GALLIUM NITRIDE BASED CIRCUITS FOR MICROWAVE SIGNAL GENERATION

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Submitted
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To

MY FAMILY

CERTIFICATE

This is to certify that the work reported in this thesis entitled **“Gallium Nitride Based Circuits for Microwave Signal Generation”** being submitted by **Ms. Rakhi Kumari** for the award of the degree of **Doctor of Philosophy** to the Indian Institute of Technology Delhi, New Delhi, India, is a record of original bonafide research work carried out by her under our guidance and supervision. The results contained in this thesis have not been submitted in part or full, to any other university or institute for the award of any degree or diploma.

We certify that she has pursued the prescribed course of research.

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ABSTRACT

The major limitations of high range and high-resolution radar at microwave and millimeter wave frequency is the unavailability of compact, efficient high-power source with low distortion using solid state devices. The Current most promising solid-state technology for high power handling is GaN/AlGaN based high electron mobility transistors (HEMT) at microwave and millimeter wave frequency. A key advantage to GaN is its ability to maintain high operating voltage at higher frequency range. This is due to the unique combination of high band gap energy resulting in higher device tolerance for high field strengths, as well as the high-speed properties of electron mobility and saturation velocity due to hetro-structure at junction and polarization effect. Due to high mobility and high saturation velocity these transistors can be operated at microwave and millimeter wave frequency. These devices can handle high voltage due to the wide band-gap of GaN and have high carrier density due to polarization effects and structure of HEMT. Hence these devices have high power handling and high-power generating capacity with less distortion at microwave and millimeter wave frequency range.

This thesis work is focused on developing GaN/AlGaN HEMT based High power sources using active integrated antenna (AIA) approach. One goal of this thesis is to develop a high-power amplifier type AIA. While most reports on GaN HEMT concentrate on power amplifiers, this design also combines AIA approach with power amplifier design to make the system compact and increase effective isotropic radiated power (EIRP). The measured EIRP of this circuit is 49 dBm. Which is better than the state-of-the-art results reported for GaN HEMT based active integrated antenna.

The second goal of this thesis is to develop GaN/AlGaN HEMT based self-oscillating AIA. This oscillator design is based on negative impedance technique and AIA approach. Here the patch antenna is connected at the output side of the oscillator and performs multiple functions and makes the system compact. It acts like a load, resonator and radiator. The two circuits using the same approach are developed using a single device. The measured EIRP of the first circuit is 18 dBm power at 1.5 GHz. The measured EIRP of the second circuit is 29 dBm at 2 GHz frequency.

The third goal of this thesis is to develop GaN/AlGaN HEMT based self-oscillating AIA, where the AIA approach is used to maximize the radiated power at second harmonic. Hence the frequency of power generation is doubled. Two circuits are designed for this purpose. The measured EIRP of the first circuit is 32 dBm at second harmonic (3 GHz) and 16 dBm at fundamental frequency (1.5 GHz). In the second circuit the negative impedance region (frequency) is increased using a coupled line in parallel with the device, the AIA approach is also used to maximize the radiated power at second harmonic. So, this circuit generates high power at higher frequency. In simulation this circuit has simulated power of 37 dBm at second harmonic of 8 GHz and 20 dBm at fundamental frequency (4 GHz). So, the proposed GaN HEMT based AIA concept can be used to generate useful power at higher frequency and this technique will be very useful in extending the frequency of operation of circuit beyond the operating frequency range of transistors used in the circuit.

The final goal of this circuit is to develop GaN/AlGaN HEMT based self-oscillating fixed frequency and frequency reconfigurable AIA high power source using feedback topology. The fixed frequency circuit implemented radiates 41 dBm power at 2.4 GHz, which is the highest EIRP using a single device. In frequency reconfigurable AIA, the frequency of oscillation changes from 2.1 GHz to 2.7GHz, when pin diodes change its state from off state to on state. The second circuit has EIRP within 1dB in both states. This circuit is very compact and can generate two frequencies by changing the biasing of pin diodes without changing the circuit footprint. This circuit is the first implementation of GaN/AlGaN HEMT based reconfigurable oscillating AIA.

