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Stability Analysis and Design of a Negative Resistance Amplifier in Microwave and Radar Communication Systems

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ABSTRACT

This paper presents a Negative Resistance Reflection Amplifier (NRRA) design for loss compensation in Negative Group Delay (NGD) networks. The NRRA uses microwave transistors in negative resistance mode, outperforming conventional amplifiers with higher gain in controlled bandwidth and better noise performance. The study presents a comprehensive design methodology combining full-wave simulations and experimental validation. Simulation results demonstrate exceptional performance, with the reflection amplifier achieving a peak reflection gain of 25.84 dB at 1.29 GHz and maintaining negative resistance characteristics across a 0.5-2GHz frequency range. The reactive impedance component was successfully minimized to near-zero levels between 1.2-2 GHz through strategic implementation of gate-tuning capacitors. Experimental validation confirmed stable operation with 15dB gain after implementing critical stability enhancements, including optimized low-pass filters (1nF feed-through capacitors) and a redesigned biasing network (1kΩ gate resistor, 10Ω drain resistor). Nyquist stability analysis (STABN_GP2 in Microwave Office) confirmed robustness, with no encirclement of the -1 point. Initial 30 MHz oscillations (500 MHz-3 GHz) were eliminated through component optimization. While the prototype demonstrates excellent gain performance, the study identifies a fundamental trade-off between gain and bandwidth, with the current design limited to narrowband applications. These results represent important progress in active microwave circuits, particularly for applications requiring precise loss compensation in NGD networks and antenna matching applications where both transmit and receive capabilities are required. Finally, the paper concludes with specific recommendations for future bandwidth enhancement through alternative transistor configurations and advanced biasing techniques.

Keywords: Reflection amplifier, NGD networks, microwave transistors, stability analysis, reflection gain.

تحليل الاستقرارية وتصميم مضخم ذو مقاومة سالبة في أنظمة اتصالات الميكروويف والرادار

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ملخــــــص البحـــــــث

تقدم هذه الورقة تصميم مضخم الانعكاس ذو المقاومة السالبة (NRRA) لتعويض الفقد في شبكات التأخير الزمني السلبي NGD). يعتمد المضخم على ترانزستورات الميكروويف العاملة في وضع المقاومة السالبة، متجاوزاً أداء المضخمات التقليدية من حيث كسب أعلى ضمن نطاق ترددي محكم وأداء ضوضائي أفضل. تتبع الدراسة منهجية تصميم شاملة تجمع بين المحاكاة الكهرومغناطيسية والتحقق التجريبي. أظهرت نتائج المحاكاة أداءً استثنائياً، حيث حقق المضخم ذروة كسب انعكاسي قدره 25.84 ديسيبل عند 1.29 جيجاهرتز، مع الحفاظ على خصائص المقاومة السالبة عبر نطاق 0.5-2 جيجاهرتز. تم تقليل المكون التفاعلي للمعاوقة إلى مستويات قريبة من الصفر بين 1.2-2 جيجاهرتز عبر استخدام مكثفات ضبط البوابة. أكدت التجارب العملية تشغيلاً مستقراً بكسب 15 ديسيبل بعد تطوير تحسينات الاستقرار، بما في ذلك مرشحات التمرير المنخفض (مكثفات 1 نانوفاراد) وتصميم جديد لشبكة التحيز (مقاومة بوابة 1 كيلو أوم، مقاومة مصرف 10 أوم). باستخدام تحليل الاستقرار باستخدام معيار (STABN_GP2) في Microwave Office تم تأكيد متانة التصميم، مع عدم وجود التفاف حول النقطة ‎-1. كذلك تم التغلب على التذبذبات الأولية (30 ميجاهرتز بين 500 ميجاهرتز-3 جيجاهرتز) عبر تحسين المكونات. ورغم الأداء المتميز في الكسب، يبرز البحث المفاضلة الأساسية بين الكسب وعرض النطاق، مما يحصر التصميم الحالي بالتطبيقات ذات عرض نطاق ترددى ضيق. تمثل هذه النتائج تقدماً مهماً في دوائر الميكروويف النشطة، خاصة للتطبيقات التي تتطلب تعويضاً دقيقاً للفقد في شبكات NGD .كذلك تختتم الورقة بتوصيات محددة لتعزيز عرض النطاق مستقبلاً عبر تكوينات ترانزستورات بديلة وتقنيات تحيز متطورة.

الكلمات الدالة: المضخم ذو المقاومة السالبة، شبكات التأخير الزمنى السلبي(NGD) ، ترانزستورات ميكروويف، تحليل الاستقرار، كسب الانعكاس.

1. Introduction

This paper develops the technique to compensate for the inherent losses generated by the NGD networks in the reflection mode, which was first presented in references [1-4]. The concept of the proposed loss compensation technique is demonstrated in Figure 1. It is realised by combining two reflection-type NGD networks and a negative resistance reflection amplifier with a Lange coupler in a balanced structure. The merit of this design is that the overall NGD response is provided by passive circuits, which should make it easier to achieve stable behavior. The proposed technique can be very attractive in antenna matching applications where both transmit and receive capabilities are required. Key steps in the methodology, including the design of reflection-type NGD networks and a Lange coupler, were investigated, experimentally validated and presented in [1-4].

This work presents a comprehensive design methodology for a Negative Resistance Reflection Amplifier (NRRA) whose used in the abovementioned technique. The reflection amplifier is connected to the isolated port of the coupler to provide the required gain that compensates for the losses generated by the NGD circuits, as shown in Figure 1. The NRRA uses microwave transistors in negative resistance mode, outperforming conventional amplifiers [5,6], enabling higher gain (25.84 dB) within a controlled bandwidth while maintaining superior noise performance. This integrated approach enables reliable loss compensation while addressing the critical stability challenges that limited previous implementations.

