



Faculty of Electronic and Computer Engineering

**DESIGN OF HYBRID RF DIPLEXER AND TRIPLEXER FOR
MULTIBAND WiMAX APPLICATION**

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Master of Science in Electronic Engineering

2018

**DESIGN OF HYBRID RF DIPLEXER AND TRIPLEXER FOR MULTIBAND
WiMAX APPLICATION**

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


Faculty of Electronic and Computer Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2018

DECLARATION

I declare that this thesis entitled “Design of Hybrid RF Diplexer and Triplexer for Multiband WiMAX Application” 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.

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Date : 13/3/2018.....

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

: Dr. Noor Azwan Bin Shairi

Date

: 13 Mac 2018

DEDICATION

The sake of Allah, my Creator and my Master,

My great messenger, Mohammad S.A.W who taught us the purpose of life,

My beloved parent Sazali and Rohani,

My beloved supervisors Dr. Noor Azwan and Assoc. Prof. Dr. Zahriladha,

My beloved families,

My beloved friends and all the people in my life who touched my heart and soul.

ABSTRACT

Radio frequency (RF) diplexer and triplexer are widely used in wireless communication system. The development of RF diplexer and triplexer are very competing in multiband Worldwide Interoperability for Microwave Access (WiMAX) application. This is due to the high demands of wireless communication system to support multi-services simultaneously. Many RF diplexer and triplexer are designed using common type of the filter. Besides, the preliminary designs are for multi-applications not specifically for multiband WiMAX application. The multiband WiMAX has been implemented around the globe as allocated by the International Telecommunication Union (ITU). Bandwidth of the multiband WiMAX application are varies depending on the countries. Therefore, the proposed RF diplexer and triplexer are developed to cope with the multiband WiMAX bandwidth. This is because of the bandwidth is purposely to allow the data to be transmitted or received based on the frequencies assigned. The proposed RF diplexer and triplexer were designed with three different resonators as to cover the multiband WiMAX bandwidth which were at 2.3, 2.6 and 3.5 GHz. The resonator types were selected based on the bandwidth achieved by the resonator. In addition, the resonators used were based on the coupled lines technique on a microstrip structure due to the flexibility during development processes such as open loop, parallel and folded structures. The proposed RF diplexer and triplexer are based on the hybrid structure which more flexible for the resonators to match with the matching network. By synthesis and analysis on the overall performances of the proposed RF diplexer and triplexer, the specific bandwidths were achieved for multiband WiMAX application. Results showed that the resonators produced bandwidths of 100 MHz for the narrow band with minimum 4 % fractional bandwidth, and 200 to 700 MHz with 10 - 20 % fractional bandwidth for the moderate band. These results showed that the resonators were achieved good agreements to be implemented in multiband WiMAX application.

ABSTRAK

Frekuensi Radio (RF) pendupleks dan triplexer digunakan secara meluas dalam sistem komunikasi tanpa wayar. Pemajuan RF pendupleks dan triplexer adalah sangat berkompertisi dalam perkembangan aplikasi jalur berbilang Worldwide Interoperability for Microwave Access (WiMAX). Ini adalah disebabkan oleh permintaan yang tinggi dalam sistem komunikasi tanpa wayar ke pelbagai perkhidmatan sokongan secara serentak. Banyak RF pendupleks dan triplexer direka untuk pelbagai aplikasi yang tidak umumnya untuk aplikasi jalur berbilang WiMAX. Jalur berbilang WiMAX telah dilaksanakan di seluruh dunia seperti yang diperuntukkan oleh pihak International Telecommunication Union (ITU). Lebar jalur untuk jalur berbilang WiMAX berbeza bergantung kepada sesebuah negara. Oleh yang demikian, RF pendupleks dan triplexer yang dicadangkan dibentuk untuk menadaptasi lebar jalur untuk jalur berbilang WiMAX. Ini adalah kerana lebar jalur adalah membolehkan data yang dihantar atau diterima mengikut pada frekuensi yang ditetapkan. RF pendupleks dan triplexer yang dicadangkan telah direka dengan tiga resonator yang berbeza untuk meliputi lebar jalur WiMAX pada 2.3, 2.6 dan 3.5 GHz. Jenis bahantara dipilih berdasarkan pada lebar jalur yang dicapai oleh bahantara itu. Di samping itu, resonator yang digunakan adalah berasaskan teknik garisan berganding pada struktur microstrip, hal ini disebabkan oleh fleksibiliti di sepanjang proses pembangunan seperti gelung terbuka, selari dan struktur dilipat. RF pendupleks dan triplexer yang dicadangkan adalah berdasarkan struktur hibrid dimana lebih fleksibel untuk resonator sesuai dengan rangkaian sepadan. Dari sintesis dan analisis, prestasi keseluruhan cadangan RF pendupleks dan triplexer, Lebar jalur tertentu dicapai jalur berbilang aplikasi WiMAX. Hasil kajian menunjukkan bahawa resonator ini menghasilkan jalur lebar sebanyak 100 MHz untuk jalur sempit dengan minimum lebar jalur pecahan 4%, dan 200 hingga 700 MHz dengan lebar jalur pecahan 10-20% bagi jalur sederhana. Keputusan ini menunjukkan resonator ini mencapai kesesuaian untuk dilaksanakan dalam aplikasi jalur berbilang WiMAX.

