Characterization of a Negative Resistance Amplifier Circuit

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Abstract

Linearity plays an important role in the design and implementation of radio frequency power amplifier. Although negative resistance circuits are non-linear circuits, they are associated with distortion, which may either be amplitude-to-amplitude distortion or amplitude-to-phase distortion. In this paper, a unique way of realizing a negative resistance amplifier is proposed using a single Metal-Semiconductor Field-Effect Transistor (MESFET). Intermodulation Distortion Test (IMD) is performed to evaluate the characteristic response of the negative resistance circuit amplifier to different bias voltages using the Harmonic Balance (HB) of the Advanced Designed Software (ADS 2016). The results obtained showed that the proposed negative resistance amplifier exhibits a stable edge gain than a conventional distributed amplifier.

Keywords

Negative Resistance Amplifier, Metal-Semiconductor Field-Effect Transistor, Intermodulation Distortion Test, Harmonic Balance.

1. Introduction

Wireless communication and microwave are usually encountered with nonlinear effect, and nonlinearity is subject to the occurrence that limits or degrades telecommunication quality of service. The problem of designing a circuit that is void of nonlinearity is usually complicated than that of a linear circuit. The nonlinearity effects also appear in solid-state materials though it is not well known, that resistors, capacitors and inductors which are passive components are expected to be linear are nonlinear at their operating ranges.

All the device that uses negative resistance circuit is becoming very important as they are essential for logic and memory circuit as discussed by [1]. The tunnelling diode (RTD) has gathered much attention in producing an NDR characteristic in which the slope is negative in the I-V curve [2]. The circuit that uses negative differential resistance device circuits has high speed particularly when Resonance tunnel diode is integrated with Hetero-Junction Bipolar Transistors (HBTs). [3] presents a negative resistance device that is enabled with HBTs demonstrates high speed in most practical monolithic microwave integrated circuit as present in voltage control oscillator (VCO) and most converters (analogue to digital). The current-voltage property of an NDR device can provide various steady states that have the capacity to increase the switching and memory functionality per design and circuit robustness and lower power consumption. An effort to implement a low power voltage controlled oscillator, a Tunnel Diode (TD) device has attracted a number of interest due to the uniqueness of a Negative Differential Resistance (NDR) circuit which arises at either a low current or a low voltage range. The negative resistance devices (NRD) are usually made of Negative Resistance Circuit (NRC) and hence they can be used interchangeably.

Negative resistance have gone beyond oscillators, and it can be seen in different emerging materials such as Chalcogenides group IV element of the periodic table [4] which include Oxygen, Sulphur but the most important is Selenium (Se) and Tellurium (Te), both have a very strong tendency to produce the nonlinear effect. Other applications of the negative differential resistance can be found in digital logic and memory device where negative resistance can produce oscillations in two different states and these states can remain constant for a particular duration of time in other to perform as a latch or as a switch. In digital memories, negative differential resistance is observed in tunnel based SRAM, CMOS. Digital applications of negative resistance device that is of interest are the ongoing research in the negative differential resistance technologies and in the production of multiple stable logic states as demonstrated in Gallium Arsenide (GaAs) resonant tunnelling structure.

Negative resistance device presents an interesting solution by compensating for pass-band insertion loss, gain enhancers tunable applications and the benefits of lower cost, smaller sizes and weight authenticate the development of fully integrated Microwave systems and Radio Frequency (RF) using MMIC technologies. [5] Proposed the realization of negative resistance device using a different configuration of FET and MOSFET respectively [6].
Negative resistance devices are progressively helping to power our world today as it is found in different applications. The oscillator is the most obvious application of a negative resistance device. Several devices that exhibit negative resistance circuit in their development and design have a greater advantage in terms of their cost, sizes, and performance when compared to other capacitive and an inductive circuit that is difficult to model. And the term negative resistance can be described as an electrical property that is characterized by its current-voltage curve. At a point on the graph of the current-voltage plot, increase in voltage will result in the decrease in current unlike when compared to a static or absolute resistor.

