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Compact LTCC Filter with 7th-Order Harmonics Suppression for 5G N77 Band Applications

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Abstract—A compact dual-mode band-pass filter (BPF) with 7th-order harmonics suppression is proposed. The proposed dual-mode BPF is designed using a three-section stepped-impedance-variable feeding line (SIVFL) and a square resonator. The high-order harmonics suppression is achieved by the SIVFL structures, and the size reduction is achieved using meandered lines and a resonator with two degenerate modes. The proposed BPF has a wide stopband up to 7th-order harmonics and a compact size of only $7 \times 7 \times 0.3$ mm. The proposed BPF is suitable for the fifth-generation (5G) N77 band applications due to its working frequency, compact size, and good performance. Comparison and discussion are implemented as well.

1. INTRODUCTION

Currently, owning to the high-capacity and speed of data transmission, the fifth-generation (5G) mobile communication has been on its excellent operation. The most attractive bands for 5G new radio (NR) are N77 (3.3–4.2 GHz), N78 (3.3–3.8 GHz), and N79 (4.4–5 GHz) [1, 2]. Therefore, there is a shapely increasing market demand of 5G band-pass filters (BPFs), which can meet the requirements of excellent performances, small size, and comparative higher density packaging. Conventional dual-mode BPFs obtain a half size compared with single-mode ones; however, those BPFs do not show a function of harmonics suppression or a performance of wide stopband [3, 4]. Modern radio frequency (RF) transceiver is a nonlinear system, and harmonics suppression and wide stopband characteristics are vital for the RF front-ends. Although low-pass filters can be added into circuits for harmonics suppression, adding extra low-pass filters will result in a huger circuit size and a higher cost of manufacture. BPFs with harmonic suppression are proposed in [5–7], but those BPFs have complicated structures, low level integration, and high in-band insertion loss.

In this letter, a compact dual-mode BPF using stepped-impedance-variable feeding lines (SIVFLs) and a ring resonator is proposed and fabricated on a 2-layer low temperature co-fired ceramic (LTCC) substrate. The SIVFLs are used to suppress the high-order harmonics, and the ring resonator is used to excite two degenerate modes. The merits of the proposed BPF are harmonics suppression up to 7th-order and 60% size reduction.

2. CIRCUIT DESIGN

The BPF is designed to cover 5G N77 band. The center frequency is 3.75 GHz, and the bandwidth is 0.9 GHz. The structure of the proposed dual-mode BPF is established in a 2-layer LTCC substrate, shown in Figure 1. The input/output (I/O) feeding lines with three-section SIVFLs are placed on the first layer, and the square ring resonator used to excite two degenerate modes is placed on the second

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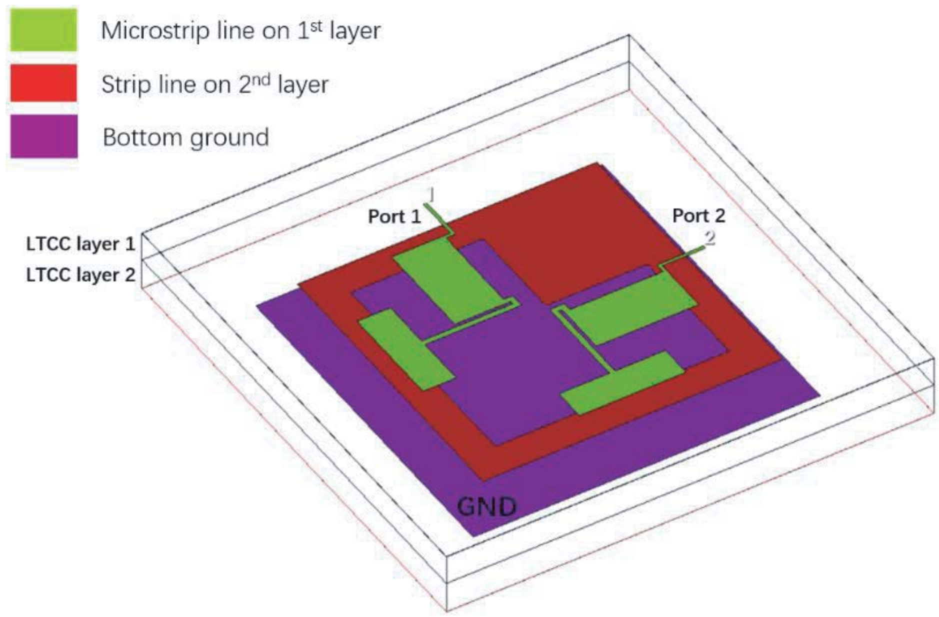

Figure 1. 3D structure of the proposed dual-mode BPF.

