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Linear Phase SIW Filter with Good Selectivity

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Abstract—This letter presents an approach to design a linear phase substrate integrated waveguide (SIW) bandpass filter with good selectivity. The topology of the proposed filter is implemented based on cross and bypass coupling schemes, which simultaneously introduce a linear phase response and good selectivity, respectively. According to the proposed topology, a multilayer SIW filter is presented to realize the two kinds of couplings and preserve a compact size. Then, the defected ground structure is adopted to further improve the out-of-band rejection. To demonstrate the proposed design method, one double-layered SIW bandpass filter is fabricated and measured. Measured results show that the proposed filter has a linear phase response and good out-of-band rejection, as well as a good agreement between simulated and measured results.

1. INTRODUCTION

Flat group delay of a bandpass filter's response is demanded in addition to its selectivity in various RF communication systems. There are two main methods to achieve flat group delay. One is to use an external delay equalizer cascaded with the bandpass filter [1]. The external equalizer would enlarge the size of the circuit and increase the insertion loss. The other way is to design a bandpass filter with an imposed linear phase response [2–4]. A positive cross-coupling scheme between nonadjacent resonators is usually adopted to produce transmission zeros (TZ) on the right-half plane. However, there will be a trade-off between the selectivity and the linear phase response in the same order of filter design. The couplings between the resonators can only be chosen to improve the flatness of group delay or the selectivity at the same time. Furthermore, due to the advanced development of modern communication systems, more and more communication modes always exist in one system. The filter with good out-of-band rejection is required to suppress the interference signals produced by other communication modes.

Substrate integrated waveguide (SIW) structure shows the merits of low profile, easy fabrication, and low insertion loss. The filters operated in SIW structures have been a hot research issue for decades. The design method of harmonic suppression for SIW filter can be classified as two main categories: 1) Feeding or input/output design. The feeding lines or the input/output ports are optimized to simultaneously excite the desired mode and suppress the unwanted modes [5, 6]. 2) Coupling design [7–11]. The couplings between spurious modes are suppressed through proper coupling design. Multilayer substrate integrated waveguides (MSIW) can provide more degrees of freedom while designing SIW filters. It can provide more flexibility to design coupling paths and preserve a compact size and good wideband response [8–11]. However, in the above publications, none of them have dealt with the filter design with linear phase and good selectivity at the same time.

In this letter, a linear phase SIW filter with good selectivity is proposed and demonstrated. First of all, the cross-coupling scheme is adopted to realize the linear phase design. Furthermore, the

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bypass coupling of spurious modes is also introduced to generate transmission zeros at the adjacent of the passband, improving its selectivity. Thanks to the multilayer structure, the proposed filter simultaneously shows a linear phase, good selectivity, and few harmonics. Then, the defected ground structure (DGS) is introduced to further improve the wideband rejection, resulting in a better rejection level up to $3.7f_0$.

2. FILTER DESIGN

Figure 1 illustrates the topology of the proposed filter with a linear phase response and good selectivity. It consists of source, load, resonators, and couplings. The resonators 1–4 and the couplings between them form the cross-coupling scheme to improve the linear phase of the passband. Simultaneously, the source, resonators 1 and 2 form the bypass coupling to produce transmission zeros around the passband to improve the selectivity of the passband. The same phenomenon can also be seen in the load section. The main and spurious modes of resonator 1 and 4 are adopted in the cross and bypass couplings, respectively. On the counterpart, the main modes of resonators 2 and 3 are used in the passband design. Compared with conventional designs with the same filter order, the proposed filter topology both have the linear phase response and good selectivity.

