UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Faculty of Electronics and Computer Engineering

PERFORMANCE EVALUATION OF SUBSTRATE INTEGRATED WAVEGUIDE BAND-STOP FILTERS

Tan Gan Siang

MSc. in Electronic Engineering

2015

PERFORMANCE EVALUATION OF SUBSTRATE INTEGRATED WAVEGUIDE BAND-STOP FILTERS

TAN GAN SIANG

A thesis submitted
in fulfillment of the requirement for the degree of Master of Science
in Electronic Engineering

Faculty of Electronics and Computer Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2015

DECLARATION

I declare that this thesis entitled “Performance Evaluation of Substrate Integrated Waveguide Band-stop Filters” is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : ....
Name : ....
Date : ....

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Electronic Engineering.

Signature : ....
Supervisor Name : ....
Date : ....

ABSTRACT

This thesis presents the findings of the research work done on the evaluation and performance of substrate integrated waveguide (SIW) band-stop filters. The conventional waveguide has the advantages of low-insertion losses and high Q in microwave communication systems but their physical sizes of rectangular waveguides are large. The introduction of substrate integrated waveguide with similar properties of low insertion loss that can be integrated with planar circuits fulfill the requirement of microwave communication systems. Many researches have carried out detail research work on SIW band-pass filters but not many researches have spent enough time on the research of performance of SIW band-stop filters. In the construction of SIW band-stop filters, resonators feature significantly to realize the structure. Resonators can be constructed from closed sections of SIW. Circular and radial shape cavity resonators are proposed to design the SIW band-stop filters. The SIW band-stop filters are designed by coupling the cavity resonator to the SIW line. The effects on the variation of parameters value of each type of resonators are investigated. CST microwave studio is used for all the simulation work in this research. The designs of the SIW band-stop filters have been realized by using standard PCB process. The measured results are found to be in consistent to the simulated results. The dual-radial cavity resonators SIW band-stop filter has shown enhanced performance in 9GHz band-stop response with a high stopband attenuation level and provide better roll-off of 0.15dB/MHz. These provide better frequency selectivity as compared to the rectangular cavity resonator in the previous research work. This band-stop filter can be used to provide better signal rejection in the X-band.

ABSTRAK

Tesis ini membentangkan hasil penyelidikan yang telah dilakukan tentang penilaian dan prestasi penapis batas jalur pandu gelombang substrat bersepadu (SIW). Pandu gelombang konvensional mempunyai kelebihan pada kehilangan sisipan rendah dan Q yang tinggi dalam sistem komunikasi gelombang mikro akan tetapi saiz fizikal pandu gelombang segi empat tepat adalah besar. Pengenalan pandu gelombang substrat bersepadu dengan sifat-sifat kehilangan sisipan rendah dan boleh disepadukan dengan litar satah memenuhi keperluan sistem komunikasi gelombang mikro dimasakini. Banyak pengelidik telah melakukan penyelidik mendalam atas penapis jalur lulus SIW tetapi tidak ramai penyelidik telah memberi masa yang mencukupi atas penyelidikan tentang prestasi penapis batas jalur SIW. Dalam pembinaan penapis batas jalur, penyalun atau resonator merupakan bahagian penting untuk menrealisasikan strukturnya. Penyalun boleh dibinadari SIW dengan bahagian tertutup mengelilingnya. Penyalun bulatan dan jejarian dicadangkan untuk mereka bentuk penapis batas jalur SIW. Penapis batas jalur SIW direka bentuk dengan menggandingkan penyalun rongga kepada talian SIW. Kesan perubahan nilai parameter-parameter bagi setiap jenis penyalun dikaji dan selidik. CST studio gelombang mikro digunakan untuk semua kerja simulasi dalam kajian ini.Rekaan penapis batas jalur SIW telah dihasilkan dengan menggunakan proses standard Papan Litar Tercetak. Keputusan pengukuran yang diambil adalah didapati bersama dengan keputusan simulasi. Penapis batas jalur SIW dengan penyalun rongga jejarian duaan telah menunjukkan prestasi peningkatan pada 9GHz dengan pelemahan batas jalur yang tinggi dan mempunyai 0.15dB/MHz kecerunan yang lebih baik. Ini memberi pemilihan frekuensi yang lebih baik dari penyalun rongga segi empat tepat dalam kerja penyelidikan sebelumnya. Penapis batas jalur ini boleh digunakan untuk memberikan isyarat penolakan yang lebih baik dalam X-band.

