Progress In Electromagnetics Research C, Vol. 29, 29–39, 2012

MINIATURIZED SUBSTRATE INTEGRATED WAVEGUIDE DUAL-MODE FILTERS LOADED BY A SERIES OF CROSS-SLOT STRUCTURES

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Abstract—A family of miniaturized substrate integrated waveguide (SIW) dual-mode filters with a series of cross-slot structures etched on the waveguide surface are investigated and presented. By introducing the series of cross-slot structures: pure cross-slot, T-shaped loaded cross-slot and H-shaped loaded cross-slot in original dual-mode SIW filters, size reductions of 22.15%, 30.56% and 56.25% are achieved, respectively. Moreover, the proposed family of SIW dual-mode filters can produce two controllable transmission zeros. Compared with SIW dual-mode filters in references and original filter, proposed filters exhibit compact size while retain good performance of bandwidth and minimum insertion loss. To verify the presented design, three SIW dual-mode filters are fabricated on the standard printed circuit board process. The measured results are in good agreement with the simulation.

1. INTRODUCTION

Recently, more and more attentions have been drawn to band-pass filters with compact size, low insertion loss, easy manufacture and low-cost. Dual-mode filters are extensively applied in many microwave/RF circuits and systems because each dual-mode resonator can be used as a doubly tuned resonant circuit. Thus, the number of resonators required for a given degree of filter is reduced to half, resulting in a compact filter configuration. There are dual-mode filters based on waveguide or metal cavity with excellent performance [1, 2]. However, the design suffers disadvantages such as being bulky, costly and difficult to fabricate, etc. In particular, it is difficult to integrated waveguide elements into

Received 23 March 2012, Accepted 17 April 2012, Scheduled 21 April 2012
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a planar circuit. Microstrip dual-mode filters have been investigated for a long time [3–8]. Microstrip dual-mode filters present low cost, compact size, easy to be integrated with other planar circuit, but low Q-factors and high radiation losses. Although microstrip dual-mode filters are compact, some method such as cross slotted [9] can be used for more size reduction. SIW is a type of dielectric-filled waveguide which is synthesized in a planar dielectric substrate with linear arrays of metal vias to realize bilateral edge walls. It is synthesized on a planar substrate with linear periodic arrays of metallic vias by standard printed circuit board (PCB) or low-temperature co-fired ceramic (LTCC). SIW dual-mode filters [10, 11] have advantages of low-cost, low-profile, high Q factors and highly integrated. However, the sizes of current SIW dual-mode filters are larger than their microstrip counterparts. Multilayer technique can be applied to develop compact SIW dual mode filter [12]. But few single layer compact SIW dual-mode filter is investigated.

In this paper, a new family of miniaturized substrate integrated waveguide dual-mode filters with a series of cross-slot structures etched on the waveguide surface are investigated and presented. The series of cross-slot structures include pure cross-slot, T-shaped loaded cross-slot and H-shaped loaded cross-slot. Size reductions of 22.15%, 30.56% and 56.25% can be achieved by introducing pure cross-slot, T-shaped loaded cross-slot and H-shaped loaded cross-slot structures in original SIW dual-mode filters. At the same time, the proposed SIW dual-mode filters can produce two controllable transmission zeros. Experimental results of the fabricated filters are agreed well with the simulated results.

2. DESIGN OF MINIATURIZED SIW DUAL-MODE FILTERS

Figure 1 shows configurations of original substrate integrated waveguide dual-mode filter and the family of miniaturized SIW dual-mode filters with a series of cross-slot structures. Original SIW dual-mode filter is shown in Figure 1(a), which uses an orthogonal input/output (I/O) feed line. Two metallic vias near particular diagonal corners are set to perturb the two degenerate modes. The resonant frequency with respect to the degenerated resonant modes (TE_{m0n} and TE_{p0q}) of the original SIW dual-mode resonator can be calculated using the following equation [13]:

$$f_{mnl} = \frac{c_0}{2\sqrt{\mu_r \varepsilon_r}} \sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2} = \frac{c_0}{2\sqrt{\mu_r \varepsilon_r}} \sqrt{\left(\frac{p}{a}\right)^2 + \left(\frac{q}{b}\right)^2} \quad (1)$$

