A down conversion K-Band mixer using current-reuse folded Double-Balanced Architecture in 130-nm CMOS Process with High Conversion Gain and Improved Linearity

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Abstract: 5G service will be gradually expanded to cover the whole country India over the next two years. The viability of 5GHz wireless systems depends primarily on the linearity of the RF downconverter. With the increasing number of portable battery-operated wireless devices, the challenge exit to achieve excellent linearity and high conversion gain. This work tries to overcome the difficulty by proposing a Current-Reuse Double-Balanced RF mixer. The K-band, 23 to 25 GHz, has been chosen for the construction of the mixer. With a conversion gain of 24.2 dB in this RF bandwidth range, the suggested mixer's design also achieves a better degree of linearity with -17.8 dBm 1-dB compression at 24 GHz. The input strength of the LO feed was maintained at a tolerable level of -3 dBm.

Keywords: K-Band, Conversion gain, Linearity, 1-dB compression point, Folded architecture, Current-reuse

1. INTRODUCTION

The fifth-generation (5G) wireless network is one of the most fascinating areas of study in recent years that promises faster speeds, lower latency, and greater capacity than its predecessors. It operates on high-frequency bands known as millimeter wave (mmWave) which offer increased bandwidth and faster data rates.A down conversion mixer is an essential component in the receiver chain of a wireless communication system, including 5G. It is used to convert high-frequency signals received by the antenna to a lower frequency that can be more easily processed by the receiver. Millimeter-wave bands beyond 24 GHz are increasingly being considered for 5G applications as a means of achieving more bandwidth and faster data transfer rates[1].The IEEE defines the term "K-band frequency" to refer to the spectrum of frequencies between 18 and 27 GHz. K band with high data speeds have drawn a lot of interest. The 23–25 GHz frequency band is used by commercial wireless point–to–point communication systems and 24-27 GHz industrial–scientific–medical (ISM) band are of interest for silicon radar technologies. The mixer's architecture can be either passive or active, depending on the component circuit topology utilized in the design. An active mixer utilizes an active device such as a transistor, while a passive mixer utilizes passive components such as diodes, transformers, and baluns.Active mixers have the advantage of providing high CG, high linearity, and low NF. They can also provide a wide bandwidth and operate at high frequencies. However, they also require a DC power supply and can introduce unwanted spurious signals due to the nonlinearities of the active devices.Passive mixers, on the other hand, have the advantage of being simpler in design and not requiring a DC power supply. They also produce fewer spurious signals and can operate at high frequencies. However, they have a lower conversion gain and are less linear compared to active mixers.

The two main forms of active down-conversion mixers are the Transducers based on Gilbert cells, featuring both switching and switching-transconductance designs [2]. In the GmSw architecture it consists of a transconductance amplifier (Gm) followed by a pair of switches. The input RF signal is applied to one of the switches, and the local oscillator (LO) signal is applied to the other switch. The output is taken from the common node of the two switches. In the switching-transconductance (SwGm) mixer architecture it uses a switching mixer followed by a transconductance amplifier. The switching mixer consists of a pair of switches that alternately connect the input RF signal and the LO signal to a load capacitor. The transconductance amplifier then converts the voltage across the load capacitor into an output current. The SwGm architecture is known for its simplicity and low power consumption.

Today, the majority of RF building blocks are implemented using CMOS technology. In particular, CMOS technology is used to implement all of the active RF blocks in RF receivers for contemporary wireless communication systems. Because CMOS technology is inexpensive and integrates with baseband chipsets [3], CMOS process and direct-conversion architecture is popular for their versatility and cost-effectiveness. Since it will use less power, it is important for the low-cost design of 5G high-speed communication transceivers to create transistors that perform linearization without the inclusion of any sophisticated structures[1]. This research proposes an ideal solution with a double balanced current reuse design and a qualitative analysis of contemporary RF down-conversion mixers. Section 2 discusses the basic aspects and topologies of RFmixer and challenges. The double-balanced down conversion mixer architecture is presented in Section 3, which demonstrates its utility by giving exceptional linearity and good conversion gain.

2. Primary elements and topologies of RF mixer and challenges in the RF receiver architectures

The down-conversion mixer is acritical building block of receiver system. Figure 1 shows how the down-conversion mixer that converts RF signals to IF. Direct conversion architecture starts the IF stage frequency at DC. By isolating the RF stage from the IF stage with distinct frequencies, the IF stage helps RF receivers achieve high gain and stability.