ACKNOWLEDGMENT

First, I would like to express my special gratitude to my main supervisor, Dato' Prof. Dr. Mohd Nor Bin Husain for giving me the opportunity to conduct this master research. I would like to thank him for his patience, encouragement and inspiration in providing me with invaluable advice and guidance throughout this research work. I would also like to thank my co-supervisor, Prof. Madya Tan Kim See for his continuous advice and support. I would like to thank all the lecturers and postgraduate students at the faculty, who have helped in one way or another, in particular, Mr. Mohamad Zoinol Abidin, Dr. Zahriladha, Mr. Sufian, Mr. Sam Weng Yik and Miss Sabariah.

I would like to thank the Malaysian Government in financing the research in the form Exploratory Research Grant Scheme (ERGS) and the MyMaster 15 programme.

Finally, I want to thank my parents, Tan Lay Keat and Lim Meng Su, my brother, Tan Gan Shen and my sisters, Tan Soo Wen and Tan Soo Fung, for their confidence in me, their encouragement and support throughout the duration of my studies.

TABLE OF CONTENTS

PAGE

DECLARATION
APPROVAL
ABSTRACT **i**
ABSTRAK **ii**
ACKNOWLEDGMENT **iii**
TABLE OF CONTENTS **iv**
LIST OF TABLES **vii**
LIST OF FIGURES **viii**
LIST OF APPENDICIES **xiii**
LIST OF ABBREVIATION **xiv**
LIST OF SYMBOLS **xv**
LIST OF PUBLICATIONS **xvii**

CHAPTER
1. INTRODUCTION **1**
  1.0 Background 1
  1.1 Original Contribution Presented in this Thesis 7
  1.2 Problem Statement 8
  1.3 Objectives 10
  1.4 Scopes 10
  1.5 Outline of the Thesis 11

2. LITERATURE REVIEW **13**
  2.0 Introduction 13
  2.1 Microwave Filters Basic Concept 14
  2.2 Impedance Transformations 15
  2.3 Lowpass to Band-stop Circuit Transformation 16
  2.4 Maxwell Equation 20
  2.5 TE Modes 22
  2.6 Resonators for Filter 24
  2.7 Rectangular Waveguide Cavities 25
    2.7.1 Resonant Frequencies 26
  2.8 Substrate Integrated Waveguide 27
  2.9 Transition of Microstrip Line to SIW 31
  2.10 Substrate Integrated Waveguide Parameters 33
  2.11 Loss Minimization 35
  2.12 Substrate Integrated Waveguide Band-stop Filter 37
  2.13 Summary 42

3. DESIGN AND SIMULATION **44**
  3.0 Introduction 44
  3.1 Design of SIW Band-stop Filter 46
    3.1.1 Substrate Integrated Waveguide Transmission Line Design 48
  3.2 Material Selection for the SIW Band-stop Filter Design 51
  3.3 Design and Simulation Results 52

3.3.1 Effective Width of the SIW Line 54
3.3.2 Width of the Resonator Input 56
3.3.3 The Effect of the Position of Resonator 57
3.3.4 The Effect of the Diameter of the Via Hole 59
3.3.5 The Effect of the Spacing between the Edge of the Via Holes 60
3.4 Transition between Microstrip Line and SIW 61
3.5 Design of Rectangular, Circular and Radial SIW Band-stop Filters 63
3.5.1 Design of Rectangular Cavity Resonator SIW Band-stop Filter 63
3.5.2 Design of Circular Cavity Resonator SIW Band-stop Filter 64
3.5.3 Design of Radial Cavity Resonator SIW Band-stop Filter 65
3.6 Dual-radial Cavity Resonator SIW Band-stop Filter 66
3.7 Summary 68