Resistance always acts as a sink to the flow of electric current while a negative resistance act as a source of electrical energy [7]. Negative resistance obeys' ohms law with resistance being less than zero. Negative resistors are theoretical; they do not exist as a discrete component. Negative resistance is dynamic in nature, therefore, they can change their ohmic resistance depending on the current flowing through the resistor or the voltage applied across the resistor. In recent times, negative resistance is usually regarded as a ''Negative Differential Resistance'' (NDR) since they exist in different materials ranging from semiconductors to insulators, conductors and also in some emerging materials like graphenes and other static and non-static logic memory. Scientific scholars disbursed the idea of negative resistance since it does not obey the law of energy conservation and these disagreements were resolved by concluding that the circuit that exhibits the negative resistance circuit device element is nonlinear. According to [8] all electrical component are mostly two, three, and sometimes four to five terminals, some of these components are very good for amplification of signals as Esaki resonant tunnel diode and negative differential resistors are also capable of amplifying signals when they are properly biased therefore a negative resistance device circuit can be designed as an amplifier.

An excellent way or a unique way of realizing a negative resistance device is the use of Metal Semiconductor Field Effect Transistor (MESFET) coupled with inductors and capacitors, a MESFET modelled as a GaAsFET is usually required for higher frequencies [9] and in order to achieve a desirable frequencies capable of operating as high as 5GHz. Two simple algorithms are presented for developing negative resistance devices using two JFET or MOSFET transistors, and sometimes bipolar transistors, and linear positive resistors. Other three terminal device that can generate a negative resistance property is by the use of a MESFET when a proper feedback is been used and all other components of resistors, capacitors and inductors are properly lumped to either the source or the drains while the gate is well grounded. The current and voltage property of a negative differential resistance circuit has a peak point and a valley point.

Different methods are also used to develop negative resistance devices with two transistors and some positive resistors. Different negative resistance methods have been used to build a microwave active band-pass filters by using up to four microstrip line [10]. Further applications of negative resistors are used to cancel out the tank circuit dissipating resistors. Negative resistance is also used as a compensation technique to realize a 2.5 GB/s limiting amplifier [11]. Negative resistance applications also appear in a read and write scheme (NRRS) which guarantee a non-destructive read design. Negative resistance characteristics received a new focus in order to incorporate the benefits of NDR based circuits into transistor technologies. In analogue circuit applications, negative resistance is seen to have a wide tuning range and it is able to tune from 5.9KΩ to 243KΩ when the current is biased between 0.1μA and 60μA [12]. Active negative resistance and positive resistors are used in the implementations of oscillators, amplifiers and filters.

RF amplifiers are designed to increase a low signal to a particular power level that is sufficient in communicating from a transmitter to the receiver through space or air. Linearity is crucial to all telecommunication devices, as it can enhance the performance of most wireless communication systems. This paper aims at realizing a negative resistance amplifier using a GaAsFET modelled MESFET as part of receiver's front end. Section 2 presents the schematic design of the negative Resistance Circuit and the small signal analysis. Section 3 describes the method of realizing the negative resistance amplifier using Advance Design System (ADS). Section 4 presents the behavior of the simulated negative resistance amplifier. Finally, section 5 discusses the behavior of the negative resistance amplifier and concludes the paper.

2. Design of a Negative Resistance Amplifier Circuit

The design negative resistance amplifier is developed around the MESFET model, and the general parameters are given as listed below

Rs = Ohmic source resistance
Rd = Ohmic drain resistance
Rg = Ohmic gate resistance
R_1 = Semiconductor resistance
Cds = Drain to source capacitance
Cgs = Gate to source capacitance
Id = Nonlinear current source
Vgs = External gate to source voltage.
Vx = Internal channel voltages for drain and source
Vds = External drain to source voltage
Vgd = External gate-to- drain voltage