Due to the above-mentioned design concept and approaches on design level, this work provides the basis for the design and implementation of GaN/AlGaN HEMT based high power sources at microwave and millimeter wave frequency. Also, the power can be further increased using spatial power combining technique. Therefore, GaN/AlGaN based high power circuits are of great interest for long range solid-state phased-array systems.

सारांश

माइक्रोवेव और मिलीमीटर तरंग आवृत्ति पर अधिक रेंज और अधिक रिज़ॉल्यूशन रडार की प्रमुख सीमाएं ठोस अवस्था उपकरणों का उपयोग करके कम विरूपण के साथ कॉम्पैक्ट, कुशल, अधिक शक्ति स्रोत की अनुपलब्धता है। अधिक शक्ति हैंडलिंग के लिए वर्तमान में सबसे आशाजनक ठोस अवस्था तकनीक माइक्रोवेव और मिलीमीटर तरंग आवृत्ति पर GaN / AlGaN आधारित अधिक इलेक्ट्रॉन गतिशीलता ट्रांजिस्टर (HEMT) है। GaN के लिए एक महत्वपूर्ण लाभ अधिक आवृत्ति सीमा पर अधिक ऑपरेटिंग वोल्टेज बनाए रखने की इसकी क्षमता है। यह अधिक बैंड गैप ऊर्जा के अद्वितीय संयोजन के कारण होता है जिसके परिणामस्वरूप अधिक विद्युत क्षेत्र की ताकत के लिए अधिक उपकरण सहिष्णुता होती है, साथ ही जंक्शन और ध्रुवीकरण प्रभाव पर हेट्रो-संरचना के कारण इलेक्ट्रॉन गतिशीलता और संतृप्ति वेग के अधिक गति के गुण होते हैं। अधिक गतिशीलता और अधिक संतृप्ति वेग के कारण इन ट्रांजिस्टर को माइक्रोवेव और मिलीमीटर तरंग आवृत्ति पर संचालित किया जा सकता है। ये उपकरण GaN के व्यापक बैंड-गैप के कारण अधिक वोल्टेज को संभाल सकते हैं और ध्रुवीकरण प्रभाव और HEMT की संरचना के कारण अधिक वाहक घनत्व है। इसलिए इन उपकरणों में माइक्रोवेव और मिलीमीटर तरंग आवृत्ति सीमा पर कम विरूपण के साथ अधिक शक्ति हैंडलिंग और अधिक शक्ति उत्पादन क्षमता होती है।

यह थीसिस काम सक्रिय एकीकृत एंटीना (AIA) तकनीक का उपयोग करके GaN / AlGaN HEMT आधारित अधिक शक्ति स्रोतों को विकसित करने पर केंद्रित है। इस थीसिस का एक लक्ष्य एक अधिक शक्ति एम्पलीफायर प्रकार का AIA विकसित करना है। जबकि GaN HEMT पर अधिकांश रिपोर्टें पावर एम्पलीफायरों पर ध्यान केंद्रित करती हैं, यह डिज़ाइन सिस्टम को कॉम्पैक्ट बनाने और प्रभावी आइसोट्रोपिक विकीर्ण शक्ति (EIRP) को बढ़ाने के लिए पावर एम्पलीफायर डिज़ाइन के साथ AIA तकनीक को भी जोड़ती है। इस परिपथ का मापा गया EIRP 49 dBm है। जो GaN HEMT आधारित AIA के लिए रिपोर्ट किए गए अत्याधुनिक परिणामों से बेहतर है।

इस थीसिस का दूसरा लक्ष्य GaN / AlGaN HEMT आधारित स्व-दोलन AIA विकसित करना है। यह दोलन डिजाइन नकारात्मक प्रतिबाधा तकनीक और एआईए दृष्टिकोण पर आधारित है। यहां पैच एंटीना दोलन के आउटपुट पक्ष पर जुड़ा हुआ है और कई कार्य करता है और सिस्टम कॉम्पैक्ट बनाता है। यह एक लोड, resonator और रेडिएटर की तरह कार्य करता है। एक ही तकनीक और एक ही