4. RESULTS, FABRICATION AND MEASUREMENT 70
4.0 Introduction 70
4.1 Results of the Rectangular Cavity Resonator SIW Band-stop Filter 71
4.1.1 The Effect of Resonator Width to the Band-stop Filter 71
4.1.2 The Effect of the Resonator Length to the Band-stop Filter 74
4.1.3 Fabrication of Band-stop Filter 76
4.1.4 Measurement Results 77
4.2 Results of the Circular Cavity Resonator SIW Band-stop Filter 78
4.2.1 The Effect of the Parameter r_c to the Band-stop Filter 78
4.2.2 The Effect of the Parameter l_c 81
4.2.3 Fabrication 83
4.2.4 Measurement Results 85
4.3 Results of the Radial Cavity Resonator SIW Band-stop Filter 86
4.3.1 The Effect of Parameter r_r to the Band-stop Filter 86
4.3.2 The Effect of Parameter θ_r to the Band-stop Filter 89
4.3.3 The Effect of Parameter l to the Band-stop Filter 91
4.3.4 Fabrication 93
4.3.5 Measurement Results 94
4.4 Dual-radial Cavity Resonator SIW Band-stop Filter 95
4.4.1 Simulation Results of the Band-stop Filters 96
4.4.2 Fabrication 98
4.4.3 Measurement Results 99
4.5 Summary 102

5. DISCUSSION: SIW BAND-STOP FILTERS 103
5.0 Introduction 103
5.1 Parameter Analysis of the SIW Band-stop Filter 104
5.1.1 Parametric Study of the SIW Line of the SIW Band-stop Filter 104
5.1.2 Parametric Study of the Rectangular Cavity Resonator SIW Band-stop Filter 107
5.1.3 Parametric Study of the Circular Cavity Resonator SIW Band-stop Filter 108
5.1.4 Parametric Study of the Radial Cavity Resonator SIW Band- 109

stop Filter
5.2 Advantages of the Radial Cavity Resonator Over the Rectangular Cavity Resonator 110
5.3 Frequency Shifting between Simulation and Measurement Results 111
5.3.1 Effect of the Tolerance of Dielectric Permittivity of the Substrate for Rectangular Cavity Resonator 111
5.3.2 Effect of the Tolerance of Dielectric Permittivity of the Substrate of Circular Cavity Resonator SIW Band-stop Filter 112
5.3.3 Effect of the Tolerance of Dielectric Permittivity of the Substrate of Radial Cavity Resonator SIW Band-stop Filter 113
5.3.4 Influence of the Permittivity Values of Substrate RO4350B 114
5.4 Losses in the Band-stop Filter 115
5.4.1 Losses of Rectangular Cavity Resonator SIW Band-stop Filter 115
5.4.2 Losses of Circular Cavity Resonator SIW Band-stop Filter 115
5.4.3 Losses of Radial Cavity Resonator SIW Band-stop Filter 116
5.4.4 Losses of Dual-radial Cavity Resonator SIW Band-stop Filter 116
5.5 Dual-radial Cavity Resonator SIW Band-stop Filter 117
5.5.1 Comparison of the Dual-radial Cavity Resonator SIW Band-stop Filter with Previous SIW Band-stop Filter Design 118
5.6 Summary 119

6. CONCLUSION AND FUTURE WORK 121
6.0 Conclusion 121
6.1 Future Work 123

REFERENCES 124
APPENDICES 133

LIST OF TABLES

TABLE	TITLE	PAGE
3.1	Single resonator SIW band-stop filter specifications	47
4.1	Constant value for parametric study of w of rectangular cavity resonator SIW band-stop filter	71
4.2	Constant value for parametric study of l for rectangular cavity resonator SIW band-stop filter	74
4.3	Constant value for parametric study of r_c of circular cavity resonator SIW band-stop filter	79
4.4	Constant value for parametric study of l_c of circular cavity resonator SIW band-stop filter	81
4.5	Constant value for parametric study of r_r of radial cavity resonator SIW band-stop filter	87
4.6	Constant value for parametric study of θ_r of radial cavity resonator SIW band-stop filter	89
4.7	Constant value for parametric study of l of radial cavity resonator SIW band-stop filter	91
5.1	Comparison of dual-radial cavity resonator SIW band-stop filter with previous paper.	119