ACKNOWLEDGEMENTS

First and foremost, I would like to take this opportunity to express my sincere acknowledgement to my supervisor Dr. Noor Azwan Shairi and my co-supervisor Assoc. Prof. Dr. Zahriladha Zakaria from the Faculty of Electronic and Computer Engineering, Universiti Teknikal Malaysia Melaka (UTeM) for their essential supervisions, supports and encouragements towards the completion of this thesis.

I would also like to express my greatest gratitude to all who have support me during completing my Master of Science in Electronic Engineering. Special thanks to all my friends who have provided assistance at various occasions. I would like to acknowledge the Ministry of Higher Education (MOHE), Universiti Teknikal Malaysia Melaka (UTeM), Faculty of Electronic and Computer Engineering (FKEKK) for scholarships and the research grants.

Special thanks to my beloved mother, Rohani Harun, my beloved father, Sazali Kamarudin, my sister, Nur Hidayah Sazali for their unconditional love, continuous moral supports, encouragement and prayers during completing this project. Last but not least, thank you to everyone who had been directly and indirectly involved in the crucial parts of realization of this project. Thank you very much!

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 |
| LIST OF AWARD | xx |
| CHAPTER | |
| 1. INTRODUCTION | 1 |
| 1.1 Research Background | 1 |
| 1.2 Problem Statement | 6 |
| 1.3 Research Objectives | 8 |
| 1.4 Research Scope | 9 |
| 1.5 Contribution of Research Work | 9 |
| 1.6 Thesis Outline | 11 |
| 2. LITERATURE REVIEW | 13 |
| 2.1 Introduction | 13 |
| 2.2 Overview of Diplexer and Triplexer | 13 |
| 2.3 Overview of Resonator | 15 |
| 2.4 Theory of Microstrip Coupling | 17 |
| 2.5 Relevant Types of Resonator | 22 |
| 2.6 Literature of Diplexer | 39 |
| 2.7 Literature of Triplexer | 46 |
| 2.8 Design Challenges | 55 |
| 2.9 Summary | 56 |
| 3. RESEARCH METHODOLOGY | 57 |
| 3.1 Introduction | 57 |
| 3.2 Flow of Project | 57 |
| 3.2.1 Flow of the Bandpass Filters Design | 59 |
| 3.2.2 Flow of the Circuit Simulation | 60 |
| 3.2.3 Flow of The Prototype Measurement | 61 |
| 3.3 Design of Bandpass filter | 62 |
| 3.3.1 Design of the Bandpass Filter Using Open Loop Coupled Line Resonator | 63 |
| 3.3.2 Design of the Bandpass Filter Using Parallel Coupled Line Resonator | 64 |