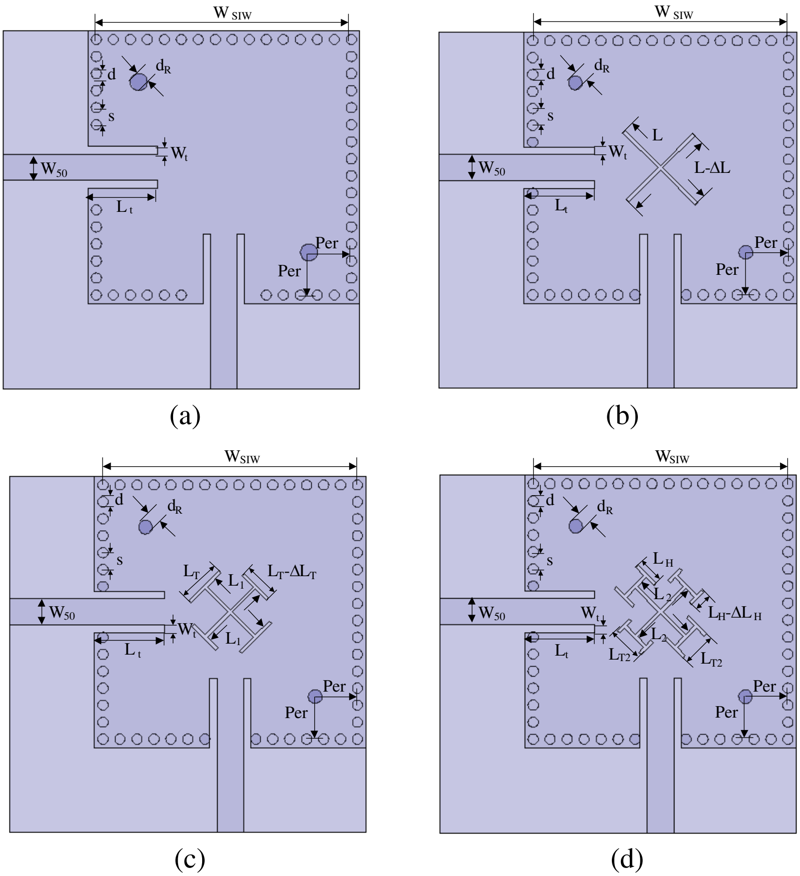


Figure 1. Configuration of original SIW dual-mode filter and the proposed family of filters, (a) original filter, (b) pure cross-slot, (c) T-shaped loaded cross-slot, (d) H-shaped loaded cross-slot.

where a and b are the effective width and length of the dual-mode SIW cavity, respectively; m, n, p and q are the indices of resonant modes; ε_r and μ_r are the permeability and permittivity of the SIW substrate; c_0 is the velocity of light in free-space. The dual-mode operation should meet some constraint such as $m \neq p$ and $n \neq q$. For a square SIW cavity, TE_{102} and TE_{201} modes resonate at the same frequency.

The miniaturized SIW dual-mode filter with pure cross-slot structure shown in Figure 1(b) consists of tilt cross-slot structure etched on the surface of original SIW dual-mode filter. Since the flowing path of electric current density on waveguide surface is rerouted and electrically stretched, the filter in Figure 1(b) is supposed to be able to miniaturize original SIW dual-mode filter.

By terminating the cross-slot on the SIW dual-mode filter with the T-shaped slot stubs, Figure 1(c) shows the T-shaped loaded cross-slot SIW dual-mode filter. Since longer flowing path of electric current density on SIW surface is observed, filter in Figure 1(c) exhibits more compact configuration than filter with pure cross-slot.

As shown in Figure 1(d), the H-shaped loaded cross-slot SIW dual-mode filter consists of cross-slot terminated by the H-shaped slot stub. The longest flowing path of electric current density on SIW surface leads to the smallest size among the proposed family of filters.

Following the physical parameters listed in Table 1, the proposed family of filters are formed on cheap substrate of Rogers RT/duriod 5880 (tm) with dielectric constant of $\varepsilon_r = 2.2$, loss tangent $\delta = 0.0009$ and $h = 0.508\,\text{mm}$. Frequency responses of the proposed filters are numerically simulated by Ansoft HFSS 11.

