Frequency Reconfigurable High Power GaN/AlGaN HEMT Based Self Oscillating Active Integrated Antenna

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Abstract—This paper presents two circuits for a high power GaN/AlGaN HEMT based self oscillating Active Integrated Antenna (AIA) using feedback topology. The first circuit, a fixed frequency high power source, is designed using a two-port T-coupled patch antenna in parallel feedback of a device. This circuit radiates 41 dBm power at 2.34 GHz frequency when being biased at $V_{gs} = -2.1$ V and $V_{ds} = 25$ V. The second circuit, a frequency reconfigurable high power source, is designed using a frequency reconfigurable T-coupled two-port patch antenna in parallel feedback of a device. Frequency reconfigurability is achieved in the second circuit by adding one more strip and two pin diodes at both sides of centre patch of the two-port patch antenna. Change of biasing voltage of pin diodes changes the frequency of oscillation of the circuit. This circuit radiates 32.4 dBm power at 2.1 GHz when pin diodes are off and radiates 32 dBm power at 2.7 GHz when pin diode is on. To the best of our knowledge, the first circuit implemented radiates the highest power using single device whereas the second circuit is the first implementation of reconfigurable oscillating AIA in GaN and also delivers the same power in both states. Each circuit measures 80 mm × 80 mm.

1. INTRODUCTION

Advanced wireless communication and phased array radar systems need highly compact lightweight transmitters. Generally, power amplifier is used in a transmitter to increase the input power from RF source to the required higher power level, which thereby increases the size of a circuit [1]. As frequency increases towards millimeter wave, solid state device has limited power generation and power handling capacity. AIA has potential application for power combining to overcome the power limitations of solid state sources at high frequency. In an oscillator type AIA, an oscillator is designed using a patch antenna as its component, here the patch antenna acts as a resonator and radiator. Direct integration of an antenna and oscillating circuit leads to the elimination of feed line as well as some part of the circuit; this minimizes the circuit size and loss [2–7].

Recently developed GaN/AlGaN HEMT has shown promising result in the design of high power amplifier due to its high breakdown voltage, high current density, and high thermal conductivity [8–13]. GaN/AlGaN HEMT is also expected to generate high power. So the design of an oscillator type AIA using GaN/AlGaN HEMT as active device can generate high power using single device, and if required the power could be further increased using spatial power combining technique [14]. As a radiating element, microstrip patch antenna is used because it is simple, has low profile, modest size, and a planar structure. Reconfigurability in the circuit can be achieved using pin diode as switch in antenna, thereby the same circuit can generate different frequencies with the change of pin diode state.

In this paper, two self oscillating high power feedback topology based compact AIAs have been implemented using a Cree CGH40010 device on an RO4350 substrate. The first circuit is a fixed

frequency self oscillating high power AIA. This circuit radiates 41.4 dBm power at 2.34 GHz frequency using a single device. The second circuit is a frequency reconfigurable self oscillating high power feedback AIA. This circuit radiates 32.4 dBm power at 2.1 GHz when diodes are OFF and radiates 32 dBm at 2.7 GHz when diodes are ON, using a single active device.

