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A Cross-Coupled SIW Filter with Quasi-Elliptic Response and Enhanced Stopband Suppression Using Opposite-Face GCPW Feeding

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ABSTRACT: This letter presents a cross-coupled SIW filter with a quasi-elliptic response and improved stopband suppression. For cross-coupled SIW filters, suppressing spurious modes often requires rearranging feeding ports but this rearrangement tends to increase port-to-port crosstalk and limit achievable out-of-band rejection. To address this inherent issue, we keep port positions unchanged and change the port configuration from conventional microstrip lines to an opposite-face GCPW feeding structure. The input and output ports are placed on opposite metal layers, with their ground planes separated by the dielectric substrate. Simulation results show that the port-to-port crosstalk is reduced from -25 to -40 dB to below -100 dB. Measured results show that the proposed filter maintains a similar stopband width as the previous design, while the suppression of the first spurious passband is improved by about 20 dB, reaching better than -50 dB. The improvement is achieved without hybrid structures or extra fabrication steps.

1. INTRODUCTION

Substrate integrated waveguide (SIW) filters are widely used in microwave and wireless circuits. They offer low loss, high quality factor, and good shielding, which makes them a practical choice for many applications [1–4]. To improve the near-band selectivity, cross coupling is often added to the filter design. This topology can create transmission zeros near the passband edges, producing a quasi-elliptic response [5–9].

However, cross-coupling also introduces another issue. The added coupling path facilitates higher-order spurious modes, such as TE_{102} and TE_{201}, to pass through. These modes cause spurious passbands that degrade out-of-band rejection. For modern multi-band systems, a clean stopband is important, and this issue becomes a major limitation for conventional cross-coupled SIW filters.

Several existing methods suppress these spurious modes. For filters that do not employ cross coupling, techniques such as reducing the spurious bandwidth [10], staggering the resonant frequencies of higher-order modes [11, 12], or using null coupling or mixed coupling [13–18] have proven effective in widening the stopband. Nevertheless, these established approaches lose effectiveness when cross coupling is introduced, as they suppress spurious modes along the main coupling path while leaving the cross coupling path unaddressed [19–25]. As a result, the spurious passband suppression in most reported quasi-elliptic SIW filters is limited to about -20 dB.

To obtain better suppression, some designs use additional cascading low-pass or band-stop filtering stages, but they increase insertion loss and circuit size. Others use hybrid resonant structures that combine SIW cavities with microstrip or other planar resonators to stagger the parasitic modes [26–31]. However, hybrid structures inevitably break the SIW's shielding nature and degrade its intrinsic quality factor, making them less attractive for high-frequency and high-performance applications.

Recently, promising solutions based on the orthogonality and mixed coupling of spurious modes have been successfully demonstrated [32–34]. One such approach, which is applicable to single-layer circuits, achieves this by arranging the coupling windows and ports such that the field nulls of the TE_{102} and TE_{201} modes coincide with both the main and cross-coupling paths; it becomes possible to achieve natural suppression of the spurious passband without resorting to hybrid structures or additional cascading. Nevertheless, this approach still faces a challenge: the required port rearrangement makes the ports closer to each other than in the conventional design. This layout causes significant electromagnetic crosstalk and parasitic coupling between the two ports. This residual spurious energy can leak through this port-to-port interaction, which limits the maximum stopband attenuation that can be achieved.

To address this inherent limitation, we change the port-feeding configuration in this letter, incorporating an "opposite-face feeding" strategy in conjunction with grounded coplanar waveguide (GCPW) ports, which are different from conventional microstrip ports on the same top metal layer with a common ground plane.

In the proposed structure, input and output ports are placed on different metal layers, with one on the top and the other on the bottom. We also use GCPW transitions instead of regular

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microstrip lines. Because the ground planes are separated and the GCPW structure confines the fields more tightly, the mutual coupling between the two ports is greatly reduced. At the same time, the fundamental TE_{101} passband and quasi-elliptic response are not affected by this change.

This modified feeding method does not require hybrid structures or extra fabrication steps. Measurement results show that the stopband width remains similar to the previous design, but the rejection of the first spurious passband is improved by about 20 dB, reaching better than -50 dB.

