A Design of TRX dual mode Baseband Analog with Dynamic Range and DC offset controller for applying NB-IoT

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Abstract**—This paper presents a design of a TRX dual mode and high dynamic range Baseband Analog for applying NB-IoT (Narrow Band Internet of Things). The primary focus of this design is achieving a large dynamic range of 70dB, which is important for maintaining signal integrity and accuracy in NB-IoT systems. The BBA architecture includes TRX mode filters, Variable Gain Amplifiers (VGA), and DC Offset Cancellers (DCOC). These components work together to provide the necessary signal conditioning and processing for the baseband signals in the NB-IoT system. The TRX dual-mode filters are designed to operate as Complex Band Pass Filters (BPF) in RX path and Low Pass Filters (LPF) in TX path. The Variable Gain Amplifiers (VGA) provide tunable gain control, allowing the system to adapt to different signal levels. This flexibility is crucial for maintaining the dynamic range and ensuring accurate signal processing. Additionally, the DC Offset Cancellers (DCOC) help to remove any DC offset present in the baseband signals, improving the overall performance and signal integrity. Also, special technique was added to remove offset by adjusting DC level of signal.**

Keywords—NB-IoT, Complex Bandpass filter, Lowpass filter, Variable Gain Amplifier, TRX dual mode, DC offset

I. Introduction

The NB-IoT system has gained significant attention from both industry and academia as an uprising wireless communication technique. One of the primary requirements for IoT systems is low current consumption to ensure enhanced battery performance [1]. To address this requirement, this paper combines the filter in both RX and TX paths into a single filter. This consolidation helps reduce power consumption by reusing circuitry and minimizing redundant components.

Another crucial aspect of NB-IoT systems is achieving high sensitivity to reliably detect and receive weak signals. So, Filters and VGAs in BBA include voltage-mode operational amplifier circuit [2]. It leads high gain, low variation and low current consumption. However, high receiver gain can lead to lower linearity, potentially causing distortions.

To balance sensitivity and linearity, First-stage filter's amplification level in the BBA design has been intentionally set lower than the gain of the second stage. This approach helps optimize the filter's performance by maintaining an adequate signal-to-noise ratio while mitigating non-linear effects.

Additionally, DC-offset in baseband circuits causes second-order distortions from third-order nonlinearity, impacting signal integrity [3]. Interactions between the input signal and DC-offset lead to undesirable second-order distortion components. Techniques like DC-offset cancellation mitigate DC-offset, improving linearity and signal quality for enhanced system performance.

So, this paper addresses the power consumption and sensitivity requirements of NB-IoT systems by incorporating a TRX dual mode filter to minimize power consumption and carefully designing the gain stages of the filter to achieve the desired sensitivity and linearity trade-off.

In addition to addressing power consumption and sensitivity requirements, this paper also focuses on mitigating the effects of DC-offset in the NB-IoT system. It incorporates DC offset cancellation techniques to minimize the presence of DC-offset and reduce distortions caused by nonlinearity in the balanced baseband circuit. By carefully addressing the DC offset issue, this paper ensures improved linearity, enhanced signal quality, and reduced unwanted artifacts, thereby optimizing the overall performance of the NB-IoT system.

II. Proposed Structure

A. Block Diagram

Figure 1 is the block diagram of Baseband Analog (BBA) and shows each path (RX, TX). The BBA consists of a 4th order filter, Variable Gain Amplifier, and DC Offset Canceller.

In RX mode, the filter acts as a Band Pass Filter (BPF) with dual-mode capability. The filters in the in-phase (I) and quadrature-phase (Q) paths are connected using cross-connected resistors.

