DEPARTMENT OF ELECTRONICS AND
COMMUNICATION ENGINEERING
INDIAN INSTITUTE OF INFORMATION
TECHNOLOGY, DESIGN AND
MANUFACTURING KANCHEEPURAM
CHENNAI - 600127

Synopsis Of

DESIGN AND DEVELOPMENT OF PASSIVE SUBSTRATE INTEGRATED WAVEGUIDE COMPONENTS

A Thesis

To be submitted by

D. THARANI

For the award of the degree

Of

DOCTOR OF PHILOSOPHY

1 Abstract

Wireless communication systems are more crowded due to multiple standards (WLAN, WiMAX, 5G, etc). Because of this, there is a huge demand in the design of multi-band passive devices such as filters, power dividers, diplexers, etc. These devices yield the benefits of simultaneous operation at multiple frequencies, reduced area and cost of fabrication. Compact microwave components have gained much importance due to the size miniaturization of modern wireless communication systems. This thesis investigates two methodologies to develop microwave components with multi-band functionality. One approach is the design of microwave components operating concurrently at several distinct bands, including the required frequencies. Another way is the development of component functioning over a wide and continuous band that covers the supporting frequency standards.

Substrate Integrated Waveguide (SIW) technology bridges the performance gap between microstrip and waveguide. It has emerged as a promising platform to develop components with low loss, low cost, compact size, the capability of easy fabrication and integration. By loading multiple Complementary split-ring resonators (CSRRs) on the top of the SIW surface, multiple passbands were obtained below the SIW cutoff frequency. This method develops SIW based multi-band microwave passive components. The slot-loading mechanism is used to design wideband microwave components.

The first part of the thesis discusses the development of SIW based dual-band power divider (PD) (for X-band), wideband PD (Ku and K-band), tri and quad-band PD (WLAN, WiMAX, 5G, INSAT). A highly compact dual-band PD is developed using the half mode SIW (HMSIW) for 5G/WLAN communications. The second part of the thesis concentrates on the design of SIW based multi/wideband filter and HMSIW diplexer. A compact SIW filter with good out-of-band rejection is demonstrated for the 5G application. Then a dual-band SIW filter useful for 5G applications is proposed. The multi-mode resonant behavior of slots and stopband property of defective ground structure (DGS) is utilized to design a wideband SIW filter useful for X, Ku and K-band applications. A highly miniaturized diplexer is introduced using HMSIW and is compatible with WiMAX/WLAN communications.

2 Introduction

Several standards exist in the modern wireless communication system to provide various communication services like WLAN, WiMAX, 5G, etc. Each of these standards operates at specific frequencies and differs from country to country. A single-band microwave component does not satisfy the requirements of modern multi-standard communication systems. The number of RF circuits increases with the number of frequency bands accommodated increases. Therefore, the design of multi-band microwave passive components is becoming a hotspot for researchers [13]. Recently, the realization of microwave components by SIW technology has gained more attention due to its combined benefits of both microstrip and waveguide [9]. The development of SIW based multi-band microwave components poses challenges because these components should perform similar functions simultaneously at multiple frequencies with low loss, good performance, and compact size.

The evanescent mode technique is preferred in the design of compact microwave components because of the ease of etching resonators on the top/bottom metallic surface of SIW. According to the theory of evanescent mode propagation, when CSRR is loaded in the SIW due to the resonant nature of CSRR, a forward passband is generated well below the SIW cut-off frequency [8]. Hence the operating frequency is reduced which ensures the miniaturization of microwave components.

In literature, most of the SIW power dividers are developed for single-band operation [8], [7]. The multi-band functionality is not considered for the multiple standards available in modern wireless communication systems. The reported HMSIW dual-band power divider [20] has a higher loss and larger size. The wideband SIW power dividers reported in the literature lack compact size. [11], [15]. Most of the reported SIW filters do not simultaneously possess low insertion loss, good band rejection characteristics, and compact size [18], [19], [14]. Some of the reported dual-band SIW filters have small bandwidth [21], [23] and high insertion loss [21]. The reported SIW filters have a wideband but at the cost of a larger size [2], [16]. Most of the reported SIW diplexers do not have low insertion loss, good fractional bandwidth and compact size [5], [4]. In this thesis, compact SIW based microwave passive components are implemented that are useful for multi-standard wireless communication.