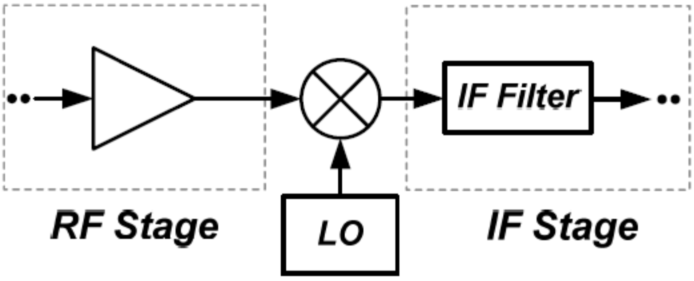

Figure 1: RF mixer block schematic diagram

The mixer selects channel frequency by adjusting the local oscillator (LO) frequency rather than the IF filter centre frequency. One local oscillator LC combination selects the channel frequency. The low IF frequency increases selectivity of RF sections in the system because the IF stages employ fixed-frequency filters, which are easier to build for strong interference rejection than variable frequency filters. The system's overall gain is dispersed across several frequency bands, achieving the desired total receiver gain without circuit stability considerations. Fixed-frequency IF filters eliminate inter-channel interferers, reducing the need for IF stage linearity.Additionally, there are many RF mixer configurations that need understanding. Often these slightly elevated techniques involve balanced transformers, which may limit their frequency range [2-4]. The main advantage of active design is a high gain and sufficient isolation. Active mixers, in contrast to passive mixers, can have a conversion gain, which will impact the model's RF design [19]. Piyush et al., in [20-23] have also claimed that energy is crucial in today’s Wireless Communication Networks and thus the power consumption for any RF circuit or devices should be as low as possible.

High-Conversion Gain K-band RF Mixers (Gain-Boosted)

A down-conversion mixer's main responsibility is to take the high-frequency RF input signal and mix it with a local oscillator (LO) signal at a higher frequency, resulting in a lower frequency intermediate frequency (IF) signal that can be more easily processed by the rest of the receiver's circuitry. If the mixer application moves to a higher frequency side, such as a K-band or Ku-band application, there are several considerations that must be considered to ensure that the mixer performs effectively. K band and Ku band applications operate at much higher frequencies than lower frequency applications, such as those in the VHF or UHF ranges. The mixer must be designed to operate effectively at these higher frequencies, which may require the use of specialized high-frequency components and materials. At higher frequencies, the local oscillator (LO) signal can leak into the RF input signal path, potentially causing interference and reducing the overall performance of the mixer. To mitigate this, the mixer must be designed with good isolation between the LO and RF signals, which may require careful layout and shielding. At higher frequencies, losses and noise in the mixer circuit can have a significant impact on the overall performance of the receiver. The mixer must be designed with low insertion loss and low noise figure, which may require the use of high-performance components and careful optimization of the mixer topology. K band and Ku band applications often require higher power handling capabilities than lower frequency applications. The mixer must be designed to handle these higher power levels without distortion or damage to the circuit components.

However, it is challenging to attain the high gain and good isolation for K band because to several technological factors. Numerous initiatives have been made to address the difficulties in CMOS mixer design field. Chang et al. employed the conventional current bleeding approach for a k band mixer at 180 nm CMOS process [6]. Current-bleeding with 0.18-micron CMOS technohogy in K-band with down-conversion mixers has been discueesd in [6, 7]. In the study presented, a high CG of 8.4 dB has been attained [6]. The alternative proposal [7, 9] included a k-band mixer together in 180-nm Cmos technology that showed improved linearity of -13.6 dBm IP1 as well as a sizable conversion gain of 10.7 dB. Chang et al. produced a K-band mixer with a peak value CG of 11.9 dB at 23 GHz and a -3-dB bandwidth of 7 GHz [8]. Yao Peng, Jin He, et al. demonstrated a 130-nm RF CMOS-designed K-band mixer. The transconductance stage's gm is limited by having the same biassing as the switch stage in differential topology. The mixers' folded double-balanced architecture divides the transconductance and switch stages' bias circuits, individually biassing the transconductance stage to higher gm. Additionally, Current reuse improves gm stage transconductance, and a cross-coupled structure boosts active loading. Besides the previously indicated advantage, this significantly raises the down-conversion mixer's conversion gain (High CG).

