Journal of Scientific & Industrial Research
Vol. 81, August 2022, pp. 821-826
10.56042/jsir.v81i08.55620

Designing of 8-Gate Fingered GaN HEMT based Frequency Mixer with Enhanced Gain for Wide Band Communication Systems

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Received 30 September 2021; revised 11 July 2022; accepted 12 July 2022

The reconfigurable mixer plays an important role in both transmitter as well as receiver section in the present wireless and digital communication systems. Also such mixer requires lot of power for up-converting and down-converting the signal without any noise. This paper deals about such type of designing of reconfigurable mixer for wide band communication applications with Gallium Nitride High Electron Mobility Transistor (GaN HEMT). This GaN HEMT transistor solves the requirement of huge power over wide range without any noise. The mixer is designed in the present paper for variable gain conversion along with power consumption trade-off for a wide range of frequency (2–8 GHz) with reconfigurable concept. Applied Wave Research (AWR) simulator was used to design the reconfigurable mixer. The gain is controlled by changing the trans-conductance of the input RF stage, and the current steering in trans-impedance stage. A broadband down-converter mixer is designed that provide different conversion gain, ranging from 25–33.5 dB with two different modes. The large bandwidth of the mixer is achieved by shunting the trans-conductance stage and with various switching stages. The results also show that there is good isolation along with conversion gain of designed reconfigurable mixer, for wide range in various communication applications.

Keyword: Bandwidth, Current-steering, Multi-standard, Reconfigurable, Trans-conductance

Introduction

Gallium Nitride High Electron Mobility Transistor (GaN HEMT) is the most ideal and newer technology for high-frequency applications as compared to Complementary Metal Oxide Semiconductor (CMOS) and Metal-semiconductor Field Effect Transistor (MESFET) transistors, as it provides high power with lesser distortion in recent years.[1,2] It can be clearly understandable with Fig. 1 that how GaN transistors are better and advantageous over the other transistors, which makes wider applications for ultra wide frequency range. Also, the strong need for low-cost, low as well as high power, high-performance multimedia, multi-standard transceivers have resulted from the rapid rise of wireless satellite communication, optical communication, and military applications using the internet platform. Radio Frequency (RF) circuits using Metal-semiconductor Field Effect Transistor (MOSFET) suffers from various problems like trade-off between speed and power consumption and noise and power dissipation. The reconfigurable smart mixers are required by a system with Ultra wideband, Li-Fi, Wi-Fi, Bluetooth, Internet of Things (IoT), ZigBee, enabled platform and cognitive interface with advanced performance and unlimited connectivity. In recent times, new GaN HEMT devices comprised of various equipments are continuously developed that surpass their predecessors, thanks to unique epitaxial architectures. The main objective in this paper is to design the high powered microwave reconfigurable mixer over wide band with the utilization of GaN HEMT at various modes.

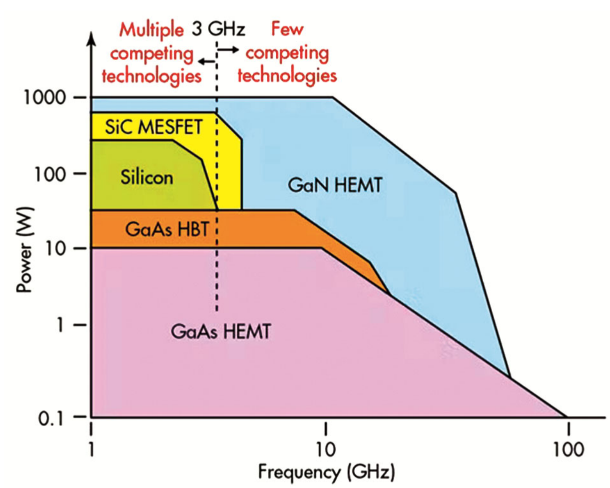

Fig. 1 — Power/frequency performance of GaAs, SiGe, InP, and GaN-based transistors[2]