डिवाइस का उपयोग करके दो सर्किट विकसित किए गए हैं। पहले परिपथ का मापा गया EIRP 1.5 GHz पर 18 dBm शक्ति है। दूसरे परिपथ का मापा गया EIRP 2 गीगाहर्ट्ज आवृत्ति पर 29 dBm है ।

इस थीसिस का तीसरा लक्ष्य GaN / AlGaN HEMT आधारित स्व-दोलन AIA विकसित करना है, जहां AIA तकनीक का उपयोग दूसरे हार्मोनिक पर विकीर्ण शक्ति को अधिकतम करने के लिए किया जाता है। इसलिए विद्युत उत्पादन की आवृत्ति दोगुनी हो जाती है। इस उद्देश्य के लिए दो सर्किट डिज़ाइन किए गए हैं। पहले परिपथ का मापा गया EIRP दूसरे हार्मोनिक (3 GHz) पर 32 dBm और मौलिक आवृत्ति (1.5 GHz) पर 16 dBm है। दूसरे सर्किट में नकारात्मक प्रतिबाधा क्षेत्र (आवृत्ति) डिवाइस के साथ समानांतर में एक युग्मित रेखा का उपयोग करके बढ़ाया जाता है, एआईए तकनीक का उपयोग दूसरे हार्मोनिक पर विकीर्ण शक्ति को अधिकतम करने के लिए भी किया जाता है। इसलिए, यह सर्किट अधिक आवृत्ति पर अधिक शक्ति उत्पन्न करता है। सिमुलेशन में इस सर्किट में 8 गीगाहर्ट्ज, दूसरे हार्मोनिक पर 37 डीबीएम की शक्ति है और मौलिक आवृत्ति (4 गीगाहर्ट्ज) पर 20 डीबीएम है। इसलिए, प्रस्तावित GaN HEMT आधारित AIA तकनीक का उपयोग अधिक आवृत्ति पर उपयोगी शक्ति उत्पन्न करने के लिए किया जा सकता है और यह तकनीक सर्किट में उपयोग किए जाने वाले ट्रांजिस्टर की ऑपरेटिंग आवृत्ति सीमा से परे सर्किट के संचालन की आवृत्ति का विस्तार करने में बहुत उपयोगी होगी।

इस सर्किट का अंतिम लक्ष्य GaN / AlGaN HEMT आधारित स्व-दोलन निश्चित आवृत्ति और आवृत्ति reconfigurable AIA अधिक शक्ति स्रोत प्रतिक्रिया टोपोलॉजी का उपयोग कर विकसित करने के लिए है। कार्यान्वित किया गया निश्चित आवृत्ति सर्किट 2.4 गीगाहर्ट्ज पर 41 डीबीएम पावर विकीर्ण करता है, जो एक एकल डिवाइस का उपयोग करके उच्चतम ईआईआरपी है। आवृत्ति Re-configuration एआईए में, दोलन की आवृत्ति 2.1 गीगाहर्ट्ज से 2.7 गीगाहर्ट्ज में बदल जाती है, जब पिन डायोड अपनी स्थिति को ऑफ अवस्था से on अवस्था पर बदल देते हैं। दूसरे सर्किट में दोनों अवस्था में 1dB के भीतर EIRP है। यह सर्किट बहुत कॉम्पैक्ट है और सर्किट पदचिह्न को बदलने के बिना पिन डायोड के बायसिंग को बदलकर दो आवृत्तियों को उत्पन्न कर सकता है। यह परिपथ GaN/AlGaN HEMT आधारित आवृत्ति Re-configuration करने योग्य दोलन AIA का पहला कार्यान्वयन है।