3 Objectives

The prime objectives of the thesis are as follows:

(a) To investigate the multi and wideband characteristics of the SIW power divider supporting multi-band communication.
  - To design and develop dual, tri, quad-band and wideband SIW power divider with equal power division, low loss, better isolation, passband performance and compact size.
  - To design and develop a highly compact power divider based on HMSIW with equal and unequal power division ratio for dual-band applications.

(b) To investigate SIW based single, dual and wideband filters with the characteristic of low loss, good out-of-band rejection (OBR) capability and miniaturized size.
  - To design and develop a low-profile SIW filter with the characteristic of good OBR for 5G applications.
  - To design and develop a miniaturized dual-band SIW filter useful for 5G applications.
  - To design and develop a compact wideband SIW filter with emphasis on good OBR.

(c) To demonstrate a compact diplexer based on HMSIW having low loss, better bandwidth and isolation.

4 Existing Gaps Which Were Bridged

The literature review reveals that the development of SIW passive components supporting multi-band communication is still infancy. For instance, to support three different standards: three power amplifiers, three filter blocks, etc., are required, and this is not an efficient solution in terms of power utilization, area, and fabrication cost [13]. The optimum solution is to utilize multi-frequency circuit components that operate simultaneously at several frequencies. This thesis demonstrates the compact, high-performance SIW-based fundamental microwave components such as power divider, filter, and diplexer beneficial for multi/wideband communications.

Design procedure:

The following steps are involved in designing SIW-based microwave components developed in the thesis using the theory of evanescent mode propagation.

- Initially the dominant mode cut-off frequency of SIW is computed by,

$$f_c(_{TE_{10}}) = \frac{c}{2W_{eff,SIW}\sqrt{\epsilon_r}} \tag{1}$$

  Here c represents the velocity of light in a vacuum, ϵ_r represents the relative permittivity of the dielectric substrate.

- The effective width of SIW '$W_{eff,SIW}$', is determined by [1]

$$W_{eff,SIW} = W_{SIW} - \frac{d^2}{0.95s} \tag{2}$$

  where W_{SIW} is the width of SIW, d and s represents the diameter of the via holes and spacing between them.

- To avoid leakage through the gap between the vias, d and s have to meet the following design constraints [10].

$$\frac{s}{d} \leq 2 \quad \text{and} \quad \frac{d}{\lambda_g} \leq 0.1 \tag{3}$$

  where λ_g denotes the guided wavelength at the corresponding operating frequency.

- The electrical length of resonators is initially assumed to be half the guided wavelength ($\lambda_g/2$) at the corresponding operating frequency and a rough estimate of the wavelength in an inhomogeneous medium.