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Many researchers have investigated the compatibility of GaN HEMT in high power and high frequency applications in recent years.[3–6] The HEMT have nonlinearity parameter that can be employed in mixing of signals. Power handling capability of GaN HEMT makes it most suitable for wide band frequency range applications. Furthermore, the demonstration of low-loss switches in AlGaN/GaN technology tends to use in various applications.[7–9]

The mixer, a key component of the transmitter and receiver has an impact on the overall performance of the system. It uses a three-port nonlinear circuit to transform the RF / microwave signal up or down to an intermediate frequency. Even though microwave frequency mixer provide the narrow gain bandwidth, yet mixer enhance the total system linearity and dynamic range.[8,9]

Materials and Methods

Microwave Mixer

The signal frequency translation can be obtained by only nonlinearity or time variability in the device. The system can easily be used for diverse mixer topologies as all the concept of mixers lies on mixing of two signals in the time domain. Assume that the two information signals of the mixer are A_1 Cos (ω_1t) and A_2 Cos (ω_2t), the multiplication of two signals as shown in Eq. (1) will result in addition and subtraction of frequencies in the signal.

$$A_1Cos(\omega_1 t) \times A_2Cos(\omega_2 t) = A_1A_2[Cos(\omega_1 - \omega_2)t + Cos(\omega_1 + \omega_2)t] \quad \ldots (1)$$

Generally, a non-linear system produces three types of the signal components i.e. DC component, harmonics and intermodulation terms. It needs only 2^{nd} order intermodulation term for any conventional communication system. If there are two frequencies at the input, namely ω_1 and ω_2, then the harmonics of the input signal can be represented as m times ω_1 and n times ω_2; where m and n refers m^{th} and n^{th} order of harmonics respectively. The intermodulation terms can be expressed as $m\omega_1 + n\omega_2$.

A down conversion mixer is used to change the signal from high frequency to low frequency, which is commonly at receiving end. When the approaching RF is down-converted to the Intermediate Frequency (IF), then it is called as down-conversion. Likewise, at the point when a mixer is utilized to change the frequency to high level at transmitting end, then it is called to be an up-conversion.

The major requirement for the designing of broadband transceivers is wireless communication, which consists of Low Noise Amplifiers (LNAs) and mixers as shown in Fig. 2. Recently, broadband circuits with bandwidths as high as several tens of GHz have been investigated in CMOS technologies.[8,9] Bipolar Junction Transistors (BJT) based RF mixers are used in radio link device, and the cost of the entire system is low but it provides low gain and poor linearity. The gain and the bandwidth of BJT mixer can be increased by using the current mirror topology.[10–14] CMOS device circuits have now been scaled down to reduce the channel length for achieving the sharpened radio frequency performance, with reduced flicker noise.[15–17] Recent work on dynamic frequency range and variable gain conversion mixer makes it possible for designing reconfigurable system to eliminate the gain controllability and dynamic frequency bandwidth limitations.[17–20] The present paper investigates about the various analyses like conversion gain, noise figure and isolations with GaN HEMT based active mixer consisting of various modes i.e Mode 1 and Mode 2. No researchers have attempted such analysis for such mixers in reconfigurable types with GaN device.

Modern communication systems enable an increasing number of radio segments and wider gain to fulfill rising demand, resulting in significant cost and density increases. For this type of communication the radio segments should be reconfigurable. The RF mixer for the reconfigurable RF wireless communication system should be designed with conversion gain variation and variable bandwidth. As a result, the primary purpose of this work is to develop a reconfigurable mixer capable of generating different gain. The authors analyzed and then simulated the entire reconfigurable down-conversion mixer design through Applied Wave Research (AWR) simulation. A 0.25 micron eight fingered based GaN HEMT device was taken to design the frequency mixer (as shown in Fig. 3).