LIST OF FIGURES

FIGURE	TITLE	PAGE
1.1	Typical block diagram of Doppler radar system	6
1.2	Block diagram of the RF front end of wireless communication systems in the base station (Hunter, 2001)	6
2.1	Band-stop filter response Lowpass to band-stop transformation	18
2.2	Band-stop transformation of (a) an inductor and (b) capacitor	19
2.3	An inverse Chebyshev prototype band-stop filter	19
2.4	Ladder prototype network for band-stop filter	20
2.5	Structure of a rectangular waveguide	22
2.6	Electric and magnetic fields for the TE_{10} mode in a rectangular waveguide	23
2.7	Typical frequency response of a rectangular waveguide	24
2.8	Cutoff frequencies of the TE_{10}-like and TE_{20}-like modes of the straight pattern SIRW vs. width W for various via diameters D (Cassivi *et al.*, 2002)	30
2.9	Dominant mode electric profiles: (a) rectangular waveguide; (b) microstrip line	31
2.10	Taper transition of microstrip line to SIW	32

2.11 Step impedance transition of microstrip line to SIW 33

2.12 Substrate integrated waveguide (Xu and Wu, 2005) 34

2.13 Simulation and measure results of the triple-band SIW band-stop filter (Han *et al.*, 2007) 38

2.14 Simulated and measured result for single stage SIW band-stop filter (Ahmad and Hunter, 2008) 39

2.15 Simulated and measured result for two stage SIW band-stop filter (Ahmad and Hunter, 2008) 39

2.16 Simulated and measured responses of the transmission mode SIW band-stop filter (Ahmad and Hunter, 2010) 40

2.17 Frequency Response of the prototype HN SIW band-stop filter (Ahmad *et al.*, 2010) 41

2.18 Simulated and measured response of SIW band-stop filter (Zakaria and Hunter, 2011) 42

2.19 Measured response of dual SIW band-stop filter (Yang *et al.*, 2012) 42

3.1 Lumped element band-stop filter 48

3.2 Resonance for single stage lumped element band-stop filter 48

3.3 A substrate integrated waveguide band-stop filter 49

3.4 Substrate integrated waveguide (Xu and Wu, 2005) 50

3.5 (a) Configuration of SIW band-stop filter (b) diameter of the via holes and spacing between the edge of the via holes 53

3.6 Frequency response of variation of effective width of SIW line 55

3.7 Frequency response of variation of width of the resonator input 57

3.8 Frequency response of variation of resonator position (a) three 58

optimum coupling position for resonator along the SIW line (b) three different coupling position with an optimum point of 20.19mm
3.9 Frequency response of variation of diameter of the via holes 60
3.10 Frequency response of spacing between the edges of via holes 61
3.11 Transition between a microstrip line and a SIW 62
3.12 Configuration of rectangular cavity resonator substrate integrated waveguide band-stop filter 64
3.13 Configuration of the circular cavity resonator SIW band-stop filter 65
3.14 Configuration of radial cavity resonator substrate integrated waveguide band-stop filter 66
3.15 Configuration of the first radial cavity resonator SIW band-stop filter 67
3.16 Configuration of the second radial cavity resonator SIW band-stop filter 68
3.17 Configuration of dual-radial cavity resonator SIW band-stop filter 68
4.1 Configuration of rectangular cavity resonator substrate integrated waveguide band-stop filter 72
4.2 Frequency response of variation of w (a) S_{11} result (b) S_{21} result 73
4.3 Frequency response of variation of l (a) S_{11} result (b) S_{21} result 75
4.4 Parameters values of the fabricated rectangular cavity resonator SIW band-stop filter 76
4.5 Rectangular cavity resonator SIW band-stop filter 77
4.6 Measured frequency response of rectangular cavity resonator SIW band-stop filter 78
4.7 Configuration of circular cavity resonator SIW band-stop filter 79