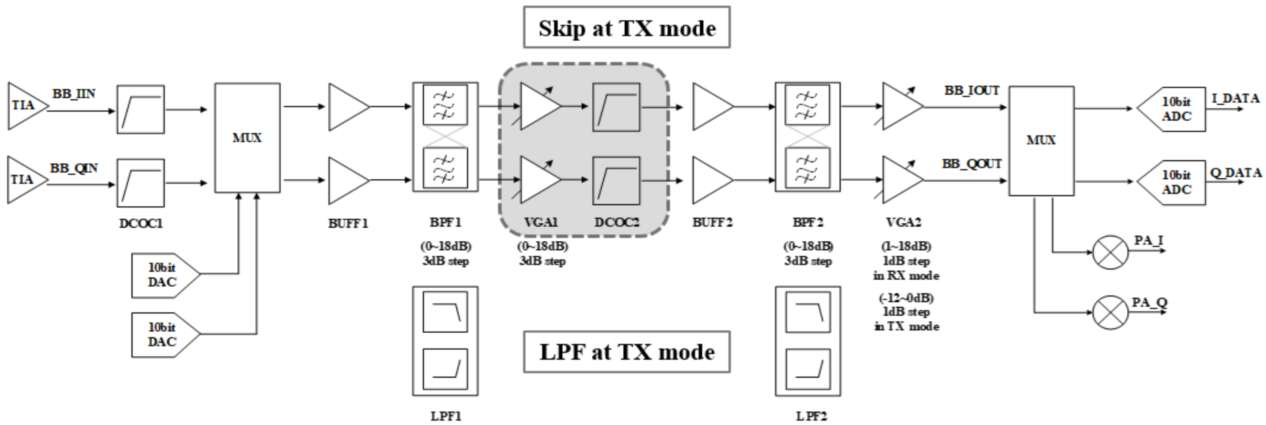

Fig. 1. Baseband Analog Block Diagram

This configuration allows the filter to provide the desired bandpass characteristics for signal processing in the I/Q paths. BPF provides gain control ranging from 0dB to 18dB (3dB step) and VGA2, operating in positive gain mode, provides gain control ranging from 1dB to 18dB (1dB step). This allows for fine-tuning of the signal levels in the RX mode. So, in RX mode, total gain is higher than 70dB. In TX mode, the configuration of the filter is altered. The I-path and the Q-path are not connected. As a result, each filter placed in the I/Q paths acts as a Low Pass Filter (LPF). This enables the BBA to perform appropriate frequency shaping for the signals in the TX mode.

In TX mode, the VGA1 is bypassed, meaning its gain control is not utilized. However, the VGA2 operates in attenuation gain mode, ranging from -12dB to 0dB. This adjustment is necessary because the output of the Digital-to-Analog Converter (DAC) is 400mV. If a positive gain were applied, the signal would risk saturating the input of the Power Amplifier (PA). And a buffer was used for the purpose of impedance separation.

In the TRX dual mode, the signal path can be summarized as follows: In RX mode, the input signal originates from the Trans-Impedance Amplifier (TIA) and is then directed to a buffer through a multiplexer (MUX). The processed signal from the RX mode filter stages is eventually routed to the Analog-to-Digital Converter (ADC) for conversion to a digital format. In TX mode, the input signal comes from the Digital-to-Analog Converter (DAC) and is passed through a buffer via the MUX. It then undergoes processing in the TX mode filter stages before being transmitted by the Power Amplifier (PA).

B. Complex Band Pass filter

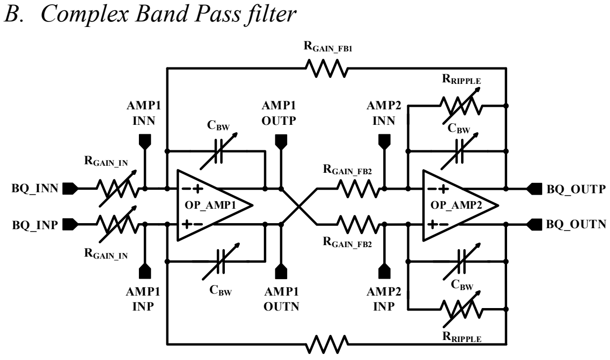

Fig. 2. Schematic of Low Pass Filter

Figure 2 illustrates the schematic of the proposed second-order Low Pass Filter, which is a component of the complex Band Pass Filter. The design of this LPF is based on the reversed Tow-Thomas Bi-Quad Filter, a commonly used technique for Low Pass Filter. The gain of the filter is controlled by the resistor array RGAIN_IN. To achieve a higher gain at AMPOUT compared to BQ_OUT, RGAIN_FB1 and RGAIN_FB2 have the same resistance. In this paper, the filters are designed with a relatively high gain of 18dB to achieve high sensitivity.

However, such high gain can potentially degrade the linearity of the filter. To address this, RGAIN_FB1 is designed to have a larger resistance than RGAIN_FB2, resulting in a lower gain at AMPOUT compared to BQ_OUT. This configuration improves the linearity of the filter. However, it may lead to a higher noise figure, which can be a concern for a receiver with high sensitivity.