$$\lambda_g = \frac{c}{f_{desired}\sqrt{\epsilon_{eff}}} \tag{4}$$

  where ϵ_{eff} is the effective permittivity of the substrate which is given by,

$$\epsilon_{eff} = \frac{\epsilon_r + 1}{2} \tag{5}$$

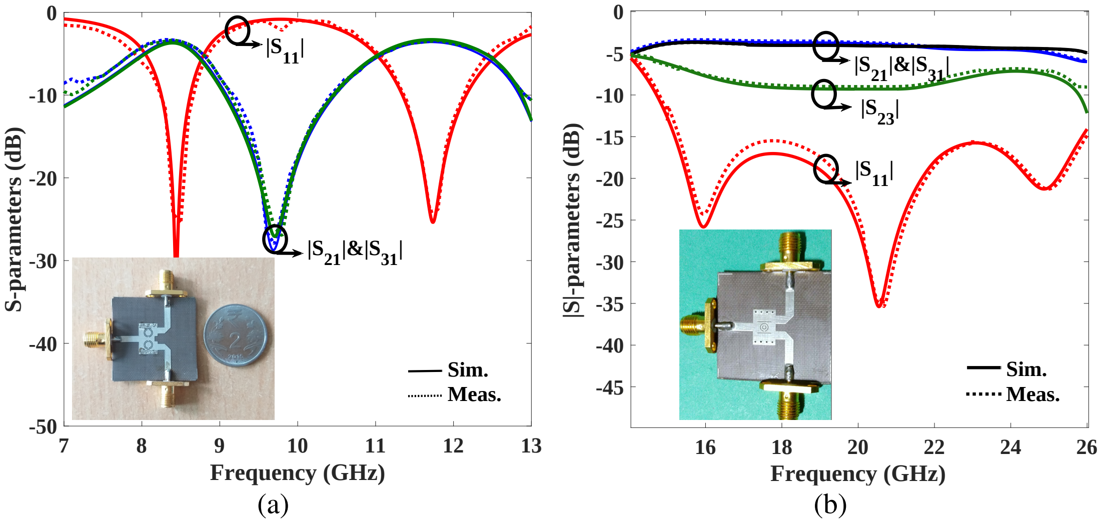


Figure 1: Simulated and measured S-parameters of (a) dual and (b) wideband SIW PD. (with fabricated prototype at the inset)

Multi/Wideband SIW power divider:

As a preliminary study to support multi-standard communication, SIW dual-band PD is developed. Here the dual resonance is provided by the double-ring circular CSRRs incorporated on the top of the SIW. The measured results in Fig. 1a show that 3-dB equal power division happens at 8.4/11.7 GHz with return loss (RL) of >23 dB and insertion loss (IL) of <0.6 dB.

The wideband approach is used to develop SIW PD to support multi-standard communication. The combined resonance provided by the CSRR and two identical slots results in 3-dB equal power division over a wideband as shown in Fig. 1b with RL of >15 dB and IL is 0.89 dB. The tri and quad-band capabilities of SIW PD are demonstrated by utilizing single-ring modified circular CSRRs (MC-CSRRs) on the top cover

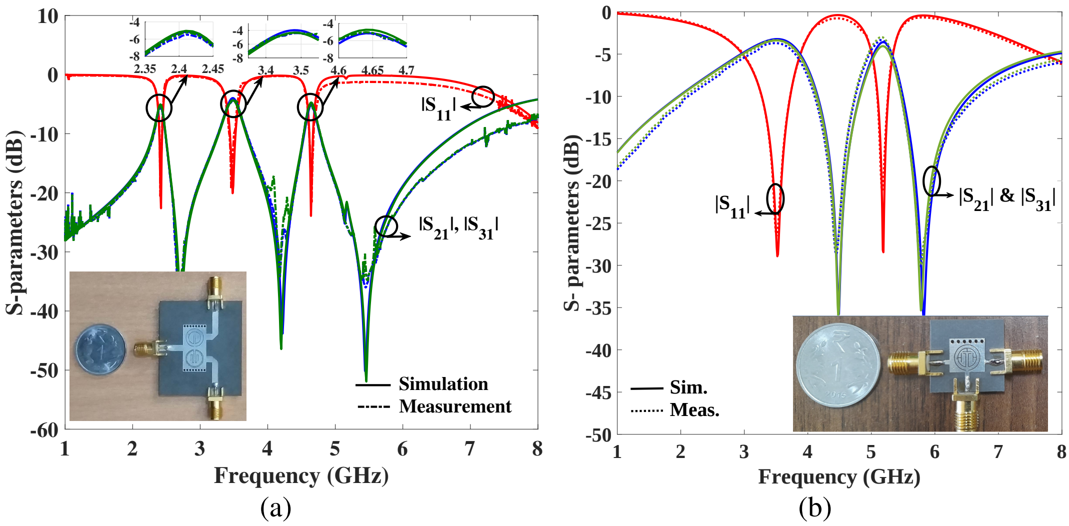


Figure 2: Simulated and measured S-parameters of (a) tri-band SIW PD and (b)dual-band HMSIW PD.(with fabricated prototype at the inset)

Table 1: Performance comparison of the proposed SIW PD with other related works.