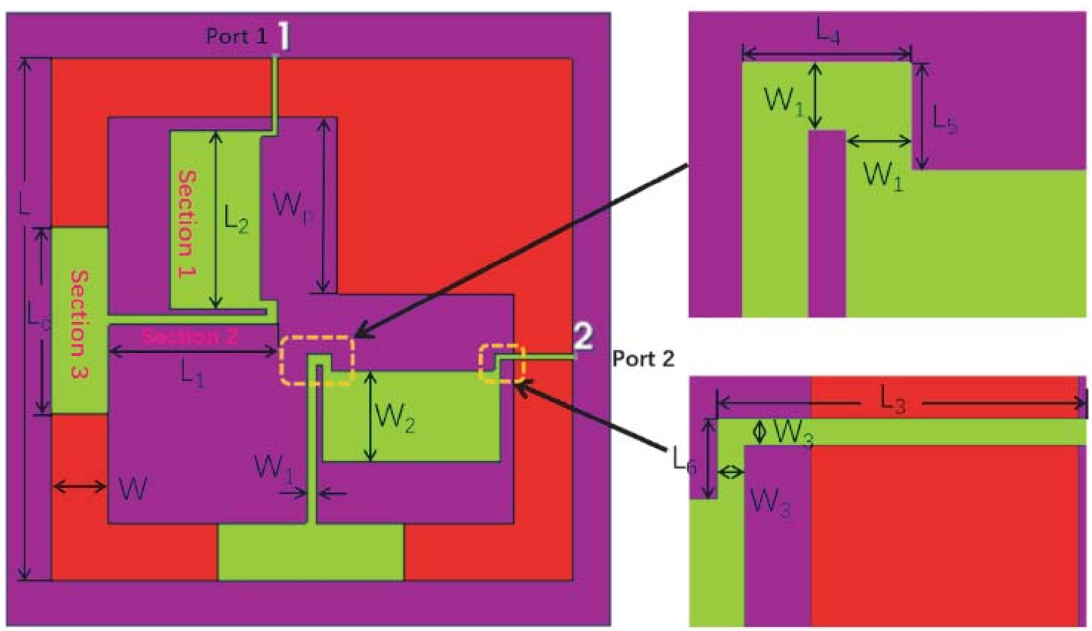

Figure 2. Planar view with parameters definitions.

layer. The bottom layer is the ground signal layer. The three-section SIVFLs can present low-pass characteristics, which can be used to suppress the high-order harmonics. The signal transition between the SIVFLs on the first layer and the resonator on the second layer is via broadband coupling effect. Figure 2 shows planar view and parameters' definitions of the proposed BPF.

Figures 3(a) and (b) show the cascaded SIVFL and the planar view with SIVFL unfolded for circuit analyzing, respectively. In Figure 3(a), two sections of a $\lambda/4$-wavelength step-impedance line are cascaded for analysis. The electrical lengths of the first and second sections are θ_1 and θ_2, respectively, and feature impedances of first and second sections are Z_1 and Z_2, respectively. The higher impedance