2. DESIGN METHODOLOGY

At microwave frequency, oscillator can be designed either using feedback topology or negative impedance technique. The circuits in this paper are designed using feedback topology. This circuit topology is of great interest due to its simple geometry, low power consumption, and low phase noise. To design oscillator using feedback topology, first a T-coupled two-port patch antenna is designed in CST microwave studio at desired frequency using an RO4350 substrate. Second simulated two-port S-parameter of a patch antenna in CST is imported in Keysight ADS. The AIA circuit is designed using a two-port patch antenna in feedback of a Cree CGH40010 device with a biasing circuit on the same substrate. Transmission line length is adjusted at both ports of the antenna to achieve the total loop phase of 360° and total loop gain greater than one at the desired frequency of oscillation. Two-port patch antenna acts as a resonator and radiator for these oscillator type AIAs. The schematic of fixed frequency AIA and frequency reconfigurable AIA are shown in Figs. 1(a) and 1(b), respectively. The bigger and smaller rectangular blocks shown in the figure are T-coupled patch antenna and transmission lines, respectively. As shown in Fig. 1(b), the frequency reconfigurability is achieved by adding one thinner patch with two MACOM's MA4SPS552 pin diodes at both sides of T-coupled patch antenna. By changing the biasing of four pin diodes from OFF state to ON state, characteristics of antenna change, and subsequently the frequency of oscillation changes.
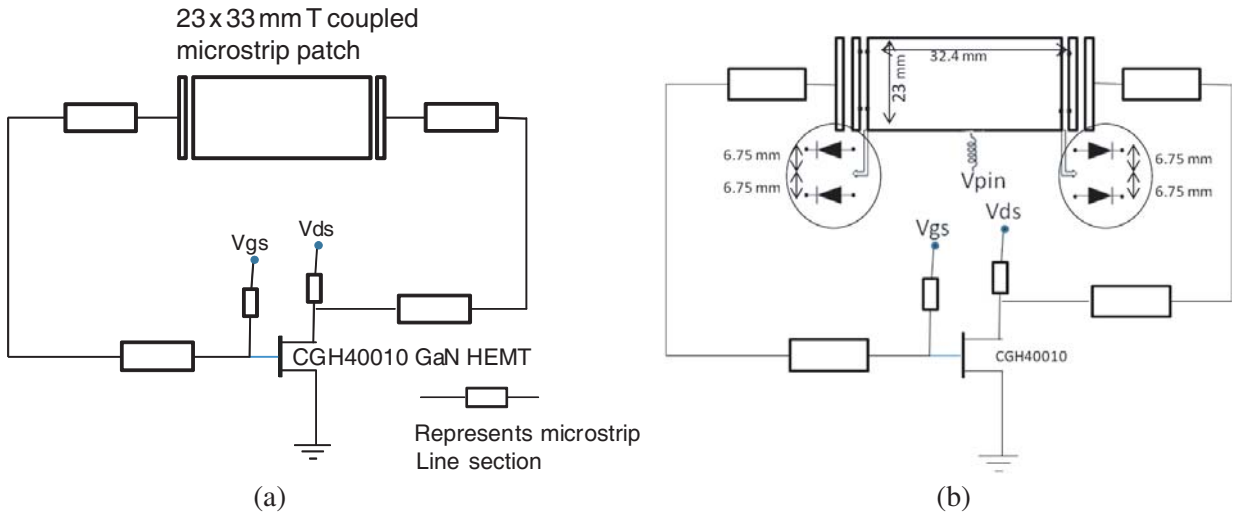

(a)   (b)

Figure 1. Schematic of (a) fixed frequency high power AIA, (b) frequency reconfigurable high power AIA.

3. AIA SIMULATION

To design a feedback high power AIA, first a two-port patch antenna is designed in CST Microwave studio at 2.4 GHz. Simulated S-parameter of the two-port patch antenna has -5.8 dB reflection coefficient and -5.8 dB transmission coefficient. Secondly, a simulated two-port S-parameter of the patch antenna in CST is imported in Keysight ADS. Biasing voltage is applied at Cree CGH40010 device via biasing circuits which are $V_{ds} = 25$ volt and $V_{gs} = -2.8$ volt. The schematic of two-port patch antenna in feedback with additional optimized length at both sides of antenna and an active device with a biasing circuit is simulated in ADS. Harmonic balance simulation is done in ADS to simulate

the frequency of oscillation, voltage, and current in circuit. The power generated in the patch antenna is calculated by Equation (1). In Eq. (1), P is the power generated in the two-port patch antenna. $V1$ and $V2$ are voltages at port1 and port2 of the patch antenna, and $I1$ and $I2$ are currents flowing toward port1 and port2 of the patch antenna, respectively.