PD	Ref.	CF (GHz)	3-dB FBW (%)	RL (dB)	IL (dB)	ISL(dB)	Size (λ_g^2)
Single	[8]	5.82	15.8	24	1.2	-	0.078
	[7]	5.39	13.73	13	1.3	-	0.043
Dual	**Proposed**	**8.4/11.7**	**4.62/6.55**	**24.5/23.8**	**0.43/0.6**	**>10**	**0.134**
Wide	[11]	9	22.3	12	1.1	>20	1.09
	[15]	9.77	70	>12.5	-	>10	1.175
	Proposed	**20.4**	**54.9**	**>15**	**0.89**	**<10**	**0.58**
Tri & Quad	[17]	3.47/4.73/6.31	-	>20	3.8/4.85/4.06	>14	0.03
		3.34/4.82/6.17/7.66	-	> 19	3.5/3.95/4.26/4.85	>12	0.02
	Proposed	**2.41/3.46/4.65**	**2.07/4.62/1.94**	**>19**	**2.21/1.51/2.11**	>12.8	**0.0193**
		2.42/3.78/4.74/5.8	**3.31/4.23/2.53/2.75**	**>17.6**	**2.72/1.36/1.61/1.7**	>10.86	**0.0193**
Dual	[6]	2.45/5.8	11.4/5.9	>34/28	1.3/2.2	-	0.0297
	[20]	2.43/3.5	13.3/6.3	>20	1.2/1.75	-	0.261
	Proposed	**3.5/5.17 (equal)**	**25.58/6.4**	**>26.3/18.22**	**<0.7/0.4**	**>10**	**0.0156**

CF: Center Frequency; FBW: Fractional Bandwidth; ISL: Isolation.

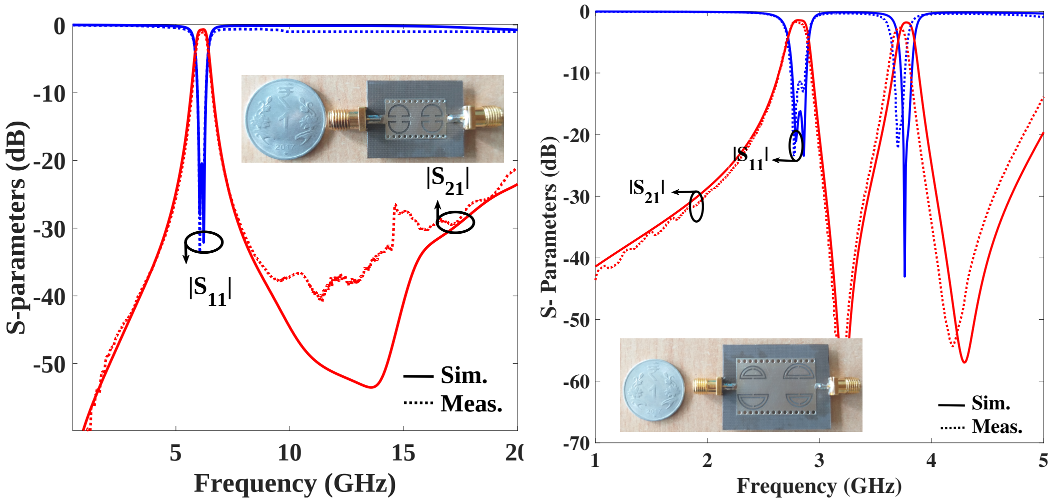
of SIW. From Fig. 2a, it is observed that the tri-band PD operates at 2.41/3.46/4.65 GHz with IL of <2.21 dB and RL of >19.34 dB.

Dual-band HMSIW power divider:

To further achieve size reduction, HMSIW is utilized to develop miniaturized dual-band PD by loading MC-CSSR. The S-parameters of equal dual-band HMSIW PD shown in Fig. 2b, reveals that the tested RL at 3.5/5.17 GHz is >18 dB.The unequal power division ratio of 2.45 dB is achieved by asymmetric location of output ports. From the comparison Table 1, it is observed that the proposed multi/wideband SIW PDs has compact size [11, [15], [17], [6], [20], minimum IL [7], [8], [11], [17], [6], [20] and good RL [7], [11], [15].