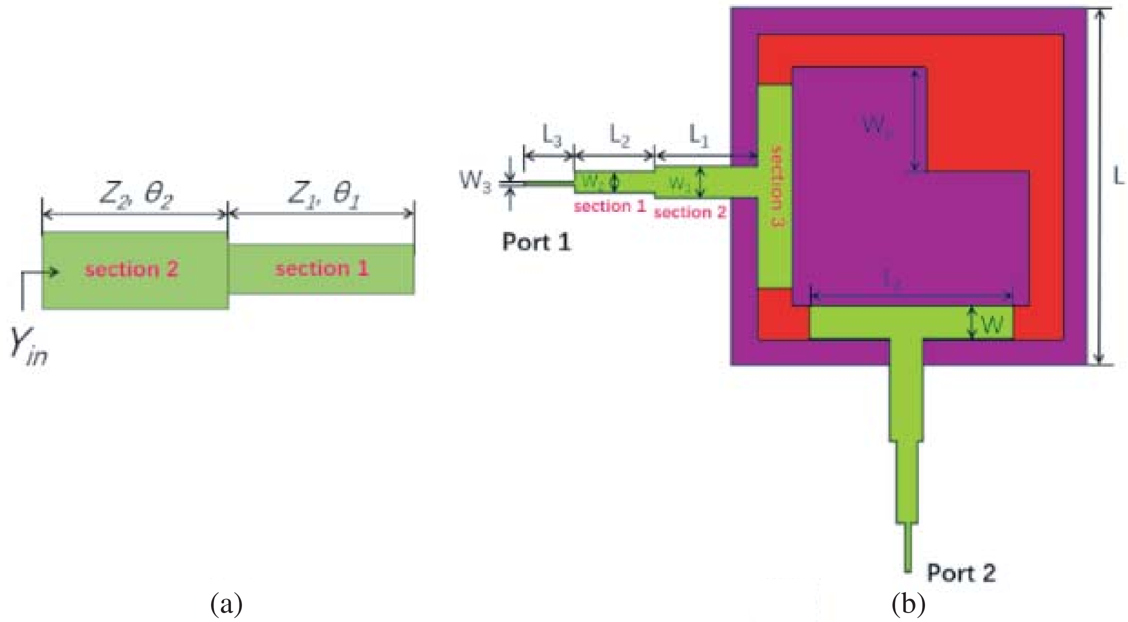

Figure 3. (a) Two section cascaded SIVFL for analyzing and (b) planar view with SIVFLs unfolding.

part is connected to ground while the lower impedance one is provided with an open-circuited end. when $0 < R < 1$ and $\theta_1 = \theta_2$, the electrical length in all arrives at the minimum value. $\theta_{T\,\min}$ is less than 90 degrees. This plays a prominent part in reducing the size during designing. Moreover, higher frequency can be obtained, which has the tendency to result in great suppression out of bandpass. The proposed structure cascades a BPF with a low-pass filter, which is used to suppress the high-order harmonics. The low-pass filter is established with Sections 1, 2, and 3, shown in Figure 3(b). By adjusting the dimension parameters of Sections 1, 2, and 3, the cut-off frequency of the low-pass structure on the top layer is expected to occur at 30 GHz. As the proposed BPF is expect to have a suppression of 5G 257 Band (26.5–29.5 GHz) signal, the cut-off frequency of the low-pass structure is set near 30 GHz. In this design, we use a 3-section low-pass structure to suppress high-order harmonics. Adding more quantity of sections in the low-pass structure can be utilized for much better suppressions, but this may result in size and compactness problems. So the trade-off between the suppression effect and compactness needs to be balanced when designing. To further decrease the size of the filter, the SIVFLs in series can be transformed into curved structures. In order to further enhance the miniaturization of the filter and save space on the board, the SIVFLs are moved from the outside of the square ring to the inside of the square ring, shown in Figure 2. The structure of BPF, which is symmetrical at 45 degrees shown in Figure 2, cites six parameters: microstrip line lengths (L_1, L_2, L_3) and widths (W_1, W_2, W_3). By altering the step impedance, the BPF's characteristic curve can be adjusted flexibly during the design process with Equations (1)–(3).

$$\lambda_g = \frac{nc}{f_0\sqrt{\varepsilon_{eff}}} \tag{1}$$

where n is the order of the filter. The impedance ratio is defined as

$$R = Z_2/Z_2 = \tan\theta_1 \tan\theta_2 \tag{2}$$

$$\theta_{T\,\min} = 2\tan^{-1}\sqrt{R} \tag{3}$$

3. SIMULATED AND MEASURED RESULTS

An AXIEM solver [8] based on the full-wave electromagnetic (EM) simulation is used for EM-optimization. And the optimal dimensions are listed in Table 1. A photograph of the proposed BPF

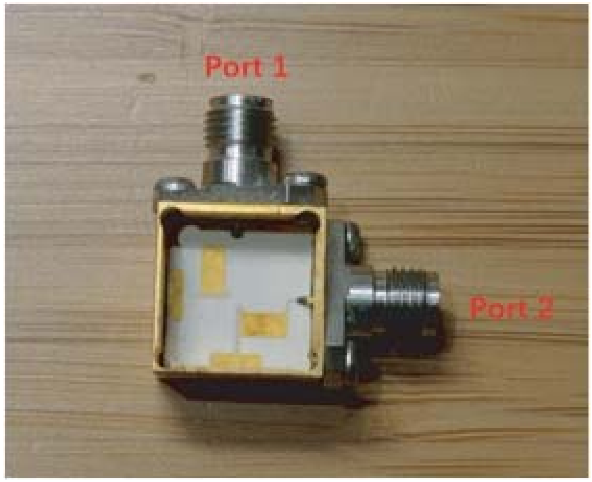

Figure 4. Photograph of the proposed BPF.

