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Advanced Compact High-Power InGaAs HEMT Self-Oscillator Active Integrated Antenna for IoT Applications

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ABSTRACT: This work presents a new negative resistance self-oscillator based on an integrated active antenna and InGaAs HEMT technology, specifically designed for Internet of Things (IoT) applications. A key aspect of this design lies in the series integration of the active circuit and the antenna patch. The fabrication and testing were carried out on an FR4 substrate with a thickness of 0.8 mm. The Harmonic Balance numerical method, implemented in Advanced Design System tool, was used for the optimization and co-simulation of the system. After simulation and measurement, the proposed self-oscillator, with a compact size of $3.4 \times 3\,\text{cm}^2$, produced very significant results. The simulated output power reached 12.87 dBm at a frequency of 3.07 GHz, while the measured output power was 12.85 dBm at 3.04 GHz, demonstrating high output power capabilities with a recorded phase noise of -78 dBc/Hz at 10 MHz. The qualitative and quantitative performance of the proposed self-oscillator antenna makes it particularly suitable for applications such as satellite mobile communications, GPS, telemetry, and telemedicine.

1. INTRODUCTION

Amidst the rapid evolution of modern technology, the Internet of Things (IoT) stands as a pivotal force, fundamentally reshaping industries across the spectrum. This transformative concept revolves around the seamless integration of smart devices and connectivity, facilitating efficient communication and data exchange on an unprecedented scale. Within this dynamic landscape, the underutilization of self-oscillating antennas emerges as a notable trend. Driven by the pursuit of high performance, minimal power consumption, low phase noise, and compact device size [1–3], the exploration and integration of self-oscillating antenna technology hold immense promise for advancing the capabilities and functionalities of IoT systems.

Active Integrated Antennas (AIAs) have gained significant attention and emerged as a rapidly growing area of research. The term "Active Integrated Antenna" means the incorporation of components that have each active and passive on a common substrate. This form of integration can offer numerous advantages, including an overall AIA size which leads to a miniaturization antenna, wider bandwidth, increased gain and improved noise performance [4, 5]. Active elements and antennas can be integrated in a variety of ways. The main types of AIAs include oscillator AIAs and amplifier AIAs (low noise or power amplifiers), mixer AIAs, and transceiver AIAs [6]. In contemporary microwave and radio systems, self-oscillator AIAs play a pivotal role in designing modules for wireless energy transfer and charging [7, 8]. These components are particularly well suited for applications such as multicarrier Radio Frequency Identification (RFID) and the IoT [9].

Self-oscillators antennas represent a fascinating area of research within the field of wireless communications, offering unique capabilities for signal generation and transmission. These antennas are characterized by their ability to generate oscillating signals without the need for an external source, thanks to the integration of active components such as transistors or diodes directly into the antenna structure. This integration enables the antenna to not only radiate but also oscillate, thereby serving as both the signal source and radiating element [10, 11]. This can be achieved by two main methods: the use of a feedback loop topology [12] or the application of resistance negative technique [13], both aimed at optimizing output power. These two methods enabled maximum power to be obtained, whether at the second harmonic with an integrated active self-oscillating antenna of the gallium nitride (GaN)-high electromobility transistor (HEMT) type or at the first harmonic with a self-oscillating AIA of the GaN-HEMT type.

This research aims to develop and streamline planar antenna structures for negative resistance self-oscillators, with a focus on enhancing key performance metrics such as output power, circuit miniaturization, energy efficiency, and signal stability, while also simplifying the measurement of output power. The study specifically investigates the application of indium gallium arsenide (InGaAs) HEMT technology for IoT devices.

The structure of the paper is as follows. Section 2 details the design and optimization methodology of the self-oscillator antenna, integrating an unstable transistor and a passive radiator on the same substrate. The inclusion of the LsCs circuit in series with the transistor's drain enhances stability and allows precise control of oscillation conditions, ensuring operation at the desired frequency. Section 3 presents the co-simulation technique and discusses the results. Lastly, Section 4 covers the fabrica-

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tion of printed circuit boards (PCBs) and provides an analysis of the measurements taken on the oscillator, evaluated in the context of IoT applications.

2. SELF-OSCILLATOR ANTENNA DESIGN AND METHODOLOGY

The proposed architecture of a self-oscillator antenna is illustrated in Fig. 1. This design incorporates an active component within the antenna structure, allowing the oscillator to generate RF signals autonomously.

