



**MULTIFUNCTIONAL RECONFIGURABLE WILKINSON
POWER DIVIDER WITH SINGLE POLE DOUBLE THROW
SWITCH FOR RF FRONT-END COMMUNICATIONS**



DOCTOR OF PHILOSOPHY

2022



Faculty of Electronic and Computer Engineering

**MULTIFUNCTIONAL RECONFIGURABLE WILKINSON
POWER DIVIDER WITH SINGLE POLE DOUBLE THROW
SWITCH FOR RF FRONT-END COMMUNICATIONS**

اونيورسيتي تيكنيكل مليسيا ملاك
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Nurhasniza Binti Edward

Doctor of Philosophy

2022

**MULTIFUNCTIONAL RECONFIGURABLE WILKINSON POWER DIVIDER
WITH SINGLE POLE DOUBLE THROW SWITCH FOR RF FRONT-END
COMMUNICATIONS**

NURHASNIZA BINTI EDWARD

**A thesis submitted
in fulfillment of the requirements for the degree of Doctor of Philosophy**



Faculty of Electronic and Computer Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2022

DECLARATION

I declare that this thesis entitled “Multifunctional Reconfigurable Wilkinson Power Divider with Single Pole Double Throw Switch for RF Front-End Communications” 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 : Nurhasniza binti Edward

Date : 30 August 2022

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

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 Doctor of Philosophy.

Signature

:

Supervisor Name

: Professor Dr. Zahriladha bin Zakaria

Date

: 30 August 2022

اونيورسيتي تېكنيكل مليسيا ملاك
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

DEDICATION

The name of ALLAH Almighty creator,

My beloved father, Edward Basir and mother, Nina Triana Asril,

My supportive family members for your encouragement and undying supports.

And to everyone.



ABSTRACT

Current and future communication systems necessitate reconfigurable structures and extended features, which are taken into account in the development of microwave devices such as: filters, antennas, and amplifiers. Reconfigurability refers to the ability to adjust or control a power divider's features dynamically while still maintaining acceptable overall performance. Power divider with adjustable power division ratio, center frequency, and transmission mode or function selectivity are the key features targeted by reconfigurable power dividers. Commonly, PIN diodes and varactors are used to achieve reconfigurability. One type of reconfigurable power divider that has recently gained popularity is switchable power dividers, in which the structure of the power divider can be adjusted to achieve different functionality. There are many techniques have been developed to achieve reconfigurable power divider, but majorities of the reconfigurable designs are focused on a single element, either on a power divider or single pole double throw (SPDT) switch. Therefore, the aim of this research is to design novel structure of reconfigurable modified Wilkinson power divider with SPDT switch function which promises a new potential functionality of the microwave devices. Two designs approaches were introduced, which are reconfigurable modified WPD and reconfigurable function modified WPD using Roger Duroid RO4350B with a dielectric constant of 3.48. To realize the concept, the techniques used in designing the reconfigurable modified WPD and reconfigurable function modified WPD have been combined to form a single structure of a novel reconfigurable modified WPD with SPDT switch function. To validate the design technique, mathematical analysis of the reconfigurable modified WPD as a SPDT switch is presented to prove the switchable mechanism. The commercial software program that has been used in the design and development of the main designs is the Advanced Design System (ADS) software. All designs were simulated, manufactured, and measured. The proposed design's total layout is 48.1 mm x 80.9 mm. The simulation results showed good agreement for both functions and frequencies, with S_{11} less than -15 dB, S_{21} more than -4.2 dB, and S_{23} less than -10 dB. The experimental results show good agreement with the simulated results. Even though there was a frequency shift in the measurement, the measurement results still correlated with the simulation results. The benefits of the reconfigurable integrated design are potentially reducing the entire structure's size, easy to fabricate and cost effective. The outcomes of the proposed reconfigurable integrated design may facilitate improvements in an integrated technique for RF front end systems.