Figure 2 presents a multilayer SIW filter based on the proposed topology, which contains three metal

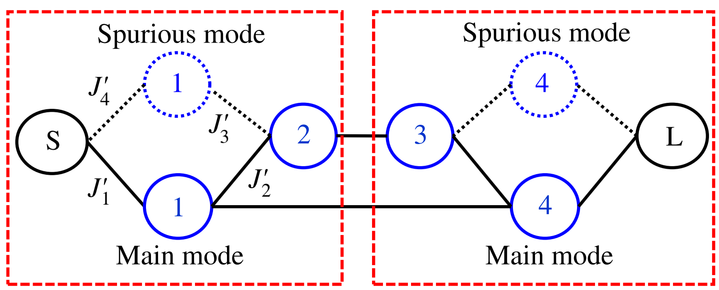


Figure 1. The topology of the proposed linear phase filter with good selectivity.

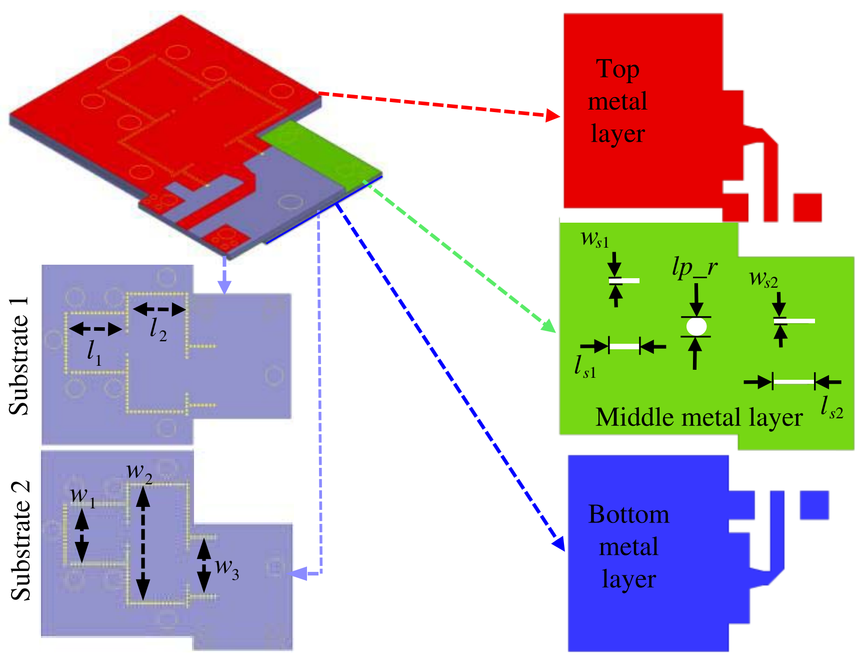


Figure 2. Configuration of the proposed multilayer SIW filter.

interfaces and two dielectric layers. The source/load and four resonators are formed and horizontally and vertically coupled to one another. The main and spurious modes of resonator 1 and 4 are TE_{201} and TE_{101} mode, respectively, while the fundamental modes of resonators 2 and 3 are TE_{101} mode.

Note that the filter of interest in this work is designed on a Rogers RT/Duroid 6002 substrate having 0.762 mm thickness with 0.0012 loss tangent.

2.1. Coupling Design

The design parameters, namely the external quality factor and the coupling coefficient for the linear phase bandpass filter, can be determined by [12]

$$M_{i,i+1} = M_{n-i,n-i+1} = \frac{\mathrm{FBW}}{\sqrt{g_i g_{i+1}}} \quad i = 1, 2, ..., \frac{n}{2} - 1 \tag{1}$$

$$M_{i,n-i+1} = \frac{\mathrm{FBW} J_i}{g_i} \tag{2}$$

$$Q_e = \frac{g_1}{\mathrm{FBW}} \tag{3}$$

where n is the order of the filter.

