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Substrate integrated waveguide filter based on novel coupling-enhanced semicircle slots for 5G applications

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Abstract The substrate integrated waveguide (SIW) technology is promising in millimeter wave circuit design because of its low radiation loss and easy manufacturing. In this letter, an SIW filter with novel coupling-enhanced semicircle slots is presented. The coupling coefficients between resonators can be enhanced by 115% with a one-octave tuning range. To demonstrate the proposed concept, a 4-pole filter prototype is designed and fabricated. The measured results show excellent agreement with the simulated results.

Keywords: SIW filter, coupling enhance, 5G
Classification: Microwave and millimeter-wave devices, circuits, and modules

1. Introduction

With the increasing requirements of high data rates in communication, the fifth generation (5G) of cellular mobile communications is considered the most promising and practical standard in millimeter wave communication [1, 2, 3]. The systems [4, 5, 6, 7] and components [8, 9, 10, 11] working at the mm-wave band have been broadly researched recently and are potential to be massively manufactured using the present technologies.

Surface acoustic wave (SAW) [12, 13, 14] and bulk acoustic wave (BAW) [15, 16, 17] filters are used extensively in mobile communication less than 6 GHz because of their small size, low cost and temperature performance at low frequencies. However, given the higher operating frequency (above 20 GHz) in 5G, the size of SAW and BAW filters is too small for economic and massive fabrication [18]. In addition, the insertion loss (IL) of SAW and BAW at millimeter-wave frequency is also unacceptably high. Therefore, the cavity filter with a reasonable size and a relatively low IL presents a promising alternative in 5G.

Substrate integrated waveguide (SIW) technology can be used to design small and low-cost cavity filters at millimeter-wave frequency using coupling matrix [19, 20]. The most common method for controlling the resonators' coupling in an SIW filter is to adjust the coupling iris width in the via wall between two resonant cavities [21, 22, 23, 24, 25, 26]. The coupling should be stronger with a larger iris width. Nevertheless, the iris width can not be much flexibly changed since the minimum distance and radius of metallized vias are limited by different processes. Expecially, the tuning of coupling will be constrained when low-cost processes with low accuracy and large minimum characteristic sizes are used to fabricate high frequency devices usually required expensive processes.

Besides coupling irises, there are other coupling structures can be used to tuning resonators coupling in filters. CPW coupling [27] or combline coupling [28] can tune coupling flexibly even between nagtive and positive coupling. However, those kinds of coupling is relatively weak and need to keep the inevitable iris coupling weak enough not to overwhelm the performance of CPW or combline couplings. A pair of cross slots [29] located upside and bottom of the SIW filter is used to generate nagtive coupling between resonators. Unfortunately, double-side structures are not quite acceptable for the advanced integrated process (InP, GaAs etc.) because those processes usually include thick and lossy substrates expensive to be removed.

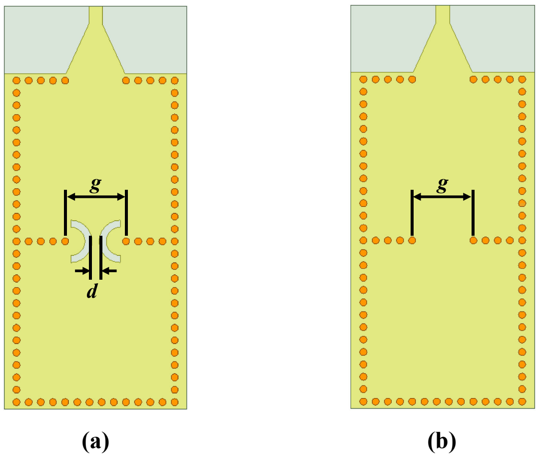

Fig. 1. Proposed coupling structure in single-port simulation configuration for coupling coefficient extraction. (a) proposed structure with semicircle slots. (b) conventional structure without semicircle slots.

In this letter, a novel coupling-enhanced semicircle slots, which can support stronger coupling based on iris coupling, is proposed to design an SIW filter. In addition, the coefficients of iris coupling strength (coupling coefficients) can be piecewise-continuously tuned during a wide range by the distance between the slot pair. The measured results of the filter show well agreement with the simulated results.

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The rest of this letter is organized as follows: Section II analyses the effects of coupling-enhanced semicircle slots by EM simulation. The designing and measurement details of a 4-pole filter are presented in Section III to demonstrate the performance of the slots. Finally, Section IV discusses the main conclusions of this work.

2. Coupling-enhanced slot analysis

The proposed and conventional coupling structure is shown in Fig. 1, where a pair of cavities is coupled by the iris in the common via wall. As shown in Fig. 1(a), a pair of semicircle slots in the top metal layer are used to enhance and adjust the coupling.