The rest of this letter is organized as follows. Section 2 describes the filter structure and the port design, Section 3 presents the measured results and a discussion, and Section 4 gives the conclusion.

2. METHODS

2.1. Conventional Design

Figure 1 shows a typical fourth-order cross-coupled SIW filter with TE_{101} and TE_{102} electric field distributions, respectively. The main coupling path goes through resonators R1, R2, R3, and R4, and there is an additional cross-coupling path between resonators R1 and R4.

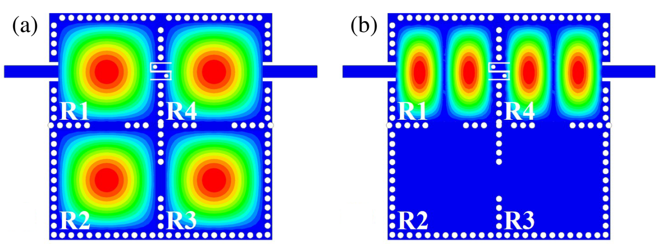

FIGURE 1. A conventional cross-coupled SIW filter with (a) TE_{101} and (b) TE_{102} electric field distributions.

For the fundamental TE_{101} mode depicted in Fig. 1(a), the main path and cross-coupling path work together to produce a quasi-elliptic response, which creates two transmission zeros near the passband [35]. Since the field of the TE_{101} mode is centrally symmetric, the exact placement of the coupling structures does not affect the fundamental coupling much. To realize the quasi-elliptic response, one of the four coupling paths needs to be electric (negative) coupling. To keep the structure symmetric and simplify the design, it is common to choose either the R1-R4 (k_{14}^{101}) or R2-R3 (k_{23}^{101}) path as the negative coupling, as the coupling topology is shown in Fig. 2 [5, 35].

However, for spurious modes, the field distribution is no longer centrally symmetric. This means that the location of the coupling structures or the feeding ports does affect the transmission of these higher-order modes. As shown in Fig. 1(b), the

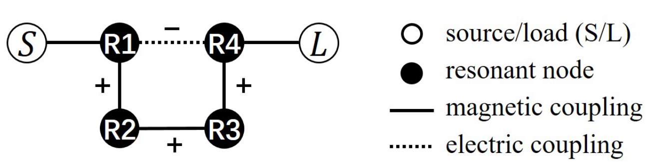

FIGURE 2. TE_{101} coupling topology of the conventional cross-coupled SIW filter.

TE_{102} mode has field nulls that happen to align with the main coupling path, so the main path (k_{12}^{102} and k_{34}^{102}) is blocked. But the cross-coupling path (k_{14}^{102}) still allows TE_{102} to propagate.

One way to address this issue is to move feeding ports to locations where the field nulls of TE_{102} and TE_{201} coincide with both main and cross-coupling paths [34], as shown in Fig. 3. This successfully suppresses the spurious passband via orthogonality. However, the necessary port relocation makes the ports closer to each other, which inevitably increases the electromagnetic crosstalk between the input and output terminals compared with the conventional design. This additional coupling acts as a bypass for residual spurious energy and limits the final stopband suppression depth.

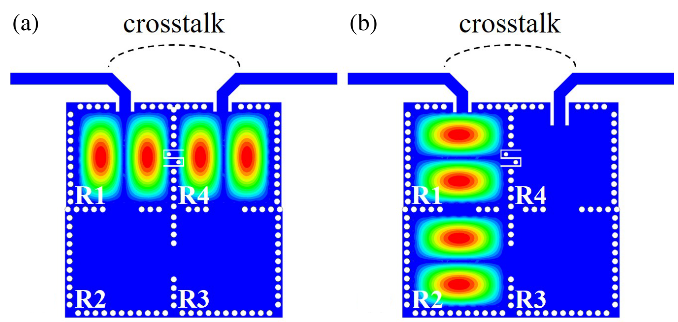

FIGURE 3. A previous design of a cross-coupled SIW filter proposed in [34] with (a) TE_{102} and (b) TE_{201} electric field distributions.