Linearity and Compression Point 1dB

Mixer is a non-linear device. In linear operation, the conversion loss of a mixer does not change. Mixers, like other nonlinear devices, suffer from increasing loss when input power is increased. The device's gain response will begin to attenuate at a certain power level. The compression point is said to occur at this degree of force. There is one-dB compression point, two dB compression points and three dB compression points referred as P1dB, P2dB, P3dB respectively. Input P1dB point is often abbreviated as IP1dB.As the input power continues to increase, at some point the gain begins to decrease. When the mixer enters compression, the output no longer grows proportionally to the input. At very high signal levels, the mixer saturates, and the gain flattens. Distortion, harmonics, and even intermodulation products are generated when its response becomes non-linear.

The 1 dB compression point or P1dB point is the RF input power that causes the gain to decrease 1 dB from the normal expected linear gain plot. If you want mixer to act linearly, you need to stay well below the one dB compression point (IP1 dB). It is crucial to choose a mixer with LO drive level that provides the necessary compression point for the application since the compression point varies with LO drive level. S. Krishnamurthy et al., designed high linearity Mixer-First Receivers for mm-wave digital mimo arrays using overlapping square-wave drive[11]. This technique improves mixer switch linearity at mm-wave frequencies, but feedback computation limits broadband operation, requiring an LNA-based front end [11]. The works [12], [13], and [14] employ trans-mission line-based passive phase shifters, which use vector interpolator-based active phase shifters and have poor linearity. This performance parameter is crucial since it evaluates dynamic range in terms of maximum input for different mixers. Dynamic range is a mixer's effective signal power range. The conversion compression point limits dynamic range. Mixers are considered linear till IP1dB. 1-dB Compression Point graphical representation is shown in Fig. 2.

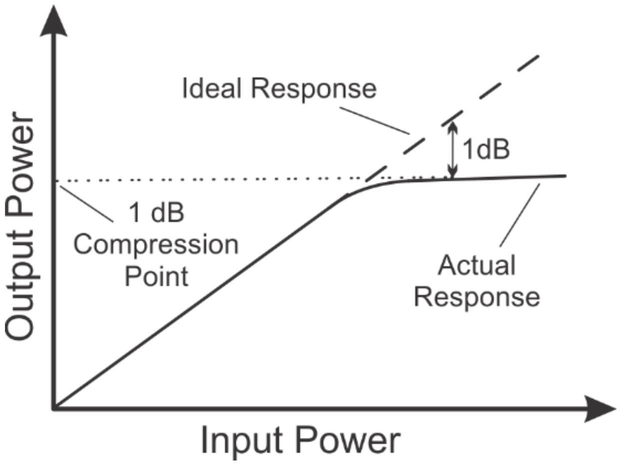

Figure 2: Compression Point 1-dB

For higher linearity the IP1dB point should also be higher. The LO drive level is typically associated with the 1-dB compression point of a mixer. The 1-dB compression point of a mixer increases as the LO drive level rises. Yet higher LO power also must have to be delivered to such mixers. Strong linearity has been studied in high transconductance differential pairs with larger dimensions, and a higher 1-dB compression point is desired.

Architecture for Folded double-balanced Down Conversion Mixer

Switching nonlinear components have finite conducting losses, which lowers conversion gain and deviates substantially from the idealised mark. Signals from the LO amplitude has a substantial impact on the conversion gain as well since it drives the nonlinear mixing elements' ON and OFF switching. A higher LO signal amplitude results in a higher conversion gain, but at the expense of more power loss. Conversion loss in actual (passive) microwave mixers typically ranges from 6 dB to 11 dB. The traditional folded double-balanced down-conversion mixer architecture is shown in Figure 3 with the transconductance, and load stages being mentioned separately.