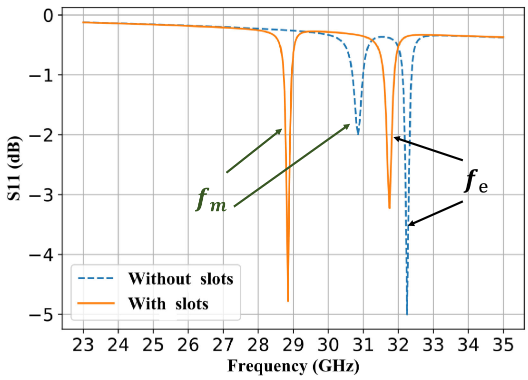


Fig. 2. Comparison of S_{11} between coupling simulation with and without semicircle slots.

The coupling coefficient (k) can be extracted from single-port simulation of the cavity pair. Fig. 2 shows two resonant frequencies f_e and f_m that correspond to virtual electric and magnetic walls between the cavities, respectively. The coupling coefficient is then calculated by [30]:

$$k = \frac{(f_e^2 - f_m^2)}{(f_e^2 + f_m^2)} \quad (1)$$

With the slots added, f_e remains approximately the same while f_m dramatically reduces, thereby resulting in a larger coupling coefficient. At f_e, with a virtual electric wall between the cavities, the electric fields on the slots are approximately zero as shown in Fig. 3(a). Therefore, f_e is hardly influenced by the introduction of the slots. On the contrary, the electric fields are much influenced at f_m, as shown in Fig. 3(b), leading to a dramatical reduction of f_m. In summary, a larger coupling coefficient (k) occurs when semicircle slots pair shows.

The coupling coefficient can be adjusted conveniently by tuning the distance (d) between the slots pair and the iris width (g) in the via wall. The coupling coefficients curve is presented in Fig. 4, which also shows its dependence on d and g. The conventional case without the slots is also shown for comparison. With the slots added, the coupling strength can be generally enhanced by 15% to 115%. The iris width g can be used as coarse tuning of the coupling, whereas the slots pair distance d can be used as fine tuning.

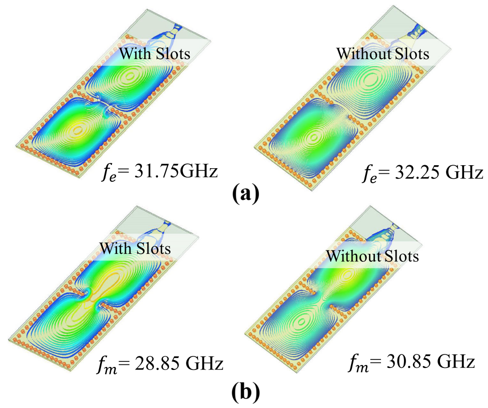


Fig. 3. Comparisons in electric fields between coupling simulation with and without semicircle slots: (a) f_e. (b) f_m.

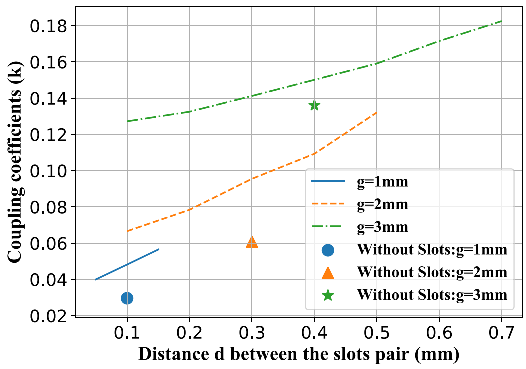


Fig. 4. Coupling coefficients (k) versus semicircle slots pair distance (d) and the iris width (g).

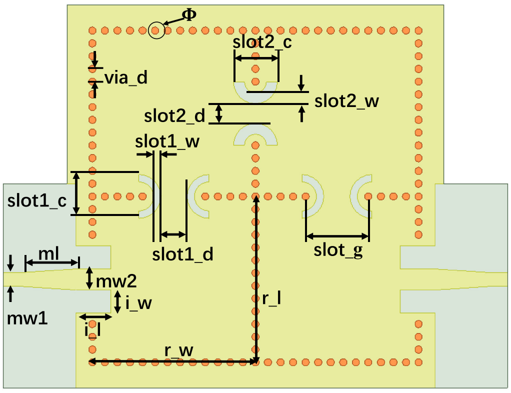
Table I. Critical dimensions of the filter

Name	Value (mm)	Name	Value (mm)
mw1	0.38	r_l	4.55
ml	1.50	slot_g	1.72
mw2	0.58	slot1_c	1.20
i_w	0.95	slot1_w	0.20
i_l	0.63	slot1_d	0.72
via_d	0.35	slot2_c	1.20
Φ	0.2	slot2_w	0.3
r_w	4.47	slot2_d	0.54

3. Filter designing and experiments

Using the coupling-enhanced semicircle slots, a four-order SIW cavity filter working at the 28-GHz band was designed and fabricated. The critical dimensions and generalized coupling matrix are shown in Fig. 5 and listed in Table I. The relationship between coupling coefficients (k) and elements (M) of generalized coupling matrix is $k = (BW/f_0) \cdot M$, in which f_0 is the center frequency of the filter's passband and BW is the 3-dB bandwidth of the filter. Moreover, the input and output couplings are realized using the same structure in [23].