$$P = 0.5Real\,[V1 * Conjugate(I1)] + 0.5Real\,[V2 * Conjugate(I2)] \qquad (1)$$

Figure 2(a) shows the frequency of oscillation and simulated generated power in patch antenna in ADS of fixed frequency high power AIA. Simulated frequency of oscillation and the generated power are 2.36 GHz and 37.13 dBm, respectively. Fig. 2(b) shows the frequency of oscillation and the simulated generated power in patch antenna in ADS of frequency reconfigurable high power AIA. The model used for pin diode in on state is 1.7 Ω. The model for off state pin diode is a capacitor of value 0.06 pF in parallel with a resistor of value 40 kΩ for simulation of the two-port frequency reconfigurable patch antenna. Simulated frequency of oscillation and generated power are 2.4 GHz and 40.2 dBm, respectively, when pin diodes are off. The frequency of oscillation changes to 2.66 GHz when pin diode is turned on. The generated power at fundamental frequency is 16 dB higher than the power generated at second harmonic in both circuits. Transient simulation is also done in ADS for both circuits to see the sustained oscillation. Generated voltages of AIAs have sustained oscillation.
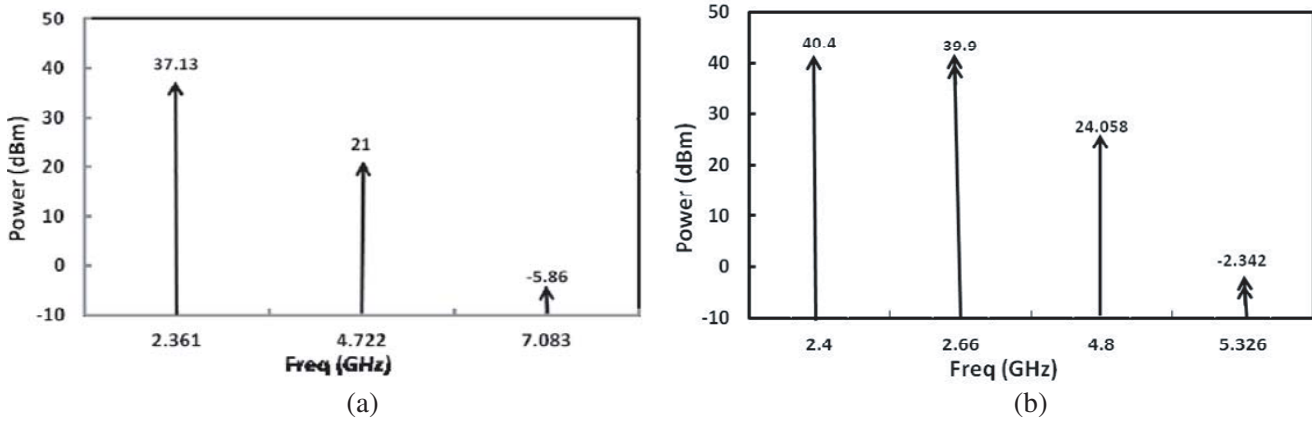

(a)

(b)

Figure 2. Simulated generated power in two port patch antenna of (a) fixed frequency high power AIA, (b) frequency reconfigurable high power AIA.

4. MEASUREMENT RESULT AND DISCUSSION

Fixed frequency and frequency reconfigurable self oscillating AIAs are fabricated on a Roger4350 substrate. All lumped components, capacitors, resistor, and inductors, are mounted on both the fabricated circuits. Fabricated circuits are mounted on a 6 mm thick aluminum plate for better heat dissipation in the device. The device is mounted in groove made on aluminum plate, and its terminals are soldered on the printed circuit of substrate. Photographs of both the fabricated circuits with all components assembled are shown in Figs. 3(a) and 3(b). The circuits are characterized in an anechoic chamber. DC biasing is given to the device of fabricated AIA circuit, and radiated power is received using a horn antenna placed at 2.25 meters in far field region. The power received by horn antenna is measured using Agilent 8562 signal analyzer, connected to the horn antenna via cable. Effective isotropic radiated power (EIRP) at fundamental frequency and harmonics are calculated using Friss transmission Equation (2).

