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Article

Design and Simulation of a Variable Gain Down Conversion Mixer for 2.4 GHz ISM Band Applications

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Abstract: In recent years, the importance of wireless sensor networks, maritime surveillance systems and autonomous marine systems has grown significantly, leading to the need for low power and high performance wireless receiver circuits in the 2.4 GHz ISM band. A low power down conversion mixer using current-reuse variable gain amplification technique is presented in this paper for maritime wireless communication. The proposed architecture is based on the concept of incorporating a variable gain amplifier inside the current-bleeding path of the mixer that allows adaptive gain control without consuming a significant amount of current through the path of the mixer. Simulated result shows a maximum gain for conversion of 17.8 dB and a VGR (Variable Gain Range) of about +44 dB and a minimum double-sideband noise figure of 7 dB. With just 5.6 mW of supply 1.8 V, the circuit provides an input third-order intercept point (IIP3) of −14.4 dBm. The results have shown that the proposed receiver front-end is suitable for marine IoT devices, shipboard wireless monitoring networks, and other maritime communication systems exhibiting low power consumption and reliable reception under different channel conditions.
Keywords: Current-Reuse Architecture, Current-Bleeding Technique, Down conversion Mixer, Variable-Gain Amplifier (VGA), Low-Power CMOS Receiver, 2.4 GHz ISM Band, Maritime Wireless Communication, Shipboard Wireless Sensor Networks.

1. INTRODUCTION

Digital technologies are becoming more common in the maritime industry to boost operational efficiency, safety, navigation, and asset monitoring. The smart ships, autonomous surface vessels, maritime Internet of Things (MIoT) systems, cargo monitoring networks, and shipboard wireless sensor networks are applications that are emerging and require the support of reliable and stable wireless communication infrastructures in marine applications where harsh environmental conditions are prevailing [1-3]. The Industrial, Scientific, and Medical (ISM) band at 2.4 GHz has gained a wide acceptance for maritime wireless applications since it is compatible with the low-power communication techniques employed in vessel monitoring system and offshore sensing systems, such as Wi-Fi, Bluetooth, ZigBee, and others [4,5]. In maritime communication environments, multipath propagation, metallic obstructions, electromagnetic interference and dynamic channel conditions due to movements of the vessels and environment are severe [6]. Therefore, the wireless receiver front-end used in maritime monitoring system should have high sensitivity, wide dynamic range and low power consumption, which means that it can receive the signal reliably. The down conversion mixer is an important components of a wireless receiver and is used to translate frequency from radio-frequency (RF) to intermediate-frequency (IF) or baseband domain. The passive mixers have very good linearity and very low static power consumption, but they have a very high conversion loss [7,8]. Active mixers, on the other hand, have conversion gain, and are thus commonly used in low-power wireless communication receivers that demand greater signal sensitivity [9,10].

Variable-gain amplifiers (VGAs) are frequently used in receiver architectures to compensate for the different levels of signals that may occur in maritime wireless networks. The reception adaptability in the changing channel conditions is enhanced, and appropriate signal levels for subsequent processing are maintained by VGAs. There are a number of co-design approaches that have been reported in the literature, namely [11-13] and [18-24] are a few that are commonly used for mixer-VGA. Gain variation techniques are used but they normally need extra bias current and have a short range of gain control. A number of current-bleeding approaches have been used to enhance the gain and power efficiency of an active mixer [14–16]. Current bleeding [17] allows the introduction of some of the bias current into the signal path, thus increasing the conversion gain and the noise contribution. Most of the reported current-bleeding mixers, however, offer a fixed gain and have not been able to take into consideration the wide dynamic range requirements with source degeneration technique in maritime wireless communication systems.

In this work, a low-power down-conversion mixer employing a current-reuse variable-gain amplification technique with inductive source degeneration technique is proposed for maritime wireless receiver applications. The proposed architecture uses VGA within the current-bleeding path to allow amplifier current to be used without increasing overall power consumption. A single control input provides a wide gain-control range suitable for varying maritime communication conditions.

The remainder of this paper is organized as follows. Section 2 describes proposed model and circuit implementation. Section 3 discusses simulation results. Finally, Section 4 concludes the paper.

2. PRAPOSED MODEL AND CIRCUIT IMPLEMENTATION

Conventional active mixer mainly consists of three stages as [i] trans-conductance stage [ii] switching stage and [iii] a load network. Conventional double balanced gilbert mixer is shown in figure 1.