An effective equivalent representation of active devices such as transistors, as well as their reliable

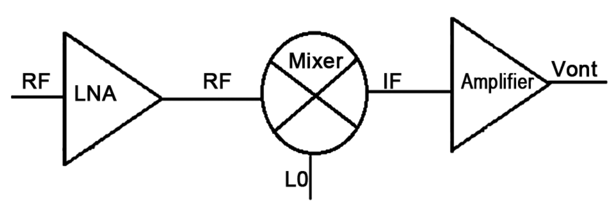

Fig. 2 — Receiver systems with frequency mixer

models has to be evaluated for such integrated circuit design in which all the parasitic effects has been considered with such design as shown Fig. 4. Heterojunction transistors are more sophisticated than other conventional transistors in terms of principle of operation, as they are widely operated in Tera-Hertz frequency.

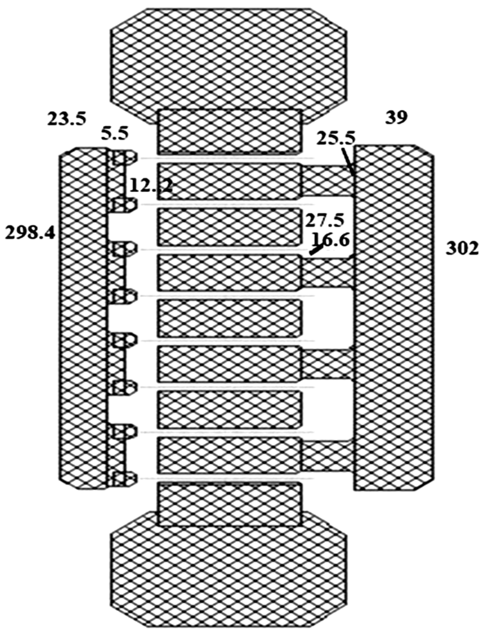

Fig. 3 — GaN HEMT Layout designed in AWR Simulator

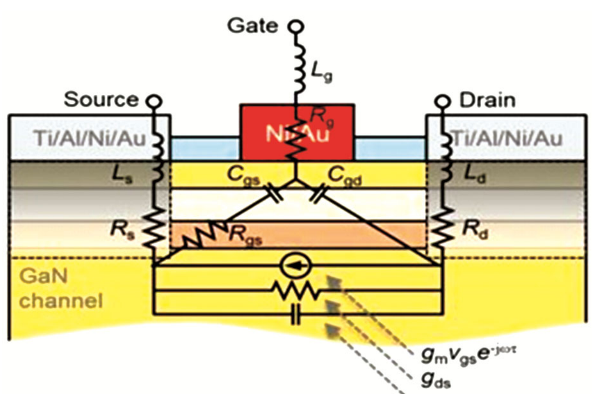

Fig. 4 — Schematic cross section of a GaN on Si substrate HEMT with its equivalent circuit

The basic flowsheet as shown in Fig. 5 shows how to extract the small and large signal S parameters for the available GaN HEMT device with total 19-parametric elements. AWR simulator was used to design the various types of reconfigurable mixer with GaN based HEMT transistors. The extrinsic components values are calculated with simulator from small signal S parameters with the foundry.

The S parameters for given intrinsic components are matched and designed (as shown in Fig. 6), with respect to V_{gs} and V_{ds} through curve fitting tool. The fixed values of extrinsic components and designed intrinsic components are framed in lookup table form to execute the harmonic balance. Subsequently, harmonic balance tells about the nonlinear characteristics of the HEMT device. Such large signal analysis can be used for any nonlinear applications like mixers, power amplifiers, low noise amplifiers etc.

Mixer Design for Reconfigurable Gain

The trans-conductance stage has to be tuned with current switching to provide the mixer with reconfigurable gain. For designing the reconfigurable wireless communication system, the mixer as shown in Fig. 7 was designed considering the conversion gain. The function of capacitors C_1 and C_2 used in present deigning are to block the DC current in trans-conductance and switching stage, so as to provide the bias independently.[6] In the current designing, the transistor gates with switching technique were used to control the gain of the mixer.