डिजाइन स्तर पर उपर्युक्त डिजाइन अवधारणा और दृष्टिकोण के कारण, यह काम माइक्रोवेव और मिलीमीटर तरंग आवृत्ति पर GaN / AlGaN HEMT आधारित अधिक शक्ति स्रोतों के डिजाइन और कार्यान्वयन के लिए आधार प्रदान करता है। इसके अलावा, spatial power combining तकनीक

का उपयोग करके शक्ति को और बढ़ाया जा सकता है। इसलिए, GaN / AlGaN आधारित उच्च शक्ति सर्किट लंबी दूरी के ठोस अवस्था phased-array systems के लिए बहुत महत्वपूर्ण हैं।

TABLE OF CONTENTS

CERTIFICATE i

ACKNOWLEDGEMENT ii

ABSTRACT iv

TABLE OF CONTENTS ix

LIST OF FIGURES xii

LIST OF TABLES xviii

LIST OF ABBREVIATIONS xx

CHAPTER 1

Introduction

1.1 Motivation 1
1.2 Background and Literature Review 3
    1.2.1 Advantage of microwave and millimetre wave 3
    1.2.2 Active integrated antenna 4
    1.2.3 Advantages of GaN HEMT over other devices 10
1.3 Working concept of AIA technique 16
1.4 Devices and substrate used in circuits 17
    1.4.1 Cree's CGH40010 GaN Descrete Transistor Die 17
    1.4.2 Rogers's 5340B substrate 17
1.5 Scope and Objective of the Work 19
1.6 Organization of the Thesis 20

CHAPTER 2

Development of GaN/AlGaN HEMT based high power amplifier type AIA

2.1 Introduction 22
2.2 Power Amplifier Design 23
    2.2.1 Biasing circuit design 24
    2.2.2 Stability Analysis 25

2.2.3 Matching Network design 28
2.2.4 PA Simulated Results 33
2.2.5 EM simulation 36
2.2.6 Circuit Fabrication 40
2.2.7 PA Measured Results 41
2.3 Power amplifier type AIA Design 43
2.3.1 AIA Design Procedure 43
2.3.2 One port patch antenna design 44
2.3.3 One port patch antenna design for AIA 46
2.3.4 AIA simulated result 47
2.3.5 Measurement of high-power AIA 50
2.3.6 PA type AIA Measured Result 51
2.4 Summary 52

CHAPTER 3

Design and development of GaN/AlGaN HEMT based self-oscillating AIA with patch antenna in series with active circuit

3.1 Introduction 53
3.2 Oscillator design 55
3.2.1 Operating principle of negative resistance oscillator design 55
3.2.2 Characteristics of oscillator at microwave and millimetre wave frequency 57
3.2.3 Simulation of oscillator` 58
3.2.4 Measurement and Result discussion 65
3.3 Oscillator type AIA Design 65
3.3.1 Operating principle 65
3.3.2 Simulated result of AIA at 1.6 GHz 67
3.3.3 Simulated result of AIA at 2 GHz 68
3.3.4 Measurement, results and discussion of circuits 74
3.4 Summary 75

CHAPTER 4

Design and development of GaN/AlGaN HEMT based self-oscillating AIA with maximum power at Second Harmonic

4.1 Introduction 76
4.2 Operating principle of oscillator which can generate maximum power at second

harmonic using AIA approach 77
4.3 Design of oscillator using AIA approach which gives maximum power at 3 GHz 78
4.3.1 Simulation of oscillator 78
4.3.2 Measurement, Results and discussion 82
4.4 Design of oscillator using AIA approach and coupled line feedback which gives maximum power at 8 GHz 83
4.4.1 Operating principle 83
4.4.2 Simulation of oscillator 85
4.4.3 Measurement, Results and discussion 91
4.5 Summary 92

CHAPTER 5

Design and development of GaN/AlGaN HEMT based Fixed and frequency reconfigurable self-oscillating AIA using feedback topology