The substrate of the filter is Rogers 5880 with a thickness of 0.127 mm, relative dielectric constant of



$$
\begin{bmatrix}
0 & 1.0352 & 0 & 0 & 0 & 0 \\
1.0352 & 0 & 0.9106 & 0 & 0 & 0 \\
0 & 0.9106 & 0 & 0.6999 & 0 & 0 \\
0 & 0 & 0.6999 & 0 & 0.9106 & 0 \\
0 & 0 & 0 & 0.9106 & 0 & 1.0352 \\
0 & 0 & 0 & 0 & 1.0352 & 0
\end{bmatrix}
$$

Fig. 5. Dimensions of the 4-order SIW cavity filter and related generalized coupling matrix.

$\epsilon_r = 2.2$, and loss tangent of $tan\,\delta = 0.0009$. The conductivity of the covered copper was set to standard value (5.8×10^7 S/m).

The proposed filter is measured by using the Agilent PNA Network Analyzer E8363B. The Thru-Reflect-Line (TRL) calibration method was utilized to eliminate the parasitic effects from measurement connectors. Fig. 6 shows that the measurement results agree well with the simulated results except for a worse return loss (RL) at the upper passband due to fabrication errors and a slightly larger insertion loss (IL).

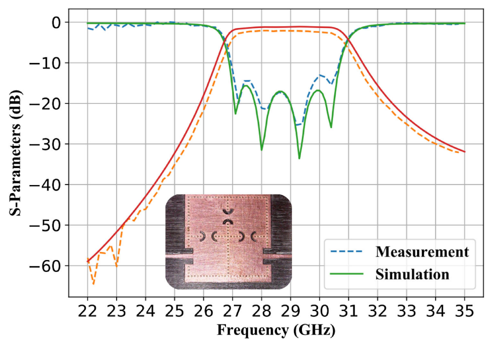


Fig. 6. Measured and simulated S-parameters and photograph of the proposed filter.

In Fig. 7, the minimum simulated IL without covered conductor loss (under PEC boundary condition) is only about 0.27 dB, which comes from the radiation of semicircle slots. Therefore, the additive 1 dB loss, compared the measurement IL against the simulated IL considering about standard cover copper conductivity, should come from the lower conductivity limited by fabrication.

The measured minimum in-band IL is 2.0 dB, the 3-dB bandwidth (BW) ranges from 27.2 GHz to 30.5 GHz, with a fractional bandwidth (FBW) of 11.4%, and the average RL is better than 15 dB. Table II compares the proposed filter with other SIW filters. The sizes of these filters are normalized by the guided wavelength (λ_g) of a 50 Ω microstrip line at center frequency. The comparison shows that the proposed filter has a good performance with a compact size.

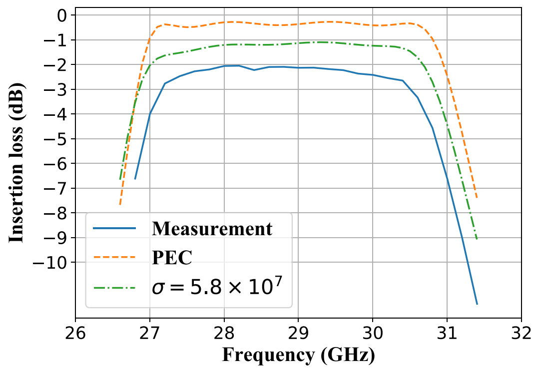


Fig. 7. Comparison of insertion loss with and without conductive loss.

Table II. Comparison with counterparts

Ref.	Poles	IL (dB)	BW (GHz)	RL (dB)	Size (λ_g, λ_g)
[23]	4	1.0	20.1–20.9	15	1.7,1.3
[24]	5	3.9	79.0–81.0	13	2.5,1.2
[25]	3	1.7	27.5–28.5	16	2.0,0.7
[26]	3	4.3	91.0–94.3	13.5	2.3,1.6
This work	4	2.0	27.0–30.8	14	1.2,1.1

4. Conclusion

A semicircle slots pair is proposed to enhance and tune the inter-resonator couplings in SIW filters. With the slots pairs utilized, the coupling coefficients can be enhanced by 15% to 115% and also tuned flexibly by changing the distance between the slot pairs. Therefore, with the proposed slot pairs, a four-pole SIW filter at 28-GHz band was designed and fabricated to demonstrate a favorable performance and compact sizes.

In addition, the proposed technique can also be implemented on integrated chips further, using metal layers, dielectric material between metal layers and through vias. With much higher accuracy and smaller sizes from integrated chip process, the proposed coupling-enhanced semicircle slots are potential to design filters at frequency of higher than 28-GHz band.

Acknowledgments

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