The mixer overall conversion gain basically depends on the DC biasing and it requires more biasing on trans-conductance stage. It also depends on the trans-conductance of the transistors. A schematic trans-conductance stage in the mixer are the array of two HEMTs (H_{1a} and H_{1b}) in left side and two HEMTs (H_{2a} and H_{2b}) in right side as shown in Fig. 7.

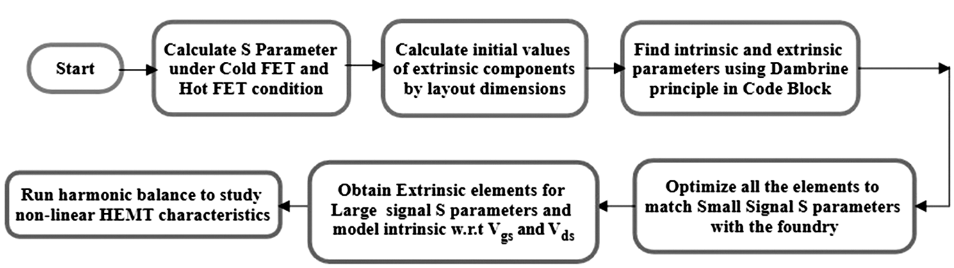

Fig. 5 —Flow sheet to evaluate the small and large signal extraction of HEMT device

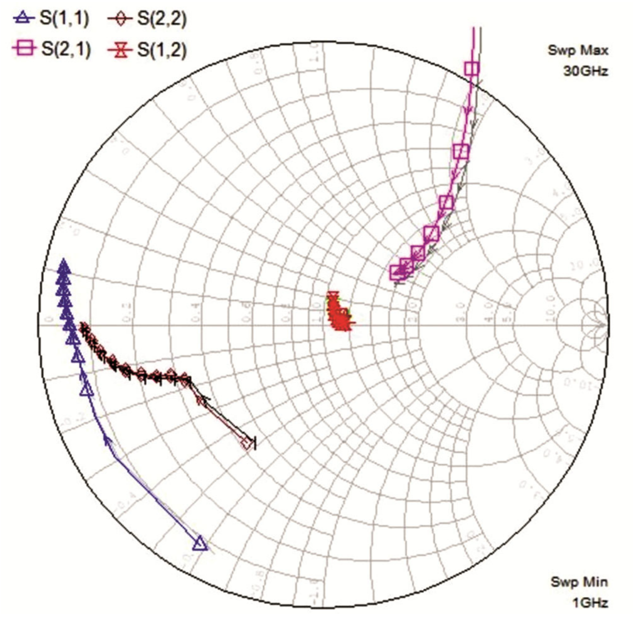

Fig 6 — Large signal S parameters showing perfect matching for V_{ds} = 4V and V_{gs} = −1.25V

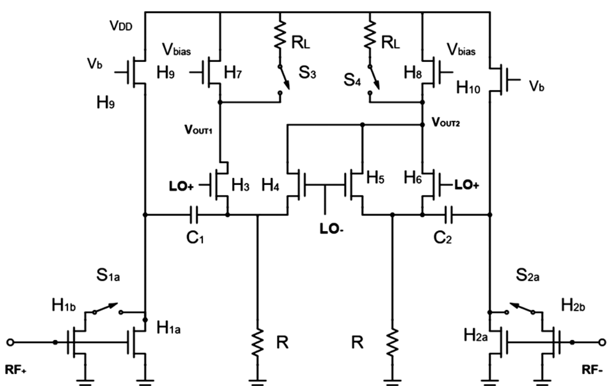

Fig. 7 — Schematic of reconfigurable mixer design

When the two switches connected to transistors H_{1b} and H_{2b} are all ON, then the total gate-width (W_{tot}) will be the summation of gate width of the two parallel combination of transistors for both the left (W_a) and right-(W_b) hand sides, as shown in Eq. 2

$$W_{tot} = W_a + W_b \quad \ldots (2)$$

Here W_a and W_b represents the width of HEMTs H_{1a} as well as H_{2a} and H_{1b} as well as H_{2b}, respectively. The overall trans-conductance of the RF device can be evaluated as shown in Eq. 3.

