LTCC Distributed-Element Bandpass Filter with Multiple Transmission Zeros Using Non-Resonating Node

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Abstract **—** A distributed-element low temperature co-fired ceramic (LTCC) bandpass filter (BPF) with multiple transmission zeros using non-resonating node (NRN) is proposed. By fully taking advantage of the LTCC technology in 3-dimentional (3-D) environment, the employed dual-mode stub-loaded stepped-impedance resonator (SIR) and the NRN are reasonably folded, and miniature circuit size can be obtained. Meanwhile, four transmission zeros are produced in both sides of the passband to realize sharp rejection skirts. For demonstration, a four-pole LTCC BPF using the NRN centered at 3.65 GHz is designed, fabricated and measured. Simulated and measured results are presented, showing good agreement.

Index Terms **—** Bandpass filter (BPF), low temperature co-fired ceramic (LTCC), non-resonating node (NRN), transmission zeros (TZ).

I. INTRODUCTION

Recently, the rapid development of modern wireless communications systems demands ever-greater functionality, higher integration, and more compact formats. It is well known that high-performance miniaturized bandpass filter (BPF) plays an important role in various communication systems [1-2]. Corresponding to this trend, lots of BPFs with size-reduction methods have been extensively studied and explored using various technologies, such as multilayer printed circuit board (PCB) [3], low-temperature co-fired ceramic (LTCC) [4-7] and high-temperature ceramic (HTC) with high dielectric constant [8]. Among them, the LTCC design technology, as one of the most promising methods, has emerged as an attractive solution for high-integration applications owing to its high level of compactness, mature multilayer fabrication and integration capability in 3-dimentional (3-D) environment.

Over the past decades, the limited frequency spectrums become more and more crowded and the high isolation between RF bands becomes a challenging issue. However, due to the relative low Q factor of the LTCC technology, the stopband roll-off of the LTCC BPF could not be satisfied in many applications. Generally, it is necessary to generate the transmission zeros (TZs) near to the passband for improving stopband rejection which can be realized by introducing bypass or cross-coupling between nonadjacent resonators in the filters [9].

In this letter, we present a compact LTCC BPF with sharp cutoff skirts by embedding the non-resonating node (NRN) without increasing the overall circuit size. Benefiting from the NRN and the extra source-load (S-L) coupling in 3-D environment, multiple TZs are realized to improve the roll-off and rejection level of the stopband.

II. FILTER DESIGN AND ANALYSIS

The planar configuration layout of the proposed four-pole BPF is shown in Fig. 1, which is composed of two dual-mode stub-loaded stepped-impedance resonators (SIRs) [4] (i.e., resonators 1/2 and 3/4), a NRN and a pair of coupled feed lines. The employed transmission lines of the BPF are reasonably folded in 3-D environment, operating as asymmetric striplines, for constructing a compact LTCC BPF, as shown in Fig. 2. The NRN is embedded between the two dual-mode resonators so that the overall circuit size of the BPF is not enlarged. Generally, The NRN structure can introduce more TZs to improve the passband selectivity [9]. The NRN is implemented with a half-wavelength resonator whose resonant frequency is far away from the central frequency of the proposed LTCC BPF.

Figure 3 shows the coupling scheme of the proposed filter. S and L indicate the source and load of the filter, respectively. Due to the NRN effect in this design, two TZs (i.e., TZ_1 and TZ_2 shown in Fig. 4) close to the passband can be generated. At the same time, in the small 3-D space in Fig.2 (a), various

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parasitic couplings are inevitably existed, which are slight and can be neglected except for the S-L coupling. Although the S-L coupling is weak, it is highly desired for generating two extra TZs (i.e., TZ_3 and TZ_4 in Fig. 4). Meanwhile, it is helpful for shifting both TZ_1 and TZ_2 towards the central frequency so that the passband selectivity can be further enhanced. As a consequence, the proposed four-pole BPF designed by combing the effects of the NRN and the S-L coupling owns four TZs in the stopbands. The desired filter response centered at 3.65 GHz with 1.08 GHz bandwidth (i.e., fractional bandwidth (FBW) = 29.6%) has four TZs at normalized frequencies $S_1 = -j7.9$, $S_2 = -j2.1$, $S_3 = j1.3$, and $S_4 = j2.4$ with a maximum in-band return loss of 16 dB. Synthesis of such coupling scheme with the NRN follows the approach in [10, 11], the corresponding coupling matrix of can be obtained:

$$M = \begin{bmatrix} & S & 1 & 2 & NRN & 3 & 4 & L \\ S & 0 & 0.7865 & 0.43 & -0.25 & 0 & 0 & 0.00127 \\ 1 & 0.7865 & 0.5 & 0 & 1.97 & 0 & 0 & 0 \\ 2 & 0.43 & 0 & -1.1 & -2.3 & 0 & 0 & 0 \\ NRN & -0.25 & 1.97 & -2.3 & -15 & -1.97 & 2.3 & 0.25 \\ 3 & 0 & 0 & 0 & -1.97 & 0.52 & 0 & 0.7865 \\ 4 & 0 & 0 & 0 & 2.3 & 0 & -1.12 & 0.43 \\ L & 0.00127 & 0 & 0 & 0.25 & 0.7865 & 0.43 & 0 \end{bmatrix}.$$