Furthermore, for the spurious response (TE_{101} mode) below the chosen main mode (TE_{201}), the bypass coupling can be decided by the location of the transmission zeros as [13]

$$\omega_z \approx -\frac{J_1' J_2'}{J_3' J_4'} |b_2| \tag{4}$$

where J_1' and J_2' are the normalized coupling coefficients between the source/resonator 2 and TE_{201} mode, while J_3' and J_4' are the normalized coupling coefficients between source/resonator 2 and TE_{101} mode. To produce transmission zeros, $|J_3' J_4'| \gg |J_1' J_2'|$. Also, the location of the transmission zeros can be controlled by the placements of the coupling irises. For a bypass coupling singlet, if the coupling irises are placed to the same sidewall and shifted away from the center, a TZ is obtained at the low-side of TE_{201} mode. On the counterpart, if the irises are placed close to opposite walls and shifted towards the center, a TZ can be obtained above the TE_{201} resonance [13].

Compared with conventional filter design, two spurious modes are adopted to form bypass couplings. By combining the cross and bypass couplings together, the filter can have the linear phase response and high selectivity simultaneously.

2.2. Out-of-Band Rejection Design

In order to indicate the characteristics of the proposed filter, Figs. 3 and 4 present the simulated results of the separated parts of the filter. Fig. 3(a) shows the configuration of the bypass coupling scheme of resonator 1&2 and the source. Two irises are center-symmetrically placed at the opposite sidewalls and shifted slightly towards the center. As predicted in the above Section 2.1, one TZ occurs above the resonance of TE_{201} mode, as shown in Fig. 4(a). The up-side selectivity of the passband can be improved by the introduced TZ. Fig. 3(b) presents the vertical coupling structure from the resonators 2 and 3. Two slots are etched on the middle metal layer to enable the coupling of the fundamental mode TE_{101}. Thanks to the mode orthogonality, only a few modes couple through the same coupling slots, which are etched near the sidewalls. As depicted in Fig. 4(b), the passband generated by the fundamental mode TE_{101} is located at 13.6 GHz. The first spurious mode is TE_{103} mode and far away from the passband. Furthermore, it can be observed that a few harmonics are generated in the frequency band up to 50 GHz.

Then, according to the coupling topology proposed in Figs. 1 and 2, the simulated results of the entire filter are presented in Fig. 4(c). The positive cross-coupling coefficient M_{14} is realized by small etched circular apertures on the middle metal layer between resonators 1 and 4, where exist the maximum magnetic fields of TE_{201} mode with the same direction. Three transmission zeros are generated at the adjacent locations of the passband, among which TZ2 and TZ3 are introduced by the two bypass coupling singlets of TE_{201}/TE_{101} mode at the input and output sections. TZ1 is generated

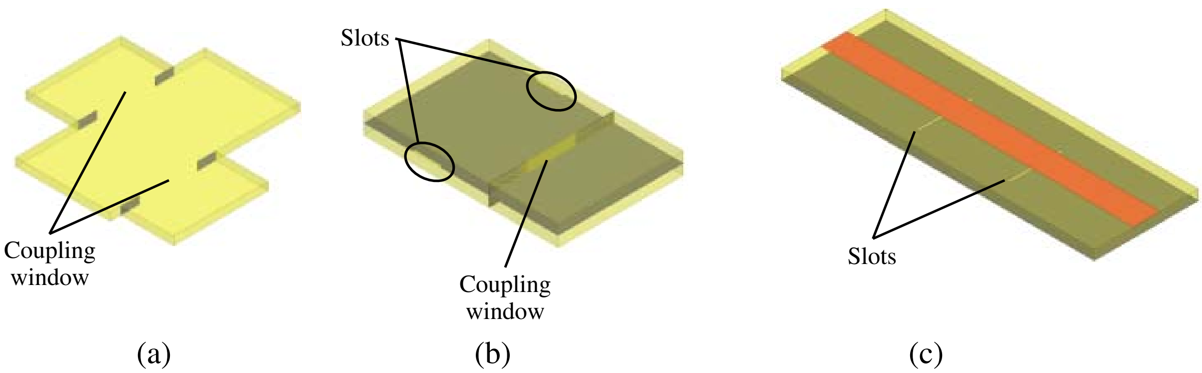


Figure 3. Configuration of the singlet. (a) Bypass coupling. (b) Vertical coupling. (c) Defected ground structure (DGS).