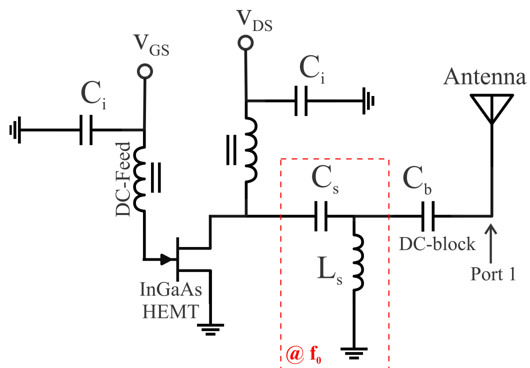

FIGURE 1. Architecture of the proposed self-oscillator antenna.

The proposed architecture includes an active component connected to two biasing circuits, a passive patch antenna, as well as a C_sL_s resonator that will be connected between the drain and frequency (RF) antenna port. The InGaAs HEMT transistor was based on its superior RF performance, particularly in terms of power and phase noise generation. Fig. 2 depicts the layout topology of the proposed self-oscillator. In this design, the active circuit and antenna patch are integrated in the series. A single FR4 dielectric substrate is used, with a height $h = 0.8$ mm, dielectric constant $\varepsilon_r = 4.4$, and loss tangent tan $\delta = 0.02$. The patch antenna functions as a resonator and an output matching network.

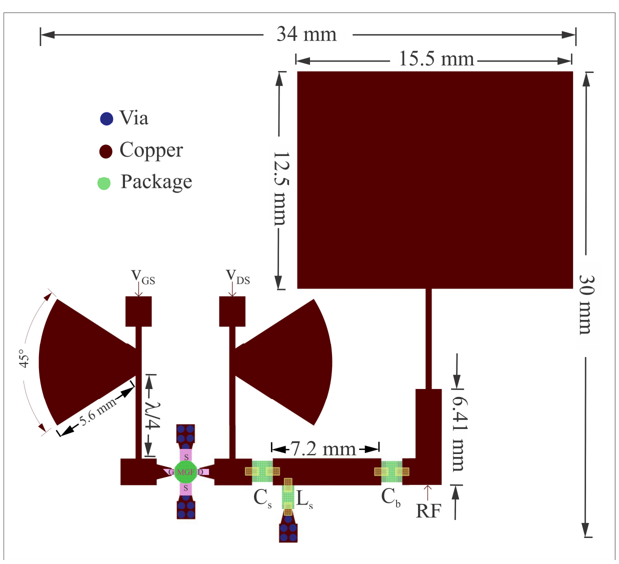

FIGURE 2. Layout of the proposed self-oscillator antenna.

The antenna excitation port is connected to the drain terminals of the MGF4918D transistor. It is biased by two DC current sources V_{DS} and V_{GS} via bias circuits. Each circuit consists of a high impedance λ/4 line that acts as a choke inductor. At the end of this line, a fan-shaped radial stub is added to improve the isolation between RF and DC ports of this circuit. This radial stub has a radius of approximately λ/8 and an arc angle of 45°. The LsCs circuit series with the transistor drain precisely selects the oscillation frequency and enhances stability by filtering out unwanted frequencies, ensuring reliable operation and reducing frequency drift [14]. Additionally, variations in the power supply voltage can reflect changes in the circuit's characteristics. This alteration can lead to a shift in the resonant frequency, as the power supply voltage influences the parameters of both the active and passive components of the oscillator. Consequently, a change in voltage can displace the resonant frequency, affecting the overall stability and performance of the system [15]. By adjusting the voltage, it is possible to control the oscillation frequency, which is essential for optimal operation of the self-oscillator antenna. The capacitance C_s, with a value of 0.3 pF, and the inductance L_s, with a value of 1.2 nH, as well as the bias voltage V_{gs} with a value of -0.4 and V_{ds}, with a value of 4 V, are determined through a well-known parametric study, as shown in Fig. 3.

The circuit was simulated using S-parameter analysis and the Harmonic Balance numerical method, both integrated into the Advanced Design System (ADS). The results of this design are presented in Section 3.

3. RESULTS AND DISCUSSION

Section 2 provides a comprehensive discussion of the proposed self-oscillator active integrated antenna. Following this, we introduce a co-simulation methodology, which effectively integrates both passive and active components [16]. The initial step in this process is to simulate the circuit using S-parameter analysis. In this study, we use this simulation method to identify the optimum values for capacitors and inductors, as well as their power supply voltage, to guarantee an adequate oscillation frequency and satisfactory stability. Fig. 3 presents the results of this simulation.