To avoid this problem without giving up the orthogonal blocking effect, we choose not to move port positions further. Instead, we keep them at the locations that satisfy the orthogonality condition and change the port configuration itself from conventional microstrip lines to an opposite-face GCPW feeding structure. This reduces port-to-port crosstalk and improves spurious passband suppression without affecting the fundamental passband or coupling topology.

2.2. Proposed Design

Figure 4 shows the structure of the proposed filter. It is a four-pole cross-coupled SIW filter with the same basic cavity arrangement as the conventional design. The difference lies in the feeding ports. Instead of placing both ports on the top metal layer as in the conventional design, we place one port on the top layer and the other on the bottom layer. Both ports are implemented by GCPW transitions instead of conventional microstrip lines.

The positions of feeding ports are kept the same as those required by the orthogonality condition. This means that the orthogonality condition for blocking TE_{102} and TE_{201} in both the main and cross-coupling paths is still satisfied. The TE_{101} fundamental mode is unaffected because its field distribution is centrally symmetric.

What is changed is the port configuration itself. In the proposed design, the input and output ports are located on opposite sides of the substrate, with their ground planes separated by the dielectric layer. This physical separation greatly reduces the electromagnetic crosstalk between the two ports. In addition, the GCPW structure confines the electric fields more tightly

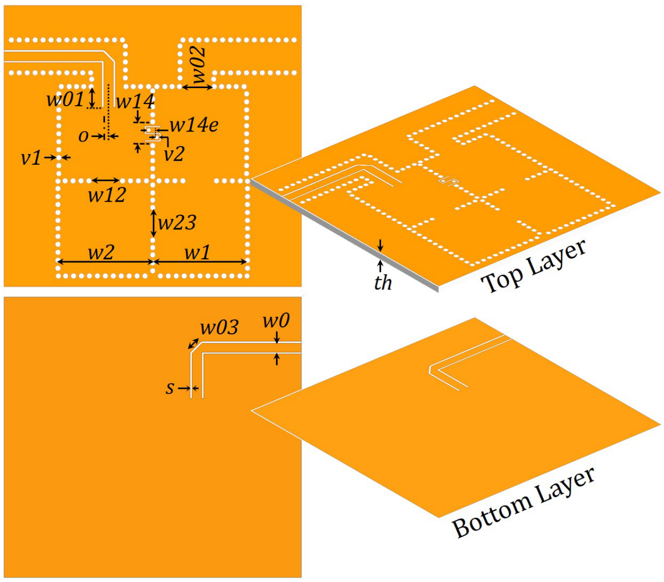

FIGURE 4. Structure of the proposed filter.

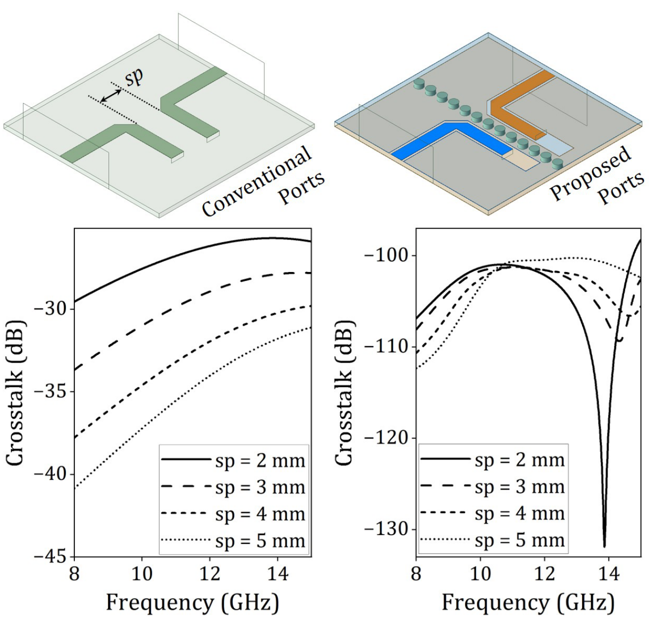

FIGURE 5. A crosstalk comparison between the conventional ports feeding and the proposed ports configuration.

between the signal trace and the adjacent ground vias, which further suppresses any parasitic coupling that might otherwise leak through the port interfaces.

