Gilbert-cell Mixer Design with High Isolation

Abstract – Herein, we proposed an innovative approach to enhance the RF-to-IF port isolation in conventional Gilbert-cell mixers. The proposed approach is based on the existing Gilbert cell mixer with an additional canceller module. The performance of the **RF/Analog IC** is verified in TSMC 180nm CMOS technology. The layout chip size, including 1 main module and 4 test structures is **4mm x 4mm**. At the RF frequency of 2.5 GHz and IF frequency of 2.4GHz, the implementation of the module provides more than 70dB of RF-to-IF isolation while consuming 10mW from 1.8V supply. In additionally, the port matching, conversion gain and linearity remain largely unaffected by this module, making it an attractive solution for high-isolation application. To further advance the practical implementation of this approach, we aim to utilize **SAMSUNG 28nm CMOS technology** for the tape out of the final design. This technology offers improved capabilities in terms of integration density, power efficiency, and overall performance, enabling the module to meet the requirements of **retro-directive wireless power transfer systems**.

Index Terms *--- Gilbert-cell Mixer, SAMSUNG 28nm CMOS, Directional Coupler, Power Combiner, Canceller Leakage Power.*

설계 공정	28nm CMOS
칩사이즈	4mm x 4 mm
회로 타입	Analog/RF
설계 분야	무선전력전송

I. INTRODUCTION

The radio frequency mixers are crucial building blocks in wireless communication systems responsible for translating the high frequency (RF) signal to lower intermediate frequency (IF) signal. Owing to asymmetries of the mixer and nonlinear nature of active devices, a fraction of RF input of the mixer appears at the output without any frequency translation [1][2]. As a result, a fraction of low-frequency beat appears in the baseband, therefore corrupting the down converted signal.

Various circuit topologies have been presented in the literature, which has focused on the isolation improvement of the mixers. C. -C. Su used two directional couple lines both formed with three microstrip lines [3] to provide up to 27.1dB of RF-to-IF isolation. D. Bhatt and co-authors used RF negative resistance compensation (NRC) technique [4] to get 45.1dB of LO-RF isolation. They also described a self-biased fully differential mixer with an integrated quadrature multiplication circuit [6] that could achieve 45dB of RF-to-IF isolation. Research of W. K. Chong [5] used complementary current-reuse technique which helps boost the RF-to-IF isolation to more than 50dB.

It can be seen from the relevant studies that the RF-to-IF isolation is generally around 30dB to 50dB. In this proposal, we propose a novel approach to enhance the RF-to-IF port isolation (more than 70dB). Our work utilizes a module as the combination of a directional coupler, an attenuator, a low-pass filter, and a power combiner. The rest of the paper is organized as follows. Section II describes the circuit design and implementation. Section III presents the simulation results of the proposed mixer. Finally, Section IV concludes the proposal and discusses future work.