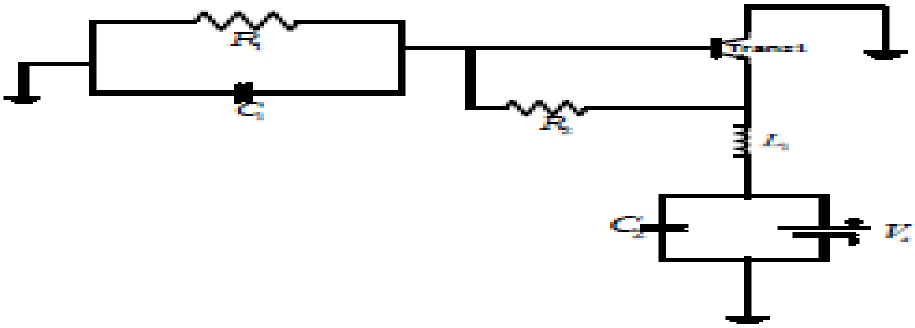

Figure 1. Negative resistance amplifier circuit

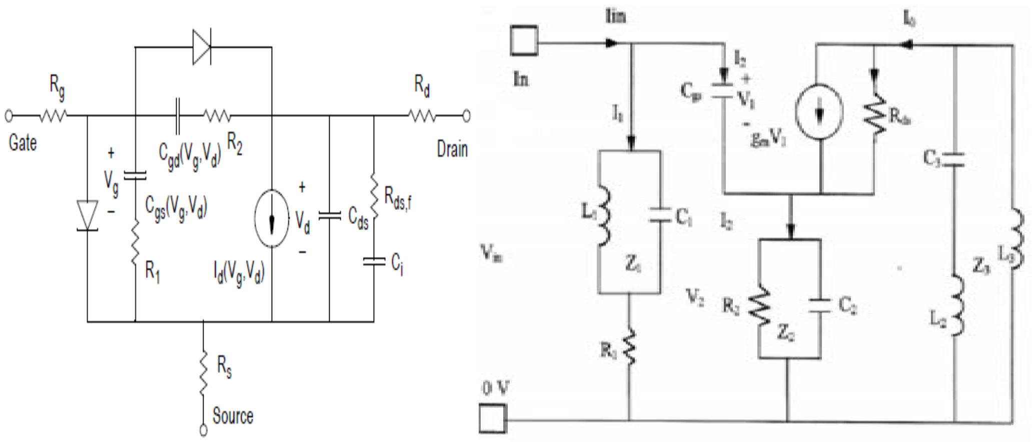

Figure 2. MESFET-Modelled Negative Resistance Amplifier Circuit

$I_{in} = I_1 + I_2$
$I_1 = Vin/(Z1 + R1)$
The impedance across L1//C1
$Z_1 = jwL_1 jwL1/(1 - w2L1C1) = jX1$
The voltage V_1 is developed across the gate to source capacitance

$$v1 = I2Zgs = Iin - \frac{Vin}{Z1 + R1} Zgs$$

$V_2 = (I2 + Io)Z2 = Vin - (Iin - \frac{Vin}{Z1+R1})$
$Io = gmV1 + \frac{V2+IoZ3}{Rds} = (gmV1Rds + V2)/Rds - Z3$

$$V2 = \frac{Z2\big((Iin(Z1+R1) - Vin)(Rds - Z3 + gmXgsRds)\big)}{(Z1+R1)(Rds - Z3 - Z2)}$$

$$= Vin\left(Iin - \frac{Vin}{Z1+R1}\right)Xgs$$

$$Zin = Vin/Iin$$

$$= \frac{Z_2(Z_1+R_1)(R_{ds} - Z_3 + g_m X_{gs} R_{ds}) + (Z_1+R_1)(R_{ds} - Z_3 - Z_2)}{(Z_1+R_1+X_{gs})(R_{ds} - Z_3 - Z_2) + Z_2(R_{ds} - Z_3 + g_m X_{gs} R_{ds})}$$

$Z2 = (R2 - jwC2R2^2)/(1 - w^2 C_2{}^2 R_2{}^2)$ ==R-jX_2

$Z3 = \frac{jwC3(L3 - w^2 L2L3C3)}{C3(1 - w\text{^}2C3(L2+L3)}$ ==jX_3

Z_{in} $= Re(Zin) + Im(Zin) = Rn + jX$

3. Materials and Methods

The N-type GaAsFET MESFET is used to realize the negative resistance amplifier circuit, which is a one port network and in order to simulate the behavior of the negative resistance amplifier. The following steps were used to realize the negative resistance circuit as shown in Figure 3. First, the negative resistance circuit was converted to a port network as shown in Figure 4. The drain of the amplifier was properly grounded. The gate was also lumped with a series inductor and in parallel with resistor and capacitor with value been selected carefully. Then, the circuit was converted to a box type negative resistance NR_1 coupled with the circulator as shown in Figure 4. The circulator enhances a lossless power match for coupling the signal and in like manner provides an input and an output terminal for the negative resistance circuit