$$EIRP = \frac{(P_{rec})}{G_r\,(\lambda/4\pi r)^2\,(CableLoss)} \qquad (2)$$

In Equation (2), P_{rec} is the received power in spectrum analyzer, G_r the gain of receiving Horn antenna used for measurement, and $(\lambda/4\pi r)^2$ the free-space loss. Note that the cable loss is taken care by dividing received power with measured cable loss. Measured maximum received power in signal
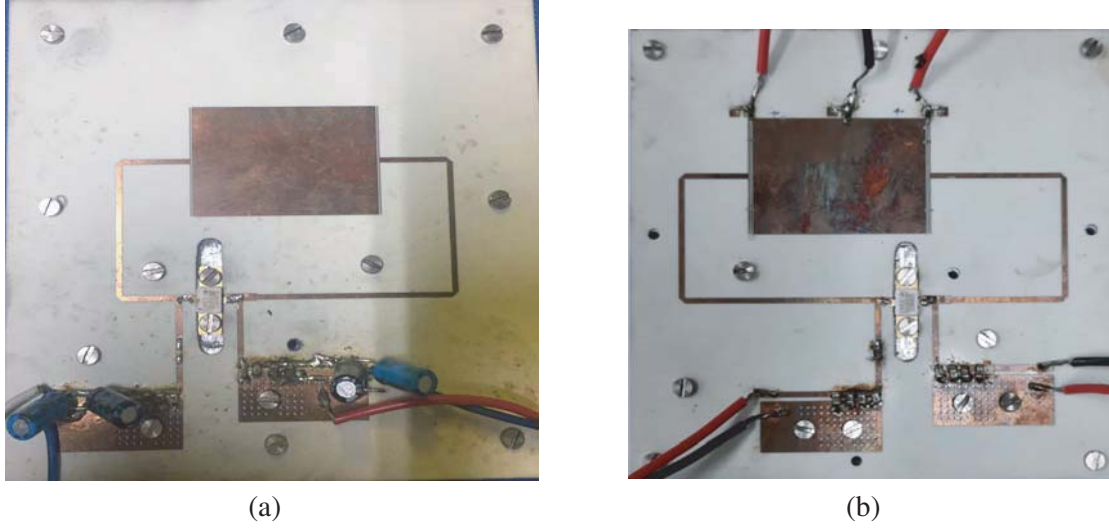
Figure 3. Photograph of fabricated. (a) Fixed frequency high power AIA. (b) Frequency reconfigurable high power AIA.
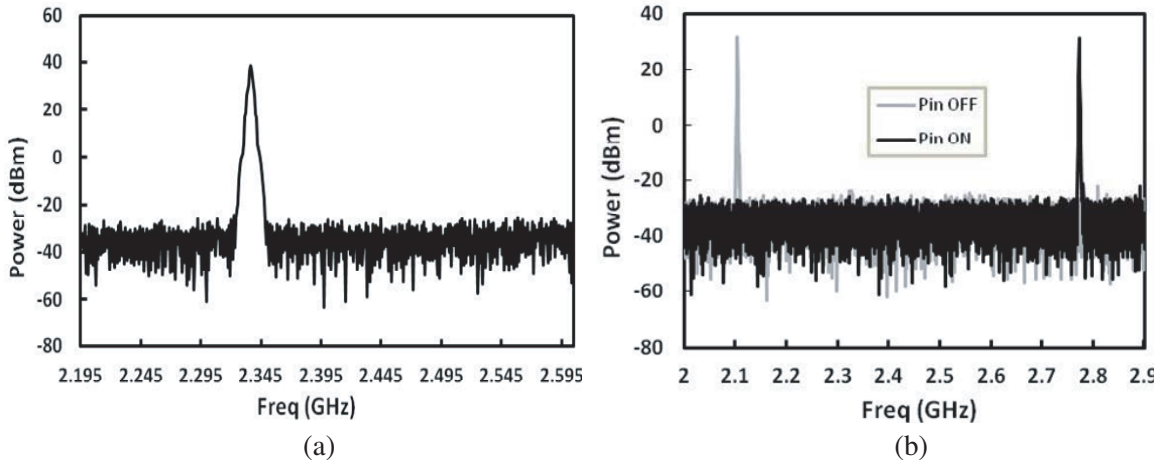

