Design of Balanced SIW Filter with Transmission Zeroes and Linear Phase

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Abstract **─** This paper provides a design method for balanced bandpass filters (BPFs) with high performance based on substrate integrated waveguide (SIW) structure. A novel balanced SIW filter with the characteristics of transmission zeroes, linear phase and wideband common-mode suppression is proposed. By analyzing the equivalent circuits of the proposed SIW filter under differential-mode (DM) and common-mode (CM) excitations, the DM transmission with CM suppression characteristic of the filter is demonstrated. The source-load coupled microstrip lines are introduced to realize the negative coupling and the design method for filters with source-load coupling is given. Good agreement is demonstrated between the simulated and the measured ones

Index Terms **─** Balanced filter, linear phase, substrate integrated waveguide (SIW), transmission zeroes.

I. INTRODUCTION

Balanced circuits have drawn much attention as they have higher immunity to environmental noise and low electromagnetic interference compared with single-ended circuits. As the key components, various balanced filters have been widely studied and demonstrated [1-7]. In the early times, the microwave differential filters were developed by microstrip line structures, such as the stretched or coupled transmission lines, the coupled stepped impedance resonators (SIR), the stepped impedance slotline multiple-mode resonators (MMR) and the double-sided parallel-strip lines (DSPSL) [1-5]. To overcome the drawbacks of high radiation loss, low power handling capability, low-factor, and maintain the benefits of low-cost, compact size and good integration, the substrate integrated waveguide (SIW) balanced filters was proposed [6,7]. In [6], the balanced bandpass filters (BPFs) are realized by the structures of half-mode substrate integrated waveguide (HMSIW) and folded HMSIW. The common-mode (CM) suppression is achieved by applying a non-coupling slot and the spectral separation of differential-mode (DM)-CM resonances in the HMSIW and folded HMSIW cases, respectively. The proposed BPFs can achieve the CM rejection level more than 40 dB over a wide frequency range. To improve the filter selectivity, a differential BPF with two transmission zeros is presented in [7] based on SIW structure. The CM suppression is realized by a new balanced SIW section on single-layer substrate technology. However, to meet stringent requirements imposed on the most recent wireless standards, a flat group delay filter response should be guaranteed to avoid signal blur besides sharp rejection.

This paper proposes a balanced SIW BPF with transmission zeroes, linear phase and wideband common-mode suppression. By analyzing the equivalent circuits of the proposed SIW filter under DM and CM excitations, the DM transmission with CM suppression characteristic of the filter is demonstrated. Another innovative point of the paper is that the source-load coupled microstrip lines are introduced and the design method for filters with source-load coupling is given. To the best of our knowledge, there is no reported work done so far on balanced BPFs with both linear phase and highly selectivity. The proposed balanced BPF is designed using the SIW scheme at 10 GHz and can achieve almost perfectly flat group delay over the central 60% of the pass band.

II. BALANCED FILTER DESIGN

The balanced filter is designed on F4B substrate, with thickness of 0.5 mm, relative permittivity of 2.65, and dielectric loss tangent of 0.001 (at 10 GHz). The geometry of the proposed balanced BPF is shown in Fig. 1 (a). The four-port circuit is ideally symmetric with respect to the vertical and horizontal symmetry plane. It is composed of six SIW cavities which are represented by R_1, R_2, R_3, R_4, R_1', and R_4', respectively.

A. Common-mode analysis

Under CM operation, the vertical symmetry plane becomes a perfect magnetic wall and the CM equivalent circuit is shown in Fig. 1 (b). R_1 and R_4 are the original resonators of the proposed balanced BPF, which operate in TE_{101} for the first resonant mode. The cavity 2(C_2) and cavity 3(C_3) are half of the original resonators R_2 and R_3 with the vertical symmetry plane being a magnetic wall

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and the other three sidewalls being electric wall. In this case, the modes for R_2 and R_3 are TE_{101} for the first resonant mode. As R_1 and R_4 are designed to resonant at the operating frequencies, the resonant frequencies of C_2 and C_3 with similar size of R_1 and R_4 will not be in the operating pass-band. Thus, it performs a bandstop characteristic under CM excitations. To verify the above inference, simulated frequency responses under CM excitations are given in Fig. 2. We can see that the CM transmission is suppressed to be lower than -17 dB in a wideband.