4.8 Frequency response of variation of r_c (a) S_{11} result (b) S_{21} result 80-81

4.9 Frequency response of variation of l_c (a) S_{11} result (b) S_{21} result 82-83

4.10 Parameters value of for fabricated circular cavity resonator SIW band-stop filter 84

4.11 Circular cavity resonator SIW band-stop filter 84

4.12 Measured frequency response of circular cavity resonator SIW band-stop filter 85

4.13 Configuration of radial cavity resonator SIW band-stop filter 87

4.14 Frequency response of variation of r_r (a) S_{11} result (b) S_{21} result 88

4.15 Frequency response of variation of θ_r (a) S_{11} result (b) S_{21} result 90

4.16 Frequency response of variation of l (a) S_{11} result (b) S_{21} result 92

4.17 Parameters value for fabricated radial cavity resonator SIW band-stop filter 93

4.18 Radial cavity resonator SIW band-stop filter 94

4.19 Simulated and measured result of radial cavity resonator SIW band-stop filter 95

4.20 Parameters values of dual-radial cavity resonator SIW band-stop filter 96

4.21 Frequency response of first radial resonator SIW band-stop filter 97

4.22 Frequency response of second radial resonator SIW band-stop filter 97

4.23 Frequency response of dual-radial resonators SIW band-stop filter 97

4.24 Fabricated single radial cavity resonator SIW band-stop filter 98

4.25 Fabricated single radial cavity resonator SIW band-stop filter 99

4.26 Fabricated dual-radial cavity resonator SIW band-stop filter 99

4.27 Frequency response of first radial resonator SIW band-stop filter 100

4.28 Frequency response of second radial resonator SIW band-stop filter 101

4.29 Frequency response of dual-radial resonators SIW band-stop filter 101

5.1 Comparison between radial and rectangular cavity resonator at 8.6GHz 110

5.2 Comparison between radial and rectangular cavity resonator at 9.9GHz 111

5.3 Frequency response of variation of dielectric permittivity of substrate for rectangular cavity resonator SIW band-stop filter 112

5.4 Frequency response of variation of dielectric permittivity of substrate for circular cavity resonator SIW band-stop filter 113

5.5 Frequency response of variation of dielectric permittivity of substrate for radial cavity resonator SIW band-stop filter 114

LIST OF APPENDICES

APPENDIX **TITLE** **PAGE**

A Data Sheet RO4350B 133

B Standard Rectangular Waveguide Data 135

LIST OF ABBREVIATION

EM - Electromagnetic

RF - Radio Frequency

RX - Receive

SIW - Substrate Integrated Waveguide

SIRW - Substrate Integrated Rectangular Waveguide

TE - Transverse Electric

TEM - Transverse Electromagnetic

TM - Transverse Magnetic

TX - Transmit

W - Width of Substrate Integrated Rectangular Waveguide

D - Diameter of Substrate Integrated Rectangular Waveguide

LIST OF SYMBOLS

C - Capacitance

L - Inductance

R - Resistance

ω - Angular frequency

ω_c - Angular cut-off frequency

ω_o - Angular centre frequency

K - Electric current density

α - Bandwidth scaling factor

c - Speed of light

λ - Wavelength

λ_o - Centre frequency wavelength

λ_g - Centre guide wavelength

Z_0 - Characteristic impedance

f_o - Centre frequency

f_c - Cut-off frequency

f_r - Resonant frequency

β - Propagation constant

ε_o - Permittivity of free space

ε_r - Relative permittivity

h - Substrate thickness

μ_r - Relative permeability

LIST OF PUBLICATIONS

Journals:

Husain, M. N., Tan, G. S., & Tan, K. S. (2014). Enhanced Performance of Substrate Integrated Waveguide Bandstop Filter using Circular and Radial Cavity Resonator. *International Journal of Engineering & Technology*, 6(2), pp. 1268-1277. *(Scopus)*

Conference papers:

Husain, M. N., Tan, G. S., & Tan, K. S. (2014). Rectangular, Circular and Radial Cavity Resonator Substrate Integrated Waveguide Bandstop Filter. In: IEEE, *Student Conference On Research & Development (SCOReD)*. Putrajaya, Malaysia, 16-17 December 2013.

Husain, M. N., Tan, G. S., & Tan, K. S. (2014). Design of a Substrate Integrated Waveguide Filter using Dual-Radial Cavity Resonator. In: IEEE, *Region 10 Technical Symposiun (TENSYMP)*. Kuala Lumpur, Malaysia, 14-16 April 2014.