The bandwidth of the filter is determined by the product of resistance and capacitance. By increasing the capacitance and reducing the resistance, the noise figure of the filter can be improved. However, this design consideration needs to be balanced with the desired performance requirements, as increasing capacitance and reducing resistance can have trade-offs in other aspects of the filter's performance.

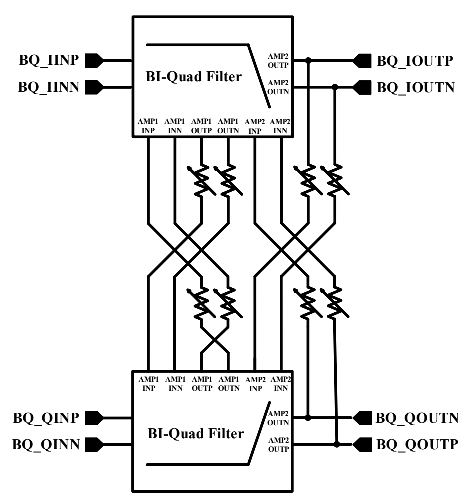

Fig. 3. Schematic of Complex Band Pass Filter

Figure 3 shows Filter (BPF) for the RX mode. In the RX mode, it is necessary for the filter to operate as a complex BPF to deny the image signal and attenuate signals from near channels. To achieve this functionality, the I/Q paths in the filter are connected using cross-coupled resistors [4]. By employing cross-coupling, the low-pass filter (LPF) is transformed into a complex BPF. This configuration enables the filter to effectively reject the unwanted image signal while allowing the desired signals within the desired frequency range to pass through.

Unlike general Band Pass Filters, this complex Band Pass Filter exhibits a unique characteristic of being able to reject negative frequency signals [5]. Negative frequency signals are those that appear in the reverse direction of time or phase, and they can arise in certain signal processing applications. However, the complex bandpass filter used in this paper can perform the corresponding task by implementing a band pass filter by symmetrically shifting the filter shape of the low pass filter.

By carefully designing and shifting the Low Pass Filter, the complex Band Pass Filter achieves the desired frequency response, allowing the desired band of frequencies to pass through while effectively rejecting negative frequency components. This characteristic of the complex Band Pass Filter makes it particularly suitable for applications where the rejection of negative frequency signals is required or desired. It offers enhanced flexibility and functionality in signal processing tasks, contributing to the overall performance and effectiveness of the system.

C. *Variable Gain Amplifiers*

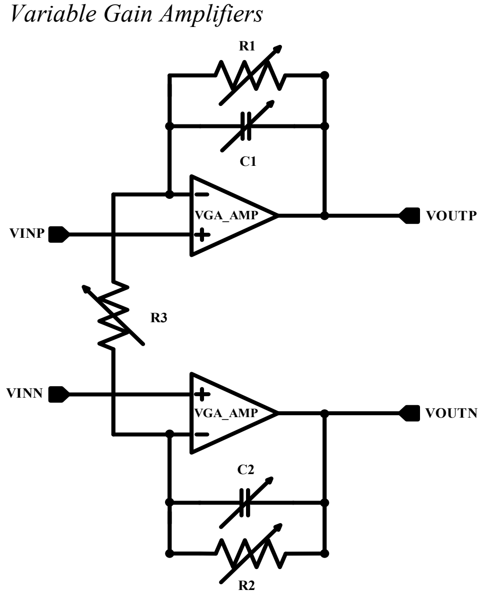

Fig. 4. Schematic of Variable Gain Amplifier

Figure 4 shows the schematic of the Variable Gain Amplifiers (VGA). This amplifier provides the capability to adjust the gain based on the input signal level using Variable Resistors and Variable Capacitors. By utilizing these adjustable components, the VGA allows for precise control over the amplification level. This flexibility in gain adjustment enables the VGA to accommodate a wide range of signal levels and adapt to different operating conditions.