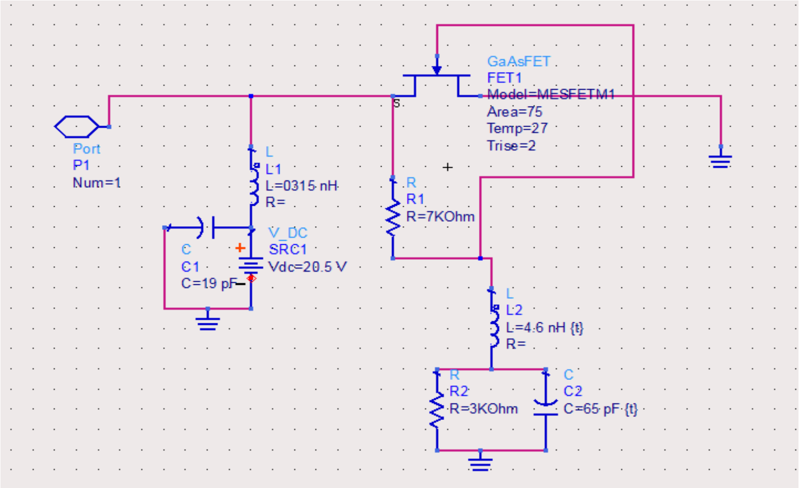

Figure 3. Negative resistance amplifier design using ADS

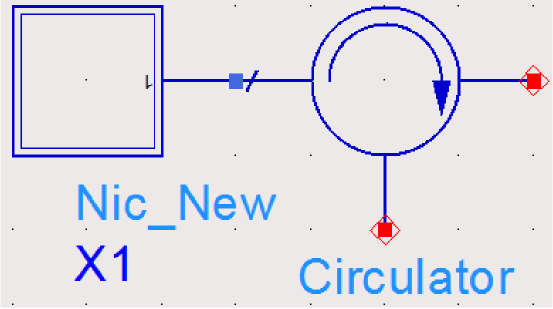

Figure 4. Circulator conversion

The second port of the circulator is connected with the source input say the P_ntone signal coupled with a current probe while port three is also connected to another current probe and terminated with a 50Ω resistor transmission line, and then grounded accordingly. The n-order determine the number of the input signal which is either a single tone signal or a two-tone signal.