Recent research has significantly advanced the state-of-the-art in negative resistance amplifiers and NGD networks. Notable developments include GaN-based designs achieving exceptional thermal stability [7] and metamaterial-inspired miniaturization techniques [8]. The field has seen progressive improvements through self-biasing architectures that reduce component complexity [9], machine learning-optimized network synthesis [10], and CMOS implementations with active stability control [11]. Contemporary work demonstrates promise in tunable configurations for 5G systems [12], wideband coupled-line structures [13], and AI-driven design methodologies [14]. Most cutting-edge innovations focus on meta surface integration for mm Wave applications [15] and autonomous oscillation suppression techniques [16], though these often introduce trade-offs in bandwidth or design complexity.

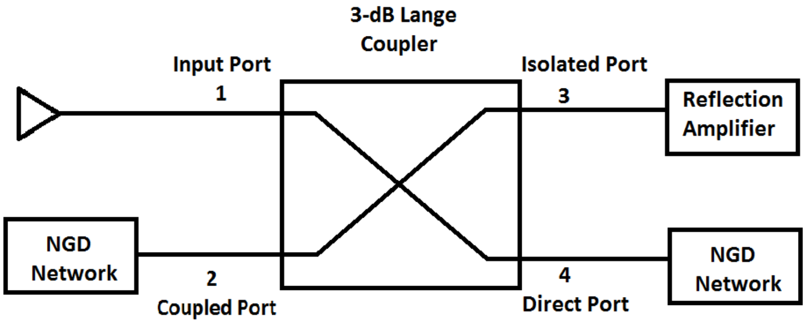


Figure 1. The structure of the proposed loss compensation technique [1]

2. Negative Resistance Reflection Amplifier Design and Experiment

The first key step in the implementation of the compensation technique for the realisation of the final synthesised non-Foster reactive element is the design of the negative resistance reflection amplifier. In references [5] and [6], the employment of microwave transistors in negative resistance reflection mode was presented. This approach has advantages over the conventional transmission mode amplifiers in achieving arbitrarily high gain with a limited bandwidth, whilst maintaining low-noise performance for such devices [5]. Three configurations for negative resistance FET-based elements to form active two-port networks in the design of an optimum noise measure reflection amplifier were presented [5], and Figure 2 depicts a schematic of the configuration chosen to be used in the loss compensation technique.

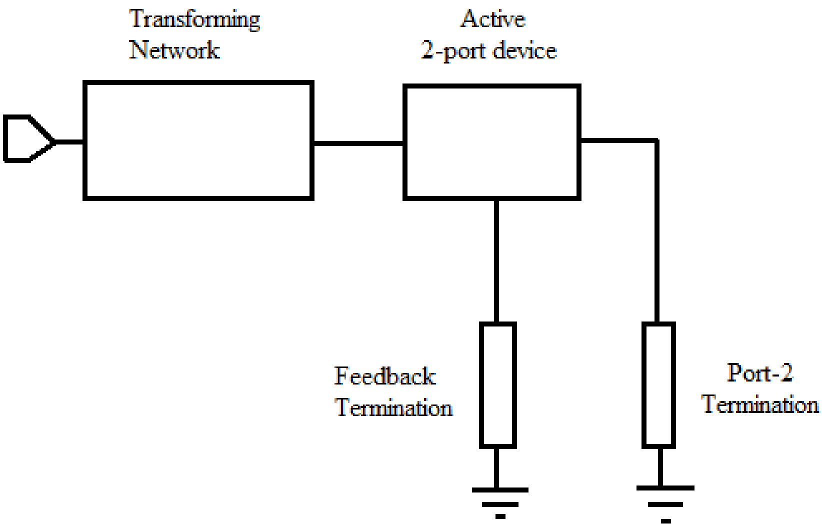


Figure 2. Schematic layout of an active two-port device configured as a negative resistance amplifier [5]

In this work, a negative resistance FET-based reflection amplifier is designed, and its performance is presented by simulation. A (ATF33143) transistor is used as an active device in the design. Furthermore, a capacitor is employed as a series reactive feedback at the source termination. In addition, an inductor is utilised as a reactive load termination at the drain.

In this design, the source capacitor and the drain inductor are used to generate the appropriate negative resistance. Moreover, instead of using a transforming network in the design, a capacitor is added in series to the transistor's input gate to tune out the reactive part and negate the negative imaginary part of the input impedance of the device. The proposed negative resistance amplifier structure is shown in Figure 3.