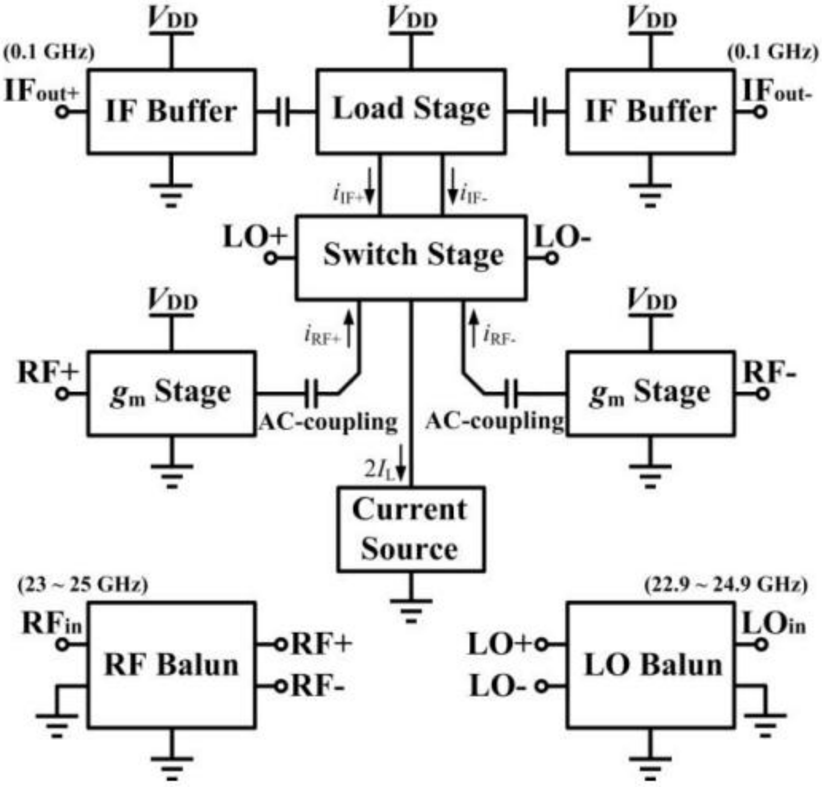

Figure 3: Dual-balanced Folded Down conversion mixer

Baluns, specialised RF circuits, allow differential RF circuits to be connected to single-ended ones [10]. Baluns link balanced and unbalanced lines without modifying their impedance. The differential architecture is RF-powered from the switched stage from. The balancing mode input balun obtained these LO signals. The switch stage transistors, driven by low overdrive gate voltages, can be made larger to reduce driving LO power. It uses 24 GHz inductors for a high-quality factor. The cross-coupled pairs used provide a high conversion gain, which necessitates an active load stage with a very high equivalent load impedance. Additionally, the transconductance of the gm stage is significantly improved by the current reuse technique, and a cross-coupled structure provides high active loading. The mixer's isolation has enhanced with inverter mode buffer amplifier stages on the balanced IF ports. The existing reusable cross-coupled differential structure's description and details make topology and architectural adaptation easy [15, 16]. This highlighted the important restrictions on gain and linearity.

3. Proposed double-balanced Current Reuse Mixer Topology

The proposed mixer’s architecture is shown in Figure 4.

