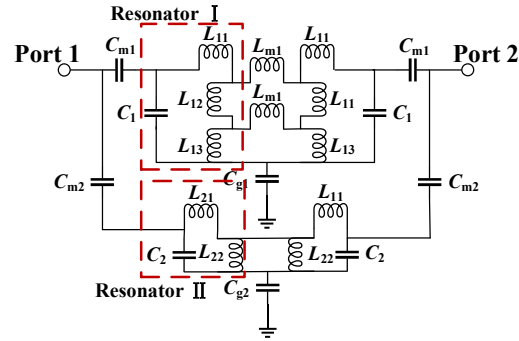


Fig. 2. The simplified lumped model of the proposed D-BPF.

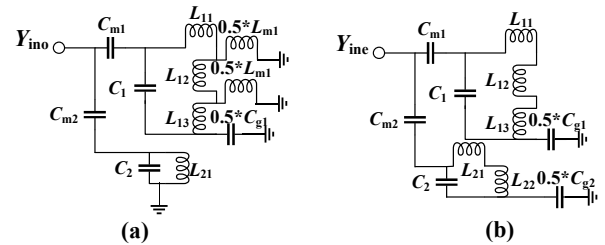


Fig. 3. (a) The odd-mode circuit and (b) the even-mode circuit.

independently adjustable CF and BW for the LB and HB, (4) the improved selectivity due to four transmission zeros (TZs), and (5) the low IL.

II. DUAL-BAND BANDPASS FILTER DESIGN

As shown in Fig. 1, the vertical configuration for the LB and HB is adopted to realize the ultra-miniaturization. Ferro A6M with the single layer thickness of 94 μ m, the dielectric constant ϵ_r of 5.9, and the loss tangent of 0.002 is utilized to construct the 13-layer layout. Single layer or multi-layer inductors and capacitors constitute the LB and HB. In order to clearly elucidate

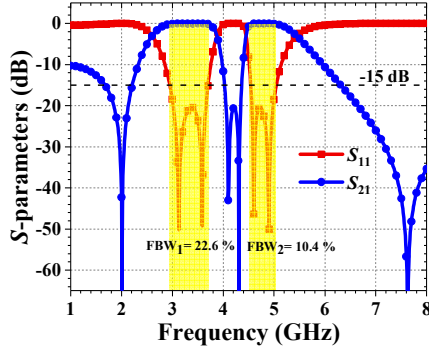


Fig. 4. The simulated frequency responses for the lumped model ($C_{m1} = 3.2$ pF, $C_{m2} = 0.6$ pF, $C_1 = 1.38$ pF, $C_2 = 0.85$ pF, $C_{g1} = 7.2$ pF, $C_{g2} = 0.96$ pF, $L_{11} = 0.42$ nH, $L_{12} = 0.84$ nH, $L_{13} = 0.42$ nH, $L_{m1} = 0.82$ nH, $L_{21} = 0.89$ nH, and $L_{22} = 0.31$ nH).

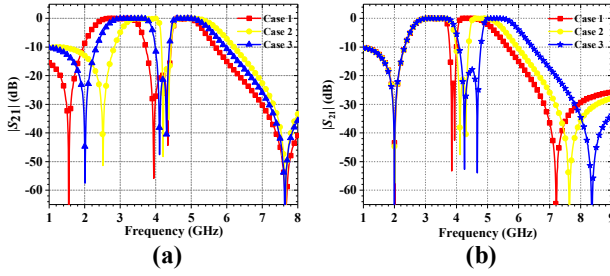


Fig. 5. (a) The variations of CF in the LB (case 1: CF = 2.95 GHz, $C_{m1} = 3.3$ pF, $C_1 = 1.63$ pF, $C_{g1} = 14.5$ pF, $L_{11} = 0.46$ nH, $L_{12} = 0.92$ nH, $L_{13} = 0.46$ nH, and $L_{m1} = 1.1$ nH, and case 3: CF = 3.85 GHz, $C_{m1} = 2.4$ pF, $C_1 = 1.38$ pF, $C_{g1} = 5.5$ pF, $L_{11} = 0.32$ nH, $L_{12} = 0.64$ nH, $L_{13} = 0.32$ nH, and $L_{m1} = 0.81$ nH) and (b) the variations of CF in the HB (case 1: CF = 4.30 GHz, $C_{m2} = 0.60$ pF, $C_2 = 0.99$ pF, $C_{g2} = 0.96$ pF, $L_{21} = 0.92$ nH, and $L_{22} = 0.31$ nH, and case 3: CF = 5.20 GHz, $C_{m2} = 0.62$ pF, $C_2 = 0.62$ pF, $C_{g2} = 1.02$ pF, $L_{21} = 0.89$ nH, and $L_{22} = 0.38$ nH).