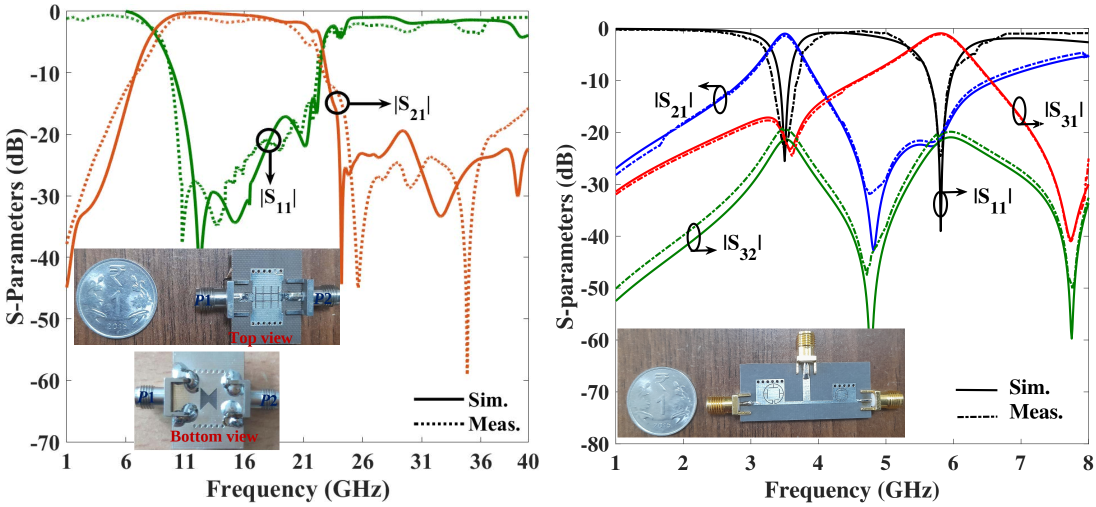
Multi/Wideband SIW filter:

A miniaturized SIW filter incorporated with D-shaped resonators useful for 5G (sub-6 GHz) applications is developed. The double-stage filter has a tested IL of 1.07 dB



(a) (b)

Figure 3: Simulated and measured S-parameters of (a) single-band and (b) dual-band SIW filter.(with fabricated prototype at the inset)



(a) (b)

Figure 4: Simulated and measured S-parameters of (a) wideband SIW filter and (b) HMSIW diplexer.(with fabricated prototype at the inset)

withfor the passband centered at 6.11 GHz as shown in Fig. 3a. The stopband rejection is better than 22 dB throughout the frequencies up to 20 GHz. Then a miniaturized dual-band SIW filter is developed utilizing the dual resonating behavior of asymmetric double-ring D-shaped resonators. Filter prototype has two passbands centered at 2.82/3.73 GHz withmeasured IL <1.76 dB/1.93 dB and the RL is >13.5 dB/20 dB at the two passbands, respectively as plotted in Fig. 3a. A compact SIW wide bandpass filter (BPF) with wide OBR beneficial for X, Ku, and K band applications is proposed. The wider passband is achieved by the multimode resonance provided by slots loaded on the top layer of SIW and the bow tie-shaped DGS enhances the stopband performance. Fig. 4a shows that the filter has a tested IL of >1.52 dB and RL is >17.6 dB. Further, the proposed filter has a stopband rejection of 16 dB up to 40 GHz.

HMSIW diplexer:

To support the recent 5G (3.5 GHz) [3] and existing WLAN (5.8 GHz) applica-

Table 2: Comparison of the proposed SIW filter and diplexer with previously reported works.

SIW Component	Ref.	CF (GHz)	3-dB FBW (%)	IL (dB)	RL (dB)	OBR (dB) freq. limit. (GHz)	Size (λ_g^2)
Single-band filter	[19]	8	5	1.7	>11	>30 (11.6-12.6)	0.1764
	[14]	3.42-3.52	-	<2.5	>10	>50 (3.5-4)	1.801
	Proposed	**6.11**	**8.96**	**1.07**	**>20**	**>22 (7.5-20)**	**0.116**
Dual-band filter	[23]	3.6/6.4	3.3/2.4	1.3/1.8	>14	> 55 (7.7-9)	0.1682
	[21]	13/14	2/1.78	2.86/3.37	>20/10	> 25 (14.4-25)	3.85
	Proposed	**2.82/3.73**	**6.38/3.48**	**1.76/1.93**	**>13.5/ >20**	**>16 (3.88-5)**	**0.0816**
Wideband filter	[2]	8.5	42	1.1	11	(11-18.5)	0.7875
	[16]	13	48	1.1	>14	(16.5-20)	1.537
	Proposed	**14.74**	**76**	**<1.5**	**>17.6**	**(23 - 40)**	**0.7035**
Diplexer	[5]	4.41/5.83	6.06/4.83	2.2/2.5	14/18	>28(ISL)	0.0835
	[4]	2.4/3.5	8.51/13.3	1.65/1.75	<13/30	18(ISL)	0.029
	Proposed	**3.5/5.8**	**9.45/10.38**	**1.32/1.12**	**23/24.7**	**>19.53(ISL)**	**0.024**