| | | |
|-----------|--|------------|
| 3.3.3 | Design of the Bandpass Filter Using Folded Coupled Line Resonator | 68 |
| 3.4 | Design of Hybrid Matching Network | 71 |
| 3.5 | Design of Diplexer | 72 |
| 3.5.1 | Diplexer Design A | 72 |
| 3.5.2 | Diplexer Design B | 76 |
| 3.5.3 | Diplexer Design C | 79 |
| 3.6 | Design of Triplexer | 80 |
| 3.7 | Summary | 82 |
| 4. | RESULT AND DISCUSSION | 83 |
| 4.1 | Introduction | 83 |
| 4.2 | Results of Filter Design | 83 |
| 4.2.1 | Bandpass Filter Using Open Loop Coupled Line Resonator | 84 |
| 4.2.1.1 | Analysis of the Resonator Gap | 84 |
| 4.2.1.2 | Simulation and Measurement Results for Verification | 86 |
| 4.2.2 | Bandpass Filter Using Parallel Coupled Line Resonator | 89 |
| 4.2.2.1 | Analysis of the Resonator Gap | 89 |
| 4.2.2.2 | Simulation and Measurement Results for Verification | 92 |
| 4.2.3 | Bandpass Filter Using Folded Coupled Line Resonator | 94 |
| 4.2.3.1 | Analysis of the Resonator Gap | 94 |
| 4.2.3.2 | Simulation and Measurement Results for Verification | 96 |
| 4.3 | Results of Hybrid Matching Network | 98 |
| 4.3.1 | Analysis of Matching Network Using Hybrid | 98 |
| 4.4 | Results of Diplexer Design | 100 |
| 4.4.1 | Design A (2.3 and 3.5 GHz) | 100 |
| 4.4.1.1 | Initial Results of Diplexer Design A | 100 |
| 4.4.1.2 | Optimization Results of Diplexer Design A | 101 |
| 4.4.2 | Design B (2.3 and 2.6 GHz) | 103 |
| 4.4.2.1 | Initial Results of Diplexer Design B | 103 |
| 4.4.2.2 | Optimization Results of Diplexer Design B | 105 |
| 4.4.3 | Design C (2.6 and 3.5 GHz) | 107 |
| 4.4.3.1 | Initial Results of Diplexer Design C | 107 |
| 4.4.3.2 | Optimization Results of Diplexer Design C | 108 |
| 4.5 | Results of Triplexer Design | 111 |
| 4.5.1 | Initial Results of Triplexer Design | 111 |
| 4.5.2 | Optimization Results of Triplexer Design | 112 |
| 4.6 | Comparison of Diplexer and Triplexer Design with Other Designs | 116 |
| 4.7 | Summary | 120 |
| 5. | CONCLUSION AND FUTURE WORK | 122 |
| 5.1 | Conclusion | 122 |
| 5.2 | Future Work | 124 |

REFERENCES
APPENDICES

125
138

LIST OF TABLES

| TABLE | TITLE | PAGE |
|-------|---|------|
| 1.1 | WiMAX Spectrum Allocation (Churchill, 2007) | 6 |
| 2.1 | The 3dB ripple response for N=5 | 30 |
| 2.2 | Studies of preliminary diplexer design | 45 |
| 2.3 | Bandpass microwave passive triplexers design | 58 |
| 3.1 | Final dimension of the open loop coupled line resonator | 63 |
| 3.2 | Summarized calculation of the angular frequency, ω | 65 |
| 3.3 | Inductance and capacitance values | 65 |
| 3.4 | Finalized values of bandpass filter impedance | 66 |
| 3.5 | Dimension of the transmission lines | 67 |
| 3.6 | The finalized transmission line of the parallel coupled lines resonator | 68 |
| 3.7 | The dimension of diplexer design A | 74 |
| 3.8 | Dimension of first bandpass filter in diplexer design A | 74 |
| 3.9 | Dimension of second bandpass filter in diplexer design A | 75 |
| 3.10 | The dimension of diplexer design B | 77 |
| 3.11 | Dimension of second bandpass filter in diplexer design B | 77 |

| | | |
|------|---|-----|
| 3.12 | The dimension of diplexer design C | 80 |
| 3.13 | The dimension of triplexer design | 82 |
| 4.1 | Summary of simulation and measurement of bandpass filter using open loop coupled line resonator | 88 |
| 4.2 | Summary of simulation and measurement of bandpass filter using parallel coupled lines resonator | 93 |
| 4.3 | Summary of simulation and measurement of bandpass filter using folded coupled lines resonators | 98 |
| 4.4 | Summary of simulation and measurement of diplexer design A | 103 |
| 4.5 | Summary of simulation and measurement of diplexer design B | 103 |
| 4.6 | Summary of simulation and measurement of diplexer design C | 110 |
| 4.7 | The summarize of simulation and measurement responses of triplexer design | 116 |
| 4.8 | Comparison between proposed diplexers with another diplexers based on the Fractional bandwidth (FBW) over multiband WiMAX application | 117 |
| 4.7 | Comparison between proposed triplexer with another triplexer based on the Fractional bandwidth (FBW) over multiband WiMAX application | 119 |