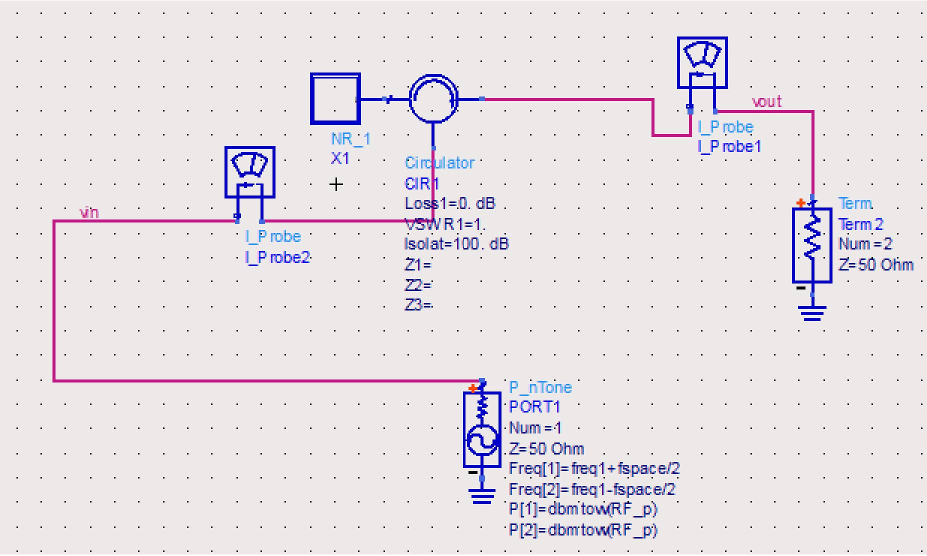

Figure 5. Negative resistance amplifier circuit simulation

Figure 5 shows the set-up of the negative resistance amplifier on the ADS tool by introducing a p_ntone signal into the designed oscillator or amplifier a probe is connected to vary the input signal while the second terminal of the probe is connected to port one of the circulator to serve as the source input signal, then the designed one port negative resistance amplifier is connected to the second port of the circulator. The port three of the circulator is used as the output port where a probe 1 is connected and is terminated with a 50 Ω resistance as the transmission line constant, The negative resistance amplifier input and the output port is labeled as Vin and Vout with respect to the terminal of the probe to be used in varying the input and the output signal. The input signal was set to different frequencies [f1] and [f2] in the order 5. The P_ntone, port was also set to an impedance of 50 Ω. The input power is then converted to dbm; it can either be in the polar form or in dbm.

4. Results and Discussions

The proposed negative resistance amplifier behavior is obtained and shown in the Figures 6-9. The frequency range used ranges from 4.0 to 6.0 GHz with respect to the MESFET modelled as a GaAsFET which is usually required for higher frequencies. Figure 6 presents the real and the imaginary impedance plot of the negative resistance amplifier. The negative resistance amplifier also shows different plots when biased at different voltages.