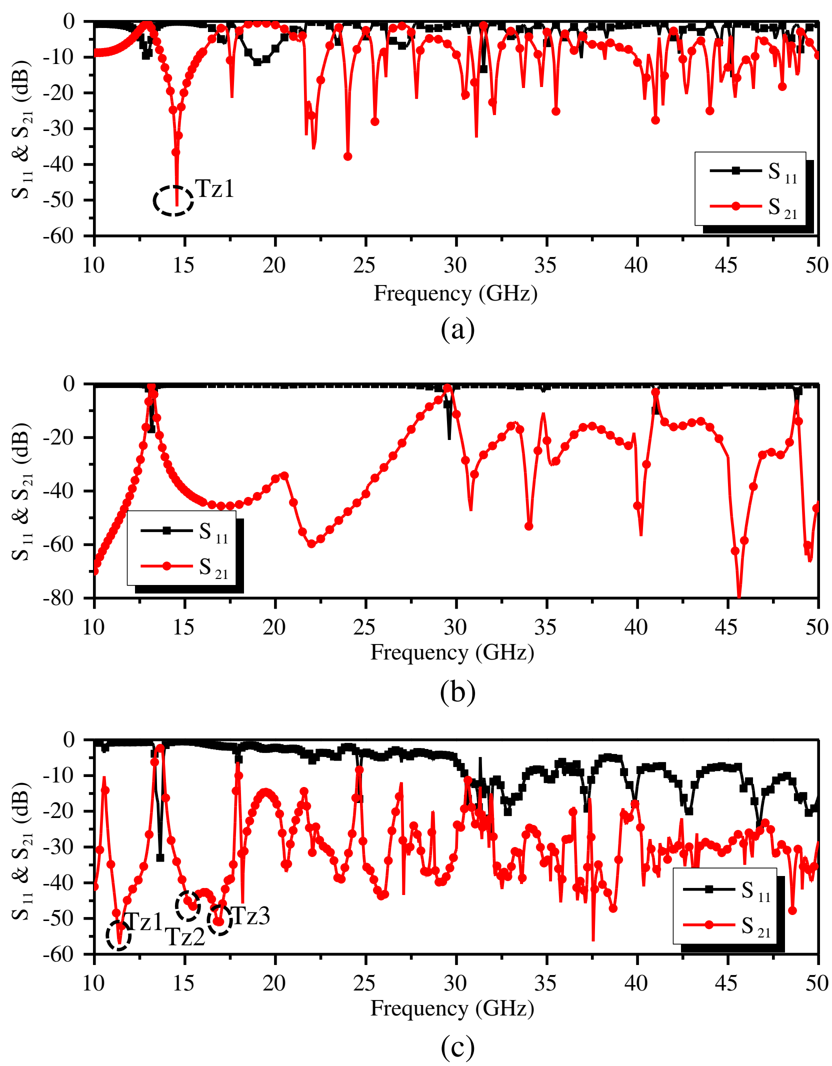


Figure 4. Simulated results. (a) Two order filter with bypass coupling. (b) Two order filter with vertical coupling. (c) Four order filter with bypass and cross-coupling without DGS.

by the weak coupling of the spurious TE_{101} mode of resonators 1 and 4. Furthermore, the out-off-band characteristic of the filter shows a good rejection except for two small resonant peaks around 16 GHz and 24 GHz. Then, two small slots etched on the ground of the input/out microstrip line are adopted to suppress the two resonant peaks and improve the rejection as shown in Fig. 3(c). The two slots are acting as defected ground structure (DGS) and shows low-pass response. Finally, the filter with linear phase response and good selectivity can be achieved.