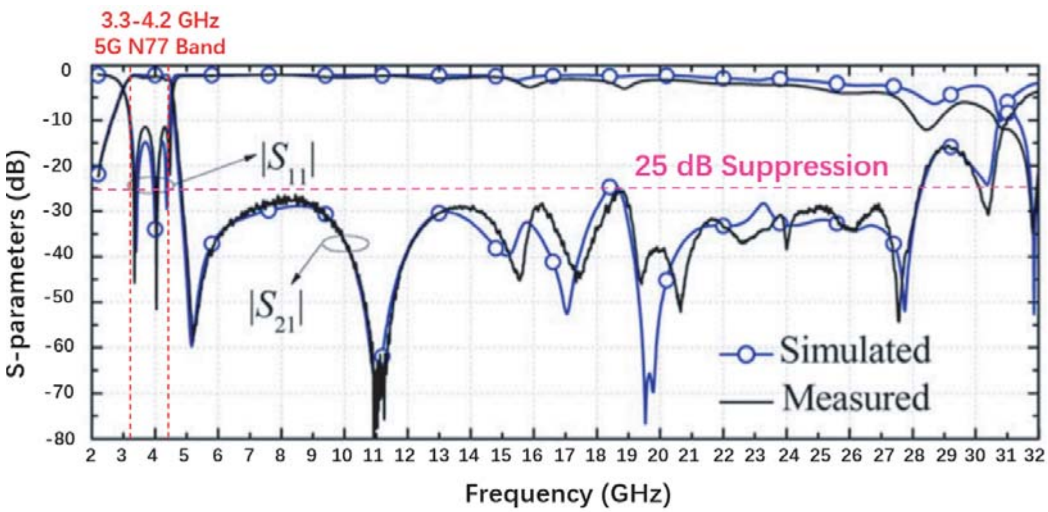

Figure 5. Simulated and measured results of proposed BPF.

is shown in Figure 4. Measurements are carried out by Agilent N5230C network analyzer, and the simulated and measured results are shown in Figure 5. The center frequency shifts from 3.75 GHz to 3.78 GHz, which is caused by the Ferro-A6 material shrinkage. Measured passband S_{21} and S_{11} are better than -0.9 dB and -12 dB, respectively. The average value of passband insertion loss is 0.84 dB. The suppressions of 2nd-, 3rd-, 4th-, 5th-, 6th- and 7th-order harmonics are 30 dB, 60 dB, 39 dB, 30 dB, 35 dB, and 60 dB, respectively. The entire size of the proposed BPF is only $7 \times 7 \times 0.3$ mm, which achieves a size reduction of 60% by using SIVFL structure and a dual-mode resonator compared with traditional planar one.

Table 1. Dimensions of the proposed filters (unit: mm).

Parameter	L	$L1$	$L2$	$L3$	$L4$	$L5$	$L6$
Value (mm)	9.055	2.9	3.07	1.4	0.44	0.22	0.3
Parameter	Lc	W	Wp	$W1$	$W2$	$W3$	
Value (mm)	3.2	1	3.05	0.17	1.57	0.1	

4. COMPARISON AND DISCUSSION

Comparison results between the proposed BPF and existing designs are summarized in Table 2. The overall performances of the proposed BPF exceed the performances of existing BPFs in terms of insertion loss, quantity of high-order harmonics suppression, and geometry complexity level. The proposed BPF is suitable for the fifth-generation (5G) N77 band applications due to its working frequency, good performance, and compact size.

Table 2. Comparisons between the proposed filter and the past designs.

Refs.	Center frequency (GHz)	In-band insertion loss (dB)	2nd-order harmonic suppression (dB)	3th-order harmonic suppression (dB)	Function of 4th, 5th, 6th, and 7th-order harmonic suppression	Geometry complexity	Compactness level	Fabrication process
[1]	2.68	1.2	14	6	No	Low	Medium	LTCC
[2]	0.62	0.95	25	6	No	High	High	LTCC
[3]	1.1	3	26	4	No	Medium	Medium	LTCC
[4]	1.1	1	8	3	No	High	High	LTCC
[5]	1.1	1.5	9	3	No	Medium	Medium	LTCC
This work	3.75	0.9	30	60	Yes	Low	High	LTCC

5. CONCLUSION

A compact and simple BPF for 5G N77 band applications is proposed and tested. Due to using the meandered SIVFL and square resonator, more than 25 dB suppression up to 7th-order harmonics and size reduction are both achieved. The proposed BPF has much better performances than existing designs. The entire size of the proposed BPF is only $7 \times 7 \times 0.3$ mm, which can be easily integrated into 5G mobile communication equipment.

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