5.1 Introduction 93
5.2 Fixed frequency AIA design 94
5.2.1 Operating principle of self-oscillating feedback AIA 94
5.2.2 Two port Patch antenna design 95
5.2.3 Two port T-coupled Patch antenna design 97
5.2.4 Simulation of fixed frequency AIA 98
5.2.5 Measurement, results and discussion of AIA 103
5.3 Frequency reconfigurable AIA design 104
5.3.1 Operating principle of frequency reconfigurable AIA 104
5.3.2 Two port patch antenna design for frequency reconfigurable AIAs 105
5.3.3 Simulation of frequency reconfigurable AIA 109
5.3.4 Measurement, result and discussion of frequency reconfigurable AIA 115
5.4 Summary 118

CHAPTER 6

Conclusions and Future Scope

6.1 Summary of the Thesis 119
6.2 Future Scope of the Work 121

REFERENCES 122

APPENDIX – I 139

APPENDIX – II 152

APPENDIX – III 153

PUBLICATIONS 157

BRIEF BIO-DATA OF THE AUTHOR 158

LIST OF FIGURES

Fig. 1.1: Schematic comparison illustrating advantages of GaN over existing technology 13
Fig. 1.2: Layer structure of High Electron Mobility Transistor (HEMT) 14
Fig. 1.3: Energy band diagram showing 2DEG formation in GaN/AlGaN HEMT 15
Fig. 1.4: Block diagram of working concept of AIA 16
Fig. 2.1: A biasing network with decoupling capacitors used in GaN/AlGaN HEMT 25
Fig. 2.2: (a) Stability factor (K) before stabilization (b) Stability measure (Δ) before Stabilization 26
Fig. 2.3: (a) Stability factor (K) after stabilization (b) Stability measure (Δ) after Stabilization 27
Fig. 2.4: Load pull simulation contour of power and power added efficiency on smith chart with varying load 28
Fig. 2.5: Load selected for the power Amplifier design on smith chart 29
Fig. 2.6: Output matching circuit (a) schematic (b) impedance of output matching network on smith chart 30
Fig. 2.7: Simulated impedance of output matching circuit on smith chart 31
Fig. 2.8: Input matching circuit (a) schematic (b) simulated return loss and output impedance of input matching network on smith chart 32
Fig. 2.9: Schematic of power amplifier 33
Fig. 2.10: Simulated Input and output return losses versus frequency of power amplifier 33
Fig. 2.11: Simulated small signal gain versus frequency of power amplifier 34
Fig. 2.12: Harmonic Balance simulated Output power versus Input power 34
Fig. 2.13: Harmonic Balance simulated PAE versus Input power 35
Fig. 2.14: Harmonic Balance simulated Power gain versus Input power 35
Fig. 2.15: Layout of power amplifier for EM simulation 36
Fig. 2.16: Schematic of power amplifier for EM co-simulation 37
Fig. 2.17: EM simulated Input and output return losses versus frequency of PA 37
Fig. 2.18: EM simulated small signal gain versus frequency of PA 38
Fig. 2.19: EM simulated Output power (Pout) versus Input power (Pin) of PA 38
Fig. 2.20: EM simulated PAE versus Input power (Pin) of PA 39
Fig. 2.21: EM simulated power gain versus Input power (Pin) of PA 39