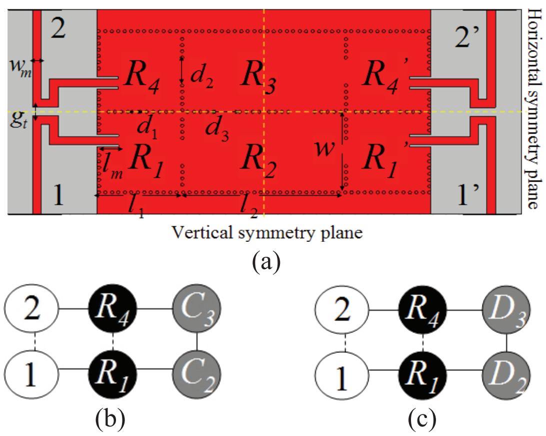


Fig. 1. Geometry and schematic topologies of the proposed balanced SIW filter: (a) geometry of the balanced BPF, (b) equivalent 2-port half bisection under CM operation, and (c) equivalent 2-port half bisection under DM operation.

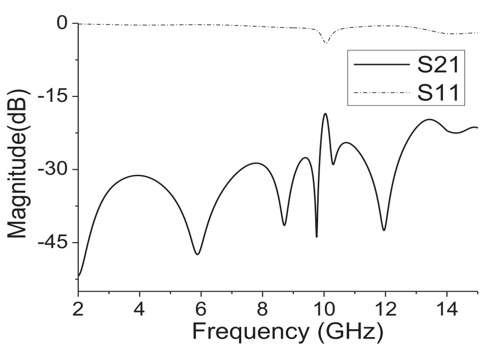


Fig. 2. Simulated results of the CM response.

B. Differential-mode analysis

While for DM operation, the vertical symmetry plane becomes a perfect electric wall, and the DM circuit can be obtained as shown in Fig. 1 (c). D_2 and D_3 are half of R_2 and R_3 with all four sidewalls being the electric wall. In this case, the modes for R_2 and R_3 are TE_{102} for the first resonant mode.

A 2-port 4-pole generalized chebyshev filter with both high selectivity and linear phase is synthesized with zeros [2.5j,-2.5j,1.4,-1.4]. Zeros [2.5j,-2.5j] in the imaginary axis are used to produce transmission zeros and zeros [1.4,-1.4] in the real axis are used to improve the phase. The synthesized S-parameters including magnitude and group delay with center frequency of f_0=10 GHz and bandwidth of BW=400 MHz are plotted as the dotted curves in Fig. 3, with the coupling matrix [8]:

$$M=\left[\begin{array}{c|cccccc} & S & 1 & 2 & 3 & 4 & L \\ S & 0 & 1.0425 & 0 & 0 & 0 & -0.0298 \\ 1 & 1.0425 & 0 & 0.9226 & 0 & 0.1471 & 0 \\ 2 & 0 & 0.9226 & 0 & 0.6488 & 0 & 0 \\ 3 & 0 & 0 & 0.6488 & 0 & 0.9266 & 0 \\ 4 & 0 & 0.1471 & 0 & 0.9226 & 0 & 1.4025 \\ L & -0.0298 & 0 & 0 & 0 & 1.4025 & 0 \end{array}\right]$$

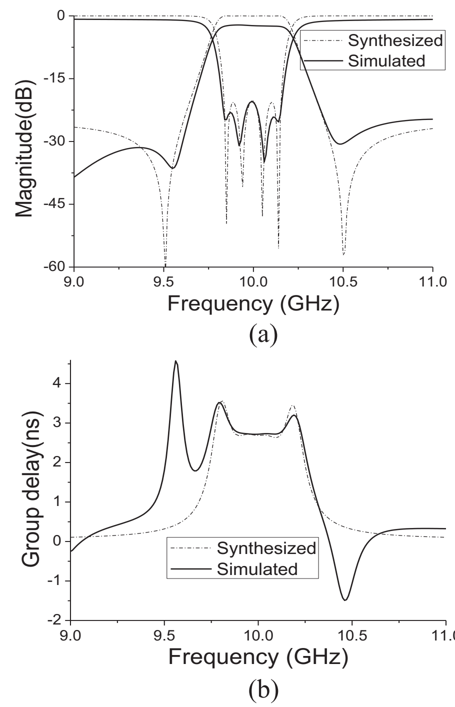
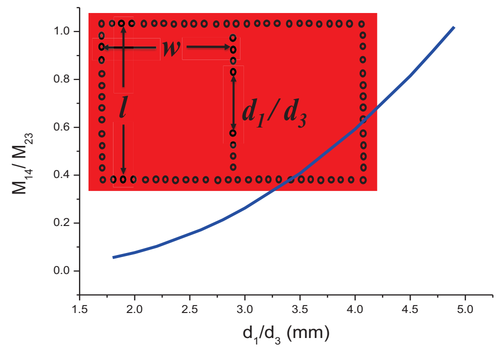