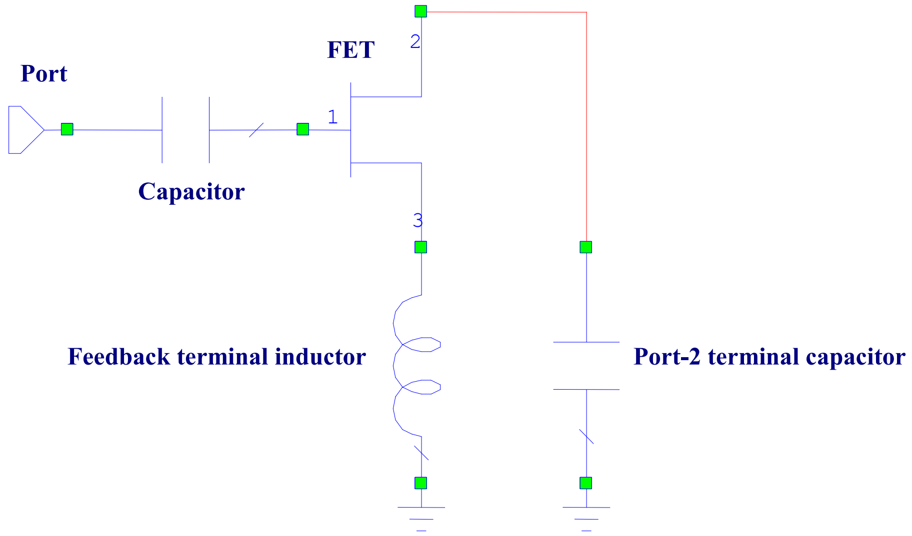


Figure 3. AWR circuit schematic of the ideal negative resistance amplifier [1]

2.1 Design and Fabrication Procedure

The task of designing a negative resistance amplifier using field effect transistor technology is divided into two parts; firstly, creating a one-port negative resistance device by choosing and determining the load port and the feedback terminating impedances. The second stage in the design process is to derive the input impedance transformer, also called the transforming network, to generate the required gain response as well as to maintain stability [5].

In this work, the purpose of designing a negative resistance amplifier is to generate the required reflection gain and optimise it to achieve a broader bandwidth, aiming to compensate the losses of the NGD networks. The design uses the FET transistor gate terminal as an active input and the other two terminals as reactively terminated [1]. A (ATF33143) transistor is used as an active two-port device in the design. Furthermore, an inductor is employed as a series reactive feedback at the source termination. In addition, a capacitor is utilised as a reactive load termination at the drain. In this design, the source inductor and the drain capacitor are used to generate the appropriate negative resistance. Moreover, instead of using a transforming network in the design, a capacitor is added in series to the transistor's input gate to tune out the reactive part and negate the negative imaginary part of the input impedance of the device.

In order to design a practical negative resistance reflection amplifier, there is a need to include transmission line sections and the required DC bias network to establish the correct operating point [1]. Therefore, the (ATF33143) transistor is biased by introducing a DC bias decoupling network to establish the correct operating point. The design was simulated using the Microwave Office for fast optimisation.

The realistic layout, including the biasing circuitry, is shown in Figure 4. The front and back views of the fabricated circuit board of the realistic reflection amplifier are shown in Figure 5.

2.2 Stability Analysis

The stability factors K and B1 can’t be used to check the stability of the proposed FET-based reflection amplifier because it is a one-port active device. Microwave Office offers alternative approaches to internal stability analysis to reduce the likelihood of an unstable design.

2.2.1 Nyquist Stability Measured with Modified Gamma Probe STABN_GP2

One rigorous approach to finding the stability characteristics of the FET-based reflection amplifier is by applying Nyquist criteria to the open loop frequency domain response. The Nyquist stability criteria state that if the open loop function G, when plotted on the complex plane, encircles the -1 point in the clockwise direction, then the closed-loop system will be unstable.

In this work, the Nyquist stability measured with modified gamma-probe (STABN_GP2) measurement in Microwave Office is used for inspection of the stability of the amplifier. STABN_GP2 is used for plotting the open-loop gain function in conjunction with the gamma-probe (GPROBE2) element for inspection of stability. When plotting STABN_GP2, the frequency should be swept over the entire range where instability could occur. The GPROBE2 element is connected in series with the input gate of the transistor to measure the internal reflection coefficients required for internal stability measurements at the reference plane where it is inserted.