LIST OF FIGURES

| FIGURE | TITLE | PAGE |
|--------|---|------|
| 1.1 | IEEE 802.16/ WiMAX network architecture (Carvalho et al., 2013) | 2 |
| 1.2 | Simplified RF front-end (Hunter 2001) | 3 |
| 1.3 | Example of diplexer system (Yatsenko et al., 2007) | 4 |
| 1.4 | Example of the diplexer integration with antenna (H. Oweis et al., 2017) | 4 |
| 1.5 | Example of diplexer system on LTCC (Kim et al., 2009) | 5 |
| 2.1 | An overview of current RF wireless standards and their applications (Ganslandt et al., 2009) | 14 |
| 2.2 | Lumped-element of the basic circuit (a) series circuit (b) parallel circuit (David M. Pozar 2005) | 16 |
| 2.3 | Structure of microstrip resonator (a) high-impedance line (b) meander line (c) circular spiral (d) square spiral (Hong & Lancaster, 2001) | 17 |
| 2.4 | Example of transmission line on microstrip substrate (Mongia et al., 2007) | 18 |
| 2.5 | Edge coupled microstrip transmission line condition (a) microstrip lines (b) inverted microstrip lines (c) suspended microstrip lines | |

| | | |
|------|---|----|
| | (d) coplanar waveguide (Mongia et al., 2007) | 19 |
| 2.6 | Broadside-coupled microstrip transmission line condition | |
| | (a) broadside-coupled microstrip lines (b) broadside-coupled inverted microstrip lines (c) broad-coupled suspended microstrip lines (Mongia et al., 2007) | 20 |
| 2.7 | Coupled dielectric wave guide condition (a) image (b) insular (c) inverted strip (Mongia et al., 2007) | 20 |
| 2.8 | Dual mode of field configuration in coupled microstrip lines (a) even-mode (b) odd-mode (Mongia et al., 2007) | 22 |
| 2.9 | Ring resonator (a) layout of the resonator (b) simulation and measurement of the response (Salleh et al., 2010) | 23 |
| 2.10 | Basic of shut circuit (Kai Chang & Lung-Hwa Hsieh, 2004) | 24 |
| 2.11 | Folded open loop resonator (Kai Chang & Lung-Hwa Hsieh, 2004) | 26 |
| 2.12 | Ring resonator (a) layout of the ring resonator (b) simulation and measurement of the responses (Zeng et al., 2011) | 27 |
| 2.13 | Basic parallel coupled-line structure (Hong & Lancaster, 2001; David M. Pozar, 2005) | 28 |
| 2.14 | Equivalent circuit in block form (Hong & Lancaster, 2001; David M. Pozar, 2005) | 28 |
| 2.15 | Lowpass prototype of the filter design (Hong & Lancaster, 2001; David M. Pozar, 2005) | 29 |

| | | |
|------|--|----|
| 2.16 | Finalized lowpass prototype circuit (David M. Pozar, 2005) | 30 |
| 2.17 | Transformation circuit forms (Hong & Lancaster, 2001; David M. Pozar, 2005) | 31 |
| 2.18 | Immittance inverter of the bandpass filter (Hong & Lancaster, 2001; David M. Pozar, 2005) | 32 |
| 2.19 | The folded coupled-line structure (a) the layout of the folded coupled-line resonator (b) simulation and measurement response of the folded coupled-line resonator (Nordin & Salleh, 2011) | 33 |
| 2.20 | Folded coupled line bandpass filter (Nordin & Salleh, 2011) | 34 |
| 2.21 | 180° or rat-race matching network (Kai Chang and Lung-Hwa Hsieh, 2004) | 35 |
| 2.22 | 180° equivalent circuit in block form (Kai Chang and Lung-Hwa Hsieh, 2004) | 35 |
| 2.23 | Even- and odd- mode decomposition of the ring hybrid when port 1 is excited with unit amplitude incident wave (a) Even mode (b) Odd mode (Kai Chang and Lung-Hwa Hsieh, 2004) | 36 |
| 2.24 | Even- and odd- mode decomposition of the ring hybrid when port 4 is excited with unit amplitude incident wave (a) Even mode (b) Odd mode (Kai Chang and Lung-Hwa Hsieh, 2004) | 38 |
| 2.25 | Configuration of Diplexer (a) configuration A (b) configuration B (Deng et al., 2006) | 40 |
| 2.26 | Diplexer design (a) the layout of the diplexer (b) the passband response | |