CHAPTER 1

INTRODUCTION

1.0 Background

The demand for microwave communication systems with high performance such as low insertion loss and high selectivity is always a challenge in this field of engineering. The high demand of higher volume of channels has made the frequency spectrum to become more crowded so much so, interference between close neighbouring channels occurs and becomes a problem. The rapid growth in the telecommunication industry is the main reason and to meet the challenges now and in the future, extensive researches on microwave components to reduce the interferences between close neighbouring channels are being carried. Among the many critical components, microwave filter is one which provide significant roles in a microwave communication system, mainly, in frequency selectivity, featuring small insertion loss and large return loss. One way to efficiently utilize the electromagnetic spectrum is to ensure enhanced performance of the microwave filters.

In microwave communication systems, signals play a very important role in delivering information. Problems occur as there is always noise in the signals or there is only a certain range of signal that is desired. Therefore, filter is an important device to provide solution to this problem. The general requirements of filters are small insertion loss, large return loss and high frequency selectivity. A high frequency selectivity filter has efficiency in frequency application due to the small guard frequency band between each channel. Another feature is that filters on demand must be small in size to cater for the industry.

Conventional rectangular waveguides are well known to have low loss and high quality factor as compared to planar counter parts. They are normally used in low-loss microwave circuit design. Because of its enclosed structure, there is no leakage of electromagnetic energy throughout the propagation. However, the integration of both planar and non-planar circuits is difficult and bulky. One of the disadvantages of conventional waveguide is their huge size as a device. A concept that can offer the solution to the integration of waveguide is substrate integrated waveguide. It is a technique that can reduce the cut-off frequency of a rectangular waveguide which the waveguide is partly or fully filled with dielectric substrate. Thus, the reduction by a factor of $1/\sqrt{\varepsilon_r}$ is achieved in comparing with the conventional rectangular waveguide that is air-filled.

Integrated waveguide techniques was filed patented in 1995 (Flanick *et al.*, 1995). The propose of substrate integrated waveguide (SIW) in the other way call post wall waveguide or laminated waveguide was investigated theoretically and practically by (Uchimura *et al.*, 1998). SIW is formed by having two periodic rows of metalized via-holes. According to the paper regarding the review of current research trends in SIW, a number of papers regarding SIW had been published in the IEEE between year 2005 to 2008 (Bozzi *et al.*, 2009). These lead to the production of novel modelling techniques for SIW components and outstanding performance SIW circuits and systems. Because of the almost similar operating mechanism of an SIW to a conventional rectangular waveguide, the characteristic of SIW is almost similar but the Q-factor of an SIW is less than conventional rectangular waveguide with air medium due to the dielectric filling and volume reduction (Cassivi, 2002).

Filters are the most popular device among the passive SIW components. A variety of different filter topologies were presented. A band-pass filter is designed by etching complementary split-ring resonators on the SIW surface to achieve circuit miniaturization (Dong *et al.*, 2009). Then, a series of cross-slot structures etched on the SIW dual-mode band-pass filter to miniaturize the filter was presented (Chen *et al.*, 2012). A band-pass filter using Quarter Substrate Integrated Waveguide Resonator loaded with a fractal-shaped was presented (Zhang *et al.*, 2011). A compact band-pass filter using quarter SIW cavity resonator with source-load cross coupling was presented (Deng *et al.*, 2011). A pseudo-elliptic SIW filters with higher-order mode resonances was presented (Salehi *et al.*, 2013). A SIW cross-coupling filter with multilayer hexagonal cavity was presented (Bo *et al.*, 2013). An X-band differential band-pass filter with high common-mode suppression using substrate integrated waveguide cavity was presented (Jin *et al.*, 2014).

There were only a few of numerical methods developed and published for SIW structures to obtain a high computational efficiency. One of the methods was presented with the combination of method of moments (MOM) and cylindrical eigenfunction expansion (Wu *et al.*, 2008). A boundary integral-resonant mode expansion (BI-RME) method was applied to analyze the lossless SIW (Bozzi *et al.*, 2006). The modelling of SIW components based on BI-RME method makes it possible to determine the wideband expression of the frequency response of SIW components without repeated frequency-by-frequency electromagnetic analyses. This algorithm has improved with the modelling of lossy SIW interconnects and components (Bozzi *et al.*, 2008). The full wave electromagnetic simulation software such as Computer Simulation Technology (CST) and