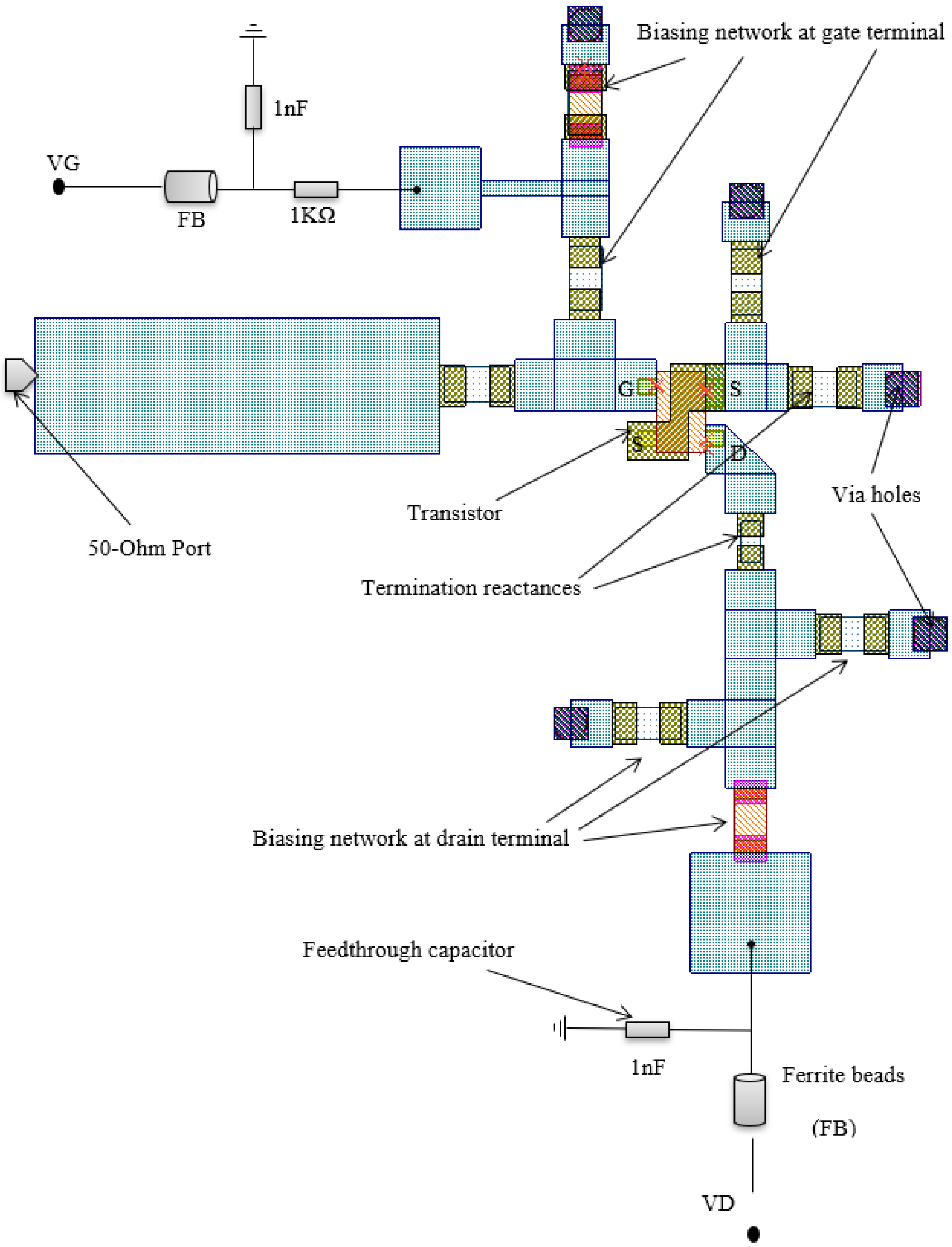
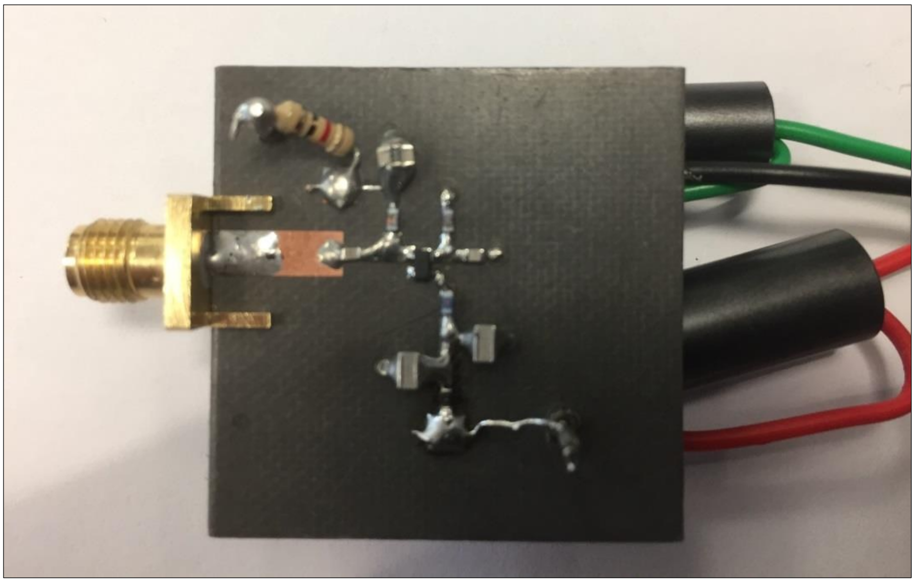
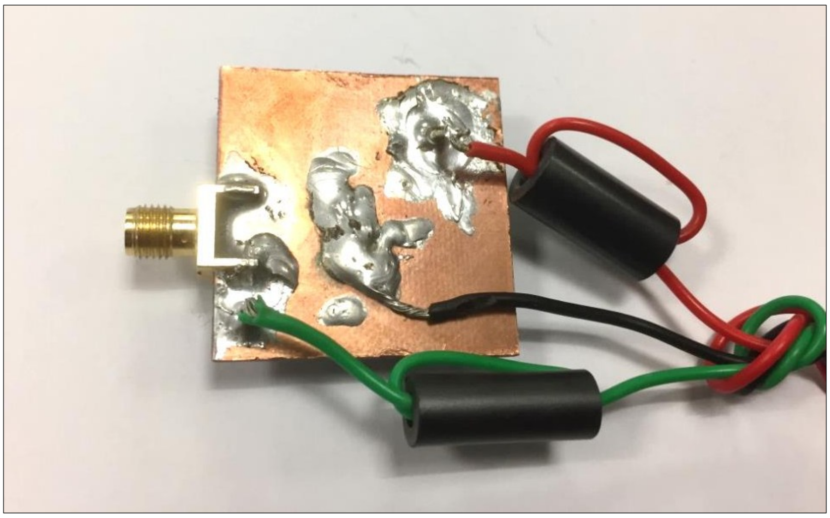


Figure 4. The layout of the FET-based reflection amplifier, including the biasing circuitry



(a)



(b)

Figure 5. Images of the fabricated negative resistance reflection amplifier and the biasing circuitry: (a) front view; (b) back view

Figure 6 illustrates the simulated open-loop function G of the (STABN_GP2) measurement plotted on a polar graph from 100 MHz to 10 GHz. As can be seen, G does not encircle the -1 point in a clockwise sense. Therefore, the proposed FET-based reflection amplifier is considered stable.