the working mechanism of the proposed D-BPF, a simplified lumped model is presented in Fig. 2. The resonator I and the resonator II operate in the LB and the HB, respectively. The direct coupling is implemented between resonators to achieve the wider BW and lower IL compared to the capacitive coupling or mutual inductive coupling. In addition, C_{m1} and C_{m2} are used for impedance matching, and C_{g1} and C_{g2} are used to generate four transmission zeros (TZs) to improve selectivity. Due to the symmetry, the odd- and even-mode circuit shown in Fig. 3 can be used to analyze S-parameters of the lumped model based on the Equations (1). However, the analysis of transmission zeros and poles is too cumbersome due to the high-order equations for the frequency. Therefore, the characteristics of the frequency responses for the lumped model of the D-BPF can be obtained by using the software ADS. As is shown in Fig. 4, the simulated results of the lumped model are given. The fractional bandwidth (FBW) is defined within the condition of $|S_{11}| < -15$ dB.

$$S_{21} = S_{12} = \frac{Y_0(Y_{\text{inc}} - Y_{\text{ino}})}{(Y_0 + Y_{\text{inc}})(Y_0 + Y_{\text{ino}})}, S_{11} = S_{22} = \frac{Y_0^2 - Y_{\text{inc}}Y_{\text{ino}}}{(Y_0 + Y_{\text{inc}})(Y_0 + Y_{\text{ino}})}. \quad (1)$$

A. Independently Controllable Center Frequency

It is helpful to adjust the center frequency of the LB or HB independently to meet more requirements of the dual-band communication. Seen from Fig. 5(a), the CF of the LB can be changed by tuning the resonator I (C_1 , L_{11} , L_{12} , and L_{13}) and then adjusting C_m , C_{g1} , and L_{m1} to the good in-band matching. In Fig. 5(a), the values of the lumped elements in case 2 are from Fig. 4.

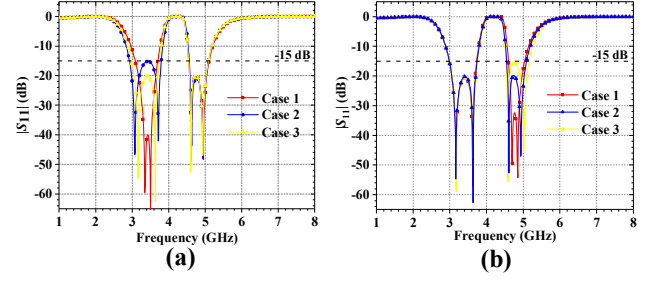


Fig. 6. (a) The variations of FBW in the LB (case 1: FBW = 19.8% and $L_{m1} = 0.89$ nH and case 3: FBW = 29.2% and $L_{m1} = 0.70$ nH) and (b) the variations of FBW in the HB (case 1: FBW = 6.3% and $L_{22} = 0.28$ nH, and case 3: FBW = 9.3% and $L_{22} = 0.36$ nH).

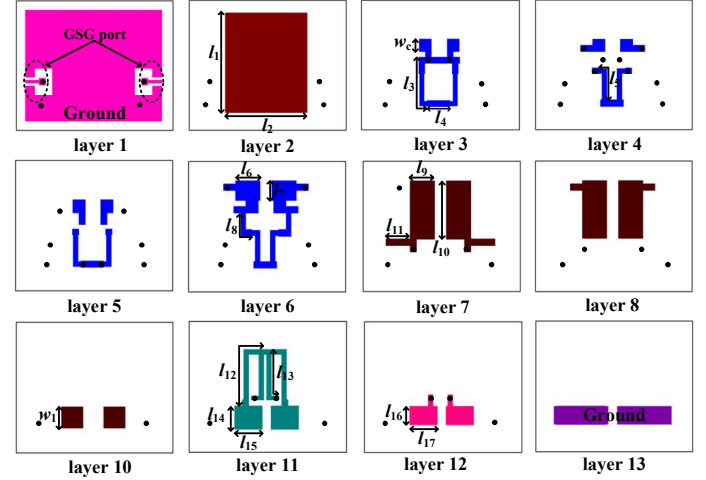


Fig. 7. The 2-D configuration of the proposed D-BPF.

Similarly, as shown in Fig. 5(b), the CF of the HB can be changed by tuning the resonator I (C_2 , L_{21} , and L_{22}) and then adjusting C_{m2} and C_{g2} to the good in-band matching. In Fig. 5(b), the values of lumped elements in case 2 are from Fig. 4.