$$g_m = V_{sat} C_{ox} W_{tot} \quad \ldots (3)$$

Here V_{sat} and C_{ox} are the saturation velocity and gate capacitance of the transistor, respectively. The RF stage has the variable trans-conductance stage, as the transistors in this stage can be altered using the switches OFF. The gain for such RF mixer can be changed by varying the trans-conductance. The equation for the total gain of trans-conductance stage is shown in Eq. (4).

$$g_{mtot} = g_{m\,1a} + g_{m\,1b} \quad \ldots (4)$$

Here $g_{m\,1a}$ and $g_{m\,1b}$ are the trans-conductance for the HEMT H_{1a} and H_{1b} respectively. When both the HEMT are ON, the mixer will produce highest gain. When the transistor H_{1a} is switch ON, and H_{1b} is switched OFF or vice versa, then the mixer shows low gain.

The total load of the mixer consists of resistor R_L and transistors H_7 and H_8 which behave as an active load. The resistor R_L is connected through the switches S_3 and S_4. The conversion gain of the mixer can be controlled by applying the bias voltage to the transistor and by doing ON and OFF, the switches S_3 and S_4 provides the gain variation. If the bias voltage applied to the H_7 and H_8 is less than the threshold voltage, then the transistors provide the high resistance. Thus, if we turn ON and OFF the switches and vary the bias voltage simultaneously, then the conversion gain of the mixer can be made variable and is controlled by the equation Eq. (5). The resistance of the transistor shows inversely proportional to the channel width. In the present paper, the HEMT with high gate width 100 μm is used as a switch.

$$Conversion\ gain = g_{mtot} X (r_o // R_L) \quad \ldots (5)$$

Results and Discussion

The microwave mixer was designed using UMS foundry 0.25 μm HEMT, which contained 8 gate fingers having width 100 μm. The ports such as RF, LO and IF as fully differential ports, the fully differential RF and LO signal were generated by passing the ac signal through balun. An output buffer is used to convert the differential signal to single output signal. The reconfigurable mixer can able to operate in two different modes (i.e. Mode-1 and Mode-2) to provide the gain variation at the output. The conversion gain in both the modes can be changed by altering the switches S_3 and S_4 connected at load.

Mode-1

The mixer conversion gain in Mode-1 is shown in Fig. 8. At this mode, both transistors H_{1a} and H_{1b} were in ON stage. The conversion gain was evaluated around 33.5 dB through simulation. It has also been observed that the conversion gain was reduced by 4.5