To verify this improvement, we simulated the port-to-port crosstalk separately for two cases, as shown in Fig. 5. In both simulations, the filter's four cavities were removed, leaving only the feeding ports with matched loads at the ends. For the left case, we used the conventional microstrip ports from [34]. The simulated crosstalk varied between -25 dB and -40 dB depending on the port spacing. For the right case, we used the proposed opposite-face GCPW ports. The simulated crosstalk dropped to below -100 dB. This confirms that the proposed port configuration effectively eliminates the unwanted coupling between the input and output terminals. Based on this result, we adopted this port configuration in the filter design presented in this letter.

2.3. Design Guideline

The design process can be divided into two steps:

1) Design the quasi-elliptic filter without considering the port configuration [5, 35]. The coupling coefficients and external quality factor are determined by the passband specifications. Dimensions of the coupling windows are tuned accordingly. At this stage, conventional microstrip ports can be used.

2) Replace the ports with the proposed opposite-face GCPW configuration. One port is placed on the top metal layer and the other on the bottom layer. The ports' positions should be kept the same as those required by the orthogonality condition to maintain the blocking effect. The GCPW transition dimensions are adjusted to match 50-ohm impedance. The fundamental passband is hardly affected by this change, but minor adjustment may be required to compensate for the altered port loading.

3. RESULTS

The proposed filter was fabricated and measured using a Rogers RT/duroid 5880 substrate (0.508 mm thickness, $\varepsilon_r = 2.2$, $\tan\delta = 0.0009$). An Agilent N5227A network analyzer and Southwest Microwave 2.4-mm end launch connectors were used for the measurements. A photograph of the fabricated filter is shown in Fig. 6.

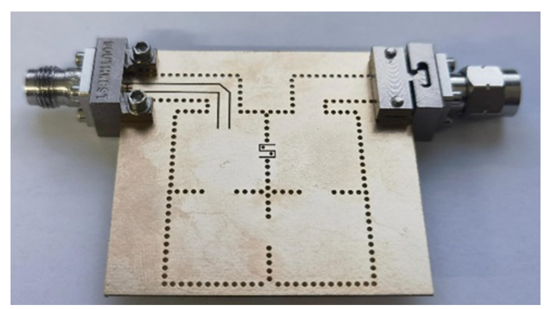

FIGURE 6. Photo of the proposed filter under test.

The filter was designed at a center frequency of 10 GHz with a fractional bandwidth of 4%. The coupling coefficients and external quality factor were specified as follows: $k_{12}^{101} = k_{34}^{101} = 0.032$, $k_{23}^{101} = 0.025$, $k_{14}^{101} = -0.005$, and $Q_e^{101} = 22.4$. Table 1 lists detailed dimensions.

Figure 7 shows simulated and measured S-parameters. The measured results agree well with the simulations. The filter exhibits a quasi-elliptic response with two transmission zeros near the passband, located at 9.6 GHz and 10.4 GHz. The passband insertion loss is about 1.7 dB. In the stopband, the first spurious passband is suppressed to better than -50 dB up to 20.3 GHz.

Figure 7 also includes simulated responses of two other designs for comparison. The first curve, corresponding to the conventional cross-coupled SIW filter in Fig. 1, offers a quasi-elliptic response but only about -10 dB of stopband suppression. The second curve, for an orthogonality-based design that

TABLE 1. Dimensions of the proposed filter (mm).

$w0$	1.34	$w01$	2.72	$w12$	4.28	s	0.28	o	0.43
$w1$	13.4	$w02$	4.48	$w23$	4.14	th	0.508	$v1$	0.8
$w2$	13.52	$w03$	2.17	$w14$	2.8	$w14e$	1.2	$v2$	0.6

TABLE 2. Comparison with reported work.