B. Independently Controllable bandwidths

The varying FBW within a certain range can be obtained by only adjusting L_{m1} in the LB or L_{22} in the HB. As is shown in Fig. 6, without changing the CF, the FBW of the LB or the HB can be controlled independently when another band is fixed. Herein, the values of the lumped elements in case 2 are from Fig. 4.

III. EXPERIMENTAL VERIFICATION

Based on the above analysis of the working mechanism of the proposed D-BPF, the D-BPF operating in 3.5/4.9 GHz using the LTCC technology can be designed and fabricated effectively. Firstly, adjust the resonator I and the resonator II to operate around 3.5/4.9 GHz. Secondly, tune C_{m1} , C_{m2} , L_{m1} , L_{22} to the required matching level and FBW. Thirdly, adjust the position of the TZs by tuning C_{g1} and C_{g2} to obtain the high selectivity. Finally, based on the preliminary values, the 3-D structure can be constructed using the method in [9] that converts the ideal capacitors or inductors into the suitable counterparts in the layout. The final dimensions shown in Fig. 7 are (units: mm) $l_1 = 3.3$, $l_2 = 2.7$, $l_3 = 1.3$, $l_4 = 0.75$, $l_5 = 1.25$, $l_6 = 0.8$, $l_7 = 0.65$, $l_8 = 0.9$, $l_9 = 0.8$, $l_{10} = 1.95$, $l_{11} = 0.8$, $l_{12} = 2.1$, $l_{13} = 1.8$, $l_{14} = 0.75$, $l_{15} = 0.9$, $l_{16} = 0.6$, $l_{17} = 0.9$, $w_c = 0.4$, and $w_2 = 0.7$. The width of the inductors L_1 and

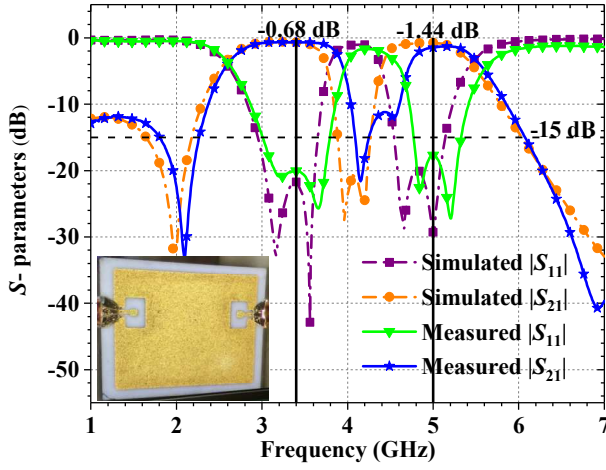


Fig. 8. The simulated and measured results of the fabricated D-BPF.

TABLE I
THE PERFORMANCE COMPARISON FOR PREVIOUS D-BPFS

Ref.	[3]	[4]	[5]	[7]	[8]	This work
f_1/f_2 (GHz)	2.41/5.61	0.9/2.45	2.4/5.2	2.45/5.25	3.32/5.17	3.4/5.0
FBW ₁ /FBW ₂	>-15 dB / 1.9%*	7.8%*/ 6.0%*	19.5%*/ >-15dB	18.0%*/ 10.9%*	15.9%*/ 10.4%*	22.9%/ 11.2%
IL ₁ /IL ₂ (dB)	1.7/1.3	2/1.5	2.35/ 1.72	1.5/2.1	1.38/1.53	0.68/ 1.44
ϵ_r	7.8	7.1	5.9	7.8	5.9	5.9
TZs/TPs	3/3	6/4	3/2	3/3	3/4	4/4
ICCF	NG	YES	NG	NO	NO	YES
ICBW	YES	NG	YES	NO	NO	YES
Size (mm ²)	3.85 × 3.38	7.2 × 6.88	5.46 × 5.59	3.35 × 2.54	11.6 × 6	3.3 × 2.8

Ref.: References. f_1 : CF of the LB. f_2 : CF of the HB. FBW₁: $|S_{11}| < -15$ dB in the LB. FBW₂: $|S_{11}| < -15$ dB in the HB. IL₁: The insertion loss in the LB. IL₂: The insertion loss in the HB. TPs: Transmission poles. ICCF: The independently controllable central frequency. ICBW: The independently controllable bandwidth. *: Estimated from the literature. NG: Not given.

L_2 is 0.15 mm, the width of the inductors L_{m1} is 0.2 mm, and the diameter of via holes is 0.1 mm. The final core size of the manufactured D-BPF excluded from the ground-signal-ground (GSG) ports is 3.3 mm × 2.8 mm × 1.2 mm.