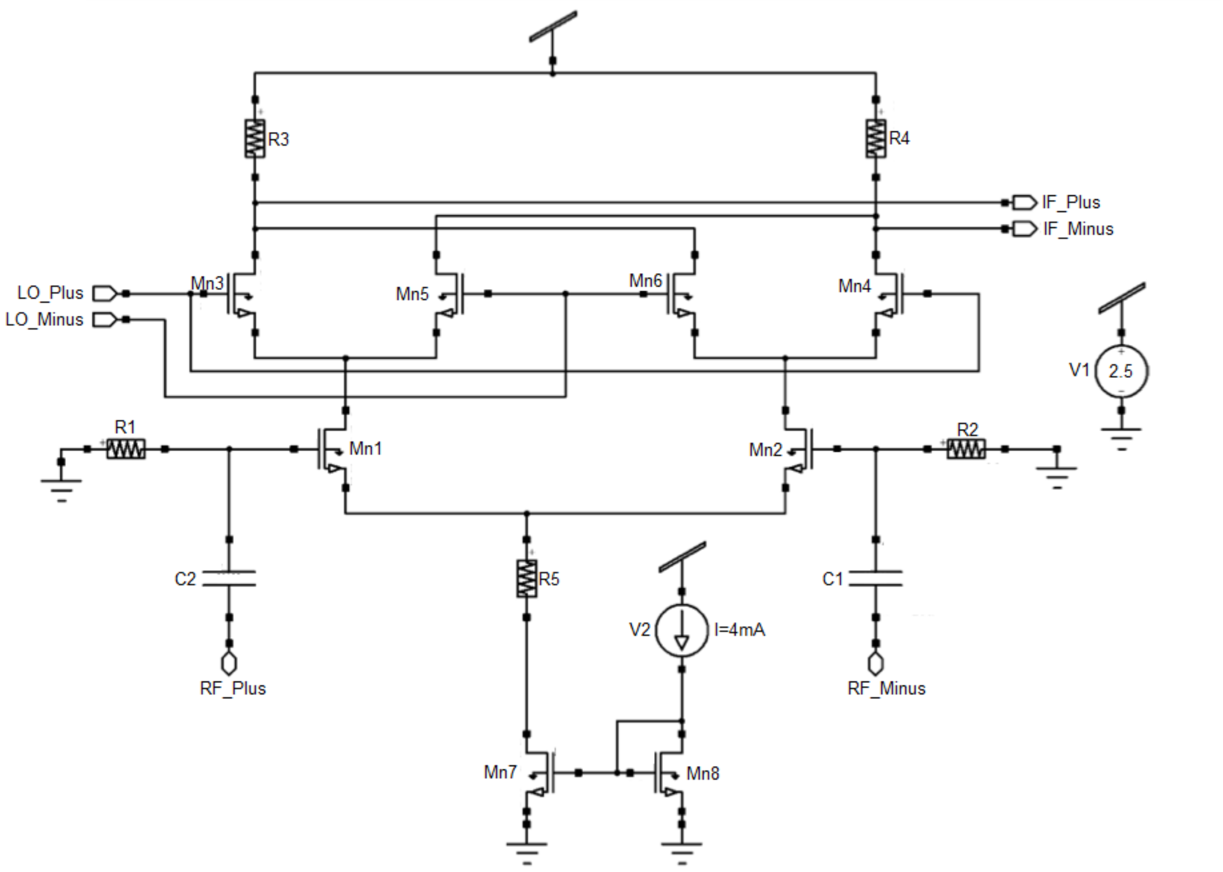

Figure 4: Proposed double-balanced Current Reuse Mixer topology

Table 1. The layout biasining parameters of resisitor & Capacitor in the Proposed double-balanced Current Reuse Mixer topology

R1,R2 (Series Segments)	9.984K ohm	Seg L=14 µm	Seg W=1µm
R3,R4,R5(Series Segments)	501 ohm	Seg L=10 µm	Seg W=1µm
C1,C2 (Top plate M=1)	253.9 f	Seg L=25 µm	Seg W=10 µm

Table 2. The layout parameters of transistors in the Proposed double-balanced Current Reuse Mixer topology

	W(Width)	M(Multipliers)	L(Length)	NF(fingers)	TW(Total Width)
MN1, MN2	12 µm	1	250 nm	8	96µm
MN3,MN4	12 µm	1	250 nm	8	96µm
MN5,MN6	12 µm	1	250 nm	8	96µm
MN7	5 µm	20	250 nm	2	200µm
MN8	5 µm	4	250 nm	2	40µm

The Gilbert-cell mixer using the current reuse method is shown in Figure 4. The current that serves as the bias in the switching pair stage can be lowered while the transconductance stage's bias current remains unchanged by introducing current-bleeding routes between the two stages. In addition, the bias voltages of the transconductance stage and the switching pair stage, measured from the drain to the source. may be kept constant while increasing RL1 and RL2. This is because a portion of the bias current in the transconductance stage is redirected from the current bleeding circuit. Hence, the greater load resistance of the load stages gives better conversion gain than standard Gilbert cell setups [25-27] through the current-bleeding approach. Let us see how a balun in the double balanced Gilbert cell mixer can improve conversion gain and linearity, We can start by analyzing the input matching between RFin and the Gilbert cell mixer. The input impedance of the Gilbert cell mixer is usually 50 ohms, while the characteristic impedance of most RF signals is also 50 ohms. However, if the RF signal is applied directly to the mixer, there may be a mismatch between the input impedance of the mixer and the characteristic impedance of the RF signal, which can cause a portion of the signal to be reflected back to the source. This can result in a reduction in the input power to the mixer, leading to a lower conversion gain.