**PEMBAHAGI KUASA WILKINSON BERBILANG FUNGSI YANG BOLEH
DIKONFIGURASI SEMULA DENGAN SUIS SATU KUTUB DUA LONTAR BAGI
KOMUNIKASI FREKUENSI RADIO BAHAGIAN DEPAN**

ABSTRAK

Sistem komunikasi semasa dan pada masa hadapan memerlukan struktur yang boleh dikonfigurasi semula dan ciri-ciri lanjutan untuk diambil kira dalam pembangunan peranti gelombang mikro seperti: penapis, antena, dan penguat. Konfigurasi semula merujuk kepada keupayaan untuk melaras atau mengawal ciri pembahagi kuasa secara dinamik sementara mengekalkan prestasi keseluruhan. Pembahagi kuasa dengan keupayaan boleh laras bagi nisbah pembahagian kuasa, frekuensi, dan mod penghantaran atau selektiviti fungsi adalah ciri-ciri utama yang disasarkan oleh pembahagi kuasa boleh dikonfigurasi semula. Kebiasaannya, diod PIN dan varaktor digunakan untuk mencapai konfigurasi semula. Satu jenis pembahagi kuasa boleh dikonfigurasi semula yang mendapat populariti baru-baru ini adalah pembahagi kuasa boleh-suis, di mana struktur pembahagi kuasa boleh diselaraskan untuk mencapai fungsi yang berbeza. Terdapat banyak teknik yang telah dibangunkan untuk mencapai pembahagi kuasa yang boleh dikonfigurasi semula, tetapi majoriti reka bentuk yang boleh dikonfigurasi semula difokuskan pada elemen tunggal, sama ada pada pembahagi kuasa atau suis satu kutub dua lontar (SPDT) sahaja. Oleh itu, tujuan penyelidikan ini adalah untuk mereka bentuk struktur baru pembahagi kuasa Wilkinson yang boleh dikonfigurasi semula dengan fungsi suis SPDT yang menjanjikan fungsi potensi baru peranti gelombang mikro. Dua pendekatan reka bentuk diperkenalkan, WPD yang diubahsuai boleh dikonfigurasi semula dan fungsi WPD yang diubahsuai boleh dikonfigurasi semula menggunakan Roger Duroid RO4350B dengan pemalar dielektrik 3.48. Untuk merealisasikan konsep ini, teknik yang digunakan dalam mereka bentuk WPD yang diubahsuai boleh dikonfigurasi semula dan fungsi WPD yang diubahsuai boleh dikonfigurasi semula telah digabungkan untuk membentuk struktur tunggal baru yang dinamakan WPD diubahsuai boleh dikonfigurasi semula dengan fungsi suis SPDT. Untuk mengesahkan teknik reka bentuk tersebut, analisis matematik bagi WPD diubahsuai boleh dikonfigurasi semula sebagai suis SPDT telah dibentangkan untuk membuktikan mekanisme boleh-suis. Program perisian komersial yang telah digunakan dalam mereka bentuk dan pembangunan reka bentuk utama adalah perisian Advanced Design System (ADS). Semua reka bentuk telah disimulasikan, dihasilkan, dan diukur. Susun atur keseluruhan reka bentuk yang dicadangkan ialah 48.1 mm x 80.9 mm. Hasil simulasi menunjukkan persetujuan yang baik untuk kedua-dua fungsi dan frekuensi, dengan S_{11} kurang daripada -15 dB, S_{21} lebih daripada -4.2 dB, dan S_{23} kurang daripada -10 db. Hasil eksperimen menunjukkan persetujuan yang baik dengan hasil simulasi. Walaupun terdapat peralihan frekuensi dalam pengukuran, hasil ukuran masih berkaitan dengan keputusan simulasi. Manfaat konfigurasi semula integrasi reka bentuk berpotensi untuk membentuk struktur yang kecil, mudah dan kos efektif. Hasil daripada reka bentuk konfigurasi semula integrasi yang dicadangkan boleh menaik taraf peningkatan dalam teknik integrasi untuk sistem RF bahagian hadapan.

ACKNOWLEDGEMENTS

I would like to express my appreciation to my main supervisor, Professor Dr. Zahriladha bin Zakaria and my co-supervisor, Dr. Noor Azwan bin Shairi for their essential research guidance, advice and motivation throughout my journey in writing this thesis. Without their continued moral support and concern, this thesis would not have been presented here.

Special acknowledgement to the postgraduate students, staffs and friends from Faculty of Electronic and Computer Engineering (FKEKK) which are Dr. Sam Weng Yik, Faza Syahirah and Ika Dewi for their knowledge contribution, technical and spiritual support.