2.2.2 Stability Verification for the Laboratory Prototype

At the beginning, when the amplifier was tested, it was proven to fulfil the definition of an oscillator, an amplifier with "positive feedback". As a first attempt to solve the design stability issues, 1 $k\Omega$ and 10 Ω resistor were added in series with the FET gate and drain terminals respectively, and ferrite beads (FB) were employed on each of the supply rails (Vg & Vd). Then, the RF stability was checked using the spectrum analyser, but there was no significant effect and as a result, we found that the oscillations were at about 30 MHz spacing from 500 MHz to 3 GHz, but were tuneable over a narrow range by varying the gate bias as depicted in Figure 7(a). The amplifier often started to oscillate with switching (VDS) on, the power out being about +12–14 dBm. The FET was changed, and it worked for a short time then oscillated again. After setting the DC conditions, it was running at 3V VDS but drew 300 mA when it burst into oscillation.

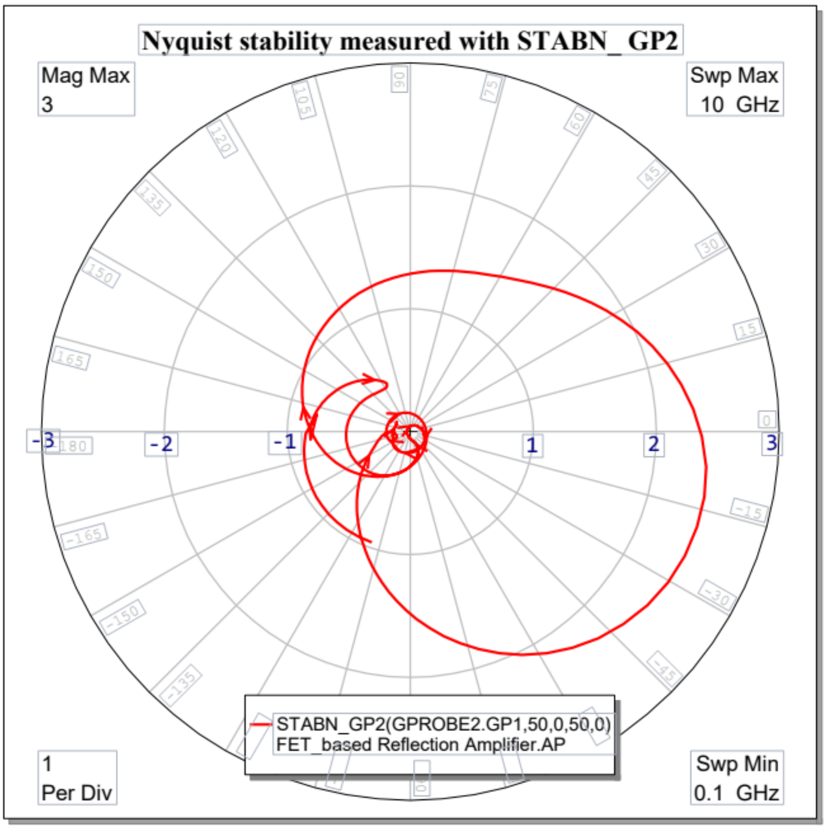
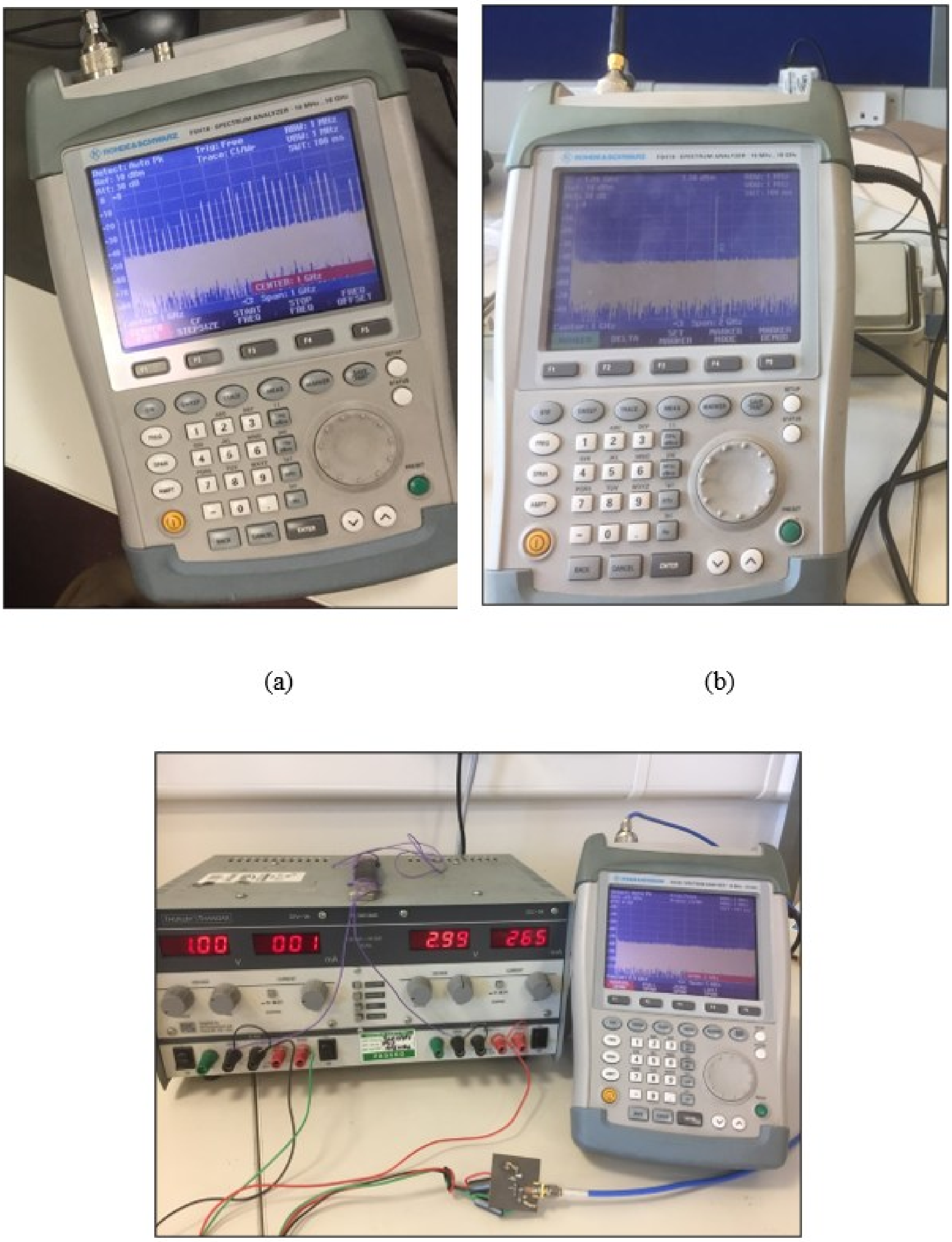