By using a balun, the single-ended RF signal can be converted to a balanced signal, which can be applied to the mixer without any impedance mismatch. If the balun has a perfect impedance transformation and converts the single-ended RF signal to a balanced signal with equal amplitudes and 180-degree phase difference. Then, the balanced RF signal can be represented as:

$$RF^{+} = \left(\frac{1}{\sqrt{2}}\right) \times RFin \qquad \ldots\ldots(1)$$

$$RF^{-} = \left(\frac{-1}{\sqrt{2}}\right) \times RFin \qquad \ldots\ldots(2)$$

The balanced RF signal is then applied to the Gilbert cell mixer, where it is multiplied by the LO signal. The output voltage can be expressed as:

$$V_{out} = K \times [(RF^{+} \times LO^{+}) - (RF^{-} \times LO^{-})] \qquad \ldots\ldots(3)$$

where K is the conversion gain of the mixer, and LO^{+} and LO^{-} are the LO signals applied to the mixer.

Now, let us consider the effects of common-mode noise and distortion. Common-mode noise is the noise that is present in both signal and ground, while differential-mode noise is the noise that is present between the signal and ground. Common-mode distortion is the distortion that is present in both the signal and ground paths, while differential-mode distortion is the distortion that is present only in the signal path.

In a double balanced Gilbert cell mixer, common-mode noise and distortion can degrade the linearity of the mixer by causing even-order intermodulation distortion (IMD) products. A balun can help reduce common-mode noise and distortion by converting the single-ended input signal to a balanced signal, which can cancel out the common-mode noise and distortion. This can improve the linearity of the mixer by reducing even-order IMD products.

Finally, let us consider the interference rejection. Adjacent channels are radio frequencies that are close to the desired frequency and can cause interference in the mixer. A balun can help reduce the interference by improving the rejection of unwanted signals, which can improve the linearity of the mixer. The mathematical analysis above shows that the use of a balun can eliminate input impedance mismatches and reduce common-mode noise and distortion, resulting in better conversion gain and linearity.

Now Let us see how the addition of the current reuse technique in the down conversion double balanced Gilbert cell mixer improves the linearity. The use of current reuse in the mixer can increase the available current for mixing, which reduces the noise figure and increases the signal power.

The noise figure (NF) of the mixer can be expressed in decibels (dB):

$$NF = 10\log\frac{P_{out}}{P_{in}} \qquad \ldots\ldots(4)$$

Assuming that the noise at the input and output is uncorrelated and that the mixer is noiseless, the noise figure can be expressed as:

$$NF = 10\log\left[\frac{(1+G)^2}{4G}\right] \qquad \ldots\ldots(5)$$

where G is the voltage gain of the mixer.

By increasing the available current for mixing, the voltage gain of the mixer is increased, which reduces the noise figure. This results in an improvement in conversion gain. Third-order intermodulation distortion (IMD3), brought on by the transistors' nonlinear behaviour in the mixer, is likewise mitigated by reusing the current. As the current from the first and third stages is recycled in the second and fourth stages, the currents in the mixer are more evenly distributed, and the number of odd-order IMD products is decreased.

4. RESULTS AND DISCUSSION

The proposed mixer design in Figure 4 has been put to the test using the ADS tool in order to achieve the requisite CG and NF using a 130-nm RF CMOS technology. To maintain the highest feasible conversion gain, the proposed architecture for a mixer operating on a CMOS technology of 130 nm has been adopted with a supply bias that is rather strong, coming in at 2.5 V.The supply's power consumption was 26.8 mW, and it is flawlessly compatible with the UMC manufacturing procedure. Figure 5 shows the conversion gain for RF frequencies up to 30 GHz. It may be simulated in the k-band (23 to 25 GHz), and a conversion gain as high as 24.2 dB is attained. The LO feed has been kept at an acceptable input power of -3 dBm. The Input compression point IP1dB has been plotted in figure 6. It is ideally suited for 24-26 GHz radio frequency range due to its point (for 1-dB) of significant input compression at -17.8 dBm and high CG.