I would also like to take this opportunity to thank my parents, Edward bin Basir and Nina Triana binti Asril and family members, Muhamad Hafiz, Syahirah, Muhammad Tajuddin and Muhammad Akhtar Izzat for their continuous support, encouragement and prosperous prayers all of these years through the course of my PhD journey. The journey is made possible with them continuously cheering by my side.

I am thankful to laboratory assistance, Imran and Muhd Sufian together with technician Research Lab I Khairul Zaman for their assistance throughout the fabrication and measurement procedures.

Finally, I would like to acknowledge Ministry of Education, Malaysia government and Universiti Teknikal Malaysia Melaka (UTeM) for the research funds. Deepest gratitude to everyone who had contributed either directly or indirectly to this research work.

TABLE OF CONTENTS

	PAGE
DECLARATION	
APPROVAL	
DEDICATION	
ABSTRACT	i
ABSTRAK	ii
ACKNOWLEDGEMENTS	iii
TABLE OF CONTENTS	iv
LIST OF TABLES	vii
LIST OF FIGURES	ix
LIST OF APPENDICES	xvi
LIST OF ABBREVIATIONS	xvii
LIST OF SYMBOLS	xviii
LIST OF PUBLICATIONS	xix
 CHAPTER	
1. INTRODUCTION	1
1.1 Research background	1
1.2 Problem statement	3
1.3 Objectives	6
1.4 Scope of research	6
1.5 Contribution of research work	7
1.6 Thesis organization	9
 2. LITERATURE REVIEW	11
2.1 Introduction	11
2.2 Background of the power divider	12
2.2.1 The scattering matrix and power divider characteristics	12
2.2.2 ABCD matrix and conversion with scattering parameters	16
2.2.3 The types of power divider and properties	19
2.3 Overview of RF switch	23
2.4 Design RF switch with PIN diode	24
2.4.1 Series Connected Switch	28
2.4.1.1 Principal operating parameters of series switch	29
2.4.2 Shunt connected switch	31
2.4.2.1 Principal operating parameters of shunt switch	32
2.4.3 Single pole double throw Switch	34
2.4.4 Compound switch	35
2.4.5 Tuned switch	36
2.5 Previous studies of reconfigurable power divider	38
2.5.1 Reconfigurable of operating frequency	38
2.5.2 Reconfigurable of function or path of the output ports	59
2.5.3 Reconfigurable of power division ratio	68
2.6 Summary	79

3.	METHODOLOGY	81
3.1	Introduction	81
3.2	Flow of research work	81
3.3	Design of reconfigurable modified WPD	90
3.3.1	Microstrip line of Wilkinson power divider	90
3.3.2	Biasing model	93
3.3.3	Design of conventional Wilkinson power divider	93
3.3.4	Design A: Reconfigurable modified WPD	96
3.3.4.1	Power divider at 2.5 GHz	98
3.3.4.2	Power divider at 3.5 GHz	99
3.3.5	Design B: Reconfigurable function modified WPD at 2.5 GHz and Design C: Reconfigurable function modified WPD at 3.5 GHz	100
3.3.5.1	Power divider function	102
3.3.5.2	SPDT switch function	103
3.3.6	Design D: Reconfigurable modified WPD with SPDT switch function	104
3.3.6.1	Power Divider Function at 2.5 GHz	106
3.3.6.2	Power Divider Function at 3.5 GHz	108
3.3.6.3	SPDT Switch Function at 2.5 GHz	109
3.3.6.4	SPDT Switch Function at 3.5 GHz	110
3.3.7	Mathematical analysis of reconfigurable feeding network as a SPDT switch for Design B, C, and D	112
3.3.7.1	The insertion loss	112
3.3.7.2	The isolation	114
3.4	Summary	115
4.	RESULTS AND DISCUSSIONS: RECONFIGURABLE MODIFIED WILKINSON POWER DIVIDER (WPD)	117
4.1	Introduction	117
4.2	Results of conventional Wilkinson power divider	118
4.3	Design A: Reconfigurable Modified WPD	120
4.3.1	Power Divider at 2.5 GHz	120
4.3.2	Power Divider at 3.5 GHz	127
4.3.3	Analysis and Effect of Fabrication Process on Design A	133
4.4	Design B: Reconfigurable Function Modified WPD at 2.5 GHz	137
4.4.1	Power Divider Function of Design B	138
4.4.2	SPDT Switch Function of Design B	146
4.4.3	Analysis and Effect of Fabrication Process on Design B	155
4.5	Design C: Reconfigurable Function Modified WPD at 3.5 GHz	159
4.5.1	Power Divider Function of Design C	160
4.5.2	SPDT Switch Function of Design C	167
4.5.3	Analysis and Effect of Fabrication Process on Design C	175
4.6	Design D: Reconfigurable modified WPD with SPDT switch function	179
4.6.1	Power Divider Function at 2.5 GHz	180
4.6.2	Power Divider Function at 3.5 GHz	188
4.6.3	SPDT Switch Function at 2.5 GHz	195
4.6.4	SPDT Switch Function at 3.5 GHz	204
4.6.5	Analysis and Effect of Fabrication Process on Design D	212

