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RESEARCH ARTICLE

High selectivity band-stop filters using coaxial-fed substrate integrated waveguide

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Abstract
A novel band-stop filter (BSF) using coaxial-fed slotted substrate integrated waveguide (SIW) is proposed in this article. The proposed BSF is designed using coaxial-fed line with extended probes penetrating through the substrate and connecting each other, instead of using the main transmission line to dispose the resonators. The SIW cavities perform the resonators excited by the probes to produce a stopband. Then, two BSFs with one and two SIW cavities are firstly designed, both of them have SIW cavity resonator modes and lower-band reflection zeroes. Then, two types of third-order BSFs using two cavity resonators and one slot resonator are presented, the high selectivity is achieved by the RZs at both sides of the stopband. Finally, one of the proposed third-order BSFs is fabricated and measured to verify the design method.

KEYWORDS
band-stop, coaxial-fed, high selectivity, substrate integrated waveguide (SIW)

1 | INTRODUCTION

Band-stop filters (BSFs), contrast to band-pass filters (BPFs), can suppress the signal in specific band, which are widely used in multiplexer systems to prevent interference with other channels, and high power amplifiers (PAs) to reject the spurious harmonic signal caused by the PAs' nonlinearity. The standard design method of the BSF is cascading the band-stop resonant elements disposed along a main transmission line connecting the input and output.[1-10] The BSFs designed using planar transmission line, such as microstrip and coplanar waveguide, own compact size, and easy integration,[1-4] whereas suffer from low power capacity and are usually applied to wideband systems. The traditional waveguide BSFs, such as rectangular waveguide and cylindrical waveguide, have advantage over high power capacity,[5-8] while the waveguide circuits suffer from large circuit size, high cost and non-easy integration with planar circuits. Substrate integrated waveguide (SIW) has high unloaded Q-factor between planar transmission line and traditional waveguide, and comparative circuit size against planar transmission line, which can be used to design BSFs with relative high power capacity and compact size.[9-11]

All the aforementioned BSFs should have a main transmission line connecting two ports to cascade the resonators, which may increase the whole circuit size. In this article, a novel BSF using coaxial-fed lines and slotted SIW is proposed. The extended probes of the two ports penetrate through the substrate and connect directly. The SIW cavity resonant modes are excited by the probes without additional occupied space. Then, two BSFs using respective one and two SIW cavities are designed by the proposed configuration. To improve out-of-band performance, two types of third-order BSFs with slots in metal planes of the SIW are presented. Finally, a third-order using two cavity modes and one slot mode with high selectivity at both sides of the stopband is achieved, and the proposed BSF is also fabricated and measured to verify the simulation results.

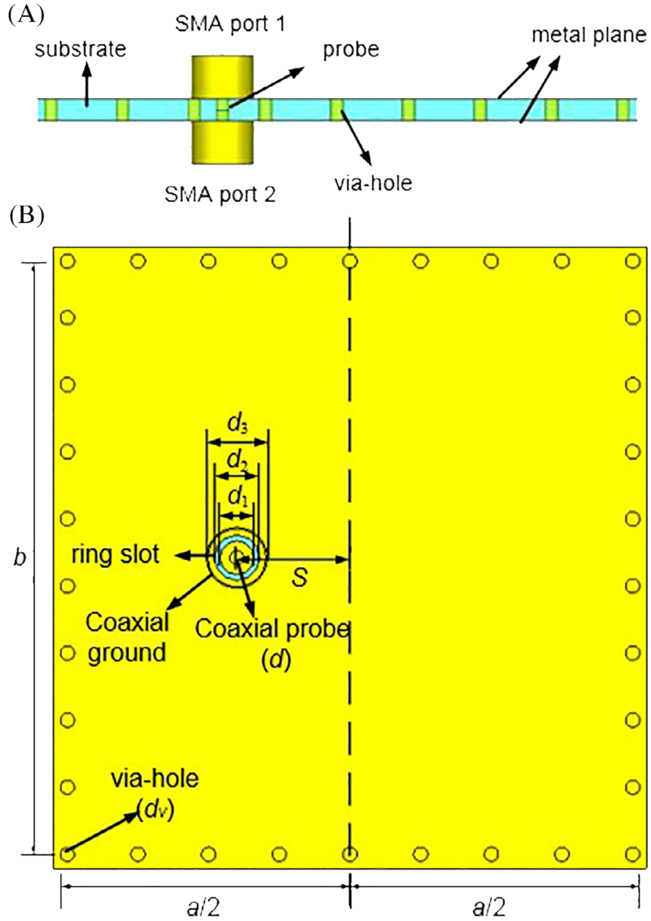

FIGURE 1 Configuration of first-order substrate integrated waveguide (SIW) band-stop filter (BSF) with $a = 40$, $b = 42$, $S = 7$, $d_1 = 3.6$, and $d_2 = 4$ (unit: mm): (A) side view and (B) top view [Color figure can be viewed at wileyonlinelibrary.com]