Fig. 2.22: Final layout of power amplifier 40
Fig. 2.23: Fabricated PA circuit with mounted lumped component 40
Fig. 2.24: Measured Output Power (P_{out}) versus Input Power (P_{in}) of power amplifier 42
Fig. 2.25: Measured drain efficiency versus Input Power (P_{in}) of power amplifier 42
Fig. 2.26: Topology of power amplifier 43
Fig. 2.27: Schematic of output matching network which is replaced by patch antenna 43
Fig. 2.28: Photograph of fabricated patch antenna matched to 50Ω 45
Fig. 2.29: Simulated and Measured result of designed patch antenna matched to 50Ω 46
Fig. 2.30: Simulated one port S-parameter (S11) of patch antenna for PA type AIA 47
Fig. 2.31: Schematic of power amplifier type AIA 47
Fig. 2.32: Simulated Input return Loss (S11) versus frequency in PA type AIA 48
Fig. 2.33: Simulated power at input of patch antenna versus input power in PA type AIA 48
Fig. 2.34: Layout of PA type AIA 49
Fig. 2.35: Photograph of fabricated PA type AIA with mounted lumped component 49
Fig. 2.36: Block diagram of measurement setup for power measurement of high-power AIA 50
Fig. 2.37: Measured EIRP and overall gain of PA type AIA versus current 51
Fig. 3.1: Low frequency noise, Q factor, and Power in different technologies 54
Fig. 3.2: Generic Block diagram for two-port negative resistance oscillator 56
Fig. 3.3: Topology of common source configuration of transistor used in oscillator 58
Fig. 3.4: Simulated S-parameter (S_{11} and S_{22}) of the GaN/AlGaN HEMT at Vgs of -2.8 volt and Vds of 28 volt 58
Fig. 3.5: Simulated Stability factor (K) and Stability measure (Δ) of device 59
Fig. 3.6: Simulated stability circle with potentially unstable region 59
Fig. 3.7: Designed terminating network (a) Schematic (b) Simulated input impedance on smith chart at 1.5 GHz 60
Fig. 3.8: (a) Schematic of terminating network at input side (b) Simulated S-parameter with input impedance on smith chart at 1.5 GHz 61
Fig. 3.9: Load matching network for oscillator 62
Fig.3.10: Simulated one port S-parameter of load matching network of oscillator 62
Fig. 3.11: Schematic of oscillator 63
Fig. 3.12: Simulated S_{11} of oscillator (Nyquist plot) 63
Fig.3.13: Simulated power in oscillator at fundamental frequency and its harmonics 64
Fig. 3.14: Layout of oscillator 64

Fig. 3.15: Photograph of fabricated oscillator circuit 65
Fig. 3.16: Topology for Oscillator Design 66
Fig. 3.17: Replacement of load network of oscillator by patch antenna 66
Fig. 3.18: Power generated at input of patch antenna at oscillation frequency and harmonics 67
Fig. 3.19: Simulated (a) one port S-parameter at output port (negative resistance at output port) on smith chart (b) real and imaginary part of output impedance 69
Fig. 3.20: Simulated (a) one port S-parameter of patch antenna for oscillator type AIA at 2 GHz on smith chart (b) real and imaginary part of output impedance 70
Fig. 3.21: Simulated S_{11} and phase at 2 GHz of oscillator type AIA (Nyquist plot) 71
Fig. 3.22: Simulated Power at input of patch antenna in oscillator type AIA at oscillation frequency and its harmonics 72
Fig. 3.23: HB simulated voltage of oscillating circuit in steady state with (a) one order and (b) three order of harmonics 73
Fig. 3.24: Layout of self-oscillating AIA at 2 GHz 73
Fig. 3.25: Photograph of fabricated self-oscillating AIA at 2GHz 74
Fig. 4.1: Architecture to double the frequency of oscillator using AIA 78
Fig. 4.2: Simulated S-parameter (S_{11}) of one port patch antenna for AIA at 3 GHz on smith chart 79
Fig. 4.3: Simulated generated power at input of patch antenna in oscillator type AIA 80
Fig. 4.4: HB simulated voltage of oscillating circuit in steady state with (a) one order and (b) three order harmonics 81
Fig. 4.5: Layout of oscillating AIA at 3 GHz 81
Fig. 4.6: Photograph of fabricated oscillating AIA at 3 GHz 82
Fig. 4.7: Measured EIRP of Active Integrated Antenna 83
Fig. 4.8: Topology of coupled line based Active Integrated Antenna 84
Fig. 4.9: The simulated (a) S-parameter with negative resistance generated at 4 GHz (b) real and imaginary part of input impedance of circuit versus frequency 86
Fig. 4.10: Simulated S parameter (S_{11}) of one port Patch antenna 86
Fig. 4.11: Simulated (a)input impedance of patch antenna on Smith chart (b) real and imaginary part of input impedance of patch antenna versus frequency 87
Fig. 4.12: HB Simulated power at input of patch antenna 88
Fig. 4.13: Simulated power at fundamental frequency and second harmonics in AIA Versus drain voltage (VDS) 89