3. RESULTS AND DISCUSSION

To demonstrate the proposed filter experimentally, the above-described multilayer SIW filter is designed with the center frequency $f_0 = 13.6$ GHz, 3-dB absolute bandwidth of 500 MHz. The low-pass prototype of a four-order linear phase filter with two finite TZs and $RL = 20$ dB is chosen [12]. Furthermore, two transmission zeros introduced by bypass couplings are located above the passband. To achieve better performance during the optimization, the cross and bypass couplings can be slightly tuned by the etched apertures on the middle metal layer and the widths and locations of the irises forms by metalized vias. Finally, the designed dimensions satisfying the requirements are listed as follows: $l_1 = 9.35$, $l_2 = 9.1$, $w_1 = 9.0$, $w_2 = 18.07$, $w_3 = 9.0$, $w_{s1} = 0.13$, $l_{s1} = 1.9$, $w_{s2} = 0.1$, $l_{s1} = 4.2$, $lp\_r = 1.3$ (unit: mm).

Figure 5 presents a photograph of the fabricated filter. Two long microstrip lines and end-launch connectors are adopted to conveniently measure the filter performance. Five screws are used to give a fixture of the two layer SIW structures. Thanks to the multilayer process, the main dimensions of the filter are only 18 mm × 18 mm. Fig. 6 shows the simulated and measured S-parameters and group

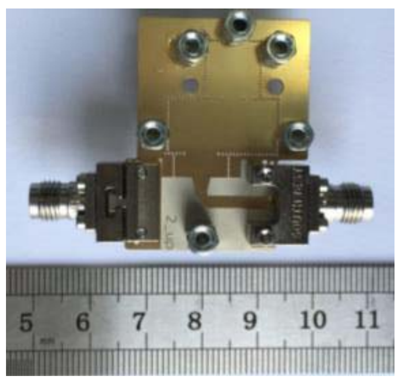


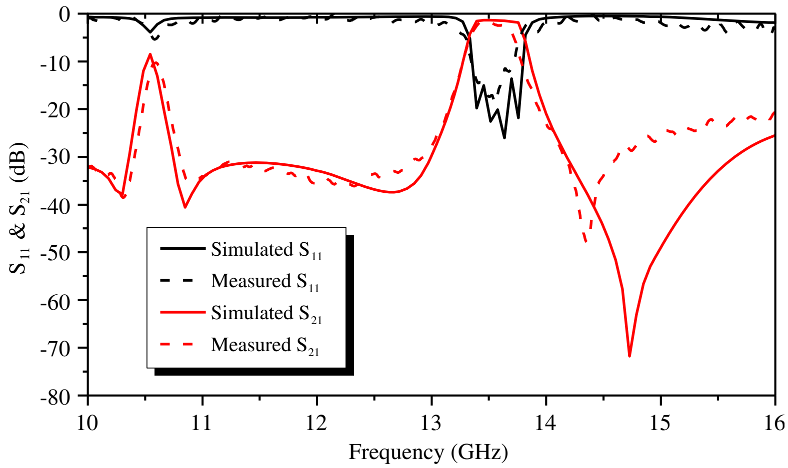
Figure 5. Photograph of the fabricated multilayer SIW filter.

Table 1. Comparison with other similar SIW filters.

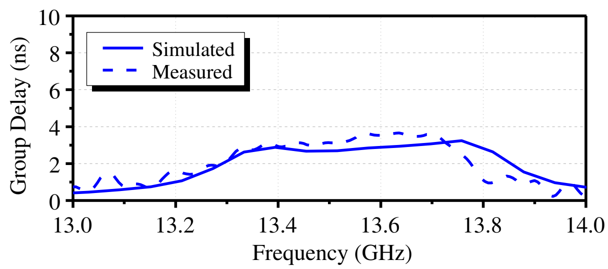
Ref	Center frequency f_0 (GHz)	Bandwidth (GHz)	order	Dimensions (λ_g^2)	TZs around passband	Linear phase	Harmonics suppression	Rejection improvement Techniques
[2]	10.0	0.1	4	$1.52 * 1.48$		Y	NA	NA
[4]	5.0	NA	4	$2.48 * 1.42$	1	Y	NA	NA
[5]	20.0	0.54	4	$1.47 * 1.62$	1	N	Up to $2f_0$: > 50 dB	Mode coupling
[10]	12.9	0.25	4	$1.85 * 0.71$	5	N	Up to $2.3f_0$: > 15 dB	Multilayer
This work	**13.6**	**0.5**	**4**	**1.39*1.39**	**2**	**Y**	**Up to 3.7f_0 : > 15 dB**	**Multilayer and DGS**