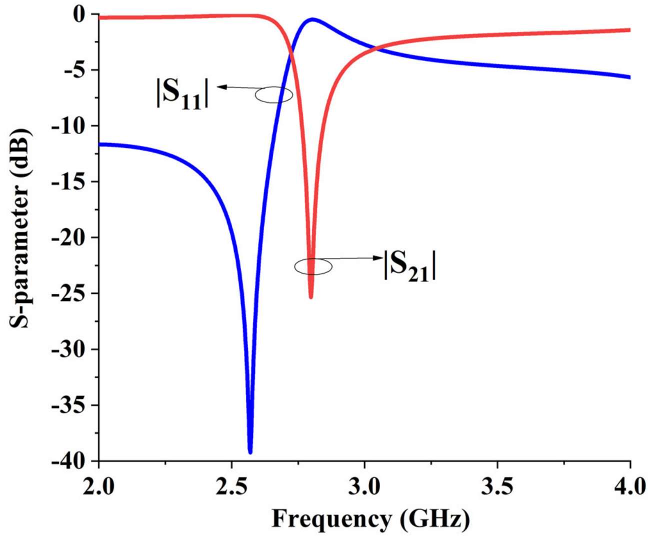

FIGURE 2 Simulated S-parameter of first-order substrate integrated waveguide (SIW) band-stop filter (BSF) [Color figure can be viewed at wileyonlinelibrary.com]

2 | PROPOSED BAND-STOP FILTER

Figure 1A,B shows the configuration of first-order SIW BSF, which includes a SIW cavity, two coaxial ports with extended probes connecting together. The diameters of the coaxial probe, coaxial ground, and metallic via-holes are $d = 1$ mm, $d_3 = 4.1$ mm, and $d_v = 1$ mm, respectively, and all of them are applied to all the filters designed in this article. The ring slots are implemented around the probes in both sides to interdict the signal to the ground, the inner and outer diameters are d_1 and d_2. All the filters are designed on a substrate with a dielectric constant (ε_r) 3.48, thickness 1.524 mm, and loss tangent 0.0037. The SIW cavity serves as a series resonator and disposes along the extended probes. The resonant frequency of the SIW cavity can be approximately calculated by Equation (1)

$$f_c = \frac{c}{2\sqrt{\varepsilon_r}}\sqrt{\frac{1}{a^2} + \frac{1}{b^2}}, \tag{1}$$

where c is light speed in air, ε_r is the relative dielectric constant, a and b are the sides length of the SIW cavity, as marked in Figure 1B. When the cavity resonates, the resonator circuit shorts the signal to the ground, thus, this circuit has a transmission zero (TZ) to form the stopband, as shown in Figure 2. The resonant frequency is 2.8 GHz with side lengths a = 40 mm and b = 42 mm. The proposed design method shows the advantage that the band-stop element is excited by the probes embedded in the SIW cavity without additional occupied space.

According to the previous design method, a second-order BSF using two SIW cavities is proposed, as shown in Figure 3. It has two layers of substrates with metallic via-holes to form the two cavity resonators, which act as two series resonators, and couple to each other through the ring slot in middle metal plane, as shown in Figure 3C. Besides, the ring slots here are used to disconnect the signal and ground. Similarly, the two SIW cavity resonators are excited by the probes of the coaxial-fed line. Simulated S-parameters are shown in Figure 4, we see that it has two TZs to form the stopband with center frequency of 2.8 GHz and two RZs at lower passband. The BSF in this design has a high selectivity and return loss in lower-band, while poor in upper-band.