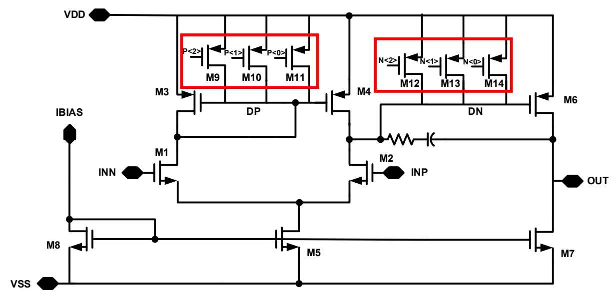

Fig. 5. Schematic of Amplifier in VGA

In this paper, the amplifier's asymmetry may cause DC offset between signals with different phases. To mitigate this, the signal is subjected to DC offset cancellation, ensuring consistent common-mode (cm) voltage levels. Additionally, Figure 5 shows the use of an amplifier in VGA2, the final output stage, to adjust the cm level. This adjustment is achieved by controlling specific MOSFETs highlighted in red. Turning on the MOSFETs connected to the DP node raises the cm level, while activating the MOSFETs linked to DN node reduces cm level. To prevent fully connected to VDD, the MOSFETs are sized with large Ron (on-resistance).

III. Experimental Result

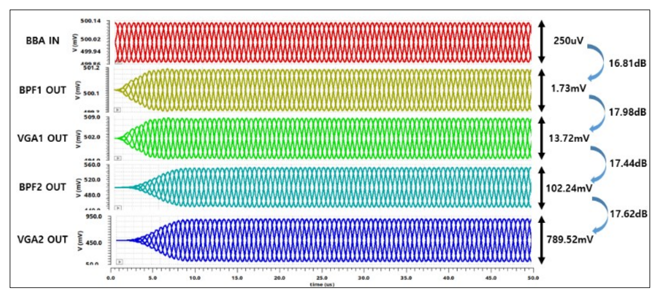

Fig. 6. Transient Simulation Result

In Figure 6, transient simulation results are presented for the sub-blocks of the proposed BBA (Baseband Amplifier), including their input and output signals. It can be observed that the I/Q signals have positive and negative components, resulting in a total of four signals with a phase difference of 90 degrees. Furthermore, each stage of the amplifier demonstrates a maximum gain of 18dB. The simulation results also indicate that the initial input level is amplified by approximately 70dB, resulting in the final output level.

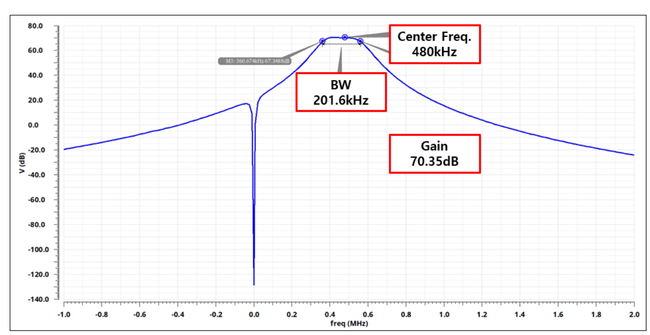

Fig. 7. AC Simulation Result

In Figure 7, the AC simulation result of the Baseband Analog in RX mode is depicted. The Baseband Analog is set to its max gain. In RX mode, the filter functions as a complex Bandpass Filter. The BBA achieves a maximum gain of 70.34dB in RX mode. To adhere to the NB-IoT (Narrowband Internet of Things) specification, the center frequency is set to 480kHz, and the bandwidth is 201.595kHz. These frequency parameters ensure the BBA's compatibility with the NB-IoT standard.

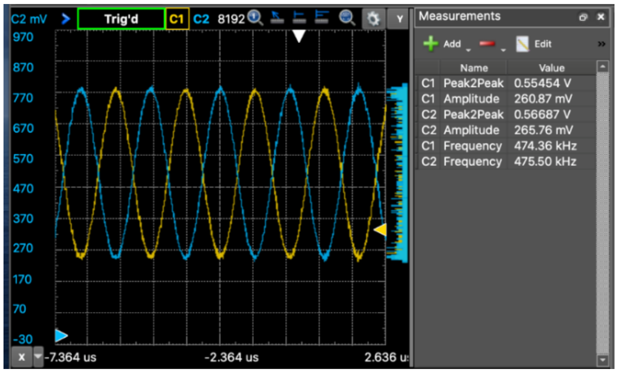

Fig. 8. Transient Measurement Result

In Figure 8, the measurement results of the IC chip, which includes the proposed BBA, are presented. The figure demonstrates that I signal exhibits minimal noise, indicating a high-quality signal transmission. Additionally, it can be observed that the common-mode (cm) level remains consistent across the I positive and I negative signals. This consistency in cm level further suggests the effectiveness of the proposed BBA in maintaining signal integrity and minimizing noise interference.