Y = yes, N = no, NA = not involved.

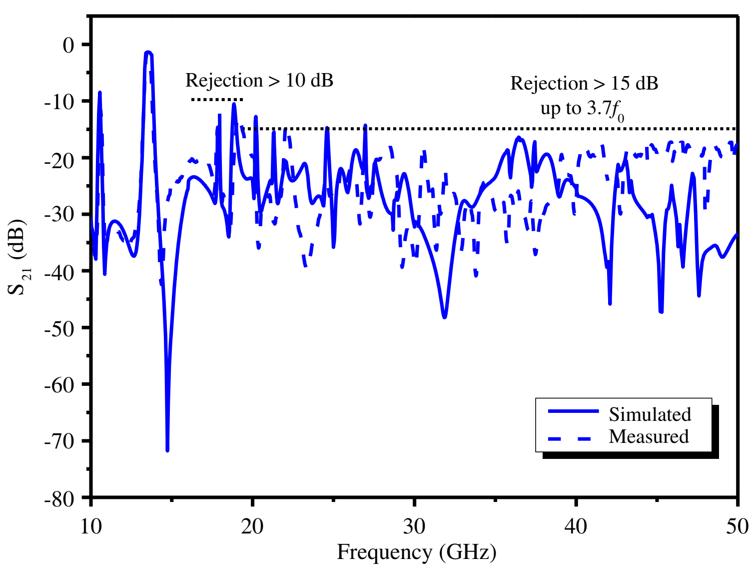
λ_g is the wavelength of the substrate at the central frequency.



(a)



(b)



(c)

Figure 6. Simulation and measured results of the proposed filter. (a) Narrowband response. (b) Group delay of the passband. (c) Wideband response.

delay of the proposed filter which agree with each other very well. Fig. 6(a) presents the details of the passband. The insertion and return losses of the passband are 1.5 dB and below 10 dB, respectively. Due to the weak coupling of TE_{101} mode through the etched circular aperture on the middle metal layer between resonator 1 and 4, a small resonant peak below 10 dB occurs at 10.5 GHz. As depicted in Fig. 6(b), the group delay shows flatness in most of the passband. Fig. 6(c) indicates the wideband response of the proposed four-order filter, which shows a good out-of-band rejection up to 50 GHz. The band rejection is better than 10 dB within the frequencies ranging from 15 GHz to 20 GHz, and is better than 15 dB up to 50 GHz.

Table 1 indicates the comparison between the proposed filter and other similar four-order SIW filters. It can be seen that the proposed filter shows the merits of linear phase, good selectivity, and compact size.

4. CONCLUSION

In this letter, an effective multilayer method is presented and validated through the design and experimental validation of a 4-order SIW filter with the linear phase response and good selectivity. The positive cross-coupling and bypass coupling are simultaneously realized in the multilayer SIW topology, resulting in flat group delay and good selectivity, respectively. Thanks to the multilayer process and DGS, a good out-of-band rejection is achieved up to $3.7f_0$. The proposed filter shows the merits of the linear phase, good selectivity, and compact size. Other multilayer fabrication techniques such as Low temperature co-fired ceramic (LTCC) and micro-electro-mechanical-system (MEMS) can also be applied in the proposed filter design.

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