II. CIRCUIT DESIGN

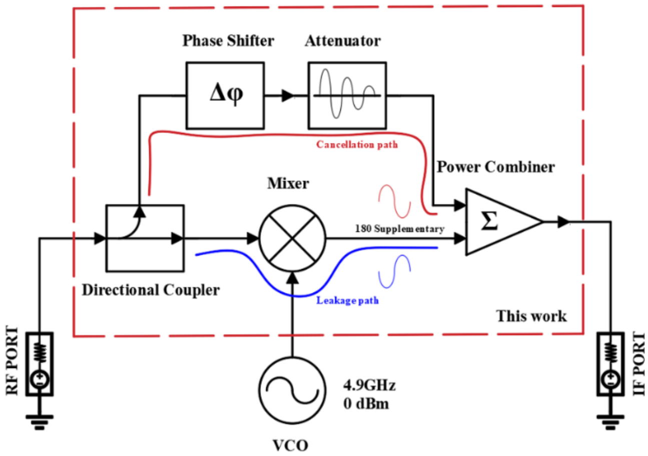

Fig. 1. Mixer with proposed canellation module

The circuit design and simulation are fully verified by **CADENCE platform Tools**. Figure 1 shows the mixer with the canceller module for isolation improvement. It utilizes a lumped element directional coupler (LEDC) to extract a portion of the power from the RF port, which serves as the cancellation signal while allowing significant amounts of power to be transmitted at the mixer input. The attenuator and phase shifter blocks are responsible for adjusting the cancellation signal's magnitude and phase, aligning it with the leakage signal at the IF port. By precisely tuning these parameters, the module ensures that the cancellation signal closely matches the undesired signal, maximizing cancellation efficiency. Finally, the lumped-element power combiner (LEPC) is included to combine IF signal which contain the intended 2.4GHz signal with cancellation signal. The module effectively suppresses the unwanted 2.5GHz leaking from RF port while preserving the desired one.

A. DOUBLE BALANCE MIXER

At the heart of any communication system, mixer plays a major role in translating input RF signal down to the IF signal of interest. As shown in Figure 2, the circuit is based on a double-balanced Gilbert structure [7]. The two LC tanks resonate at the desired RF frequency ideally to give an infinite impendence. Transistors M1-M2 are the gm stage for the RF input signal. The small channel lengths are designed mainly to reduce the imaginary part looking into this stage. Also, those transistors are biased with large overdrive voltage to ensure good linearity. On the other hand, the switching transistors (M3-M6) are optimized to have a small overdrive

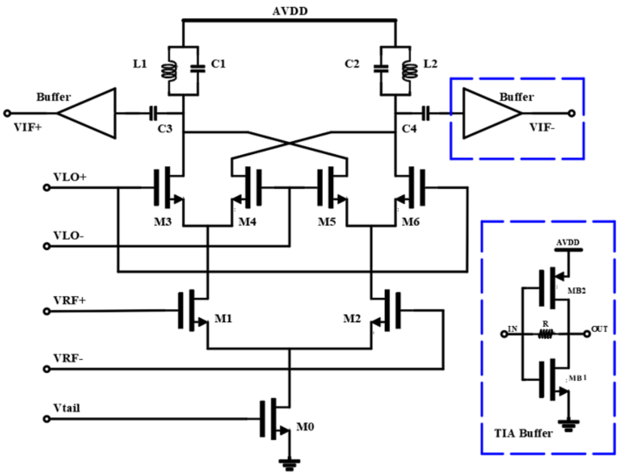

Fig. 2. Schematic of double balance mixer

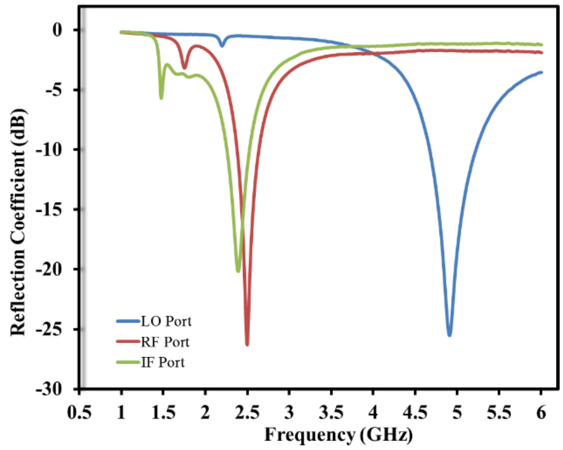

Fig. 3. Port's reflection coefficient.

voltage and thus allow better switching.

For the sake of a completeness, at the front of 3 ports, there are transformers placed off-chip to convert differential signal to single ended one served for measurement as well as the matching networks should be well considered there to obtain the sufficient conversion gain as designed. For such circuit, π matching network C-L-C (not included here) is the best-suited candidate to meet the required performance.

Figure 3, figure 4 and figure 5 show the overall performance of the core mixer. In terms of reflection coefficient (Figure 3), it exhibits excellent matching with values that are well below 20 dB within the operation frequency, indicating efficient power transfer. Figure 4 shows the simulated conversion gain versus the RF power. The mixer achieves approximately 4.5 dB, additionally, the 1dB compression point is at -15dBm. For the presented data, LO frequency is 4.9GHz and the power level is selected at 0dBm, RF input power at 2.4GHz.