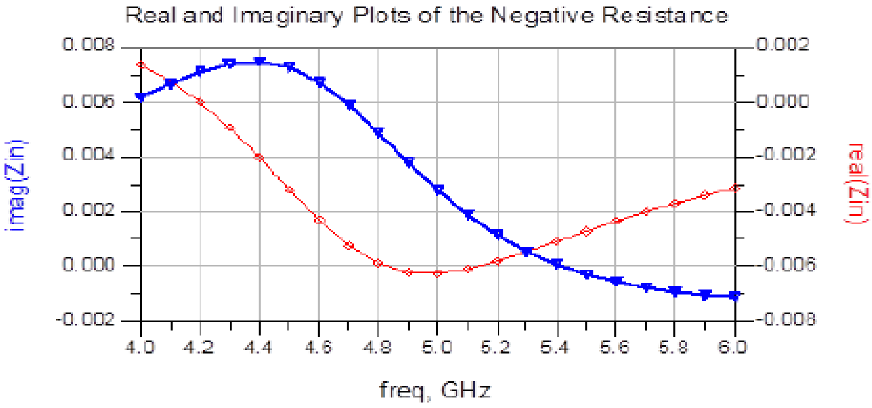

Figure 6. Real and imaginary plots of negative resistance amplifier circuit

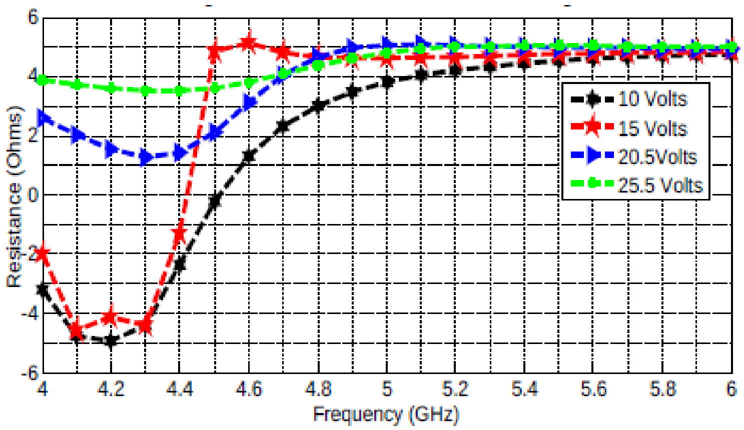

Figure 7. Negative resistance amplifier’s responses Bias Voltages

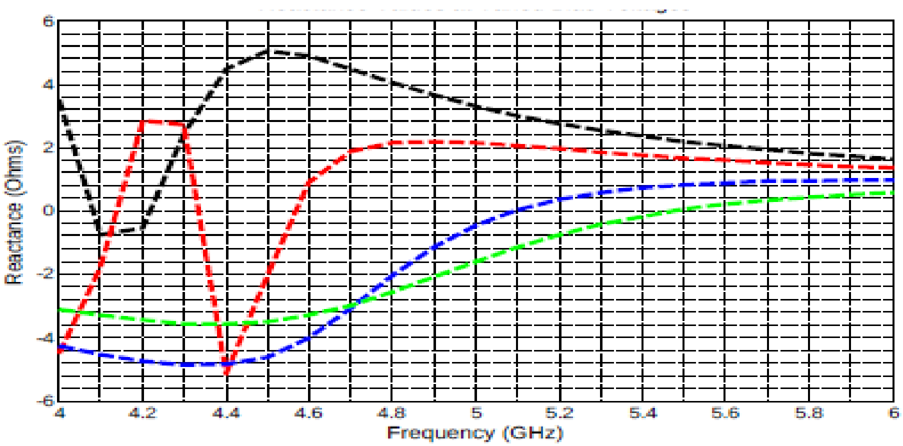

Figure 8. Plot of reactance value against frequency

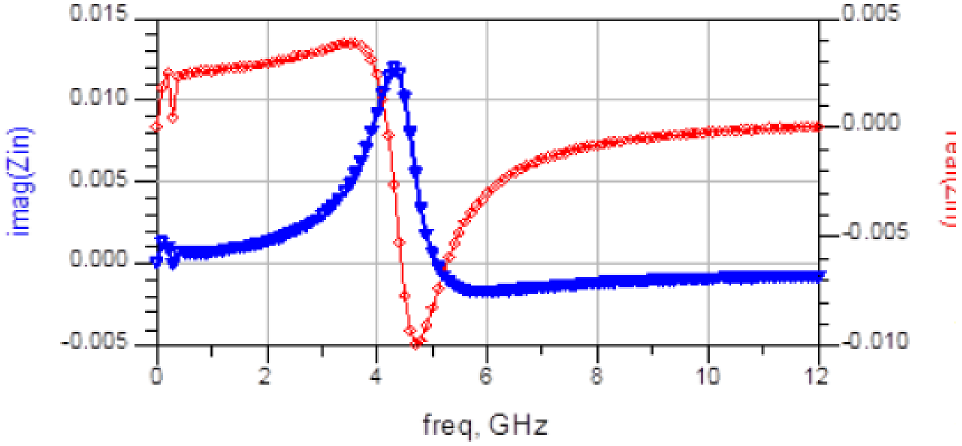

Figure 9. Real and imaginary plots of the negative resistance amplifier circuit

The measured values for resistance and impedance for the negative resistance circuit is shown in the table below; The negative resistance amplifier was tested between a wider frequency of 0-6 GHz band, The diagram above reveals that at 0-4.3 GHz, The real impedance increases while the imaginary part decreases appreciably. At the frequency of 0-4.3 GHz, the negative resistance behavior changes. At a frequency of 4.3 - 5.0 GHz**.**

Table 1. Simulated value for impedance and resistance

S/N	Frequency	Zin (Ω)	Resistance Rn (Ω)
1	4.00	0.006 < 7	Positive
2	4.30	0.007 < 9	-0.1
3	4.50	0.008 < 10	-3.1
4	4.80	0.007 < 10	-6.1
5	5.00	0.005 < 10	-6.3
6	5.40	0.05 < 10	-4.9
7	5.70	0.04 < -10	-3.9
8	5.90	0.04 < -10	-3.8
9	6.00	0.003 < -10	-2.83

Figure 9 shows the gain stability of the negative resistance amplifier circuit. The gain of the negative resistance is plotted against a wider range of RF input power in dBm. Figures 7 and 8 show the behavior of the negative resistance amplifier impedance plot. The plot revealed both the real and the imaginary plot at a frequency of 4 GHz to 6 GHz. Both the real and the impedance are plotted with respect to frequency in GHz. The peak value of the real impedance can be obtained by using the marker on the ADS tool, The real part of the negative resistance amplify presents a negative resistance at a frequency of 4.2GHz, while the imaginary plot presents a negative resistance at 5.4 GHz. Figures 7 and 8 show the effect of the bias voltages on the negative resistance amplifier. When the bias voltage is at 10V to 15V, the negative resistance amplifier has a higher negative resistance values. On the other hand, when biased at 20V to 25V, the negative resistance amplifier presents positive resistance value.