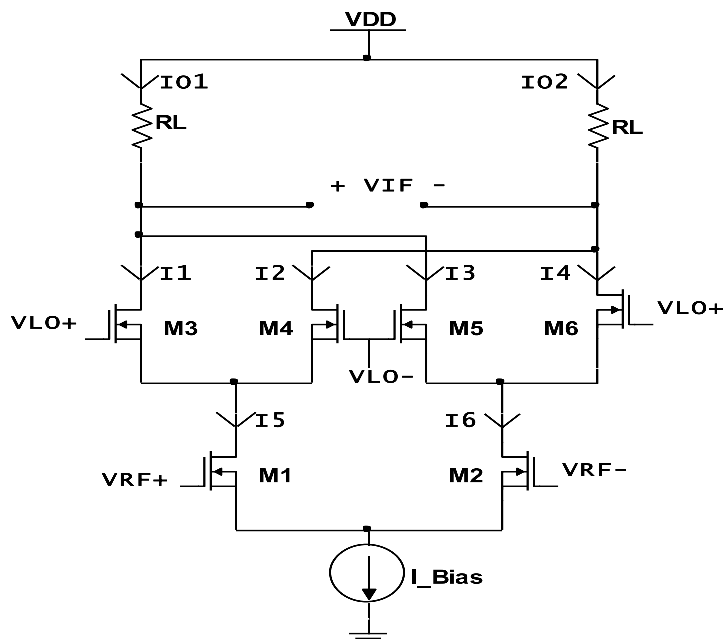

Figure 1. Double balanced gilbert mixer

The RF input signal is first amplified by the trans-conductance stage and then commutated by the LO switching pair. The down converted signal is subsequently amplified by the VGA stage. The overall voltage conversion gain can be expressed as

$$A_v = G_m R_{out} \quad (1)$$

Current passing through trans-conductance stage (transistors M1 and M2) are I_5 and I_6

$$I_5 = I_{DC} + I_{RF} \cos \omega_{RF} t \quad (2)$$

$$I_6 = I_{DC} - I_{RF} \cos \omega_{RF} t \quad (3)$$

$$I_{Bias} = I_5 + I_6 = 2I_{DC} \quad (4)$$

I_{DC} is the DC bias current through trans-conductance stage (transistors M1 and M2) and $\omega_{RF} = 2\pi f_{RF}$ is the angular frequency of input RF signal. Currents I_5 and I_6 are switched by LO switching transistors M3-M6.

$$I_1 - I_2 = I_5 s(t) \quad (5)$$

$$I_4 - I_3 = I_6 s(t) \quad (6)$$

$$s(t) = \frac{4}{\pi}[\sin \omega_{LO}t + \frac{1}{3}\sin 3\omega_{LO}t + \frac{1}{5}\sin 5\omega_{LO}t + ..] \quad (7)$$

Where s(t) denotes LO switching function and ω_{LO} is LO frequency. Output currents through load resistors R_L are given as:-

$$I_{O1} = I_1 + I_3 \quad (8)$$

$$I_{O2} = I_2 + I_4 \quad (9)$$

Differential Output current through load resistors RL is given as –

$$I_{OUT} = I_{O1} - I_{O2} \quad (10)$$

$$I_{OUT} = (I_1 + I_3) - (I_2 + I_4) \quad (11)$$

$$I_{OUT} = (I_1 - I_2) - (I_4 - I_3) \quad (12)$$

$$I_{OUT} = I_5 s(t) - I_6 s(t) \quad (13)$$

$$I_{OUT} = (I_5 - I_6)s(t) \quad (14)$$

$$I_{OUT} = 2I_{RF}\cos \omega_{RF}t.s(t) \quad (15)$$

$$I_{OUT} = \frac{4}{\pi}I_{RF}[\sin(\omega_{LO} - \omega_{RF})t + \sin(\omega_{LO} + \omega_{RF})t \ + \frac{1}{3}\sin(\omega_{LO} - \omega_{RF})t + \frac{1}{3}\sin(\omega_{LO} + \omega_{RF})t$$

(16)