4.7	Comparison of Results	221
4.8	Summary	225
5.	CONCLUSION AND RECOMMENDATIONS FOR FUTURE WORKS	226
5.1	Conclusion	226
5.2	Recommendations for future work research	228
	REFERENCES	230
	APPENDICES	246



LIST OF TABLES

TABLE	TITLE	PAGE
2.1	Comparison of passive power dividers	22
2.2	Summary of reconfigurable power divider (operating frequency) of several researchers	56
2.3	Summary of reconfigurable power divider (function or path of the output ports) of several researchers	66
2.4	Summary of reconfigurable power divider (power division ratio) of several researchers	77
3.1	Design specification of conventional Wilkinson power divider	83
3.2	Description and labeling of modified WPD designs	84
3.3	Roger Duroid RO4350B substrate properties	95
3.4	Design A specification	96
3.5	Summary of circuit operation for Design A at 2.5 GHz	98
3.6	Summary of circuit operation for Design A at 3.5 GHz	99
3.7	Design B and C specification	100
3.8	Summary of circuit operation for Design B and C as a power divider	103
3.9	Summary of circuit operation for Design B and C as a SPDT switch	104
3.10	Design D specification	106
3.11	Summary of circuit operation for power divider Design D at 2.5 GHz	107
3.12	Summary of circuit operation for power divider Design D at 3.5 GHz	108
3.13	Summary of circuit operation for SPDT switch Design D at 2.5 GHz	109
3.14	Summary of circuit operation for SPDT switch Design D at 3.5 GHz	111
4.1	Summary of simulated and measured results of Design A at 2.5 GHz	127
4.2	Summary of simulated and measured results of Design A at 3.5 GHz	133
4.3	Summary of simulated and measured results of Design B as a power divider	145
4.4	Summary of simulated and measured results of Design B as an SPDT switch	154
4.5	Summary of simulated and measured results of Design C as a power divider	167
4.6	Summary of simulated and measured results of Design C as an SPDT switch	174
4.7	Summary of simulated and measured results of Design D as a 2.5 GHz power divider	188
4.8	Summary of simulated and measured results of Design D as a 3.5 GHz power divider	195
4.9	Summary of simulated and measured results of Design D as an SPDT switch at 2.5 GHz	203

4.10	Summary of simulated and measured results of Design D as an SPDT switch at 3.5 GHz	211
4.11	The summary of modified WPD designs	221
4.12	Comparison results with previous works based on reconfigurable power divider	223