| | |
|---|----|
| (Chuang & Wu, 2014) | 42 |
| 2.27 Diplexer design and performances (D. Chen et al., 2015) | 43 |
| 2.28 Diplexer design (a) The layout and proposed Direct-feed coupled line (b) the responses of the passband (Chen et al., 2016) | 44 |
| 2.29 Triplexer configurations in multiband front-end system (a) configuration A (b) configuration B (Deng et al., 2006) | 47 |
| 2.30 Triplexer layout (Lai et al., 2013) | 49 |
| 2.31 Triplexer designed (a) layout of the triplexer (b) response of the triplexer (Wu et al., 2012) | 51 |
| 2.32 Triplexer design (a) layout of the triplexer (b) response of the triplexer (Taravati & Khalaj-Amirhosseini, 2013) | 52 |
| 3.1 Flow chart of the work flow | 58 |
| 3.2 Flow of the modelling process | 59 |
| 3.3 Flow chart of the simulation process | 60 |
| 3.4 Flow chart of the measurement process | 62 |
| 3.5 Proposed open loop resonator (S. J. Zeng et al., 2011) | 63 |
| 3.6 The structure of bandpass filter using open loop ring resonator | 64 |
| 3.7 Proposed parallel coupled lines resonator | 67 |
| 3.8 The analysis of the separation gap between resonators | 68 |
| 3.9 The bandpass filter using folded coupled line resonators | 69 |
| 3.10 Proposed folded coupled line bandpass filter | 70 |

| | | |
|------|--|----|
| 3.11 | Proposed L-stubs into the bandpass filter | 70 |
| 3.12 | Proposed 180° matching network | 71 |
| 3.13 | Scheme of the diplexer design A | 72 |
| 3.14 | The layout of the diplexer design A | 73 |
| 3.15 | The optimized diplexer design A | 75 |
| 3.16 | Scheme of the diplexer design B | 76 |
| 3.17 | The layout of the diplexer design B | 78 |
| 3.18 | The optimized diplexer design B | 78 |
| 3.19 | Scheme of the diplexer C | 79 |
| 3.20 | The layout of the diplexer design C | 79 |
| 3.21 | Scheme of the triplexer design | 81 |
| 3.22 | The layout of the triplexer design | 81 |
| 4.1 | The analysis of the separation of the resonator to the feeding line | 84 |
| 4.2 | The analysis of the distance length of the feeding line to the tapping position | 85 |
| 4.3 | The analysis of the coupling gap between two resonators | 86 |
| 4.4 | The simulation and measurement response of the bandpass filter using open loop resonator (a) The return loss, S_{11} (b) the insertion loss, S_{21} | 87 |
| 4.5 | The Initial response of the parallel coupled line resonators | 89 |
| 4.6 | The analysis of the separation gap between the transmission line of the parallel coupled line resonators | 90 |