tions, a highly compact diplexer is proposed based on the HMSIW. Two HMSIW BPFs incorporated with MC-CSRR of distinct dimensions are cascaded to function at these frequencies. Selectivity factor (S.F.) of the proposed diplexer is computed by,

$$S.F. = \frac{\Delta f_{3dB}}{\Delta f_{20dB}} \tag{6}$$

Where Δf_{3dB} is 3-dB bandwidth and Δf_{20dB} is 20 dB bandwidth. The measured IL of the diplexer is 1.32/1.12 dB, isolation between the two output ports is $>$19.5 dB and S.F. is 13.2/17.9 % as depicted in Fig. 4b. Table 2 shows the performance comparison of proposed SIW filters and diplexer. The proposed single, dual-band and wideband filter provide low IL [19], [14], [21], wide OBR [19], [14], [2] and compact size [19], [14], [21], [23], [2], [16]. The proposed diplexer has low IL, compact size, and acceptable ISL [4].

5 Most Important Contributions

The key accomplishments of this research work are as follows:

- The SIW based dual, tri, quad-band, and wideband SIW PDs are demonstrated for multi-band communications. The proposed PDs yield the benefits of equal power division, lower loss [7], [6], [8], [11], [17], [20], adequate isolation, better return loss and reduced size [6], [11], [15], [17], [20].

- The miniaturized dual-band equal and unequal PDs with good FBW and low loss [6], [20] are achieved using HMSIW.

- A dual-band SIW filter is demonstrated for 5G applications with low loss, good FBW and smaller footprint [21], [22], [23]. A wideband SIW based BPF with features of low loss, good passband performance, wide OBR and compact size [2], [16] is developed.

- HMSIW diplexer with the merits of low loss, good FBW [5], [12], acceptable isolation [5] and miniature size [5, [12] has been developed.

- Equivalent circuits are extracted for the proposed multi-band SIW PDs and filters. The frequency response of lumped element models validates the full-wave simulations.

6 Conclusion and Future scope

6.1 Conclusion

The multi-band characteristics of SIW based microwave passive components such as power divider, filter and diplexer are explored in this thesis to support the modern multi-standard wireless communication system. Dual, tri, quad-band and wideband PDs are developed that are useful for multi-band/ wideband applications: including WLAN, WiMAX (5G), INSAT, X-band, Ku-band, and K-band frequencies. A miniaturized

SIW filter with low loss and good band rejection capability has been developed for 5G communications. Then a compact dual-band SIW filter has been demonstrated for 5G applications. A highly compact diplexer with better isolation is developed using HMSIW for WiMAX(5G)/WLAN applications. The proposed SIW based microwave components are compared with the state of arts in literature. The proposed components outperform others by miniaturized size, low insertion loss, acceptable isolation and simple structure.

6.2 Future scope

Based on the proposed work, further investigations can be made to enhance the performance of the SIW based microwave components.

- The design of tri and quad-band SIW PDs with reduced size and arbitrary power division needs exploration.
- The methods that improve the isolation between the output ports of the proposed power divider should be investigated.
- The strategies to improve the selectivity and isolation accomplishment of the proposed diplexer need to be examined.

7 Organization of the Thesis

The proposed outline of the thesis is as follows:

(a) Chapter 1: Introduction

(b) Chapter 2: Literature review

(c) Chapter 3: SIW based power dividers

(d) Chapter 4: SIW based filters

(e) Chapter 5: SIW based diplexer

(f) Chapter 6: Conclusion and Future Scope

8 List of Publications

1. **D. Tharani**, K. Selvajyothi, S. S. Karthikeyan, R. K. Barik, Q. S. Cheng. Compact HMSIW Diplexer Loaded With Modified Circular Complementary Split Ring Resonators for WiMAX /WLAN applications. *Journal of Electromag. Waves and app.*, Vol. 36, 1980-1995, (2022).