Where $\omega_{LO} - \omega_{RF} = \omega_{IF}$, is the required IF is output frequency. Voltage conversion gain (A_V) of the mixer is given as-

$$A_V = \frac{\frac{4}{\pi}I_{RF}R_L}{2V_{RF}} = \frac{2}{\pi}g_m R_L \quad (17)$$

g_m of transistors at trans-conductance stage is given by –

$$g_m = \sqrt{2\mu_n C_{ox}\frac{W}{L}I_{DC}} \quad (18)$$

Where I_{DC} is the bias current passing through trans-conductance stag

So conversion gain is rewritten as-

$$A_v = \frac{2}{\pi}\sqrt{2\mu_n C_{ox}\frac{W}{L}I_{DC}}R_L \tag{19}$$

IIP3 (Third order input intercept point) is is given by –

$$A_{IIP3} = \sqrt{\frac{4}{3}\left|\frac{\alpha_1}{\alpha_2}\right|} \tag{20}$$

IIP3 is the parameter of the mixer to estimate the performance of the mixer in terms of intermodulation distortion. IIP3 of the mixer

Where α_1 and α_3 are coefficients of first order and third order terms of i_{ds}-v_{ds} characteristics of trans-conductance stage MOSFETs respectively, Expression of α_1 and α_3 are given as-

$$\alpha_1 = \sqrt{\mu_n C_{ox}\frac{W}{L}I_{DC}} \tag{21}$$

$$\alpha_3 = -\left(\mu_n C_{ox}\frac{W}{L}\right)^{\frac{3}{2}}\frac{1}{8\sqrt{I_{DC}}} \tag{22}$$

So A_{IIP3} in terms of I_{DC} is given as

$$A_{IIP3} = \sqrt{\frac{6I_{DC}}{\mu_n C_{ox}\frac{W}{L}}} \tag{23}$$

$$V_{ds} = V_{bias} - I_{ds}R_D \tag{24}$$

The current-bleeding technique is used to achieve high gain and low power. In this technique, a current source is inserted between stage [i] and stage [ii] to direct some current from switching pair. In the proposed design, the conventional current-bleeding source is replaced by the VGA, while the mixer output is directly connected to the input of VGA to realize a variable-gain block.

L3 and L4 are added to form a Pi type matching network consisting of parasitic capacitances at the source of LO transistor and the drain of RF transistors, leading to improved tuning of the mixer. Figure. The pi type network (shown in 2) consists of the gate to source parasitic capacitance of each LO transistor (M7 and M8) and the drain to gate parasitic capacitance of the RF trans-condutance stage transistors (M3). L2 inductance also cancels the capacitances of transistors M9, M10 and M4.