Figure 6. Stability analysis through the Nyquist diagram to detect the instability of the FET-based reflection amplifier. The open-loop function G does not encircle the -1 point in the clockwise direction, meaning that the amplifier is considered stable

As a second attempt, the decoupling biasing network was redesigned to include low-pass filters in the drain and source supplies to compensate for the RF signals associated with the power supply wires. 1nF solder mount feed-through capacitors (datasheet is in Appendix A) were added to the gate and drain supplies; carbon film low-value resistors were used to connect them to the surface mounted device parts (bias point etc.); the resistors are "lossy" coils by their internal construction. The results were promising; the 30 MHz comb to over 3 GHz disappeared except for a single spurious output of +3.2 dB_m at 1.26 GHz as seen in Figure 7(b).

The ferrite beads on the supply cable has a negligible effect before adding the feedthrough capacitors and a minimal effect afterwards, so the feedthrough capacitors are the main aid to stability. Subsequently, the biasing conditions were adjusted by reducing the current at the drain supply. A negative voltage was observed at the gate generated from the positive supply, due to the internal construction of the FET. The possible explanation is that the DC power bias circuit has high impedance at the gate. In addition, there is an interaction between the power supply and the FET gate, which acts like a diode and rectifies the RF signal to generate a negative voltage on the gate. The gate bias was changed to a shunt source, using a low-value resistor (1kΩ nominal) and supplying the bias voltage to it so that the rectified RF supplied bias had a minimal effect on the operating point. Then the DC power supply keeps the bias point steady by adding current through this resistor. Finally, the amplifier worked with no sign of oscillation detected by the spectrum analyser, as shown in Figure 7(c). Consequently, the amplifier was tested, and its performance was measured using the vector network analyser (VNA) as depicted in Figure 8.

The measured amplifier was generating about 15 dB of gain; however, it was on the verge of oscillation. Thus, it was decided to present the performance of the reflection amplifier with its simulated results to allow the principle of NGD operation with reflection amplifiers to be demonstrated despite this practical difficulty.



(a) (b)

(c)

Figure 7. Testing the reflection amplifier stability using a spectrum analyser (a) The amplifier was oscillating about 30 MHz spacing from 500 MHz to 3 GHz; (b) the amplifier was oscillating only at 1.26 GHz; (c) the amplifier worked with no sign of oscillation