The diagonal elements are determined by:

$$M_{i,i} = \frac{f_0^2 - f_i^2}{\Delta f \cdot f_i}. \quad (1)$$

Here, the parameters f_0 and Δf are the central frequency and the bandwidth of the filter, respectively. And f_i is the resonant frequency of the i th resonator (i = 1, 2, 3 or 4). The whole structure is finely tuned and optimized so as to meet our specifications, which is performed using the commercial software high frequency structure simulator (HFSS). The simulated responses of the proposed filter together with the ideal circuit responses are plotted in Fig. 4. The parameters in Fig. 2 (b) for simulation are listed in Table 1, and the diameters of via holes are all set as 0.15 mm.

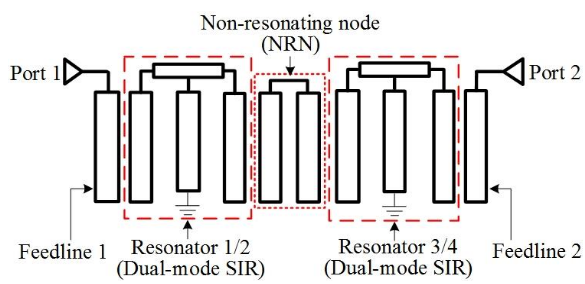

Fig. 1. Planar configuration sketch of the proposed BPF.

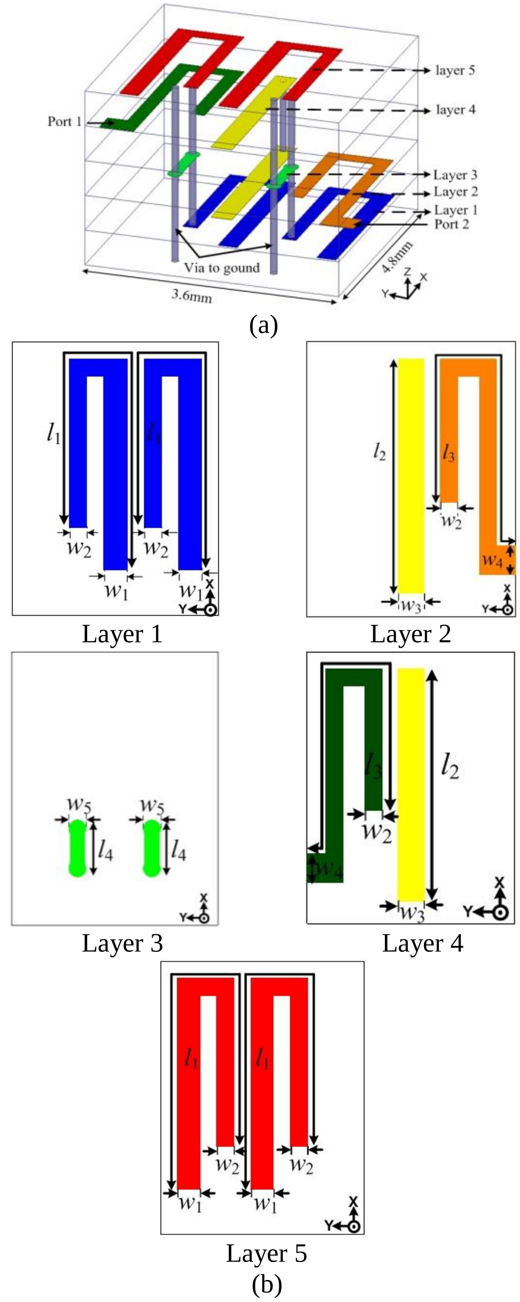

Fig. 2. Structure of the proposed LTCC BPF using the NRN (top and bottom ground are not shown). (a) 3-D view and (b) layout.

Table 1: Dimensions of the proposed LTCC BPF in Fig. 2

Parameters	l_1	l_2	l_3	l_4	w_1
Value (mm)	7.7	4.1	6.745	1	0.4
Parameters	w_2	w_3	w_4	w_5	
Value (mm)	0.3	0.45	0.5	0.25	

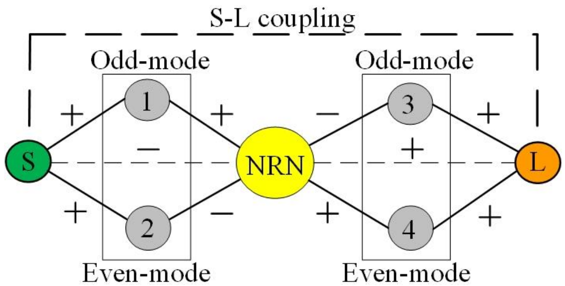

Fig.3. Coupling scheme of the proposed LTCC BPF.