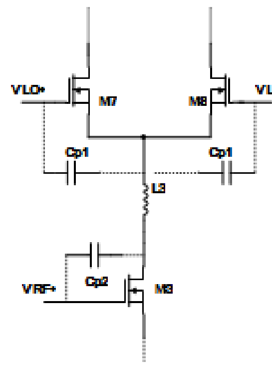

Figure.2. Tuning of added L3 inductance with parasitic capacitances

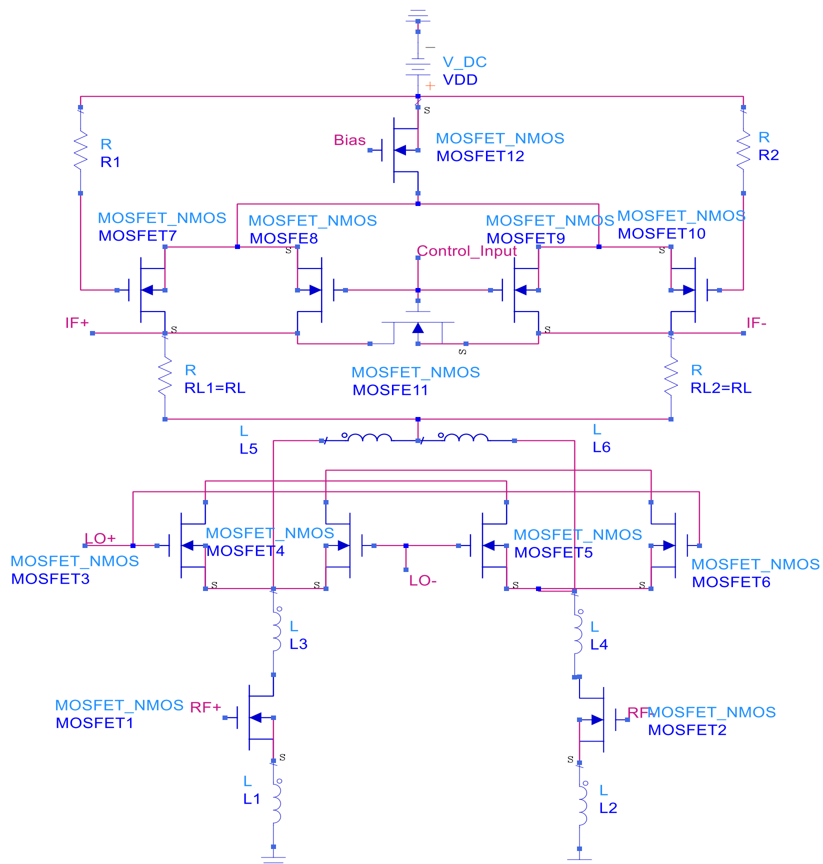

Figure 3. Proposed Mixer

Source degeneration techniques are widely used in CMOS mixer design to improve linearity, stabilize transconductance and enhancing overall circuit performance. Proposed mixer integrated a current-bleeding variable gain amplifier (VGA) with inductive degeneration technique as shown in figure 3. The circuit consists of two main blocks [i] the mixer stage and [ii] the VGA stage. The conventional fixed-gain current-bleeding concept is modified to realize a wide-range VGA with a different topology. As a result, the proposed design provides variable conversion gain without much added power consumption while inherently performing current bleeding.

3. SIMULATION RSULTS

The proposed mixer is simulated by Keysight Advanced Design System (ADS) software using 65nm CMOS process technology with 0 dBm LO power at 1.8 DC supply voltage. . LO frequency in terms of RF frequency is given by

$$f_{LO} = f_{RF} \pm f_{IF} \tag{24}$$

Conversion gain (A_v) of the down conversion mixer is defined as the ratio of output IF power level to input RF power level. Simulated conversion gain as function of input RF power level is shown in figure. 4.

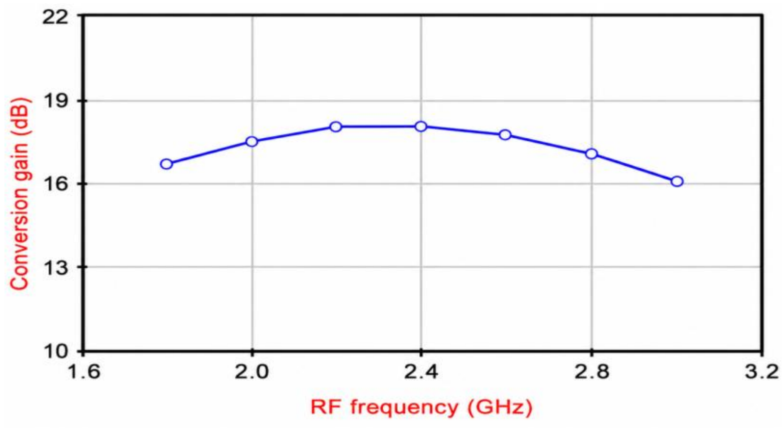

Figure 4. Variation of simulated conversion gain with RF Frequency

Figure 4 presents variation of simulated conversion gain with RF frequency range of 1.8–3.0 GHz, while the LO frequency varied from 1.8–3.0 GHz. During simulation, an RF input power of −40 dBm and an optimized LO input power of 0 dBm is used with IF signal of 50 MHz The maximum simulated voltage conversion gain achieved is 17.8 dB.

Figure 5 shows the simulated 1-dB compression point (P1dB) as a function of the control input. As the control input is varied, the P1 dB changes from -17.5 dBm to – 35.0 dBm, resulting in a tuning range of about 17.5 dB. The gradual reduction in P1 dB with increasing control input indicates a trade off between conversion gain and large signal linearity.