To verify the miniaturized capability of the proposed SIW dual-mode filters with cross-slot structures, Figure 2 shows simulated magnitudes of S parameters for original SIW dual-mode filter and the proposed family of filters. It is observed from Figure 2 that as evolved from Figure 1(a) to Figure 1(d), the resonant frequencies of degenerated resonant modes decrease from $f_1 = 15.79\,\text{GHz}$, $f_2 = 16.37\,\text{GHz}$ to $f_1 = 12.05\,\text{GHz}$, $f_2 = 12.44\,\text{GHz}$. As opposed to $f_0 = 16.08\,\text{GHz}$ (as concluded from Figure 2(a)) of original SIW dual-mode filter with the length of 15 mm, the center frequency of its corresponding pure cross-slot SIW dual-mode filter is lowered to 14.24 GHz (as concluded from Figure 2(b)). To achieve $f_0 = 14.24\,\text{GHz}$, the length of original SIW dual-mode filter should be 17 mm. Therefore, size reduction of 22.15% can be concluding by using pure cross-slot in original SIW dual-mode filter. As T-shaped loaded cross-slot structure is introduced in original SIW dual-mode filter, its center frequency is observed to be further decreased to 13.30 GHz (as concluded from Figure 2(c)). To achieve $f_0 = 13.30\,\text{GHz}$, the length

Table 1. Physical parameters of original SIW dual-mode filter and the proposed family of filters (unit: mm).

Symbol	Value	Symbol	Value	Symbol	Value	Symbol	Value
W_{SIW}	15.0	d	0.6	s	1.0	L_t	4.1
W_t	0.45	W_{50}	1.55	d_R	0.8	P_{er}	2.5
L	6	ΔL	0.5	L_1	4	L_T	2.5
ΔL_T	0.5	L_2	4	L_{T2}	1.5	L_H	1.5
ΔL_H	0.5						

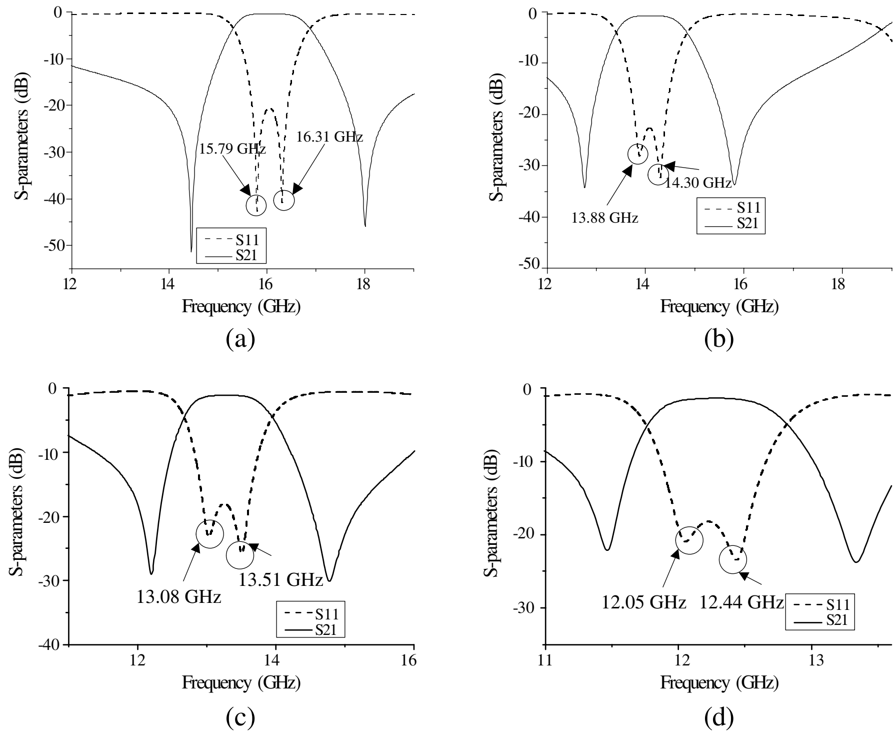


Figure 2. Simulated S parameters of original SIW dual-mode filter and the proposed family of filters, (a) original filter, (b) pure cross-slot, (c) T-shaped loaded cross-slot, (d) H-shaped loaded.