The probe station MPI TS150 and the network analyzer R&S ZVA67 are used to measure the fabricated D-BPF. Fig. 8 shows the results of the full-wave simulation from the software HFSS, the final measured results, and the photo of the tested chip. Seen from Fig. 8, the measured FBWs of the LB and the HB are 22.9% and 11.2% with the CF 3.4 and 5 GHz, which cover the commercial bands for 5G, that is, 3.3-3.6 GHz and 4.8-5.0 GHz. The measured ILs are 0.68 dB and 1.44 dB at the two CFs. Compared with the simulated results, some small deviation of TZs and slight frequency shift may be due to the inevitable fact that the dielectric constant is actually deviated from 5.9. In general, the agreement between the full-wave simulated and measured results can verify the D-BPF.

In order to highlight the advantages of the proposed D-BPF, the performance comparison with the previous D-BPFs is listed in Table I. As for the LB, the lowest IL in the LB and the

maximum FBW in two passbands can be obtained to meet the requirements of the wideband and the low loss. In spite of the lower IL of the HB in [3], the smaller BW and poorer selectivity cannot be ignored. Furthermore, a simple design guide for the ICCF and ICBW is presented to adapt different dual-band communication standards in the sub-6 GHz.

IV. CONCLUSIONS

In this paper, a novel on-chip multi-layer D-BPF in LTCC is presented and implemented. The simplified lumped-element model is given to reveal the working mechanism of the proposed D-BPF. Based on the analysis, the D-BPF operating at 3.5 GHz and 4.9 GHz is designed, simulated, manufactured, and measured. The acceptable agreement between the simulated and measured results confirms the design theory and exhibits the advantages including the ultra-miniaturization, the excellent pass-band matching level, ultra-low loss in the LB, the ICCF and ICBW, and the wide bandwidths in the LB and HB. Finally, it can be hopeful that this dual-band BPF will be widely used in the dual-band RF wireless circuits and on-chip systems for 5G applications in the sub-6 GHz.

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REFERENCES

- [1] W. Zhao, Y. Wu, Y. Yang, and W. Wang, "LTCC bandpass filter chips with controllable transmission zeros and bandwidths using stepped-impedance stubs," *IEEE Trans. Circuits Syst. II: Express Briefs*, vol. 69, no. 4, pp. 2071-2075, Apr. 2022.
- [2] G. Brzezina and L. Roy, "Miniaturized, lumped-element filters for customized system-on-package L-band receivers," *IEEE Trans. Microw. Theory Techn.*, vol. 4, no. 1, pp. 26-36, Jan. 2014.
- [3] H. Joshi and W. J. Chappell, "Dual-band lumped-element bandpass filter," *IEEE Trans. Microw. Theory Techn.*, vol. 54, no. 12, pp. 4169-4177, Dec. 2006.
- [4] A. Pourzadi, A. Isapour, and A. Kouki, "Design of compact dual-band LTCC second-order Chebyshev bandpass filters using a direct synthesis approach," *IEEE Trans. Microw. Theory Techn.*, vol. 67, no. 4, pp. 1441-1451, Apr. 2019.
- [5] Y. X. Guo, L. C. Ong, M. Y. W. Chia, and B. Luo, "Dual-band bandpass filter in LTCC," *IEEE MTT-S Int. Microw. Symp. Dig.*, pp. 2219-2222, Jun. 2005.
- [6] Y.-C. Lin, H.-H. Huang, and T.-S. Horng, "Synthesis of LTCC multiband bandpass filter using reflection and transmission zeros," *IEEE MTT-S Int. Microw. Symp. Dig.*, 2014, pp. 1-4.
- [7] C.-W. Tang, S.-F. You, and I.-C. Liu, "Design of a dual-band bandpass filter with low-temperature co-fired ceramic technology," *IEEE Trans. Microw. Theory Techn.*, vol. 54, no. 8, pp. 3327-3332, Aug. 2006.
- [8] L. Hao, Y. Wu, W. Wang, and Y. Yang, "Design of on-chip dual-band bandpass filter using lumped elements in LTCC technology," *IEEE Trans. Circuits Syst. II: Express Briefs*, vol. 69, no. 3, pp. 959-963, Mar. 2022.
- [9] W. Zhao, Y. Wu, Y. Yang and W. Wang, "Novel on-chip wideband filtering power dividers with high selectivity and ultra-wide out-of-band suppression in LTCC technology," *IEEE Trans. Circuits Syst. II: Express Briefs*, vol. 69, no. 11, pp. 4288-4292, Nov. 2022.