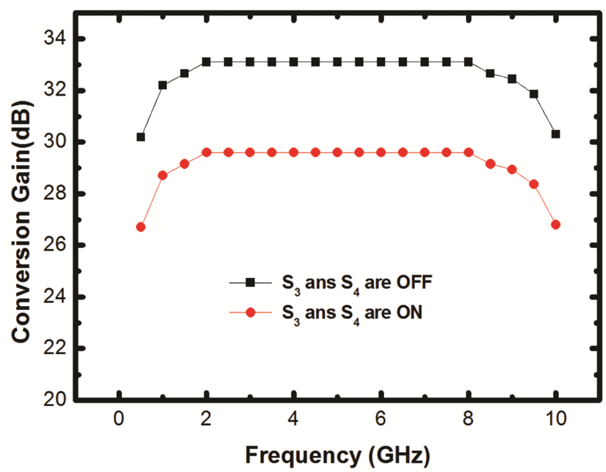

Fig. 8— Voltage conversion gain in Mode-1

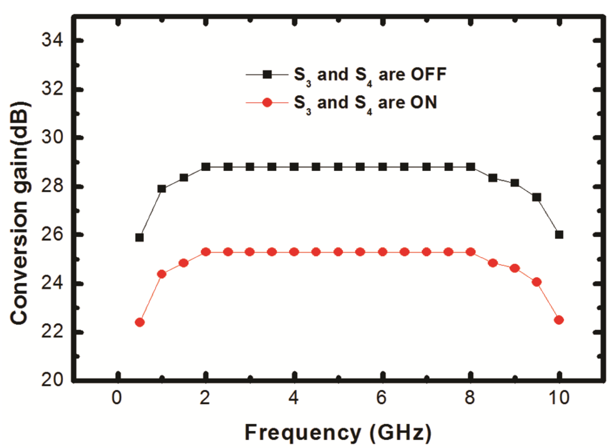

Fig. 9 — Voltage conversion gain in Mode-2

dB if both the switches S_3 and S_4 were in ON condition.

Mode-2

The mixer conversion gain in Mode-2 is shown in Fig. 9. At this mode, the transistor H_{1a} was in ON stage whereas the transistor H_{1b} was in OFF stage by switching OFF S_1. The conversion gain was decreased to 28.8 dB and it was also observed that the gain was flat throughout the band. If the S_3 and S_4 switches were ON, the gain was again reduced by 3.5 dB, similar to Mode-1.

Wang and his colleague in 2011 obtained the reconfigurable mixer with CMOS technology providing the measured conversion gain of 6–24 dB in the band of 2–10 GHz in all modes i.e. Mode 1–3.[(17)] In contrast with it, the designed mixer with GaN HEMT technology provides the conversion gain of 29–33.5 dB and 25.3–28.8 dB for Mode 1 and Mode 2 respectively. Similarly, Bao and his research team also investigated lesser

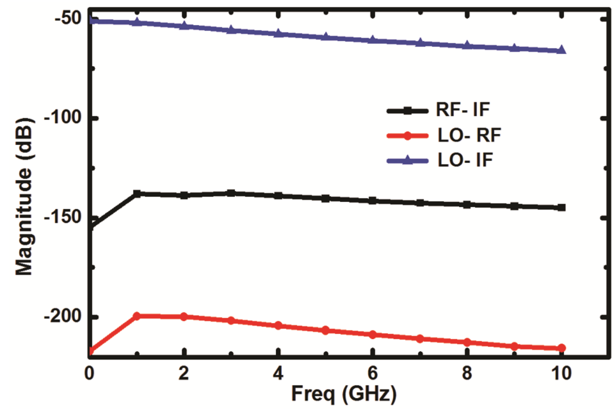

Fig. 10 — Simulated results showing Inter-port isolation for GaN HEMT mixer circuit

conversion gain for reconfigurable passive mixer with 0.18 µm CMOS technology i.e. 4 −22 dB at the range of 1–10 GHz.[19]

Port to port isolation

Many researchers like Bao *et al*. 2014 and Wang and his team (2011) found port to port isolation of the microwave mixer with the CMOS technology within the range of −80 dB[19,20] but the results of port to port isolation obtained with the present investigations with GaN HEMT based microwave mixer were found excellent isolations as compared to CMOS technology. It has been observed from the simulated results as shown in Fig.10, that the simulated isolation was approximately in the range of −135 to −142 dB for RF to IF, whereas the simulated isolation for LO to IF was approximately in the range of −55 to −68 dB. The port to port isolation was measured at different power level, starting from 0–15 dBm. The results show that the proposed mixer shows the better isolation among all the ports and also better compared to CMOS and MESFET technology.

Conclusions

The microwave mixers were designed through simulation for receiver section in communication systems for frequency translation and excellent results were obtained. Future progresses are in process to implement and fabricate the same design as fabrication measuring devices for GaN devices are very limited. On the basis of simulation, designed mixer with GaN HEMT devices with 0.25 µm length and 100 µm width having 8 gate fingers provide a large voltage conversion gain which is reconfigurable in nature as compared to existing CMOS mixer. The study with various modes produces excellent conversion gain and isolations over wide frequency range. It was observed that the gain of the microwave mixer can be controlled by varying the trans-conductance parameter and the effective gate width of the devices.

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