of original SIW dual-mode filter should be 18 mm. Therefore, size reduction of 30.56% can be concluding by using T-shaped loaded cross-slot in original SIW dual-mode filter. The center frequency is observed to be further decreased to 12.25 GHz (as concluded from Figure 2(d)) when the H-shaped loaded cross-slot structure is introduced in original SIW dual-mode filter. To achieve $f_0 = 12.25$ GHz, the length of original SIW dual-mode filter should be 20 mm. Therefore, size reduction of 56.25% can be concluding by using H-shaped loaded cross-slot in original SIW dual-mode filter.

For pure cross-slot SIW dual-mode filter, Figure 3 shows the simulated insertion loss of different slot length L and ΔL. When the slot length L increases from 4 mm, 5 mm to 6 mm, the center frequencies decrease from 15.45 GHz, 14.82 GHz to 14.08 GHz, as shown in Figure 3(a). When ΔL increases from 0.5 mm, 0.75 mm to 1.0 mm, higher transmission zeros increase from 15.81 GHz, 16.09 GHz

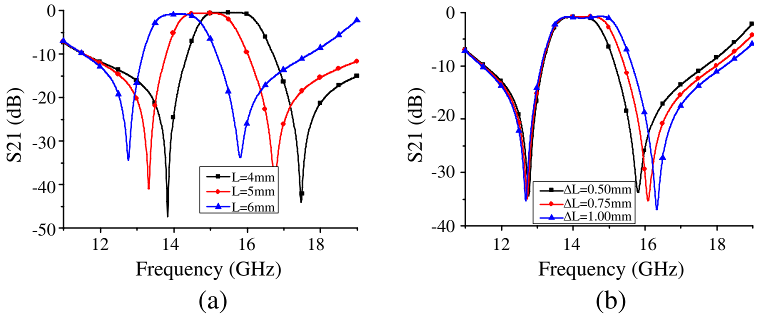


Figure 3. Simulated insertion loss of different slot length L and ΔL for pure cross-slot SIW dualmode filter.

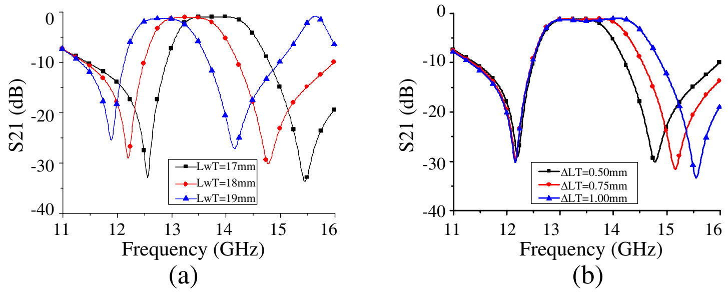


Figure 4. Simulated insertion loss of different whole slot length L_{WT} and difference between the two T-shaped stubs ΔL_T for T-shaped loaded cross-slot SIW dual-mode filter.

to 16.32 GHz, as shown in Figure 3(b). Therefore, the center frequency and transmission zeros of pure cross-slot SIW dual-mode filter can be adjusted.

For T-shaped loaded cross-slot SIW dual-mode filter, Figure 4 shows the simulated insertion loss of different whole slot length L_{wT} and difference between the two T-shaped stubs ΔL_T. The whole slot length of T-shaped loaded cross slot L_{wT} is defined as follows:

$$L_{wT} = 2 \times L_1 + 4 \times L_T \tag{2}$$

when the whole slot length of T-shaped loaded cross slot L_{wT} increases from 17 mm, 18 mm to 19 mm, the center frequencies decrease from 13.76 GHz, 13.27 GHz to 12.81 GHz, as shown in Figure 4(a). When the difference between the two T-shaped stubs ΔL_T increases from 0.5 mm, 0.75 mm to 1.0 mm, higher transmission zeros increase from 14.78 GHz, 15.16 GHz to 15.55 GHz while lower transmission zero remains the