   (https://doi.org/10.1080/09205071.2022.2051754)

2. **Duraisamy, T.**, Kamakshy, S., Sholampettai Subramanian, K., Barik, R., Cheng, Q. Design and implementation of compact tri- and quad-band SIW power divider using modified circular complementary split-ring resonators. *International Journal of Microwave and Wireless Technologies*, Vol. 14, 1241 – 1249, (2022).

   (https://doi.org/10.1017/S1759078721001720)

3. **D. Tharani**, K. Selvajyothi, S. S. Karthikeyan. Highly Miniaturized Dual-band Power Divider based on HMSIW for 5G/ WLAN Applications. *IETE Journal of Research*, (2021). (https://doi.org/10.1080/03772063.2021.2007800)

4. **T. Duraisamy**, S. Kamakshy, S. S. Karthikeyan, R. K. Barik, Q. S. Cheng. Compact Wideband SIW Based Bandpass Filter for X, Ku and K Band Applications. *Radio Engg.*, Vol. 30, 288-295, (2021). (http://dx.doi.org/10.13164/re.2021.0288)

5. **D. Tharani**, R.K. Barik, Q. S.Cheng, K. Selvajyothi, S. S. Karthikeyan. Compact dual-band SIW filters loaded with double ring D-shaped resonators for sub-6 GHz applications. *Journal of Electromag. Waves and app.*, Vol. 35, 923-936, (2021). (https://doi.org/10.1080/09205071.2020.1865211)

6. **Tharani Duraisamy**, Rusan Kumar Barik, Qingsha S. Cheng, Selvajyothi Kamakshy, Karthikeyan Sholampettai Subramanian. Miniaturized SIW filter using D-shaped resonators with wide out-of-band rejection for 5G applications. *Journal of Electromag. Waves and app.*, Vol. 34, 2397-2409, (2020).

   (https://doi.org/10.1080/09205071.2020.1816219)

7. **T. Duraisamy**, R. K. Barik, K. Sholampettai Subramanian, S. Kamatchi. A novel SIW based dual-band power divider using double-circular complementary split ring resonators. *Microw. Opt. Technol. Lett.*, Vol. 61, 1529-1533, (2019). (https://doi.org/10.1002/mop.31772)

8.1 Presentations in conferences

D. Tharani, Rusan Kumar Barik, Qingsha S. Cheng, K. Selvajyothi, S.S. Karthikeyan. A compact wideband SIW power divider with CSRR and slots for Ku and K band applications. *IEEE MTT-S International Microwave and RF Conference (IMaRC)*, 1-4, (2019). (https://doi.org/10.1109/IMaRC45935.2019.9118741)

References

1. **Cassivi, Y.**, **L. Perregrini**, **P. Arcioni**, **M. Bressan**, **K. Wu**, and **G. Conciauro** (2002). Dispersion characteristics of substrate integrated rectangular waveguide. *IEEE Microwave and Wireless components letters*, **12**(9), 333–335.

2. **Chen, R. S.**, **S.-W. Wong**, **L. Zhu**, and **Q.-X. Chu** (2014). Wideband bandpass filter using u-slotted substrate integrated waveguide (siw) cavities. *IEEE Microwave and Wireless Components Letters*, **25**(1), 1–3.

3. **Curry, T.** and **R. Abbas** (2020). 5g coverage, prediction, and trial measurements. *arXiv preprint arXiv:2003.09574*.

4. **Danaeian, M.** (2020). Miniaturized half-mode substrate integrated waveguide diplexer based on sir–csrr unit-cell. *Analog Integrated Circuits and Signal Processing*, **102**(3), 555–561.

5. **Danaeian, M.** and **K. Afrooz** (2019). Compact metamaterial unit-cell based on stepped-impedance resonator technique and its application to miniaturize substrate integrated waveguide filter and diplexer. *International Journal of RF and Microwave Computer-Aided Engineering*, **29**(2), e21537.

6. **Danaeian, M.**, **A.-R. Moznebi**, and **K. Afrooz** (2020). Super compact dual-band substrate integrated waveguide filters and filtering power dividers based on evanescent-mode technique. *AEU-International Journal of Electronics and Communications*, **125**, 153348.