In order to improve the upper-band performance, two types of third-order BSFs are designed here, namely, Type I and Type II. For Type I, a rectangular slot in middle metal plane is employed, as shown in Figure 5A. For Type II filter, two rectangular slots in top and bottom planes, as shown in Figure 5B are additionally employed. The slot in middle metal plane is served as a half wavelength resonator, the frequency is calculated using Equation (2). Thus, Type I has three reflection poles, namely, f_1, f_2, and f_3, where f_1 and f_2 are produced by the two SIW cavities, f_3 is produced by the slot. Figure 6 shows the frequencies

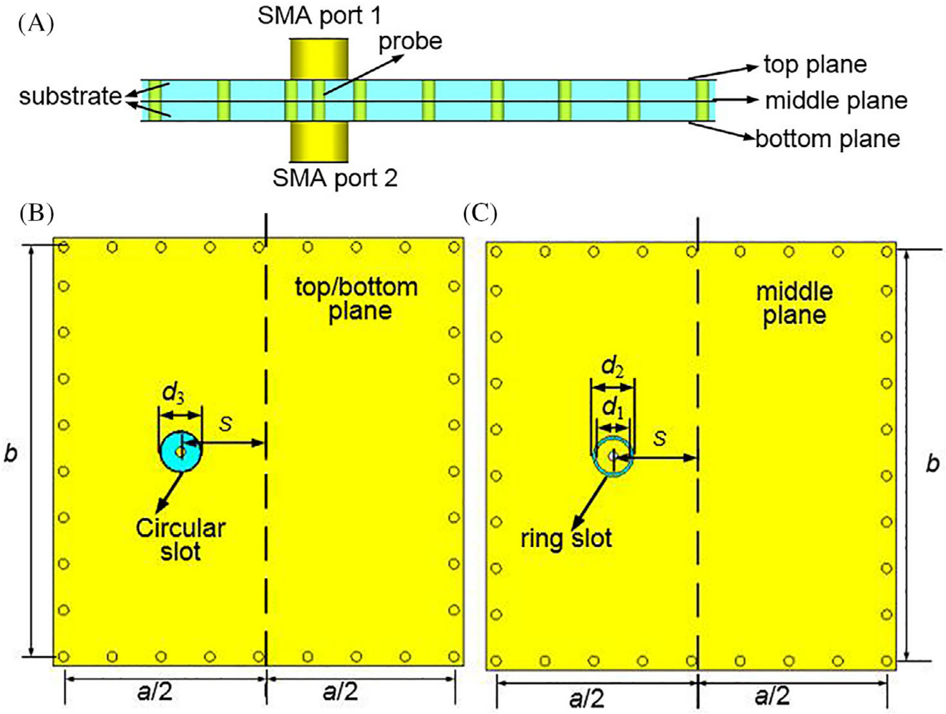

FIGURE 3 Second-order substrate integrated waveguide (SIW) band-stop filter (BSF) with $a = 40$, $b = 42$, $S = 7$, $d_1 = 4$ $d_2 = 4.2$, and $d_3 = 4.1$ (unit: mm): (A) side view, (B) top and bottom metal plane, (C) middle metal plane [Color figure can be viewed at wileyonlinelibrary.com]

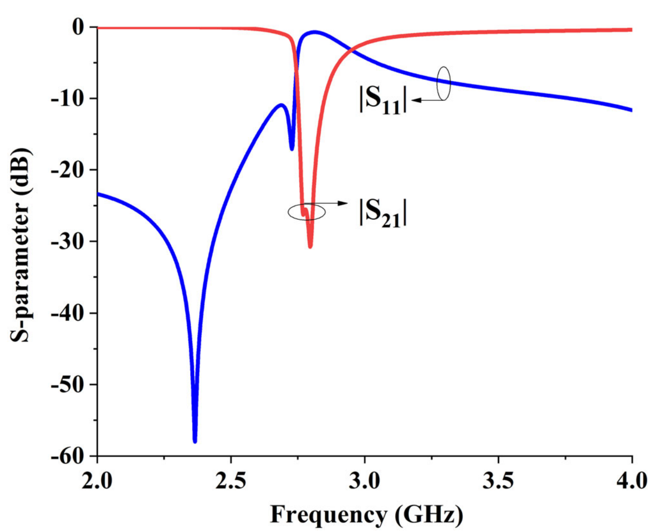

FIGURE 4 Simulated S-parameter of the second-order substrate integrated waveguide (SIW) band-stop filter (BSF) [Color figure can be viewed at wileyonlinelibrary.com]