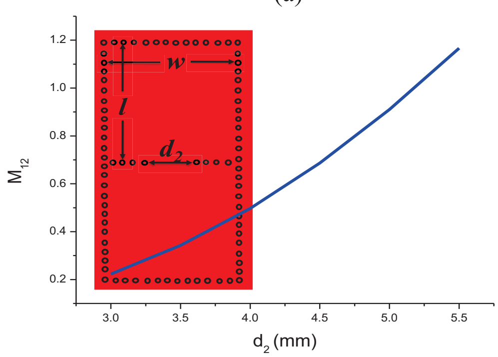
Fig. 3. Synthesized and simulated frequency responses of the equivalent 2-port half bisection under DM operation: (a) S-parameters and (b) group delay.

The dimensions of d_1, d_2, d_3 and l_m in Fig. 1 (a) for the required M_{14}, M_{12}, M_{23} and M_{S1} can be determined from Fig. 4 (a)-(c) with the method in [9] respectively.

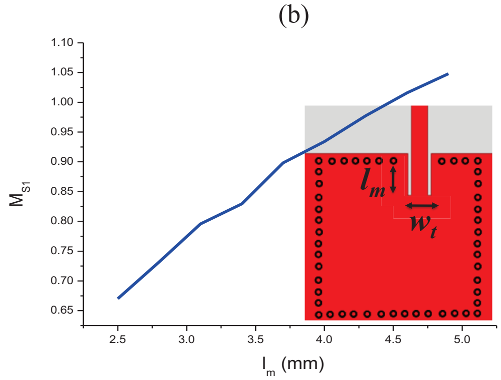
The 50-Ω coupled microstrip lines in Fig. 1 (a) are proposed to realize the source-load coupling in this paper. While magnetic coupling (positive coupling in the coupling matrix) can be achieved with an inductive window between two adjacent SIW resonators [10], the coupled microstrip lines can achieve the electric coupling (negative coupling in the coupling matrix). Thus, both positive and negative couplings can be realized in the same plane. However, there is no relative handling with the source-load coupling M_{SL} in the existing literature. The proposed 50-Ω coupled microstrip lines to realize the source-load coupling are treated as two coupled resonators in this paper shown in Fig. 5 (a) for the first time. The relationship between the source-load coupling M_{SL} and the distance g_t between the coupled microstip lines is shown in Fig. 5 (b). Then the dimension of g_t for the required M_{SL} can be determined from Fig. 5 (b) [9].



(a)

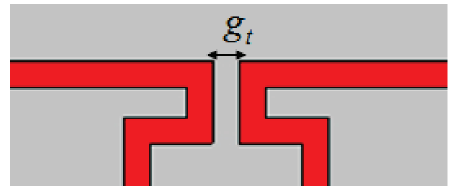


(b)

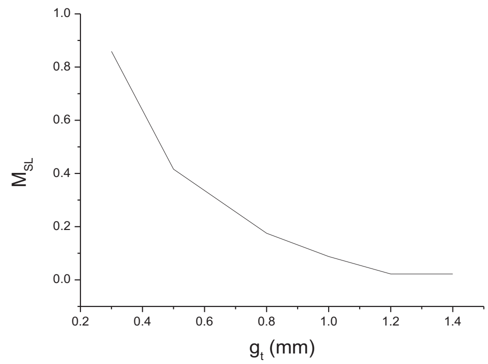


(c)

Fig. 4. Design curves for the 2-port BPF: (a) relationship between the coupling coefficient M14/M23 and the iris distance d between resonator 1 and 4 or resonator 2 and 3, (b) relationship between the coupling coefficient M12 and the iris distance d between resonator 1 and 2, and (c) relationship between the coupling coefficient MS1 and the insertion length of lm.



(a)



(b)

Fig. 5. Geometry of the source-load coupling and the design curve: (a) geometry of the source-load coupling and (b) relationship between the source-load coupling coefficient M_{SL} and the distance g_t between microstip lines.

After optimization, the simulated results of the 2-port BPF are plotted as the solid curves in Fig. 3. The mismatch of the group delay in the stop-band is due to the existence of the transmission zeroes. In addition to this, good agreement can be achieved between the synthesized results and the simulated ones.