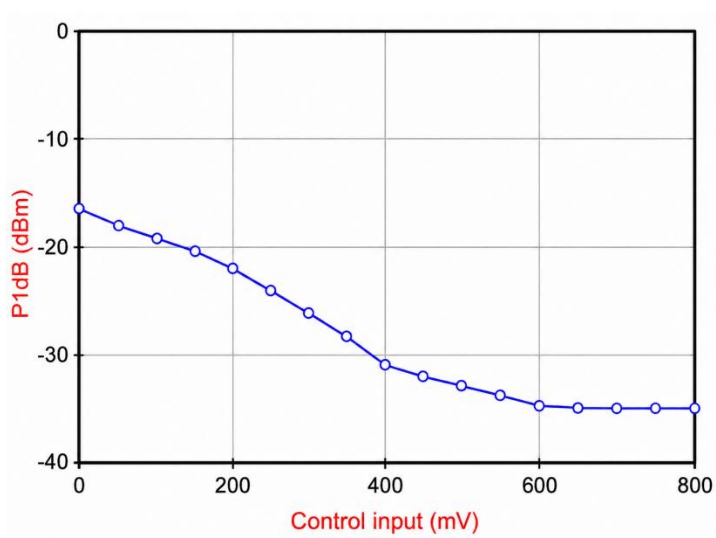

Figure 5. 1dB compression point vs control input

The simulated relationship between the conversion gain and IIP3 is presented in figure 6. The conversion gain rises from about −30 dB at IIP3 about −30 dBm to 16 dB at IIP3 about +30 dBm. The conversion gain is high in the IIP3 range from −15 dBm to +10 dBm and starts to saturate beyond this point and is almost constant at about 16 dB.

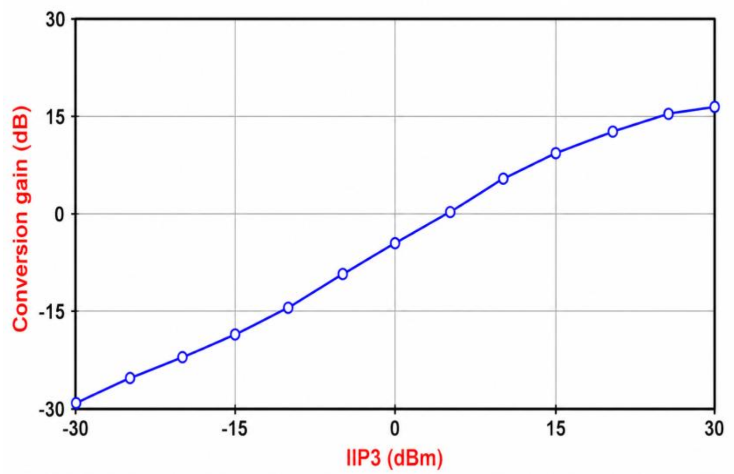

Figure 6. Variation of CG and IIP3

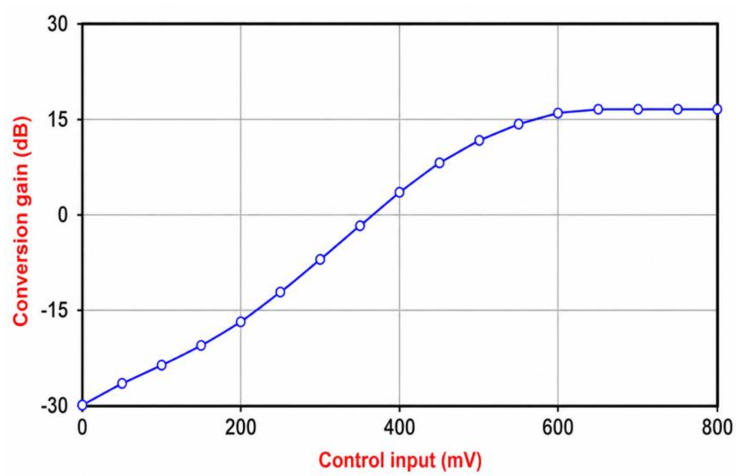

Figure 7. IIP3 vs control voltage

The conversion gain is shown in Figure 7 as a function of the control input. The conversion gain is raised from around -30 dB at 0 mV to about 16 dB at 800 mV, giving a tuning range of almost 46 dB. The gain rises sharply between 200 and 500 mV, and comes to saturation for control input levels greater than 600 mV.