However, the isolation, illustrated in Figure 5, is relatively low, around -18dB at 2.5GHz. This implies the presence of RF leakage signal transfer from the RF input to the IF output.

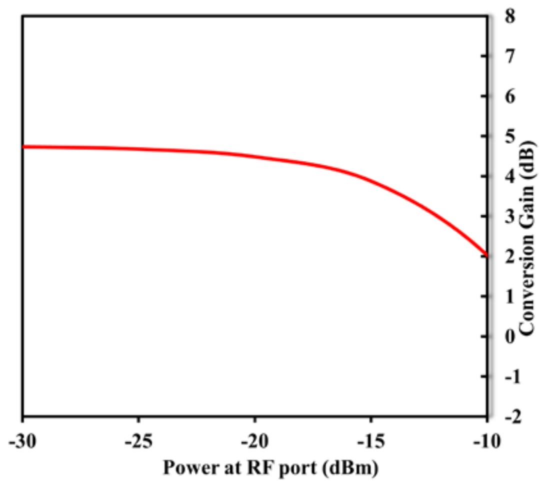

Fig. 4. Conversion gain and 1dB compression point

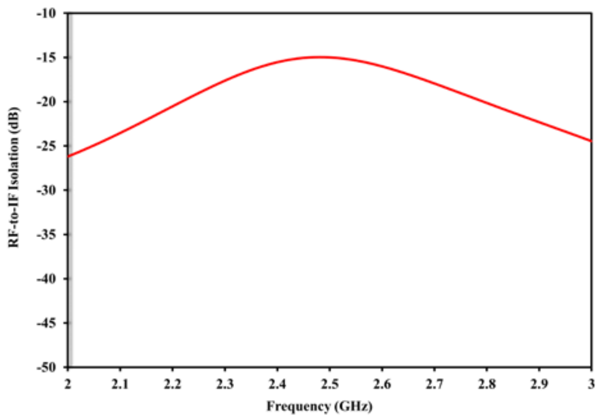

Fig. 5. RF-to-IF port isolation

B. LUMPED ELEMENT DIRECTIONAL COUPLER

The LEDC is a commonly used block in RF and microwave systems for power splitting. It exhibits good performance around the center frequency over a limited band. In [8], all six conventional LEDCs were analyzed using the even and odd modes method and the transmission wave matrix description. Among the available options, the topology shown in Figure 6 is chosen for the canceller module. The choice is influenced by the consideration that inductors, which tend to be large and area-consuming, are preferred to be minimized. Also, this topology has good symmetry. Lumped-element values of the proposed circuit are given by:

$$C_s = \frac{1}{\omega_0 Z_0},$$

$$L = \frac{Z_0}{\omega_0},$$

$$C_b = \frac{k}{Z_0 \omega_0},$$

where Z_0, ω_0, k are the characteristics impedance, operating angular frequency, and coupling ratio respectively. The intended coupling factor is -10dB. The simulated characteristic of the coupler is presented in Figure 7. This LEDC achieves a narrowband response with matching value (S11) below -45dB. The insertion loss (S21) is approximately -1dB, indicating maximal power transmitted to mixer input.

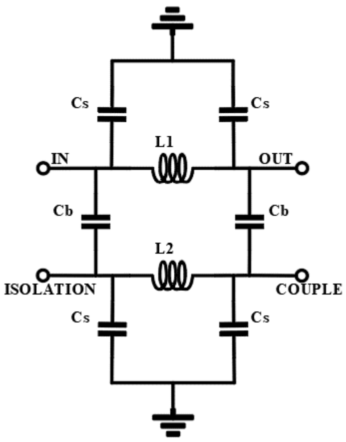

Fig. 6. Lumped element directional coupler.