variation against the slot length L_1, which indicates that the increasing slot length L_1 results in a decrement of f_3, while it has little effect on f_1 and f_2, thus the bandwidth of the filter can be adjusted by choosing a short length of the slot. The simulated S-parameter of Type I filter is shown in Figure 7, it has two RZs at lower passband and one RZ at upper passband. The three RZs is produced by the source-load coupling, which can maximally produce N RZs (N is the order of the BSF). The additional RZ at upper passband is produced to improve the upper-band selectivity. The in-band insertion loss (IL) and return loss (RL) are 20 dB and 0.85 dB.

$$f_s = \frac{c}{2L_1\sqrt{\varepsilon_r}}, \tag{2}$$

To further improve the out-of-band performance, two slots in top and bottom planes, as shown in Figure 5B are employed, namely Type II filter. The frequency tuning of the three resonant modes and four RZs vs the slot length L_2 is provided in Figure 8, where the fourth RZ, namely, f_{RZ4} is the RZ of the parasitic band. These two slots have little effect on the three resonant modes and the first three RZs, while the fourth RZ shifts to the stopband when increases the slot length, and then improve the return loss between the third and the fourth RZs, which can improve the upper-band performance. Figure 9 plots the comparison of the simulated results between Type I and Type II BSFs, which indicates that the proposed Type II BSF has high selectivity and good out-of-band return loss at both sides of the stopband, as shown in Figure 9 with red-solid line. After simulation and optimization, a BSF with center frequency 2.796 GHz, fabrication bandwidth (FBW) 6.6%, in-band IL

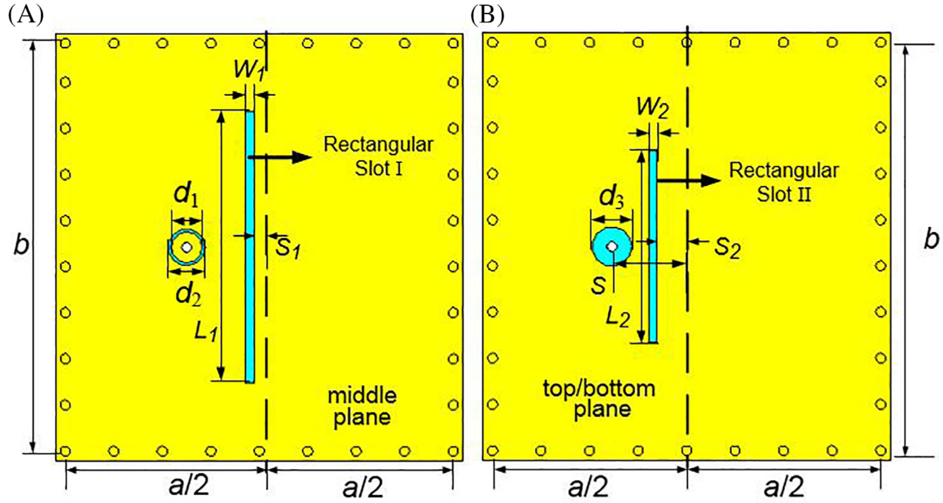

FIGURE 5 (A) Slot I in middle plane and (B) slot II in top/bottom plane [Color figure can be viewed at wileyonlinelibrary.com]

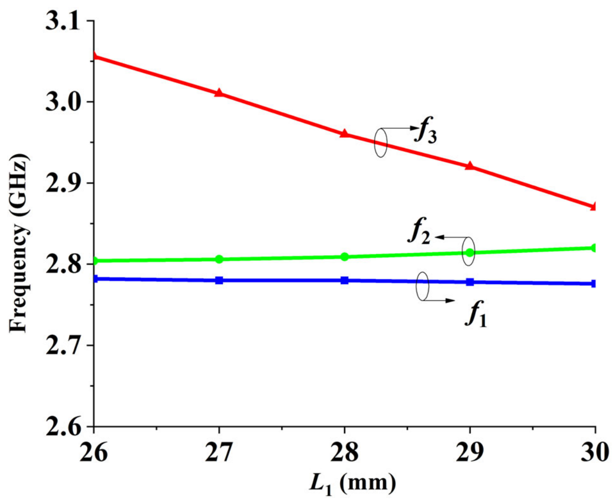

FIGURE 6 Frequency tuning vs L_1 of the three resonant modes [Color figure can be viewed at wileyonlinelibrary.com]