Fig. 4.14: HB simulated voltage of oscillating circuit in steady state with (a) one order and (b) three order harmonics 90
Fig. 4.15: Layout of oscillating AIA at 8 GHz 91
Fig. 4.16: Photograph of oscillating AIA at 8 GHz 91
Fig. 5.1: Topology of feedback back type self-oscillating high-power AIA 95
Fig. 5.2: Topology of two port patch antenna 96
Fig. 5.3: Photograph of fabricated two port patch antenna 96
Fig. 5.4: Measured S-parameter of patch antenna at 2.4 GHz 97
Fig. 5.5: Topology of two port T-coupled patch antenna 97
Fig. 5.6: Simulated S-parameter of T-coupled patch antenna 98
Fig. 5.7: Schematic of Fixed frequency High power feedback topology-based AIA 99
Fig. 5.8: Simulated S11 and loop phase of the feedback AIA 99
Fig. 5.9: HB simulated Power enter at two port patch antennae at fundamental Frequency and its harmonics 100
Fig. 5.10: HB simulated voltage of oscillating circuit in steady state with (a) one order at port1 (b) three order at port1 (c) one order at port2 (d) three orders at port 2 102
Fig. 5.11: Layout of Feedback AIA at 2.4 GHz 102
Fig. 5.12: Photograph of fabricated feedback AIA 103
Fig. 5.13: Measured EIRP of fixed frequency AIA 104
Fig. 5.14: Schematic of Frequency reconfigurable patch antenna 105
Fig. 5.15: Model of pin diode in on and off state 105
Fig. 5.16: Schematic of frequency reconfigurable patch antenna with one pin diode at each side of patch 106
Fig. 5.17: Simulated S-parameter of two port patch antenna with one pin diode in patch antenna in (a) ON state and (b) OFF state 107
Fig. 5.18: Schematic of frequency reconfigurable two port patch antenna with two pin diodes at each side of patch 108
Fig. 5.19: Simulated S-parameter of two port patch antenna with two pin diodes at Both side of patch antenna in (a) ON state and (b) OFF state 109
Fig. 5.20: Schematic of Frequency reconfigurable high-power AIA (a) patch antenna with one pin diode each side (b) patch antenna with two pin diodes each side 110

Fig. 5.21: Simulated (Nyquist plot) S_{11} and phase loop of frequency reconfigurable AIA with two pin diodes each side of patch in (a) ON state and (b) OFF state 111

Fig.5.22: Simulated generated power in Frequency reconfigurable high-power AIA having one pin diode at each side of patch in (a) ON state and (b) OFF state 113

Fig.5.23: Simulated generated power in Frequency reconfigurable high-power AIA having two pin diodes at each side of patch in (a) ON state and (b) OFF state 114

Fig.5.24: Layout of Frequency reconfigurable AIA with two pin diodes at both side of Patch antenna 114

Fig. 5.25: Photograph of frequency reconfigurable AIA with two pin diodes, each side 115