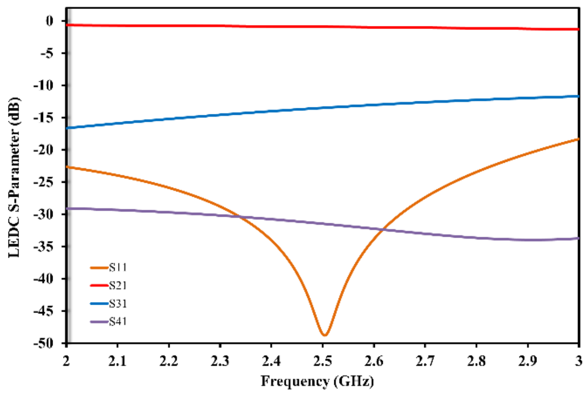

Fig. 7. LEDC simulated S-parameter.

The coupling factor (S31) is lower than expected at -12dB, which is attributed to the low Q factor of the on-chip devices. The isolation (S41) is at -32dB, indicating a directivity of approximately 20dB.

C. ATTENUATOR AND PHASE SHIFTER

To ensure proper alignment between the signal in the cancellation path and leakage path, an attenuator and phase shifter are added in cascade. As shown in Figure 8, the choice of a symmetric T-shape is based on its simplicity and good impedance matching properties [9]. The attenuator factor is determined by calculating the difference in power between the 2 paths, as stated by the equation:

$$Attenuator(dB) = Isolation_{RF-to-IF} - Coupling\ _{LEDC}$$

In this design, the attenuator factor is calculated to be -6dB. However, to account for passive losses and provide some margin, an attenuator factor of -5dB is chosen. The phase shifter is calculated and designed to introduce a 180-degree phase difference between the two paths. The capacitors are realized as banks to allow for fine-tuning in subsequent adjustments. The analysis of both circuits, including the values of the devices used, are thoroughly covered in [9].

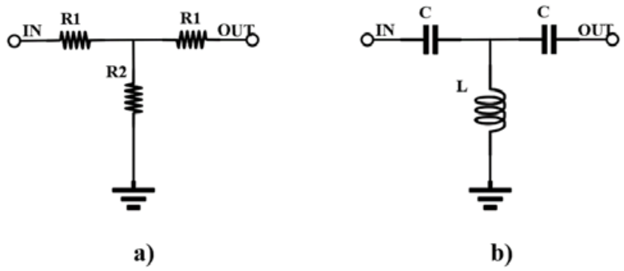

Fig. 8. a) T-shape attenuator, b) T-shape high pass phase shifter

$$R_1 = Z_0\left[\frac{10^{\frac{A}{20}}-1}{10^{\frac{A}{20}}+1}\right];\ \ R_2 = 2Z_0\left[\frac{10^{\frac{A}{20}}}{10^{\frac{A}{10}}+1}\right]$$

$$L = \frac{Z_0}{\omega\sin(\varphi)};\ \ C = \frac{\sin(\varphi)}{\omega Z_0(1-\cos(\varphi))}$$

Where Z_0, A, ω, φ are the characteristics impedance, attenuator factor, operating angular frequency, and phase shift respectively.

D. POWER COMBINER

The power combiner plays a crucial role in this signal cancellation process. Various techniques can be employed such as resistive power dividers, hybrid coupler, Wilkinson power combiner (WPC). In this module, lumped element WPC, as shown in Figure 9, is chosen owing to its wideband and compact size.

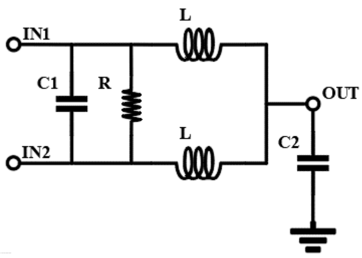

Fig. 9. Lumped element Wilkinson power combiner

According to analyses in [10], the component values of Wilkinson power combiner is given as below:

$$C_1 = \frac{1}{2Z_0};C_2 = \frac{1}{Z_0};L = \frac{Z_0}{\omega};R = 2Z_0$$

where Z_0, ω are the characteristics impedance, operating angular frequency, respectively. Figures 10 and 111 show the simulated characteristics of the LEPC. The desired frequency is 2.5GHz. All ports exhibit matching values below -20dB. The combining performance, as shown in Figure 11, when combining two in-phase signals, is approximately 1.8dB. For differential phase signals, the combining performance gives an attenuation of -61dB. While theoretically, the differential phase performance could be negative infinite, achieving -60dB of extra cancellation is considered good enough provided that the two signals being combined are precisely equal in magnitude and opposite in phase.