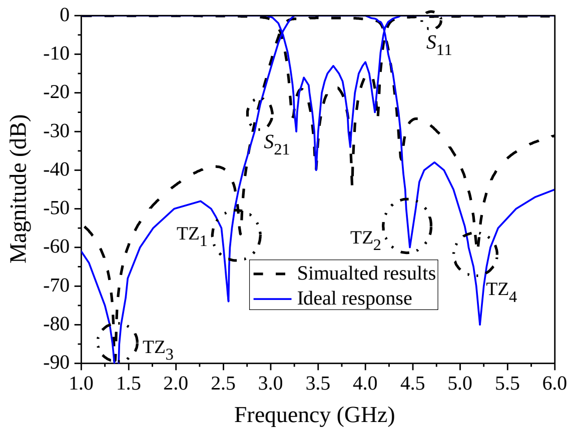

Fig. 4. Ideal responses and simulated S-parameters of the proposed LTCC BPF.

III. RESULTS AND DISCUSSION

To verify the proposed idea, the proposed BPF is designed and fabricated. Figure 5 shows the photograph of the proposed four-pole LTCC BPF mounted on the test board (Rogers 4003c with dielectric constant $\varepsilon_r = 3.38$ and thickness h = 32 mil), and the configuration of the LTTC wafer is shown in Fig. 2. It consists of seven metal layers (the top and bottom ground are not shown) and 14 ceramic sheets (LTCC Ferro A6-M substrate with a constant of 5.9 and a loss tangent of 0.001). Each sheet has a thickness of 0.1 mm. The BPF size is 4.8×3.6×1.4 mm^3 (i.e., electrical size is $0.14\lambda_g \times 0.11\lambda_g \times 0.04\lambda_g$, where λ_g is the guided wavelength of the stripline at 3.65 GHz). The measured S-parameter results of the proposed filter plotted in Fig. 6 are accomplished by using E5071C network analyser. It exhibits a center frequency of about 3.65 GHz, an insertion loss (IL) of approximately 1.4 dB and the return loss is better than 15 dB. Four transmission zeros are realized to obtain a sharper stopband roll-off and improve the selectivity of the proposed BPF significantly. Slight discrepancies between the simulated and measured results can be attributed to fabrication tolerance and test implementation. Comparisons of this design with some reported BPFs using the NRN are summarized in Table 2 in terms of electrical performance and circuit size. Compared with the BPFs based on the substrate integrated waveguide (SIW) [9], LTCC [11, 12], and PCB [13] technologies, it can be found that the proposed LTCC BPF shows evident size reduction and has a wider FBW. The more TZs can improve the passband selectivity effectively.

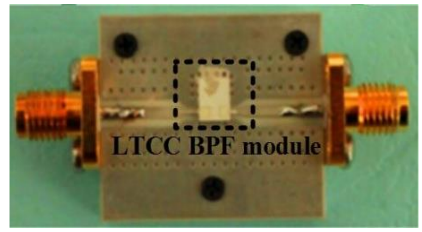

Fig. 5. Photograph of the LTCC BPF.

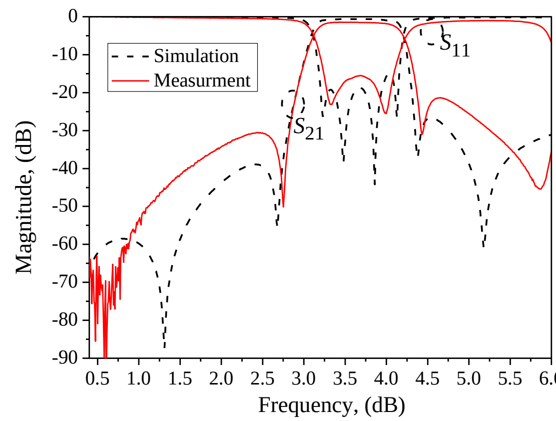

Fig. 6. Simulated and measured results of the proposed LTCC BPF.

Table 2: Performance comparison with previous works with NRN

Ref.	Techn-ology	f_0 (GHz)/ IL (dB)	TZ	Filter Order/FBW	Electrical Size ($\lambda_g \times \lambda_g \times \lambda_g$ at f_0)
[9]	SIW	5/1.6	2	2/3%	1.09×1.09×0.03
[11]	LTCC	3.45/1.2	2	4/8.7%	0.49×0.4×0.02
[12]	LTCC	58.6/2.8	2	4/3.92%	1.49×1.16×0.24
[13]	PCB	1.4/1.86	3	4/10%	1.54×0.09×0.017
This work	LTCC	3.65/1.4	4	4/29.6%	0.14×0.11×0.04

VI. CONCLUSION

In this letter, a compact distributed-element LTCC BPF with four TZs using the NRN has been presented. The proposed filter has the advantage of sharp cutoff skirts and good in-band performance. The design procedures of the BPF based on the coupling matrix have been given. The proposed filter has multiple TZs, compact size and good passband performance, which makes it competitive for application in microwave communication systems.

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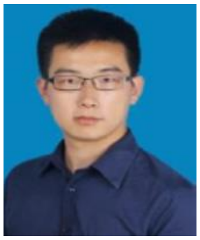

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