Fig. 5.26: Photograph of setup for RF power measurement of AIA 116

Fig. 5.27: Measured EIRP of frequency reconfigurable AIA in both states 117

LIST OF TABLES

Table 1.1: Applications of Active Integrated Antennas (AIA) 9
Table 1.2: Material properties of common microwave semiconductors 10
Table 1.3: Competitive Advantages of GaN Device 13
Table 2.1: Design Target for Power Amplifier and Power amplifier Type AIA 23
Table 2.2: Simulated load required in Load pull simulation for maximum gain and power 29
Table 2.3: Simulated load required in load pull simulation for maximum PAE 29
Table 2.4: Simulated values of load impedance and source impedance required for power amplifier design at load selected in load pull simulation 29
Table 2.5: Dimensions of transmission lines used in input and output matching circuit 32
Table 2.6: Space left for mounting lumped component 36
Table 2.7: Input impedance of output matching network of amplifier and one port patch antenna 46
Table 2.8: Comparison of GaN HEMT based AIAs with this work 52
Table 3.1: Design Target for oscillator and oscillator type AIAs 55
Table 3.2: HB simulated Result at input of patch antenna at fundamental frequency of 1.5 GHz 67
Table 3.3: HB simulated Result at input of patch antenna at fundamental frequency of 2 GHz 71
Table 3.4: Comparison of simulated and measured Result at 1.5 GHz self-oscillating AIA 74
Table 3.5: Comparison of simulated and measured Result at 2 GHz self-oscillating AIA 75
Table 4.1: Design Target for two self-oscillating AIAs which gives maximum power at second harmonic 77
Table 4.2: Measured EIRP of Active integrated antenna 83
Table 5.1: Design Target for two self-oscillating AIAs using two ports patch antenna in feedback 94
Table 5.2: Dimension of T-coupled two port patch antenna 97
Table 5.3: Dimension of frequency reconfigurable T-coupled two port patch antenna 108

Table 5.4: Harmonic Index and frequency of oscillation with pin diode, each side of two port patch in ON and OFF state 112

Table 5.5: Comparison of EIRP of previously reported self-oscillating AIA with this Work 117

LIST OF ABBREVIATIONS

ADS	Design System
AESA	Active Electronically Scanned Array
AIA	Active Integrated Antenna
AlGaN	Aluminium Gallium Nitrid
BSF	Band Stop Filter
COAs	Coupled Oscillator Arrays
CST	Computer Simulation Technology
CW	Continuous Wave
dB	Decibel
dBc	Decibel reference to Carrier
dBm	Decibel reference to 1 mW
DC	Direct Current
DSRC	Dedicated short-range communication
EIRP	Effective Isotropic Radiated Power
EM	Electromagnetic
EV	Electric Vehicle
FOV	Field of view
GaAs	Gallium Arsenide
GaN	Gallium Nitride
GHz	Giga Hertz
GPS	Global Positioning System
HBT	Hetero-junction Bipolar Transistor
HJFET	Hetero-Junction Field Effect Transistor
HEMT	High Electron Mobility Transistor
HF	High Frequency

Hz	Hertz
IME	Impedance Mismatch Efficiency
IEEE	Institute of Electrical and Electronics Engineering
IMN	Input Matching Network
IMPATT	IMPact ionization Avalanche Transit-Time diode
InGaP	Indium Gallium Phosphide
LDMOS	lateral-diffused metal–oxide–semiconductors
LFN	Low frequency noise
MAG	Maximum Available Gain
MEMS	Micro-electromechanical systems
µF	Micro Farad
MHz	Mega Hertz
MIC	Microwave Integrated Circuit
MMIC	Microwave Integrated Circuit
MPT	Microwave Power Transmission
mW	Milli Watt
nH	Nano Henry
OMN	Onput Matching Network
PA	power Amplifier
PAE	Power Added Efficiency
PCB	Printed Circuit Board
pF	Pico Farad
PIN	P type – Intrinsic – N type
PPM	Parts per million
PSD	power spectral density
Q factor	Quality factor
Q point	Quiescent Point
RADAR	Radio Detection and Ranging
RF	Radio Frequency
RFID	Radio Frequency Identification
SA	Spectrum Analyzer/ Signal Analyzer

SiC	Silicon Carbide
SMA	Sub Miniature version A type
S-Parameter	Scattering Parameter
TL	Transmission Line
TRM	Transmit/Receive Modules
TX	Transmitter
UMTS	Universal Mobile Telecommunications Service
VCO	Voltage Controlled Oscillator
VEDs	Vacuum Electron Devices
VHF	Very High Frequency
VNA	Vector Network Analyzer
WiFi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
2-DEG	Two-Dimensional Electron Gas
5G	The Fifth Generation of cellular networks