	Drawbacks	f_0 (GHz), FBW (%)	Order, IL (dB), Size (λ_r^2)	Stopband extension, suppression
[14]	Lack of TZ near passband	13, 4.6	2, 1.7, 0.69	$2.12f_0$, -20 dB
		13.2, 4.55	2, 1.5, 0.47	$2.27f_0$, -20 dB
[15]		5.8, 2.1	4, 3.2, 0.46	$4.03f_0$, -30 dB
[16]		9, 2.1	3, 2.8, 0.46	$4.02f_0$, -27 dB
[26]	Using hybrid resonant structures that degrade superiorities of SIW	5.94, 11.2	4, 0.97, 0.17	$2.24f_0$, -24 dB
[27]		9.08, 17.3	4, 1.57, 0.19	$2.08f_0$, -20 dB
[28]		10.1, 11.7	4, 1.22, 0.5	$2.9f_0$, -20 dB
[29]		10, 22.7	4, 1.2, 0.85	$2f_0$, -36 dB
[19]	The stopband suppression is inadequate	10.07, 9.3	3, 1.06, 0.64	$1.98f_0$, -25 dB
[20]		8.5, 6.1	3, 1.7, 0.52	$2.08f_0$, -20 dB
[21]		10, 9.23	4, 0.79, 0.95	$2f_0$, -20 dB
[23]		12.9, 1.9	4, 2, 1.36	$2.32f_0$, -15 dB
[34]	–	10, 4	4, 1.65, 2	$2.03f_0$, -35 dB
This work		10, 4	4, 1.7, 2	$2.03f_0$, -5 dB

f_0: central frequency. FBW: fractional bandwidth. IL: insertion loss. λ_r: wavelength in the dielectric.

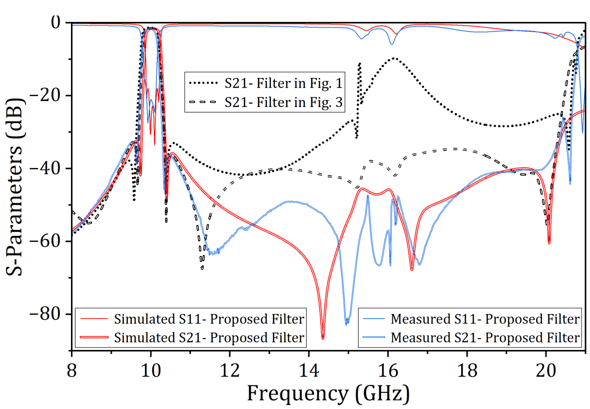

FIGURE 7. Simulated and measured results of the proposed filter and two conventional filters for comparison.

uses conventional microstrip ports, extends the stopband width to about 20 GHz but provides roughly -35 dB of rejection. The proposed filter maintains a similar stopband width as the previous orthogonality-based design while improving the rejection depth to better than -50 dB. This demonstrates the effectiveness of the opposite-face GCPW feeding configuration in eliminating port-to-port crosstalk, which is the main bypass for residual spurious energy.

Table 2 provides a broader comparison with other reported cross-coupled SIW filters. Among these works, those without cross coupling lack the quasi-elliptic response, while those using hybrid structures often degrade the quality factor and shielding of SIW. For designs that claim to have wide stopbands, suppression is typically limited to about -20 dB. The proposed filter avoids these drawbacks. It maintains the SIW's quasi-elliptic response and self-shielding nature, and achieves a stopband suppression of better than -50 dB, which is noticeably better than most reported designs.

The measured results confirm that the proposed filter achieves both a quasi-elliptic response and a wide stopband with high rejection, without requiring hybrid structures or additional fabrication steps.

4. CONCLUSION

In this letter, we propose a cross-coupled SIW filter with a quasi-elliptic response and a wide stopband. Improvement is obtained by replacing the port configuration. The port positions are kept the same as those required by the orthogonality condition to maintain the blocking of TE_{102} and TE_{201}. The port configuration itself is changed from conventional microstrip lines to an opposite-face GCPW structure, with input and output ports placed on different metal layers. This change reduces the port-to-port crosstalk by eliminating the main bypass path for residual spurious energy. Measurement results show that stopband suppression is improved by about 20 dB, reaching better than -50 dB, while the stopband width and quasi-elliptic response remain unaffected. The proposed method does not require hybrid structures or additional fabrication steps, and it is suitable for high-performance SIW filter applications requiring both good selectivity and high out-of-band rejection.

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