Parameter S_{11}, known as the reflection coefficient, helps analyze how much of the signal is reflected and provides insights into the circuit's stability and performance. In passive circuits, S_{11} typically assumes negative values, indicating signal loss. Conversely, in active circuits, such as oscillators, S_{11} can exhibit positive values, signifying that the circuit is providing gain, an essential condition for sustaining oscillations. Analyzing the positive values of S_{11} during simulations allows us to confirm the oscillator's proper functionality and provides crucial insights into its stability and performance at the required frequency range.

Figure 3 presents a parametric study illustrating the influence of inductance L_s, capacitance C_s, and power supply voltage on the reflection coefficient. In this study, we select $C_s = 0.3$ pF and $L_S = 1.2$ nH, with a V_{ds} of 4 V and V_{gs} of -0.4 V.

The second step is to simulate the circuit using harmonic balance simulation to verify the start-up condition and to vali-

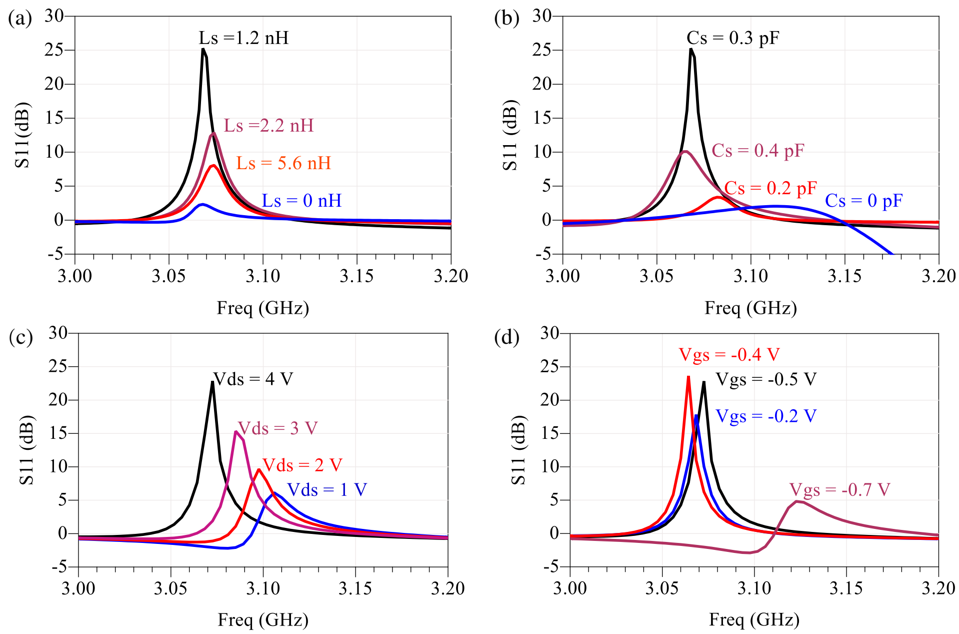

FIGURE 3. Analyses of s-parameters in the self-oscillator antenna proposed (a) and (b) influence of inductance L_s and C_s on the reflection coefficient. (c) and (d) influence of polarisation V_{ds} and V_{gs} on the reflection coefficient.

date the output power for the self-oscillator antenna. Harmonic balance simulation is an essential technique for analyzing nonlinear circuits, such as oscillators and power amplifiers. This method allows for the determination of signal levels at different harmonic frequencies, providing an accurate picture of the circuit's performance under real operating conditions. By performing a harmonic balance simulation, we can verify that the circuit generates the expected output power while meeting linearity and efficiency specifications.

To further verify the start-up conditions for oscillations, we employ admittance analysis. At the resonant frequency, the total admittance of the system must satisfy two key conditions: first, the real part of the admittance must be negative to counteract losses in the system; second, the imaginary part must be zero to ensure resonance [17]. These criteria for stable oscillation can be expressed as follows [18]:

$$Y_T^r(V \cong 0, wo') < 0$$

$$Y_T^i(V \cong 0, wo') = 0$$

Additionally, the derivative of the imaginary part of the admittance with respect to frequency must be positive:

$$\frac{\partial(Y_T^i(V \cong 0, wo'))}{\partial w} > 0$$

These conditions collectively ensure that the system can sustain stable oscillations. Fig. 4 shows the results of the start-up condition for the self-oscillator antenna.