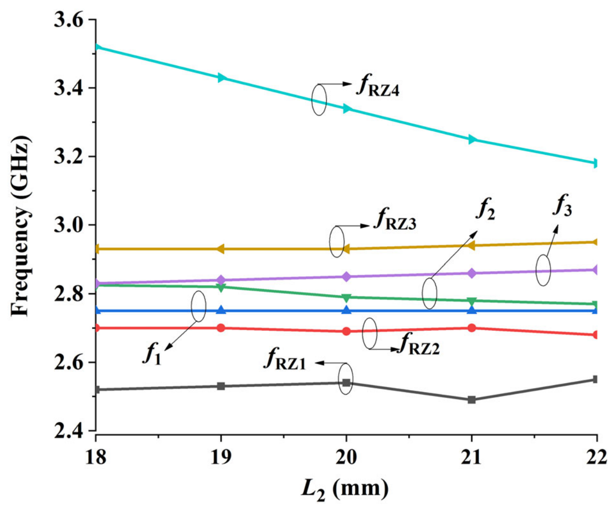

FIGURE 8 Frequency variation vs L_2 of the three resonant modes and four RZs [Color figure can be viewed at wileyonlinelibrary.com]

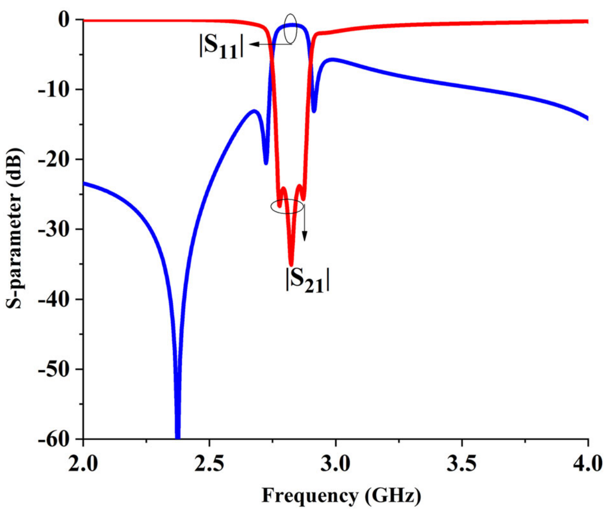

FIGURE 7 Simulated S-parameter of the Type-I substrate integrated waveguide (SIW) band-stop filter (BSF) [Color figure can be viewed at wileyonlinelibrary.com]

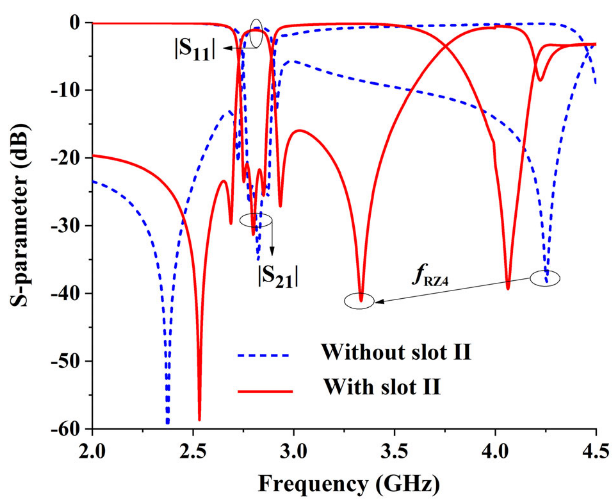

FIGURE 9 Comparison of simulated results between Type I and Type II band-stop filter (BSF) [Color figure can be viewed at wileyonlinelibrary.com]