Table 1 shows the negative resistance and reactance values as obtained between the frequencies of 0-4.3 GHz. The negative resistance amplifier presents a positive resistance while the reactance of the circuit predominate.
The negative resistance amplifier is also simulated along a wide range of frequencies between 0- 10 GHz, the impedance plot is as shown in the Figure 9. The resistive part increases in frequency from 4.3 GHz to 5.0 GHz. Finally, Figure 10 also shows the plot of the gain of the negative resistance amplifier against the RF input power in dBm. The negative resistance amplifier appears to be more stable at a wider RF input power. Table 2 also presents the S-parameters of the negative resistance amplifier using the frequency of 4GHz-6GHz at a step of 100MHz using the ADS software.

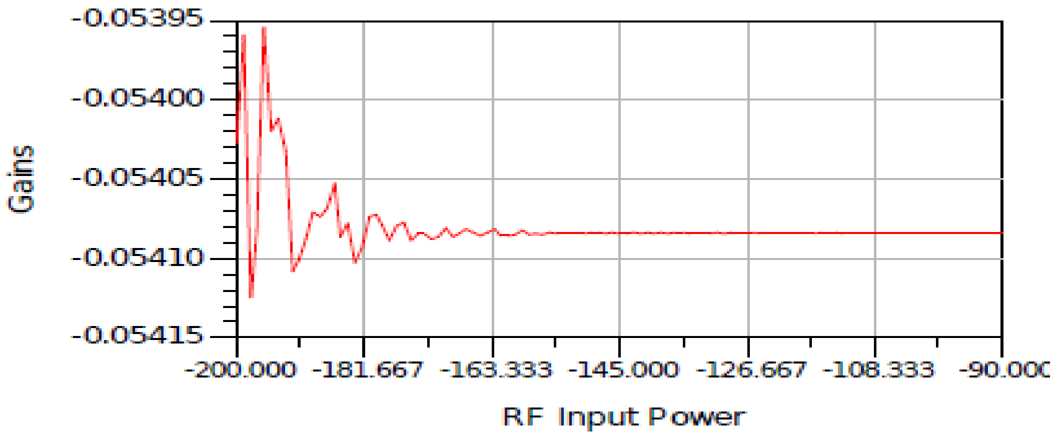

Figure 10. Gain stability of negative resistance amplifier against RF input power in dBm.

Table 2: S-Parameters of the negative resistance amplifier circuit

S/N	Frequency (GHz)	S
1	4.000	1.000/-179.611
2	4.100	1.000/-179.620
3	4.200	1.000/-179.629
4	4.300	1.000/-179.638
5	4.400	1.000/-179.646
6	4.500	1.000/-179.654
7	4.600	1.000/-179.661
8	4.700	1.000/-179.669
9	4.800	1.000/-179.676
10	4.900	1.000/-179.682
11	5.000	1.000/-179.689
12	5.100	1.000/-179.695
13	5.200	1.000/-179.701
14	5.300	1.000/-179.706
15	5.400	1.000/ -179.712
16	5.500	1.000/-179.717
17	5.600	1.000/-179.722
18	5.700	1.000/-179.727
19	5.800	1.000/179.732
20	5.900	1.000/-179.736
21	6.000	1.000/-179.741

5. Conclusion

The advanced design system software has been used to simulate the behavior of a negative resistance amplifier, the negative resistance amplifier intermodulation distortion is influenced by the various biased voltages and it presents a lower power output in dBm. The fundamental frequency for the two-tone signal of the negative resistance amplifier is more compact than that of the conventional distributed amplifier hence the negative resistance circuit is more linear than that of the conventional amplifier which is widely spaced.

The negative resistance amplifier also demonstrated a stable gain over a wider range of RF input power in dBm faster than when compared with the conventional distributed amplifier that has significant ripple effects. The negative resistance amplifier when it is perfectly realized with the appropriate bias voltage, can be used as a promising resolution to improve the nonlinearity that is usually present in most RF power amplifier in the communication or wireless industries. It is worthy of note that the bias voltage for a negative resistance device needs to be well observed as this can affect the performance of any negative resistance amplifier device.

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