LIST OF FIGURES

FIGURE	TITLE	PAGE
1.1	Phase array antenna system	3
1.2	RF front-end's transmitter and receiver (Shairi et al. 2013)	5
2.1	(a) Two two-port networks cascade; (b) its equivalent form	16
2.2	Power divider of lossless T-junction (Pozar, 2005)	19
2.3	Resistive Power Divider (Pozar, 2005)	21
2.4	Cross-section of PIN diode (Skyworks, 2021)	26
2.5	PIN diode Single Pole Single Throw (SPST) switches. (a) Series SPST switch (b) Shunt SPST Switch (Skyworks, 2021)	26
2.6	SPST and SPDT switch schematics (a) SPST switch (b) SPDT switch (Skyworks, 2021)	28
2.7	Shunt-connected PIN diode switches (a) SPST switch (b) SPDT switch (Skyworks, 2021)	31
2.8	Shunt SPDT Switch design (a) Series and (b) Shunt SPDT switch (Skyworks, 2021)	35
2.9	Common compound switch configurations (a) ELL (series-shunt) and (b) TEE SPST switch (Skyworks, 2021)	36
2.10	Tuned switch. (a) Tuned series switch and (b) Tuned shunt switch (Skyworks, 2021)	37
2.11	Lumped circuit equivalent (Skyworks, 2021)	37
2.12	(a) Schematic of the reconfigurable feeding network (b) The arrangement of PIN diodes (c) The proposed design configuration in CST (Zhou et al., 2013)	39
2.13	(a) The structure and (b) layout of the frequency reconfigurable power divider (Zhang et al., 2015)	40
2.14	Simulation results of (a) S_{11} , (b) S_{22} , (c) S_{21} , and (d) S_{32} of the proposed power divider (Zhang et al., 2015)	41
2.15	(a) Structure and (b) layout of the frequency reconfigurable power divider (Zhang et al., 2015a)	42
2.16	Simulation results of reflections at port 1 to 3. (a) S_{11} , (b) S_{22} , and (c) S_{33} (Zhang et al., 2015a)	43
2.17	Simulation results of (a) S_{32} , (b) S_{21} , and (c) S_{31} (Zhang et al., 2015a)	44

2.18	(a) The configuration of the proposed power divider and (b) photograph of the fabricated power divider (Chen et al., 2019)	44
2.19	Simulated and measured frequency response of the proposed tunable power divider, (a) S_{11} , (b) S_{21} , (c) S_{22} , and (d) S_{23} (Chen et al., 2019)	46
2.20	(a) The proposed broadband bandwidth tunable power divider and (b) the fabricated two-way power divider (Chen et al., 2019a)	47
2.21	Simulated results of (a) S_{11} and S_{21} , (b) S_{22} and S_{23} . Measured responses of (c) S_{11} and S_{21} , (d) S_{22} and S_{23} for different C_p of the power divider (Chen et al., 2019a)	48
2.22	(a) The circuit configuration and (b) a photograph of the fabricated tunable power divider (Zhang and Che, 2016)	49
2.23	Simulated and measured results of the designed tunable power divider: (a) S_{11} , (b) S_{22} , (c) S_{21} , and (d) S_{32} (Zhang and Che, 2016)	49
2.24	The prototype of power divider. (a) Configuration (b) Photograph (Zhang et al., 2016)	50
2.25	(a) Photograph of the fabricated power divider and (b) equivalent circuit of proposed T-junction power divider (Li et al., 2020)	52
2.26	(a) Circuit layout (b) Photograph of the tunable WPD (Lin et al., 2017)	52
2.27	Measured scattering parameters (a) S_{11} , S_{21} , and (b) S_{32} of the tunable WPD (Lin et al., 2017)	53
2.28	(a) Proposed tunable TLT with two varactors. (b) Design application for WPD. (c) Photograph of proposed tunable WPD (Wang et al., 2018)	54
2.29	Simulated and measured results of proposed tunable WPD: (a) S_{11} , (b) S_{21} , (c) S_{22} , and (d) S_{23} (Wang et al., 2018)	55
2.30	(a) Configuration of the proposed function-reconfigurable circuit. (b) Prototype of the proposed function-reconfigurable circuit under test (Chen et al., 2017)	59
2.31	Simulated and measured results of proposed reconfigurable circuit at SPDT state. (a) Port 2 is 'ON'. (b) Port 2 is 'OFF' (Chen et al., 2017)	60
2.32	(a) Configuration of the proposed N-way reconfigurable Gysel power divider. (b) N-way reconfigurable power divider structure based on N-way Wilkinson power divider (Fan et al., 2017)	61
2.33	Fabricated four-way reconfigurable Gysel power divider. (a) Top view (b) Bottom view (Fan et al., 2017)	62
2.34	(a) Proposed structure of power divider with full structure (b) Photograph of fabricated proposed design (Feng et al., 2021)	63
2.35	Reconfigurable SPDT or PD's layout (Ji et al., 2020)	64
2.36	The simulated S-parameters during (a) SPDT switch and (b) 3-dB PD (Ji et al., 2020)	65
2.37	Configuration of the dividing ratio tunable power divider. (a) Circuit layout. (b) Photograph of fabricated circuit. Simulation and measurement results of different power dividing ratios at 1 GHz. (c) 1:2 (d) 1:100 (Ye et al., 2018)	69