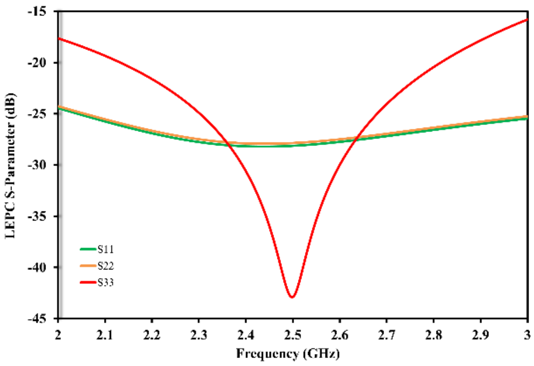

Fig. 10. LEPC simulated S-parameter.

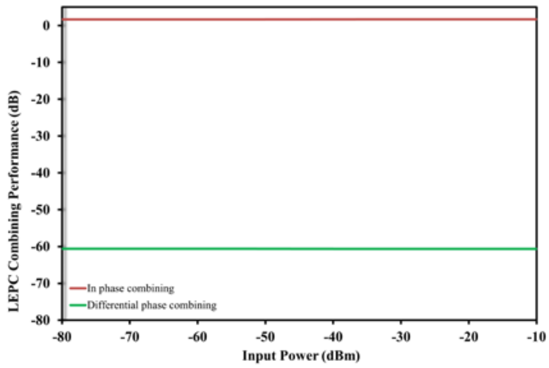

Fig. 11. LEPC combining performance.

E. CHIP LAYOUT AND DESIGN FLOW

Figures 12 and Figure 13 describe the floor plan and circuit design flow as well as design tool respectively.

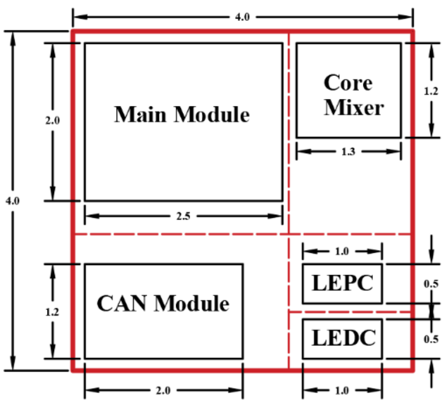

Fig. 12. Chip floor plan (dimensions in mm).

III. SIMULATION AND MEASUREMENT

The results and discussion revolve around the integration of the core mixer with the proposed canceller module and its impact on the overall system performance. The small signal performance was measured using a vector network analyzer (PNA E8361C, Agilent). The large signal performance was measured using a signal generator (SMBV 100A, R&S) and spectrum analyzer (FSV, R&S). The noise figure was measured using a noise figure analyzer (N8975A, Agilent) and a smart noise source (N4002A, Agilent). Figure 14

	TOOLS		
	ANSYS	cadence	SIEMENS
Schematic		Virtuoso Schematic Editor L	
Simulation		Spectre RF 19	
Waveform		Virtuoso ADE L/XL	
Layout		Virtuoso Layout L	
DRC,LVS			Calibre nmDRC/LVS
LPE			Calibre PEX
Post-Sim		Spectre RF 19	
Waveform		Virtuoso ADE L/XL	
PCB	Ansys Electronics		PADS

Fig. 13. Design flow and tools.

compares the insertion loss of the ports between the implementation of the module and the standalone mixer performance. S11 remained unchanged, as the module was implemented between port 2 and port 3 (RF and IF). However, the implementation of this module widened the matching band of S22 and S33 and also reduced matching values. Nonetheless, all matching values remained below -15dB, which is considered acceptable.