Figure 4. Measured EIRP of (a) fixed frequency high power AIA, (b) frequency reconfigurable high power AIA.

analyzer is -2.32 dBm at the fundamental frequency of 2.34 GHz in fixed frequency high power AIA. Measured cable loss at 2.34 GHz is 5.41 dB. Free path loss is -46.9 dB. The gain of horn antenna is 8.5 dB. EIRP calculated from Friss transmission equation is 41.4 dBm. Fig. 4(a) shows the measured EIRP of fixed frequency AIA. The highest EIRP achieved is 41.4 dBm at bias voltages of $V_{ds} = 25$ V and $V_{gs} = -2.1$ V. Measured received powers in the signal analyzer are -10.5 dBm and -12.8 dBm at fundamental frequencies 2.1 GHz and 2.7 GHz when all pin diodes are off and on, respectively, in frequency reconfigurable high power AIA. Measured cable losses are 5.3 dB and 5.5 dB, and free path losses are -45.9 dB and -48.1 dB at 2.1 GHz and 2.7 GHz, respectively. Gains of horn antenna are 8.3 dB and 8.8 dB at 2.1 GHz and 2.7 GHz, respectively. EIRPs calculated from Friis transmission equation are 32.4 and 32 dBm in two states of antenna. EIRP at the second harmonic is 16 dB lower than the fundamental frequency. Fig. 4(b) shows the measured EIRP of frequency reconfigurable AIA in both states. Measured EIRP of this frequency reconfigurable active integrated antenna is lower than the power simulated inthe patch antenna in ADS and frequency also expanded in lower and higher sides. This may be due to approximate model of pin diode as well as the HEMT used in simulation. The comparison of EIRP of previously reported self oscillating AIA with this work is reported in Table 1.

Table 1. Comparison of EIRP of previously reported self oscillating AIA with this work.

Refs.	Frequency (GHz)	Active Device used	EIRP (dBm)	DC to RF Efficiency (%)	Frequency reconfigurable	No. of device
[15]	5.8	GaAs MESFET	12.8	25.7	NO	1
[16]	0.87 2.77	HJ-FET	7.5 5.1	31 43	YES	1 1
[17]	5.05	HJ-FET	10.1	-	NO	1
[18]	5.267	HJ-FET	18.3	31.3	YES	1
[19]	69.6	GaAs PHEMT	-13.2	0.12	NO	2
[20]	3.01	GaN PHEMT	32.13	24	NO	1
This work	**2.34**	**GaN PHEMT**	**40.1**	**47**	**NO**	**1**
This work	**2.1 and 2.7**	**GaN PHEMT**	**32 and 32.4**	**24**	**YES**	**1**

This GaN/AlGaN PHEMT based circuit achieved the highest EIRP with high efficiency using single active device. This circuit also proves the concept to design high power frequency reconfigurable AIA using feedback topology.

5. CONCLUSION

In this paper, we propose GaN/AlGaN HEMT based High power self oscillating fixed and frequency reconfigurable AIAs. Feedback topology was used to implement both the circuits. Both circuits working perfectly after fabrication. The fixed frequency AIA has the highest EIRP of 41.4 dBm at 2.34 GHz using single device. In frequency reconfigurable AIA, the frequency of oscillation changes from 2.1 GHz to 2.7 GHz, when pin diodes change its state from off state to on state. The second circuit has EIRP within 1 dB in both states. This circuit is very compact and can generate two frequencies by changing the biasing of pin diodes and without changing the circuit footprint. Therefore, the proposed GaN HEMT based AIAs can be used to generate useful power at higher frequency, and the power can also be further increased using spatial power combining technique. This circuit topology can also be used to design a high power voltage controlled oscillator.

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