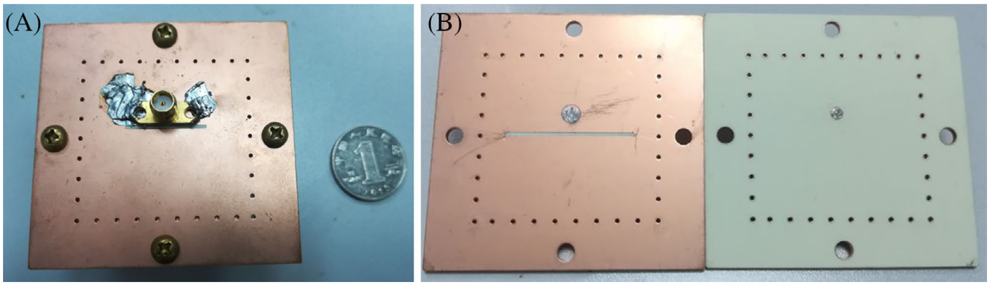

FIGURE 10 Photograph of the proposed band-stop filter (BSF): (A) whole view and (B) view of middle metal plane [Color figure can be viewed at wileyonlinelibrary.com]

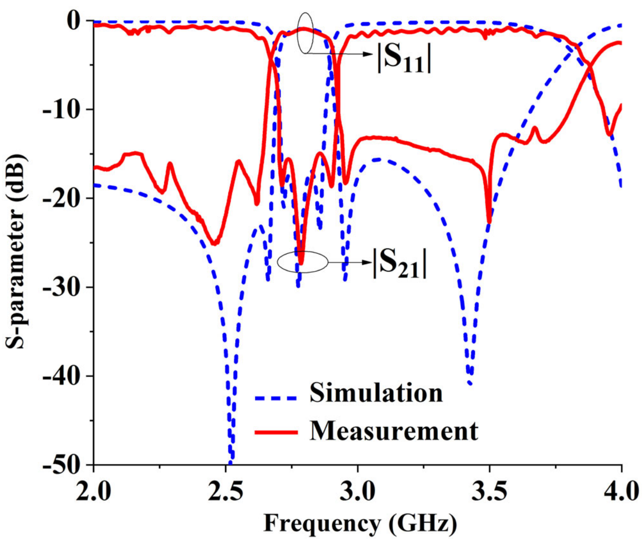

FIGURE 11 Simulation and measurement of the proposed band-stop filter (BSF) [Color figure can be viewed at wileyonlinelibrary.com]

of 18 dB, and in-band RL of 0.9 dB is achieved. The $|S_{11}|$ of nearby out-of band is about 16 dB. The final dimensions of the Type-II BSF are (unit: mm): $a = 40$, $b = 42$, $d_1 = 4.4$, $d_2 = 4.6$, $L_1 = 30$, $L_2 = 20.1$, $W_1 = 0.8$, $W_2 = 0.8$, $S = 5.1$, $S_1 = 0.9$, and $S_2 = 3.1$. (The configuration is shown in Figures 3A and 5A,B).

3 | EXPERIMENTAL RESULTS

Finally, the proposed Type II BSF is fabricated and measured, the photographs are given in Figure 10A,B, and the measured results are plotted in Figure 11 with the comparison to the simulated results. The measured in-band RL and IL are 1.3 dB and 15 dB, respectively. The $|S_{11}|$ of nearby out-of-band is about 13 dB, and the FBW slightly increases to 7.2% with the center frequency 2.792 GHz. The little difference between the simulation and measurement is due to the fabrication error and the small gap exists between two circuit layers. The measurement shows that the proposed BSF has compact size, high selectivity, and good out-of-band $|S_{11}|$ performance.

Table 1 presents the comparison with other reported BSFs, we see that the proposed BSFs have narrow band due to higher quality factor, compact size, and high selectivity.

4 | CONCLUSION

Novel BSF using coaxial-fed and slotted SIW cavities is proposed in this article. The SIW cavity resonator is excited by coaxial-fed line connecting the two ports without additional occupied space, and performs the desired stopband. Then, a first-order and second-order are designed, respectively. To improve the out-of-band performance, two types of BSFs using two cavity modes and one slot mode are presented. The slot in the middle plane acts as a resonant mode without additional circuit size to form a third-order BSF. Finally, the proposed third-order BSF is fabricated and measured, the measurement shows that the BSF has good band-stop property with compact size and high selectivity.

TABLE 1 Comparison with other reported BSFs

Work	Freq. (GHz)	In-band IL	FBW	Structure	Selectivity	Out-of-bandRL (dB)	Size
6	28	40	4%	Cavity	High	20	Large
7	13.3	19	4%	Cavity	Low	20	Large
9	9	30	5%	SIW	Low	10	Small
11	10.5	20	30%	SIW	Low	15	Small
This work	2.79	15	7.2%	SIW	High	13	Small

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