The output power results, shown in Fig. 5(a), confirm the expected performance and demonstrate the circuit's reliability. The output power is 12.87 dBm at an oscillation frequency of 3.07 GHz. The amplitudes of the second and third harmonics are minimal and do not affect the fundamental signal spectrum,

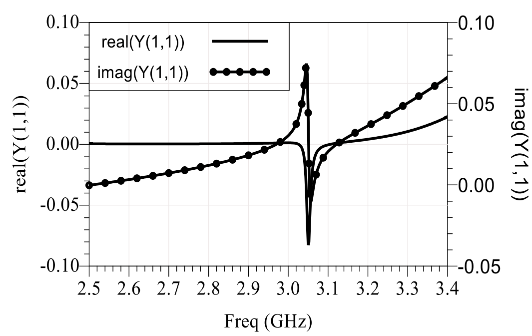

FIGURE 4. Verification of the start-up condition for the self-oscillator antenna proposed.

with the second harmonic at -4.858 dBm and the third harmonic at -15.72 dBm. Fig. 5(b) shows that the self-oscillator antenna exhibits a sinusoidal waveform in the time domain.

4. EXPERIMENTAL VALIDATION

The proposed Self-Oscillator Antenna Integrated Active (SOAIA) fabricated using PCB technology is shown in Fig. 6.

The experimental validation of the circuit was performed using a Keysight E4407B spectrum analyzer, covering the frequency range from 5 kHz to 26.5 GHz. In the measurement setup presented in Fig. 7(a), we first calibrated the spectrum analyzer. Next, we connected the RF port of the self-oscillator antenna to the spectrum analyzer using an SMA cable. Finally, we adjusted the bias voltages to $V_{gs} = -0.4$ V and $V_{ds} = 4.2$ V. Fig. 7(b) shows the measured output power.

Based on the measurements, the oscillator operates at a frequency of 3.04 GHz with an output power of 12.85 dBm, which

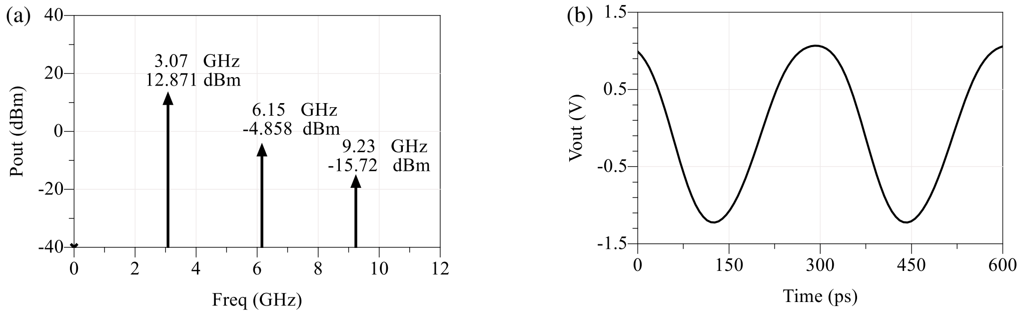

FIGURE 5. Harmonic Balance analysis of self-oscillator antenna proposed. (a) Power spectrum of the output as a function of frequency. (b) Output voltage as a function of time domain.

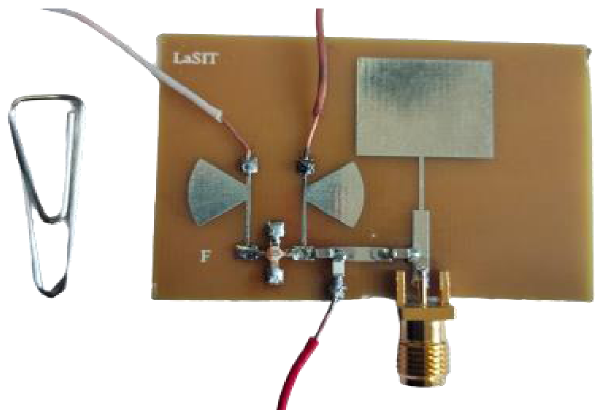

FIGURE 6. Image of manufactured prototype.

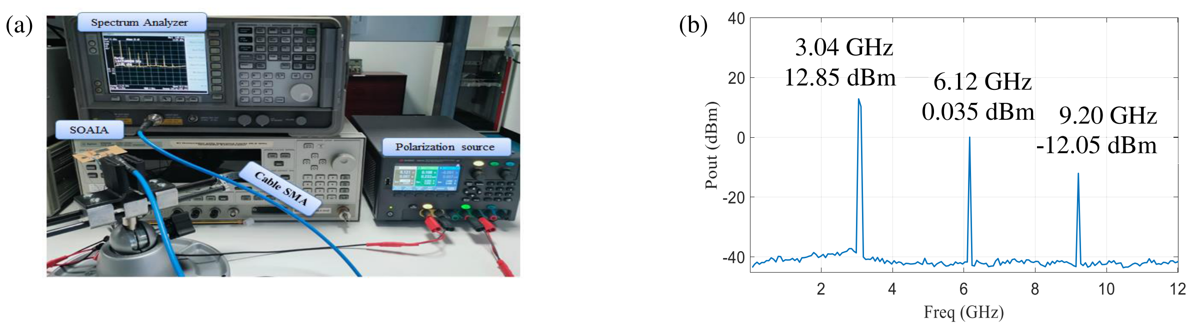

FIGURE 7. (a) Measurement setup. (b) Experimental validation of the output power.