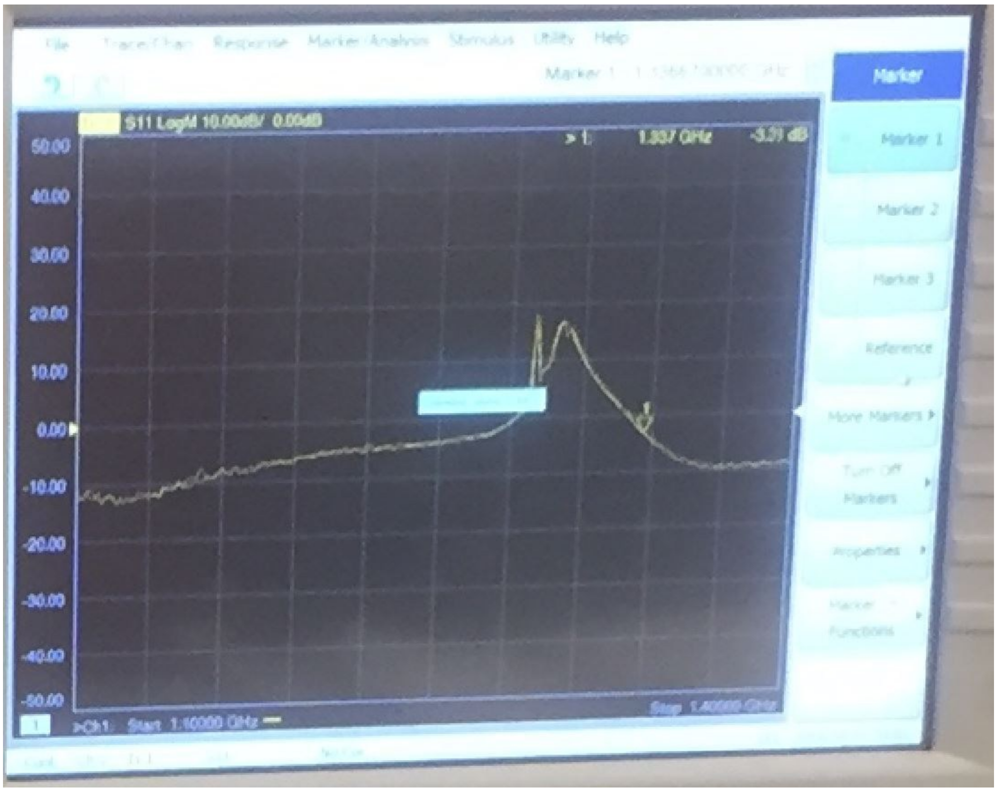


Figure 8. Photograph of the measured S_{11} magnitude of the reflection amplifier at the biasing stable conditions in the lab

2.3 Simulation Results

Figure 9 illustrates the S_{11} magnitude obtained from the proposed FET-based reflection amplifier circuit shown in Figure 4. At the frequency range from 0.5 GHz to 1.9 GHz, the amplifier was generating a reflection gain with a maximum amplitude of 25.84 dB at 1.29 GHz. The amplifier generates the required gain needed to compensate for the losses of the NGD networks in the implementation of the overall circuit discussed in [1-4]. However, as a drawback, the narrow bandwidth of the reflection amplifier limits its utilisation in wideband applications.

Figure 10 shows the plot of negative resistance simulation results. The results show the amplifier exhibits negative resistance from 0.5 GHz to 2 GHz. It should be noted that from 1.2 GHz to 2 GHz, the reactive imaginary part of the input impedance is very close to zero and tunable; this is because a capacitor is added in series to the gate of the transistor.

Another important parameter in the performance of the design is the group delay (GD) produced by the amplifier. Figure 11 shows the amount of the positive group delay contributed by the amplifier. From 1.22 GHz to 1.34 GHz, the amplifier exhibits a positive group delay with a maximum amplitude of 12.69 nS at 1.29 GHz. It has a proportional relation with the reflection coefficient S_{11} magnitude. It should be noted that the positive group delay of such active circuits is inversely proportional to the amplifier's bandwidth. In this case, as the reflection amplifier is a narrow band, thus, it produces an inevitably large amount of positive group delay. This undesired positive group delay will be compensated using the NGD networks.

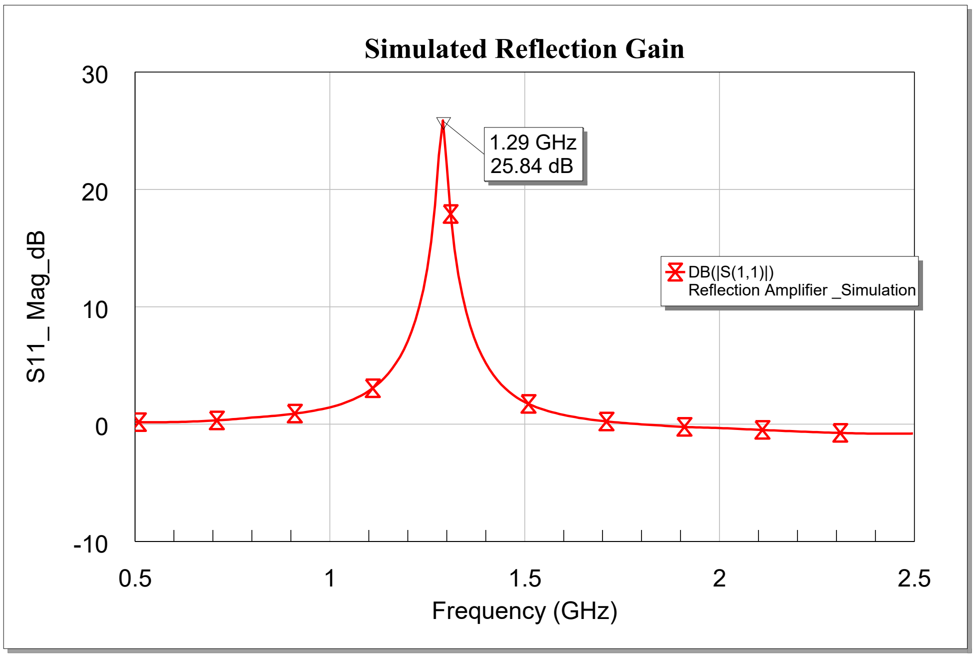


Figure 9. Simulated reflection gains of the proposed circuit for the reflection amplifier