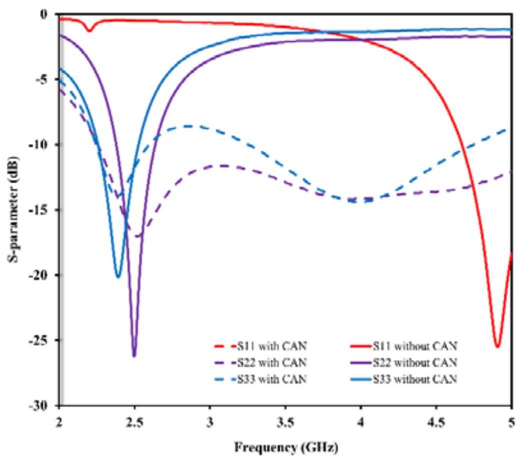

Fig. 14. Affection of CAN module in terms of reflection coefficient.

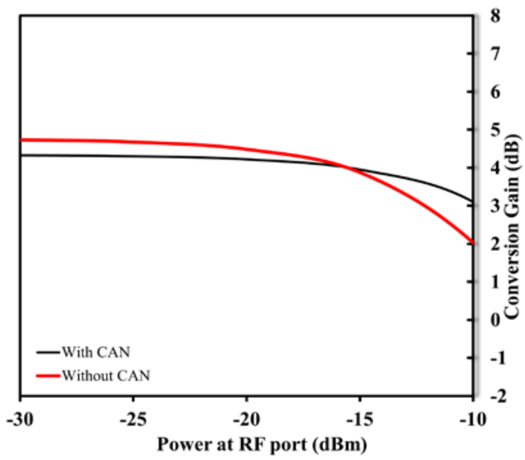

Fig. 15. Affection of CAN module in terms of linearity.

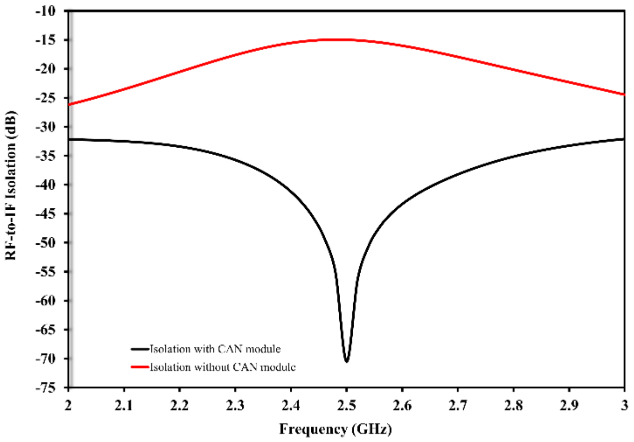

Fig. 16. Affection of CAN module in terms of isolation.

The conversion gain and 1 dB compression point for both versions is described in Figure 15. The results show a decrease in gain of approximately 0.5dB, while the compression point remains unchanged at around -15dB. Thus, the impact of this module on the mixer's conversion gain and compression point is minimal.

Figure 16 summarizes the isolation between the RF and IF ports. The data demonstrates a significant improvement in isolation, increasing from -17dB to over -70dB. This represents an additional cancellation of more than 50dB. Although the desired extra cancellation is -60dB, achieving perfect inputs for the lumped element power combiner (LEPC) becomes really hard due to discrete values of the inductor and capacitor components.

IV. CONCLUSION

This work proposed a method to enhance the isolation of a conventional Gilbert cell mixer. The implementation was carried out using TSMC180nm CMOS technology, and the simulation showed some promising results. The integration of the canceller module demonstrated acceptable matching at all the ports, with a minor impact on conversion gain and the 1 dB compression point. Additionally, a significant improvement in isolation was achieved, enabling isolation levels to reach -70dB. Moving forward, our future research will concentrate on expanding the operating bandwidth of the cancellation while preserving the achieved level of isolation. The implemented mixer chip will be used in a retro-directive beamforming system for wireless power transfer application.

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