| | | |
|------|---|-----|
| 4.7 | The finalized response of the bandpass filter using parallel coupled line resonator | 91 |
| 4.8 | The simulation and measurement response of the bandpass filter using parallel coupled line resonator (a) The return loss, S_{11} (b) the insertion loss, S_{21} | 92 |
| 4.9 | The bandpass response using folded coupled line resonator | 94 |
| 4.10 | The analysis of the separation gaps between the L-stubs and the bandpass filter using folded coupled line resonator | 95 |
| 4.11 | The finalized response of the bandpass filter using folded coupled line resonator | 96 |
| 4.12 | The simulation and measurement response of the bandpass filter using folded coupled line resonator (a) the return loss, S_{11} (b) the insertion loss, S_{21} | 97 |
| 4.13 | The responses of the rat-race matching network | 99 |
| 4.14 | Simulation of the diplexer A | 100 |
| 4.15 | The simulation and measurement response of the diplexer design A (a) the layout of the diplexer A (b) the return loss, S_{11} (c) the insertion loss of bandpass filter 1, S_{21} (d) the insertion loss of bandpass filter 2, S_{31} | 103 |
| 4.16 | Simulation of the diplexer B | 104 |
| 4.17 | The simulation and measurement response of the diplexer design B | |

| | | |
|------|--|-----|
| | (a) the layout of the diplexer B(b) the return loss, S_{11} (c) the insertion loss of bandpass filter 1, S_{21} (d) the insertion loss of bandpass filter 2, S_{31} | 106 |
| 4.18 | Simulation of the diplexer C | 108 |
| 4.19 | The simulation and measurement response of the diplexer design C (a) the layout of the diplexer C (b) the return loss, S_{11} (c) the insertion loss of bandpass filter 1, S_{21} (d) the insertion loss of bandpass filter 2, S_{31} | 110 |
| 4.20 | Simulation of the triplexer | 111 |
| 4.21 | The simulation and measurement response of the triplexer (a) the layout of the triplexer (b) the return loss, S_{11} | 113 |
| 4.22 | The simulation and measurement response of the triplexer in insertion loss, S_{21} | 114 |
| 4.23 | The simulation and measurement response of the triplexer in insertion loss, S_{31} | 115 |
| 4.24 | The simulation and measurement response of the triplexer in insertion loss, S_{41} | 115 |

LIST OF APPENDICES

| APPENDIX | TITLE | PAGE |
|----------|---|------|
| A | FR-4 Data Sheet | 138 |
| B | Calculation Details for bandpass filter using parallel coupled lines resonators | 139 |

LIST OF ABBREVIATIONS

| | | |
|-------|---|--|
| ADS | - | Advanced Design System |
| EBG | - | Electromagnetic Band-Gap |
| IEEE | - | Institute of Electrical and Electronic Engineers |
| ITU | - | International Telecommunication Union |
| LTCC | - | Low Temperature Co-fired Ceramic |
| LTE | - | Long Term Evolution |
| RF | - | Radio frequency |
| WiFi | - | Wireless Fidelity |
| WiMAX | - | Worldwide Interoperability for Microwave Access |
| WLAN | - | Wireless Local Network Area Networking |

LIST OF SYMBOLS

| | | |
|--------------|---|--------------------------|
| W | - | Width |
| L, l | - | Length |
| S | - | Separation |
| G | - | Gap |
| V | - | Voltage |
| I | - | Current |
| D | - | Diameter |
| ϵ_R | - | Dielectric constant |
| h | - | Thickness |
| λ | - | Quater wavelength |
| β | - | Propagation constant |
| Z | - | Characteristic Impedance |
| J | - | imaginary part |
| Ω | - | Angular frequency |
| Δ | - | Delta or Initialism |
| Γ | - | Reflection coefficient |
| T | - | Transmission coefficient |

LIST OF PUBLICATIONS

1. Sazali, M.A., Shairi, N.A. and Zakaria, Z., 2017. Microstrip Triplexer Design: A Review. *Journal of Telecommunication, Electronic and Computer Engineering (JTEC)*, 9(2-13), pp.81-86.
2. Sazali, M.A., Shairi, N.A. and Zakaria, Z., 2018. Hybrid Microstrip Diplexer Design for Multi-band WiMAX Application in 2.3 and 3.5 GHz Bands. *International Journal of Electrical and Computer Engineering (IJECE)*, 8(1).
3. N. A. Shairi, M. A. Sazali, Z. Zakaria, I. M. Ibrahim, M. K. Zahari, B. H. Ahmad, "Hybird Triplexer Design using Microstrip Coupled Line Resonators for Multiband WiMAX Front End," *7TH IEEE International Symposium on Microwave, Antenna, Propagation, and EMC Technologies (MAPE), 2017.*