2.38	(a) Schematic of the proposed tunable power divider (b) Details of the utilized L-shaped stub (c) Fabricated prototype (Abbas et al., 2017)	70
2.39	(a) Performance at equal power division (b) Performance at the maximum tunable power division (Abbas et al., 2017)	71
2.40	(a) Layout and photograph of the proposed tunable PD (b) S_{21} and S_{31} . (c) S_{11} and phase difference between the two output ports (Guo et al., 2016)	72
2.41	(a) Configuration of the proposed power divider. Simulated results of the device for (b) equal and (c) unequal power division (Abbas et al., 2016)	73
2.42	(a) Configuration proposed reconfigurable unequal power divider (b) Photograph of proposed reconfigurable power divider (Fan et al., 2015)	74
2.43	Simulated and measured outcomes of (a) 1:5 and (b) 1:0 transmission mode (Fan et al., 2015)	75
3.1	The general flows of the research work	82
3.2	Dry film sheet laminator	86
3.3	Vacuum exposure unit	87
3.4	The flow of the fabrication process	87
3.5	Heat gun and lead free solder paste	88
3.6	Reconfigurable power divider experimental setup	89
3.7	Microstrip line model	90
3.8	Microstrip cross section demonstrating electric field	91
3.9	RF biasing circuit	93
3.10	The circuit configuration of the conventional or ideal WPD at (a) 2.5 GHz and (b) 3.5 GHz	94
3.11	Setting of 'linecalc' tool in ADS software	95
3.12	The circuit configuration of Design A and position of the PIN diode (D1-D8)	97
3.13	The circuit configuration of Design B and C position of the PIN diode (D1-D6)	102
3.14	The circuit configuration of Design D and position of the PIN diode (D1-D16)	105
4.1	S_{11} , S_{12} , and S_{13} results for ideal WPD at 2.5 GHz	119
4.2	S_{11} , S_{12} , and S_{13} results for ideal WPD at 3.5 GHz	119
4.3	The circuit layout and configuration of Design A with the position of the PIN diode (D1-D8)	120
4.4	The circuit operation of Design A operating at frequency of 2.5 GHz	121
4.5	Simulation of Design A's S-parameter results for ideal design (a) without and (b) with PIN diode at 2.5 GHz	123
4.6	Simulation of S-parameter result for Design A (real component included) at 2.5 GHz	124
4.7	Prototype of reconfigurable modified WPD (Design A)	125