corresponds to the requirements for IoT applications, ensuring efficient performance and reliable communication in this frequency range.

A comparison between the output power obtained from experimental testing and simulation results is detailed in Table 1. This comparison indicates a close alignment between the measured and simulated outcomes.

Figure 8 presents the phase noise results. The results are -62.6 dBc/Hz, -78.2 dBc/Hz, and -95 dBc/Hz at frequencies of 1 MHz, 10 MHz, and 100 MHz, respectively. Consequently, we can affirm that the proposed circuit generates acceptable phase noise.

The performance of the self-oscillator Active Integrated Antennas presented in this paper is compared to that of recent publications within the same field effective transistor (FET) family, as shown in Table 2. The newly proposed SOAIA demonstrates significant improvements across several performance indicators. Refs. [9] and [21] in the table use a feedback loop configuration and Rogers's substrate. On the other hand, our design utilizes a negative resistance configuration on an FR-4

TABLE 1. Comparison between simulated and measured output power.

		Simulated	Measured
Oscillation frequency f_0 (GHz)		3.07	3.04
Polarisation	$V_{GS}(V)$	-0.4	-0.4
	$V_{DS}(V)$	4	4.2
Output Power (dBm)		12.87	12.85

TABLE 2. Comparison between the proposed SOAIA and recent published works.

Ref.	Year	F_o (GHz)	Antenna Type	Active Device	Output Power (dBm)	Structure used /substrat
[19]	2022	0.879	Dipole antenna	FET	6.7	XCP+ZOR / FR-4
[20]	2020	0.916	Monopole antenna	FET	5.1	Cross-coupled pair/RO4003C
[9]	2023	5.682–5.707	Patch antenna	BFP520	7.21@5.698 GHz	Feedback SIW/ RO4003C
[21]	2017	0.916	Loop antenna	FET	7.98	Feedback loop /RO4003C
This work	-	3.047	Patch Antenna	InGaAs HEMET	12.85	Resistance negative / FR-4

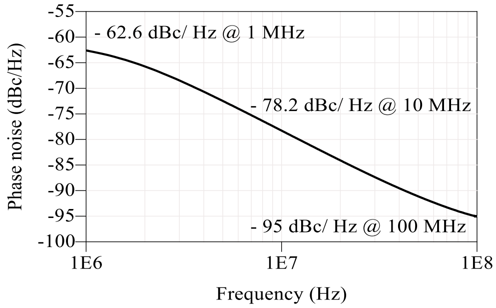

FIGURE 8. Phase noise of the self-oscillator antenna proposed.

substrate, which reduces manufacturing costs and simplifies the circuit complexity. While the studies in [19] also used an FR-4 substrate, they achieved an output power of only 6.7 dBm. Similarly, the work in [20], which used a cross-coupled pair technique, reached just 5.1 dBm with a more complex architecture. In contrast, our proposed design achieved an output power of 12.85 dBm, highlighting a substantial enhancement in the power performance of the self-oscillator antenna while maintaining a simpler configuration.

5. CONCLUSION

In this study, we have developed and optimized a new negative resistance oscillator using an integrated active antenna and HEMT InGaAs technology, specifically designed for Internet of Things (IoT) applications. By integrating an unstable transistor with a passive radiator on a common substrate and incorporating the LsCs circuit in series with the transistor's drain, we have significantly improved the stability and control of oscillation conditions. The compact and high-performance oscillator produced notable results: a simulated output power of 12.87 dBm at 3.07 GHz and a measured output power of 12.85 dBm at 3.04 GHz, demonstrating high output power capabilities, along with a phase noise of -78 dBc/Hz at 10 MHz. The used co-simulation techniques confirmed the effectiveness of our design, and the fabricated printed circuit board demonstrated reliable performance in real-world testing. This research highlights the potential of self-oscillator antennas to enhance IoT systems with high performance, low power consumption, and reduced size. Future work could focus on further optimizing oscillator performance and exploring its application in array self-oscillating antennas.

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