The simulated noise figure (NF) of the proposed mixer against IF frequency is shown in figure 8. For the center tapped inductor configuration between L5 and L6 in conjunction with the proposed current-bleeding amplification technique, both flicker and thermal noise components are well suppressed. This results in simulated NF ranging from ~22 dB at 10 kHz to ~6.7 dB at 100 MHz. The effect of the flicker (1/f) noise is seen in the lower frequencies of IF, as described above, where a rapid decrease in NF is observed; beyond 10 MHz the value of NF is close to 6.7 dB, which is a stable value for the wideband noise performance. The very low and stable NF of the achieved design illustrate the excellent receiver sensitivity enhancement that has been achieved with the proposed architecture while maintaining the conversion gain. The almost flat NF above 10MHz indicates that thermal noise is the predominant noise factor while flicker noise is negligible.

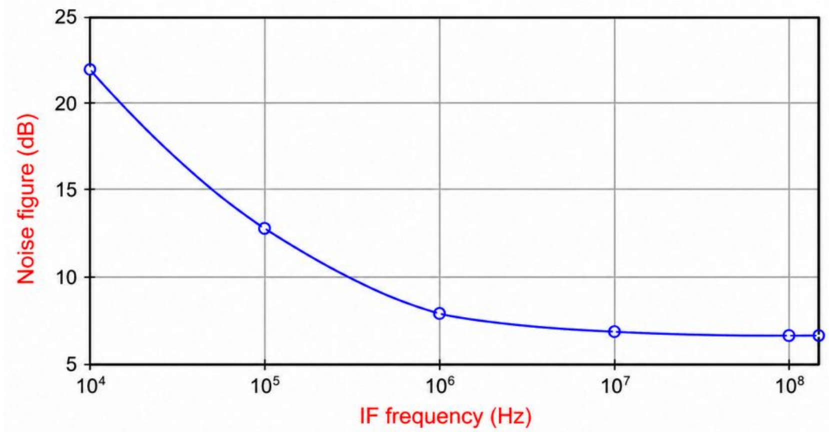

Figure 8. simulated NF vs IF frequency

The simulated NF drops from ~ 22 dB at 10 kHz to 6.7 dB at 100 MHz and is almost flat outside of 10 MHz. As seen in figure 9, the simulated port-to-port isolation is greater than 35 dB over the 1.8-3.0 GHz RF frequency range, while the LO–IF, LO–RF, and RF–IF isolations are ~ 52-57 dB, 35-48 dB and 38-45 dB, respectively. With the output buffer disabled, the mixer core takes 4.8-5.4 mW from a 1.8 V supply, the VGA stage consumes 2.3 mA, the LO switching stage consumes 0.25 mA and the RF stages consumes 3.4 mA.

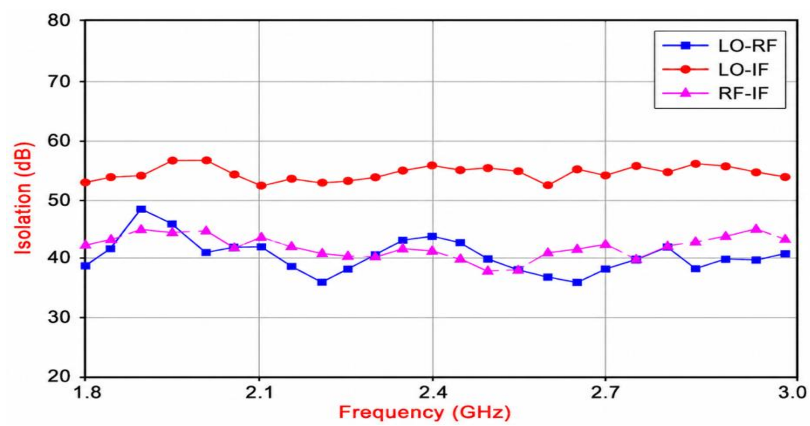

Figure 9. port to port isolation vs RF Frequency

4. CONCLUSION

In this paper, we presented a low-power 2.4 GHz CMOS receiver mixer for maritime wireless communication and shipboard monitoring applications. The proposed mixer achieved 17.8 dB conversion gain and a wide gain-control range exceeding 44 dB over 1.8–3.0 GHz operation. The mixer exhibited an 8 dB DSB noise figure, greater than 34 dB port isolation and consumed only 4.8–5.4 mW from a 1.8 V supply. The current-bleeding VGA architecture and Inductive source degeneration technique enabled efficient gain tuning under varying channel conditions while maintaining low power operation. These results demonstrate the suitability of the proposed design for compact and energy-efficient wireless receiver systems.

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