4.8	Comparison between simulation and measurement results in terms of Design A's S-parameters, (a) S11, (b) S21 and (c) S23 at 2.5 GHz	126
4.9	The circuit operation of Design A operating at frequency of 3.5 GHz	128
4.10	Simulation of Design A's S-parameter results for ideal design (a) without and (b) with PIN diode at 3.5 GHz	129
4.11	Simulation of S-parameter result for Design A (real component included) at 3.5 GHz	130
4.12	Comparison between simulation and measurement results in terms of Design A's S-parameters, (a) S11, (b) S21 and (c) S23 at 3.5 GHz	132
4.13	Effect of width, W, of Design A on S-parameters, (a) S11, (b) S21 and (c) S23 at 2.5 GHz	135
4.14	Effect of width, W, of Design A on S-parameters, (a) S11, (b) S21 and (c) S23 at 3.5 GHz	137
4.15	The circuit layout and configuration of Design B with the position of PIN diodes (D1-D6)	138
4.16	The circuit operation of Design B and C as a power divider	139
4.17	Simulation of Design B's S-parameter results for ideal design (a) without and (b) with the PIN diode as a power divider at 2.5 GHz	140
4.18	Simulation of S-parameter result for Design B (real component included) (a) without and (b) with matching stub as a power divider at 2.5 GHz	142
4.19	Prototype of modified WPD with SPDT switch function (Design B)	143
4.20	Comparison between simulation and measurement results in terms of Design B's S-parameters, (a) S11, (b) S21 and (c) S23 as a power divider at 2.5 GHz	145
4.21	The circuit operation of Design B and C as an SPDT switch	147
4.22	Simulation of Design B's S-parameter results for ideal design (a) without and (b) with PIN diode as an SPDT switch at 2.5 GHz	149
4.23	Simulation of S-parameter result for Design B (real component included) (a) without and (b) with matching stub as an SPDT switch at 2.5 GHz	150
4.24	Comparison between simulation and measurement results in terms of Design B's S-parameters, (a) S11, (b) S21, (c) S31 and (d) S23 as an SPDT switch at 2.5 GHz	153
4.25	Effect of width, W, of Design B on S-parameters, (a) S11, (b) S21 and (c) S23 as a power divider at 2.5 GHz	156
4.26	Effect of width, W, of Design B on S-parameters, (a) S11, (b) S21, (c) S31 and (d) S23 as an SPDT switch at 2.5 GHz	158
4.27	The circuit layout and configuration of Design C with the position of PIN diodes (D1-D6)	160
4.28	Simulation of Design C's S-parameter results for ideal design (a) without and (b) with PIN diode as a power divider at 3.5 GHz	161

4.29	Simulation of S-parameter result for Design C (real component included) (a) without and (b) with matching stub as a power divider at 3.5 GHz	163
4.30	Prototype of modified WPD with SPDT switch function (Design C)	164
4.31	Comparison between simulation and measurement results in terms of Design C's S-parameters, (a) S11, (b) S21 and (c) S23 as a power divider at 3.5 GHz	166
4.32	Simulation of Design C's S-parameter results for ideal design (a) without and (b) with PIN diode as an SPDT switch at 3.5 GHz	168
4.33	Simulation of S-parameter result for Design C (real component included) (a) without and (b) with matching stub as an SPDT switch at 3.5 GHz	170
4.34	Comparison between simulation and measurement results in terms of Design C's S-parameters, (a) S11, (b) S21, (c) S31 and (d) S23 as an SPDT switch at 3.5 GHz	173
4.35	Effect of width, W, of Design C on S-parameters, (a) S11, (b) S21 and (c) S23 as a power divider at 3.5 GHz	176
4.36	Effect of width, W, of Design C on S-parameters, (a) S11, (b) S21, (c) S31 and (d) S23 as an SPDT switch at 3.5 GHz	178
4.37	The circuit layout and configuration of Design D with the position of PIN diodes (D1-D16)	180
4.38	The circuit operation of Design D as a power divider at 2.5 GHz	181
4.39	Simulation of Design D's S-parameter results for ideal design (a) without and (b) with PIN diode as a power divider at 2.5 GHz	183
4.40	Simulation of S-parameter result for Design D (real component included) (a) without and (b) with matching stub as a power divider at 2.5 GHz	184
4.41	Prototype of reconfigurable modified WPD with SPDT switch function (Design D)	185
4.42	Comparison between simulation and measurement results in terms of Design D's S-parameters, (a) S11, (b) S21 and (c) S23 as a power divider at 2.5 GHz	187
4.43	The circuit operation of Design D as a power divider at 3.5 GHz	189
4.44	Simulation of Design D's S-parameter results for ideal design (a) without and (b) with PIN diode as a power divider at 3.5 GHz	190
4.45	Simulation of S-parameter result for Design D (real component included) (a) without and (b) with matching stub as a power divider at 3.5 GHz	192
4.46	Comparison between simulation and measurement results in terms of Design D's S-parameters, (a) S11, (b) S21 and (c) S23 as a power divider at 3.5 GHz	194
4.47	The circuit operation of Design D as an SPDT switch at 2.5 GHz	196