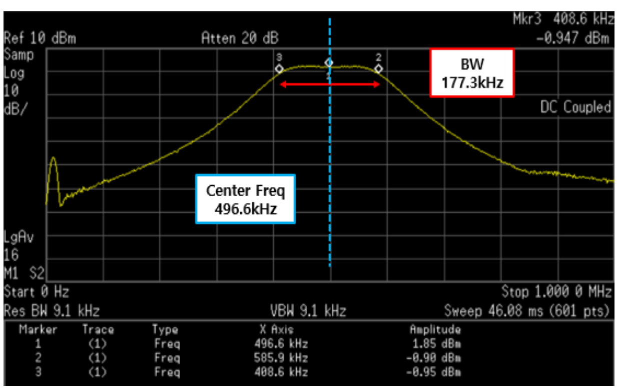

Fig. 9. Filter Shape Measurement Result

In Figure 9, the measured filter shape of the proposed BBA is presented. It is noted that while there may be slight variations compared to the simulation results, the overall shape of the filter is very similar. The measured results indicate that the center frequency of the filter is 496.6kHz, and the bandwidth is 177.3kHz. These measurements provide valuable insights into the actual performance of the BBA's filter and validate its effectiveness in achieving the desired frequency response characteristics.

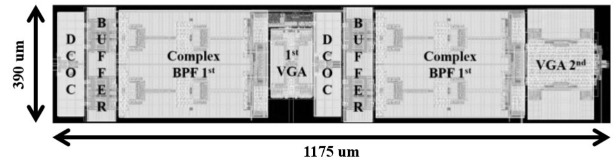

Fig. 10. Top layout of proposed Baseband Analog

Figure 10 shows the total layout of the proposed baseband analog (BBA), focusing on preventing dc offset through symmetrical routing of the I/Q path and also current path. The filter component occupies the largest portion of the layout. By using only single TRX dual filter, the layout area can be diminished. Total area is 390 um x 1175um.

IV. Conclusion

This paper propose Dual mode Baseband Analog for NB-IoT applications. The aim is to minimize current consumption and area. The filter is designed to act in dual (RX,TX) mode, contributing to these objectives. In RX mode, the filter functions as a Complex Bandpass Filter (BPF) with a maximum gain of 72.31dB. The BBA achieves this gain at a center frequency of 496.6kHz, accompanied by a bandwidth of 177.3kHz. In TX mode, the filter transforms into a Low Pass Filter (LPF). In this mode, the BBA exhibits a gain of -3.42dB and a bandwidth of 89.1kHz. Overall, the proposed TRX dual mode BBA offers advantages such as reduced current consumption and die area while meeting the specific requirements of NB-IoT applications in both RX and TX modes.

TABLE I. Performance Summary

Parameters	*RX mode*	*TX mode*
Gain [dB]	72.31 (@496.6kHz)	-3.42 (@89.1kHz)
3dB-Bandwidth [kHz]	177.3	89.1
Current Consumption [mA]	8.314	7.876
Supply Voltage [V]	1	
Area [mm^2]	0.458	
Process	CMOS 130nm	

Acknowledgment

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References

[1] SONG, Zheng, et al. A 180nm CMOS wireless transceiver by utilizing guard band for narrowband IoT applications. In: 2015 IEEE Asian Solid-State Circuits Conference (A-SSCC). IEEE, 2015. p. 1-4.

[2] D'AMICO, Stefano, et al. A CMOS 5 nV $/\surd $ Hz 74-dB-Gain-Range 82-dB-DR Multistandard Baseband Chain for Bluetooth, UMTS, and WLAN. IEEE journal of solid-state circuits, 2008, 43.7: 1534-1541.

[3] ABIDI, A. A. General relations between IP2, IP3, and offsets in differential circuits and the effects of feedback. IEEE Transactions on Microwave Theory and Techniques, 2003, 51.5: 1610-1612.

[4] L. Thomas, "The Biquad: Part I-Some practical design considerations," in IEEE Transactions on Circuit Theory, vol. 18, no. 3, pp. 350-357, May 1971, doi: 10.1109/TCT.1971.1083277.

[5] Kim, Jungah & Lee, Yongho & Chang, Shinil & Shin, Hyunchol. (2020). Low-Power CMOS Complex Bandpass Filter with Passband Flatness Tunability. Electronics. 9. 494. 10.3390/electronics903049