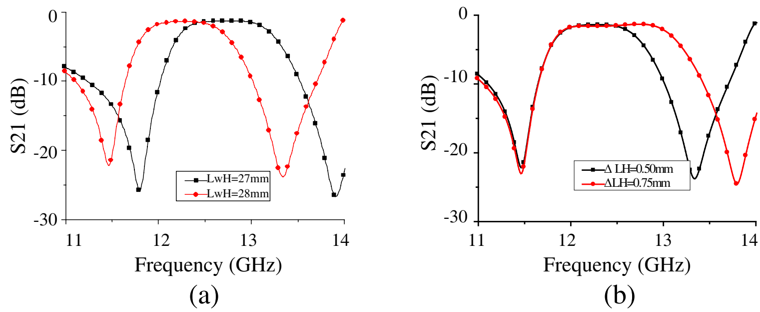


Figure 5. Simulated insertion loss of different whole slot length L_{WH} and difference between the two H-shaped stubs ΔL_H for H-shaped loaded cross-slot SIW dual-mode filter.

same, as shown in Figure 4(b). Therefore, the center frequency and transmission zeros of T-shaped loaded cross-slot SIW dual-mode filter can be adjusted.

For H-shaped loaded cross-slot SIW dual-mode filter, Figure 5 shows the simulated insertion loss of different whole slot length L_{wH} and difference between the two H-shaped stubs ΔL_H. The whole slot length of H-shaped loaded cross slot L_{wH} is defined as follows:

$$L_{wH} = 2 \times L_2 + 4 \times L_{T2} + 8 \times L_H \tag{3}$$

When the whole slot length of H-shaped loaded cross slot L_{wH} increases from 27 mm to 28 mm, the center frequencies decrease from 12.69 GHz to 12.25 GHz, as shown in Figure 5(a). When the difference between H-shaped stubs ΔL_H increases from 0.5 mm to 0.75 mm, higher transmission zeros increase from 13.34 GHz to 13.79 GHz, while lower transmission zero remains the same, as shown in Figure 5(b). Therefore, the center frequency and transmission zeros of H-shaped loaded cross-slot SIW dual-mode filter can be adjusted.

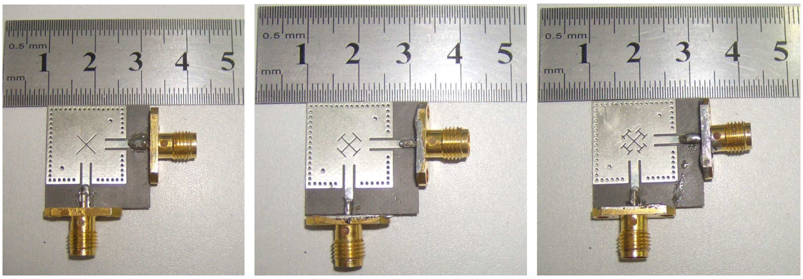
For comparison, the center frequency, 3 dB fractional bandwidth, effective normalized circuit size (ENCS) and minimum simulated insertion loss of the filters in references [14, 15], original SIW dual-mode filter and the proposed family of miniaturized filters are listed in Table 2. In this table, the effective normalized circuit size (ENCS) is given by:

$$\text{ENCS} = \text{effective physical size}/\lambda_g \times \lambda_g \tag{4}$$

where λ_g is the guided wavelength of the center frequency. As seen from Table 2, the proposed family of miniaturized filters with a series of cross-slot structures have advantages of small ENCSs while retain good performance of bandwidth and minimum insertion loss.

Table 2. Performance comparisons among published SIW filters, original SIW dual-mode filter and the proposed family of miniaturized filters.

	Simulated center frequency (GHz)	Simulated 3 dB fractional bandwidth (%)	Effective normalized circuit size (ENCS)	Simulated minimum insertion loss (dB)
Ref. [14]	5.00	4.00	1.12×1.12	0.7
Ref. [15]	14.42	2.64	1.07×1.07	2.6
Original SIW dual-mode filter	16.05	9.41	1.19×1.19	0.41
Pure cross-slot	14.09	9.16	1.04×1.04	0.79
T-shaped loaded cross-slot	13.30	8.12	0.99×0.99	0.96
H-shaped loaded cross-slot	12.25	6.86	0.91×0.91	1.21



(a) (b) (c)

Figure 6. Photograph of fabricated miniaturized SIW dual-mode filters with (a) pure cross-slot, (b) T-shaped loaded cross-slot, (c) H-shaped loaded cross-slot.