4.48	Simulation of Design D's S-parameter results for ideal design (a) without and (b) with PIN diode as an SPDT switch at 2.5 GHz	198
4.49	Simulation of S-parameter result for Design D (real component included) (a) without and (b) with matching stub as an SPDT switch at 2.5 GHz	199
4.50	Comparison between simulation and measurement results in terms of Design D's S-parameters, (a) S11, (b) S21, (c) S31 and (d) S23 as an SPDT switch at 2.5 GHz	202
4.51	The circuit operation of Design D as an SPDT switch at 3.5 GHz	204
4.52	Simulation of Design D's S-parameter results for ideal design (a) without and (b) with PIN diode as an SPDT switch at 3.5 GHz	206
4.53	Simulation of S-parameter result for Design D (real component included) (a) without and (b) with matching stub as an SPDT switch at 3.5 GHz	208
4.54	Comparison between simulation and measurement results in terms of Design D's S-parameters, (a) S11, (b) S21, (c) S31 and (d) S23 as an SPDT switch at 3.5 GHz	210
4.55	Effect of width, W, of Design D on S-parameters, (a) S11, (b) S21 and (c) S23 as a power divider at 2.5 GHz	213
4.56	Effect of width, W, of Design D on S-parameters, (a) S11, (b) S21 and (c) S23 as a power divider at 3.5 GHz	215
4.57	Effect of width, W, of Design D on S-parameters, (a) S11, (b) S21, (c) S31 and (d) S23 as an SPDT switch at 2.5 GHz	217
4.58	Effect of width, W, of Design D on S-parameters, (a) S11, (b) S21, (c) S31 and (d) S23 as an SPDT switch at 3.5 GHz	220

LIST OF APPENDICES

APPENDIX	TITLE	PAGE
A	Rogers RO4340B data sheet	246
B	BAP64-02 PIN diode data sheet	247
C	Wilkinson Power Divider	251



LIST OF ABBREVIATIONS

ADS	- Advanced Design System
DC	- Direct Current
EM	- Electromagnetic
LNA	- Low noise amplifier
MCMC	- Malaysian Communications and Multimedia Commission
PIN	- Positive-intrinsic-negative
RF	- Radio Frequency
SPDT	- Single pole double throw
TEM	- Transverse-electromagnetic
UV	- Ultraviolet
VNA	- Vector network analyzer
WPD	- Wilkinson power divider
WLAN	- Wireless Local Area Network

LIST OF SYMBOLS

c	- Speed of Light
ϵ_o	- Permittivity of Free Space
ϵ_r	- Dielectric Constant of Material
ϵ_{eff}	- Effective Dielectric Constant
F	- Operating Frequency
k_0	- Free Space Propagation Constant
λ_m	- Microstrip Wavelength
Z_o	- Characteristic Impedance



LIST OF PUBLICATIONS

1. Edward, N., Shairi, N.A., 2021. Design of A Compact Multifunctional Power Divider Loaded with Short-ended Stub. *International Journal of RF and Microwave Computer-Aided Engineering*. [Submitted]
2. Edward, N., Shairi, N.A., Othman, A., Zakaria, Z., Saiful Bahri, I.D., 2020. Reconfigurable modified Wilkinson power divider using pin diode switch. *Bulletin of Electrical Engineering and Informatics (BEEI)*, 9(3), pp. 1067–1073. [Scopus]
3. Edward, N., Othman, A., Shairi, N.A., Zakaria, Z., 2019. Switchable Function between Wilkinson Power Divider and Single Pole Double Throw Switch in 3.5 GHz Band. Presented at IEEE, 2019 IEEE International Conference on Automatic Control and Intelligent Systems (I2CACIS). Selangor, 29 June 2019. [Scopus]
4. Edward, N., Shairi, N.A., Zakaria, Z., Sutikno, T., Saiful Bahri, I.D., 2019. Tunable function of feeding network and SPDT switch for WIMAX application. *Indonesian Journal of Electrical Engineering and Computer Science (IJECS)*, 14(3), pp. 1574-1580. [Scopus]
5. Edward, N., Shairi, N.A., Zakaria, Z., Bahri, I.D.S., 2019. Analysis of switching and matching stubs in reconfigurable power divider with SPDT switch function. *TELKOMNIKA (Telecommunication Computing Electronics and Control)*, 17(1), pp. 86–94. [Scopus]
6. Edward, N., Zakaria, Z., Shairi, N.A., Bahri, I.D.S., Hamid, M.H.A., 2019. Modified Wilkinson Power Divider with Switchable Function using PIN Diode Switches.