7. **Danaeian, M.**, **A.-R. Moznebi**, **K. Afrooz**, and **A. Hakimi** (2017). Miniaturized filtering siw power divider with arbitrary power-dividing ratio loaded by open complementary split-ring resonators. *International Journal of Microwave and Wireless Technologies*, **9**(9), 1827–1832.

8. **Danaeian, M.**, **A.-R. Moznebi**, **K. Afrooz**, and **H. Hakimi** (2016). Miniaturised equal/unequal siw power divider with bandpass response loaded by csrrs. *Electronics Letters*, **52**(22), 1864–1866.

9. **Deslandes, D.** and **K. Wu** (2001). Integrated microstrip and rectangular waveguide in planar form. *IEEE microwave and wireless components letters*, **11**(2), 68–70.

10. **Deslandes, D.** and **K. Wu** (2002). Design consideration and performance analysis of substrate integrated waveguide components. *In 2002 32nd European microwave conference*. IEEE.

11. **He, Z.**, **C. Jiang You**, **S. Leng**, and **X. Li** (2017). Compact power divider with improved isolation and bandpass response. *Microwave and Optical Technology Letters*, **59**(7), 1776–1781.

12. **Karamzadeh, S.** (2018). Miniaturized half mode siw diplexer loaded by csrr. *International Journal of RF and Microwave Computer-Aided Engineering*, **28**(9), e21446.

13. **Kawai K, O. H., Furuta T** and **N. S** (2011). Multi-band radio frequency circuits for mobile terminals. *NTT Docomo Technical Journal*, **13**(3), 23–29.

14. **Li, L.**, **D. Zhao**, **J. Bai**, **Q. Wang**, and **Z. Lei** (2019). A tunable third-order bandpass filter based on combining dual-mode square-shaped substrate integrated waveguide resonator with triangular-shaped resonator. *International Journal of RF and Microwave Computer-Aided Engineering*, **29**(1), e21454.

15. **Moznebi, A.-R.** and **K. Afrooz** (2017). Compact power divider based on half mode substrate integrated waveguide (hmsiw) with arbitrary power dividing ratio. *International journal of microwave and wireless technologies*, **9**(3), 515–521.

16. **Muchhal, N.** and **S. Srivastava** (2019). Design of wideband comb shape substrate integrated waveguide multimode resonator bandpass filter with high selectivity and improved upper stop-band performance. *International Journal of RF and Microwave Computer-Aided Engineering*, **29**(9), e21807.

17. **Pradhan, N. C.**, **K. S. Subramanian**, **R. K. Barik**, and **Q. S. Cheng** (2021). Design of compact substrate integrated waveguide based triple-and quad-band power dividers. *IEEE Microwave and Wireless Components Letters*, **31**(4), 365–368.

18. **Rezaee, M.** and **A. R. Attari** (2015). Fourth-order dual mode substrate integrated waveguide filter. *Microwave and Optical Technology Letters*, **57**(7), 1550–1553.

19. **Sánchez-Soriano, M. Á.**, **S. Sirci**, **J. D. Martínez**, and **V. E. Boria** (2016). Compact dual-mode substrate integrated waveguide coaxial cavity for bandpass filter design. *IEEE Microwave and Wireless Components Letters*, **26**(6), 386–388.

20. **Song, K.**, **M. Luo**, **J. Yao**, and **Y. Zhou** (2020). Dual-passband bandpass-filtering power divider using half-mode substrate integrated waveguide resonator with high frequency selectivity. *International Journal of RF and Microwave Computer-Aided Engineering*, **30**(9), e22309.

21. **Xie, H.-W.**, **K. Zhou**, **C.-X. Zhou**, and **W. Wu** (2020). Compact wide-stopband siw dual-band filter with closely spaced passbands. *Electronics letters*, **56**(16), 822–825.

22. **Yang, Z.**, **B. You**, and **G. Luo** (2020). Dual-/tri-band bandpass filter using multimode rectangular siw cavity. *Microwave and Optical Technology Letters*, **62**(3), 1098–1102.

23. **Zhang, H.**, **W. Kang**, and **W. Wu** (2018). Miniaturized dual-band siw filters using e-shaped slotlines with controllable center frequencies. *IEEE Microwave and Wireless Components Letters*, **28**(4), 311–313.