C. Design of the balanced filter

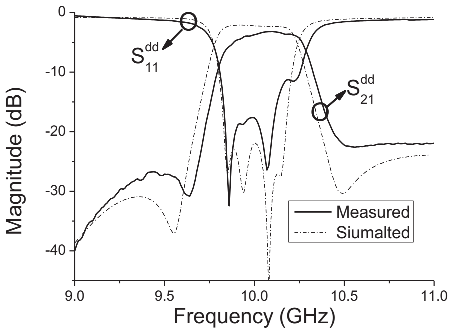
The procedure for the design of the balanced SIW filter with both transmission zeros and linear phase is outlined as follows:

Step 1) **Determine the requirement of the balanced filter.** Based on the desired frequency response, center frequency, bandwidth and transmission zeros can be determined.

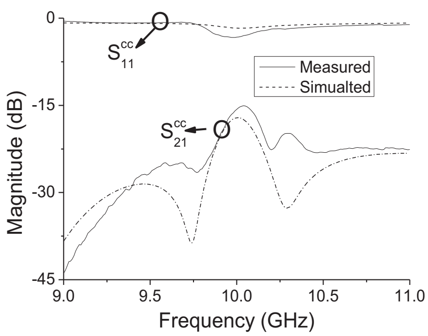
Step 2) **Design the 2-port filter.** The 2-port filter is synthesized according to the requirement in step 1 and the coupling matrix are calculated [8]. Then, the dimensions of the 2-port filter can be determined from the extracted design curves with the method in [9].

Step 3) **Realize the balance filter.** By duplicating the 2-port filter along the vertical symmetry plane, The balanced filter can be achieved.

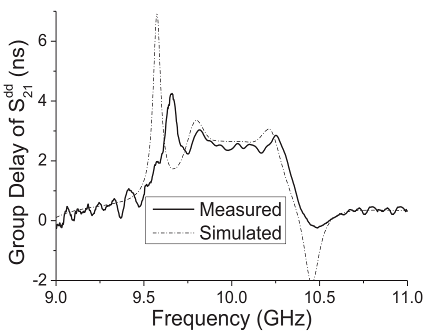
Based on the above analysis of the CM and DM operations, a balanced BPF with transmission zeroes, linear phase and wideband common-mode suppression can be achieved with the main design parameters: g_t=1.4 mm, l_m=3.29 mm, l_1=12.87 mm, l_2=25.28 mm, w=13 mm, w_m=1.35 mm, d_1=1.9 mm, d_2=4.5 mm, d_3=4.08 mm. The simulated results of the balanced BPF under DM and CM operations are plotted as the dotted curves in Figs. 6 (a) and (b), respectively. The group delay responses of the balanced BPF are plotted as the dotted curves in Fig. 6 (c).



(a)



(b)



(c)

Fig. 6. Measured and simulated responses of the filter: (a) DM responses, (b) CM responses, and (c) group delay responses.

III. RESULTS AND DISCUSSION

Figure 7 shows the photograph of the fabricated filter. The simulated and measured results of the filter are plotted in Fig. 6. The measured central frequency is 10.02 GHz, and 3-dB bandwidth is 400 MHz. The in-band insertion loss and return loss are better than -3.5 dB and -12 dB, respectively. The two transmission zeroes are located at 9.55 GHz and 10.5 GHz. The group delay equalization is over 60% of the pass-band. The measured results include the influence of the limited fabrication precision and measurement errors, thus they are somewhat worse than the simulated results

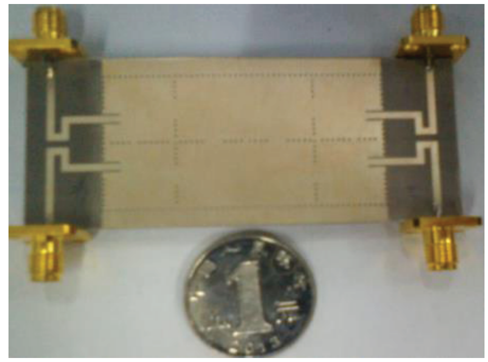


Fig. 7. Photograph of the fabricated differential filter.

IV. CONCLUSIONS

In this paper, a new balanced SIW BPF with high performances is proposed. The design of the balanced filter is simplified through designing a 2-port filter with high performance and duplicating it along the vertical symmetry plane. The source-load coupled microstrip lines are introduced and the design method for filters with source-load coupling is given. Simulated and measured results show that the presented filter has the performances of linear phase, high out-of-band rejection, and good common suppression which can be applied to the microwave system of high quality.

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