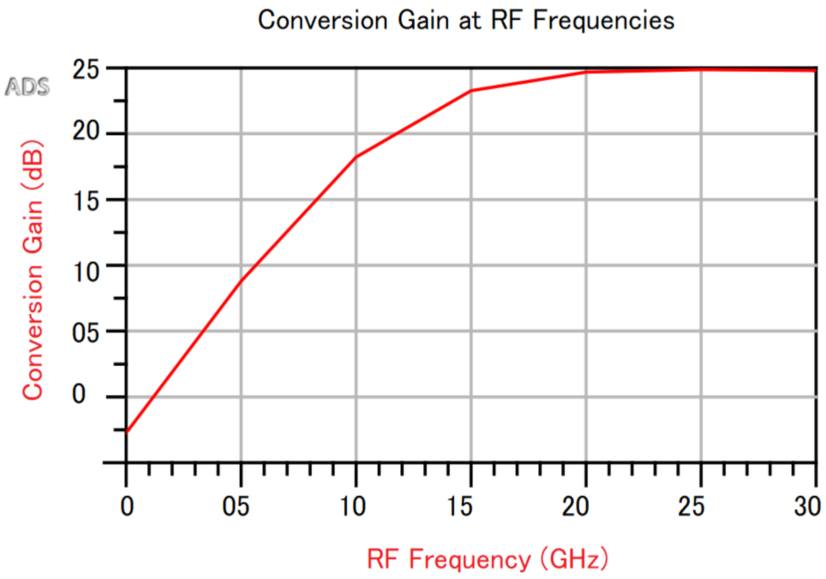

Figure 5: Conversion gain simulation in the k-band

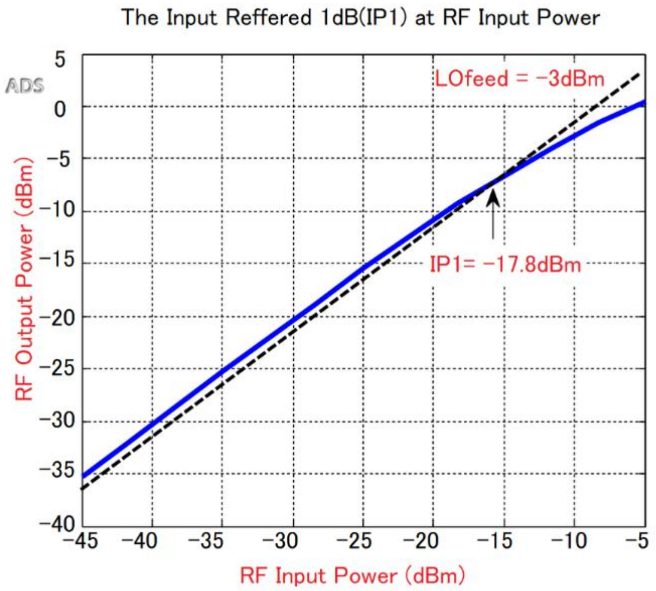

Figure 6: Input compression point IP1dB

Table 3 compares the recommended double balanced current reuse down-conversion mixer's performance to various well-known and published designs. It evaluates the metrics such as conversion gain, linearity, and other relevant specifications that are commonly used to evaluate mixer performance. Fom the table the recommended architecture for Folded Dual-balanced current reuse design to other published designs, one can assess its competitiveness and suitability.

Table 3. The performance and comparison with earlier efforts

References	[2]	[5]	[17]	[18]	This Research Work
CMOS Technology	0.18µm	65nm	65nm	0.13µm	0.13µm
Topology	Active Mixer with cross-coupled outputs	current-bleeding with gain-boost	Cascode Topology with Transformer Coupling	An Improved Noise Factor Gilbert Mixer	architecture for Folded Dual-balanced current reuse
Conversion gain (dB)	12dB	12dB	9.5dB	11.4dB	24.2dB
Linearity (1dB compression pt.)	-	-5.2dBm	-3.8dBm	4.4dBm	-17.8dBm
Special features	Low-ohmic switches for high Gm	CG-improvement bleeding method	Harmonic suppression noise-reduction transformer	PMOS switch circuits with improved Noise Factor .	Double-balanced design offers optimal linearity

5. CONCLUSION

After qualitatively examining current RF mixer, this research suggests an optimal design for reusing current that has a pair of balanced circuits.. We thoroughly investigate the high conversion gain and current reuse cross-coupled double-balanced functioning of multi-band down-conversion mixer topologies. Many limitations on traditional mixing topologies and challenges with RF receiver architectures have been observed. The proposed design, which utilises a 130-nm Radio frequency (UMC) design with two balanced cross-couplings, tries to incorporate all of these components. High linearity as a -17.8 dBm compression point has been obtained using a differential pair with high transconductance(for 1-dB). The suggested mixer had better conversion gain performance (24.2 dB). Additionally, the ability to operate across many bands has been demonstrated by modelling in the ADS environment. Because to its improved conversion gain and higher compression point, the work that is now being presented is novel.

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