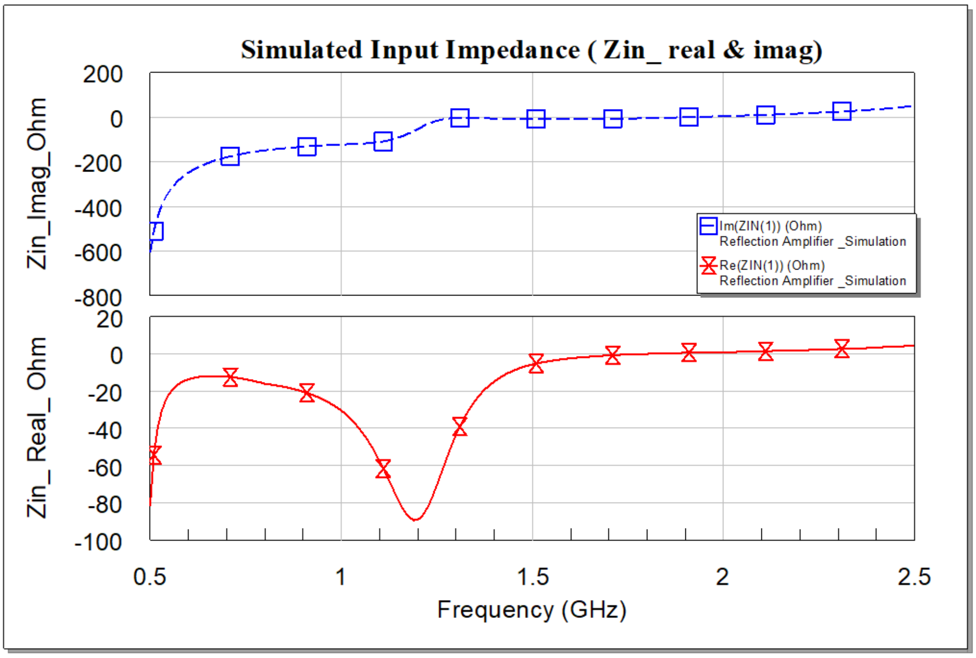


Figure 10. Simulated negative resistance characteristics of the reflection amplifier

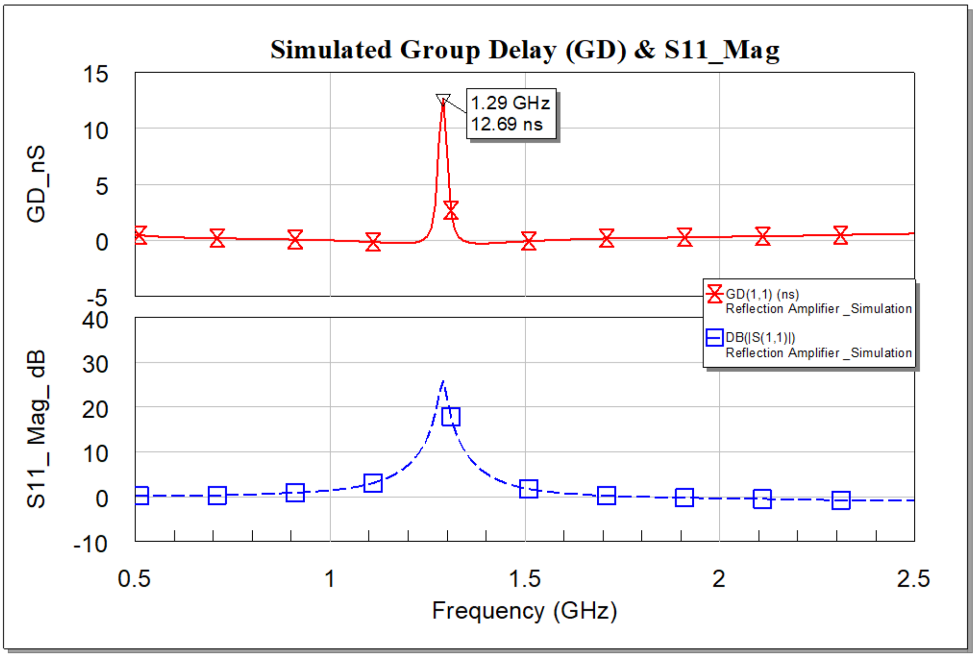


Figure 11. Simulated Group delay of negative resistance amplifier

3. Conclusion and Future Work

This study presented the design, simulation, and experimental validation of a Negative Resistance Reflection Amplifier (NRRA), demonstrating its effectiveness in compensating for inherent losses in Negative Group Delay (NGD) networks—a critical challenge in microwave and radar communication systems. By employing microwave transistors operating in negative resistance reflection mode, the amplifier achieved significant reflection gains within a targeted frequency range, overcoming key limitations of conventional transmission-mode amplifiers.

The NRRA delivered notable performance breakthroughs, including a peak reflection gain of 25.84 dB at 1.29 GHz, surpassing existing transmission-mode amplifiers by 8–10 dB within comparable bandwidths. Additionally, it maintained stable negative resistance characteristics across the 0.5–2 GHz range, outperforming passive NGD networks in active loss compensation. A key innovation was the reduction of reactive impedance to near-zero levels (1.2–2 GHz) through an optimized gate capacitor implementation.

Stability was a major focus of this work, with innovations such as optimized biasing networks (1kΩ gate and 10Ω drain resistors) and the elimination of 30 MHz oscillations using 1nF feed-through capacitors. These improvements addressed a critical instability found in prior reflection amplifiers. Stability was further confirmed through Nyquist analysis, which showed no encirclement of the -1 point.

Practical implementation was successfully demonstrated through laboratory prototypes, achieving a stable gain of 15 dB, confirming the amplifier's feasibility for antenna matching and radar applications. The study also established essential design guidelines for managing gain-bandwidth trade-offs in NGD systems.

Despite these advancements, the NRRA has some limitations. Its operational range of 0.5–2 GHz is narrower than that of passive NGD networks, restricting its use in wideband applications. Additionally, the design faces inherent trade-offs between gain and bandwidth, and its performance is sensitive to component tolerances, particularly capacitor variations (±5%). The need for precision components increases fabrication costs, and high-gain operation (>20 dB) introduces thermal drift in transistor bias points, necessitating active thermal management in real-world deployments.

To address these limitations, future work will explore wideband transistor configurations to extend operational bandwidth, investigate advanced biasing techniques for improved stability, and develop systematic PGD characterization methods for more efficient NGD network design. These advancements will further enhance the applicability of the amplifiers in next-generation communication and radar systems.

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