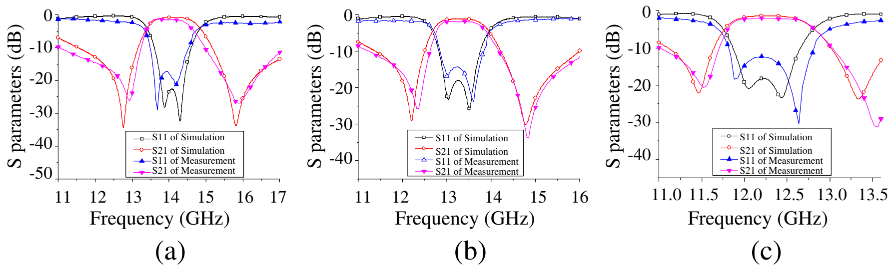


Figure 7. Simulated and measured frequency responses of the proposed family of SIW dual-mode filters with (a) pure cross-slot, (b) T-shaped loaded cross-slot, (c) H-shaped loaded cross-slot.

3. EXPERIMENTAL RESULTS AND DISCUSSION

Photography of the fabricated miniaturized SIW dual-mode filters loaded by a series of cross-slot structures are shown in Figure 6. The simulated and measured S_{11} and S_{21} parameters for the proposed family of filters are shown in Figure 7. Good agreement can be observed between simulated and measured frequency responses of the proposed filters.

Figure 7(a) shows simulated and measured S parameters of pure cross-slot SIW dual-mode filter. As shown in Figure 7(a), the pure cross-slot SIW dual-mode filter has a center frequency of 13.94 GHz with a bandwidth of 1.08 GHz. The measured insertion loss of the proposed filter is 1.38 dB over passband, while the simulated result is 0.79 dB. Two transmission zeros of $f_1 = 12.96$ GHz and $f_2 = 15.88$ GHz can be observed.

Figure 7(b) shows simulated and measured S parameters of T-shaped loaded cross-slot SIW dual-mode filter. As shown in Figure 7(b), the T-shaped loaded cross-slot SIW dual-mode filter has a center frequency of 13.30 GHz with a bandwidth of 0.92 GHz, The measured insertion loss of the proposed filter is 1.76 dB over passband, while the simulated result is 0.96 dB. Two transmission zeros of $f_1 = 12.36$ GHz and $f_2 = 14.80$ GHz can be observed.

Figure 7(c) shows simulated and measured S parameters of H-shaped loaded cross-slot SIW dual-mode filter. As shown in Figure 7(c), the H-shaped loaded cross-slot SIW dual-mode filter has a center frequency of 12.26 GHz with a bandwidth of 0.84 GHz, The measured insertion loss of the proposed filter is 1.97 dB over passband, while the simulated result is 1.21 dB. Two transmission zeros of $f_1 = 11.52$ GHz and $f_2 = 13.56$ GHz can be observed.

The measured insertion losses in Figure 7 are a little larger than simulated results, which is mainly caused by the high loss tangent of substrate and high transmission loss of connectors. The proposed family of filters has attractive frequency response and smaller size with respect to the other SIW dual-mode filters.

4. CONCLUSION

The new methods of designing miniaturized SIW dual-mode filters with a series of cross slot structures have been presented in this paper. By using the methods of introducing pure cross-slot, T-shaped loaded cross-slot and H-shaped loaded cross-slot in original SIW dual-mode filters, we found filters with size reductions of 22.15%, 30.56% and 56.25%, respectively. Compared with SIW dual-mode filters in references and original filter, the proposed family of filters exhibit compact size while retain good performance of bandwidth, minimum insertion loss and controllable transmission zeros. Measured results validate the predicted ones well. It is our belief that this developed family of filters is effective in the exploration of size-reduction dual-mode SIW filter.

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