A Novel RF Hilbert Transformer Single Sideband Mixer

Hao Yan, Hanxiang Zhang, Powei Liu, Saeed Zolfaghary Pour, Jonathan Casamayor, Mitch Plaisir, Bayaner Arigong
Florida A&M University - Florida State University College of Engineering, USA
barigong@eng.famu.fsu.edu

***Abstract*—In this paper, a novel single sideband (SSB) mixer is presented. Different from conventional SSB mixer topology, the proposed SSB mixer is designed from RF Hilbert transformer. The upconverted signal from single balanced mixer is divided into two paths, and one is transformed by RF Hilbert transformer. The other path signal experiences simple phase delay, and the recombined two signal cancel out one of the sideband signals. This new SSB mixer topology applies only one single balanced mixer and resolves the size issue of low frequency coupler in conventional topology. To demonstrate proposed topology, a prototype SSB mixer is designed and fabricated. The simulation and experiment results align well with theoretical prediction.**

***Keywords*—SSB mixer, RF Hilbert transformer, RF signal processing.**

I. INTRODUCTION

Frequency conversion (i.e., up-converting intermediate frequency to radio frequency or vice versa) is critical step in radar, electronic warfare, satellite communication, and wireless communication [1]-[3]. Currently, with the limited spectrum allocation and congested bands, improving spectrum efficiency is becoming serious issue, especially with increasing demand for high-speed data streaming and booming mobile devices. There are several approaches proposed to improve the spectrum efficiency, and single sideband (SSB) modulation [4]-[5] is one of the methodologies to double the spectrum efficiency. In practical implementation, this modulation is realized in frequency conversion stage by leveraging vector modulation to cancel either upper sideband or lower sideband. Therefore, SSB mixer is widely investigated in 5G/NextG [6]-[7], Terahertz technology [8], Photonic Microwave [9], Beamforming techniques [10]-[11]. In RF frequency range, the typical circuit topology for SSB mixer design is shown in Fig. 1 (a), where two identical mixers, two 90° hybrid couplers, and one 0° power combiner are applied to create in-phase and quadrature signal paths and cancel out one sideband signal. Instead of frequency conversion, manipulating the RF waveform with desired signal processing function attracts great interest in recent to perform variable mathematical operations as integration [12], differentiation [13], time inversion [14], Fourier transformation [15], edge detection [16], and Hilbert transformation [17]-[21].

Inspired from real-time RF signal processing, in this paper, a novel SSB mixer topology is proposed leveraging RF Hilbert transformer. Different from conventional topology, our proposed SSB mixer consists only one single balanced mixer, and the sideband cancellation is achieved by network composed of RF Hilbert transformer, delay line, and power combiner. This is the first time a RF signal processing SSB mixer is proposed to overcome the issues in conventional SSB mixers, where well

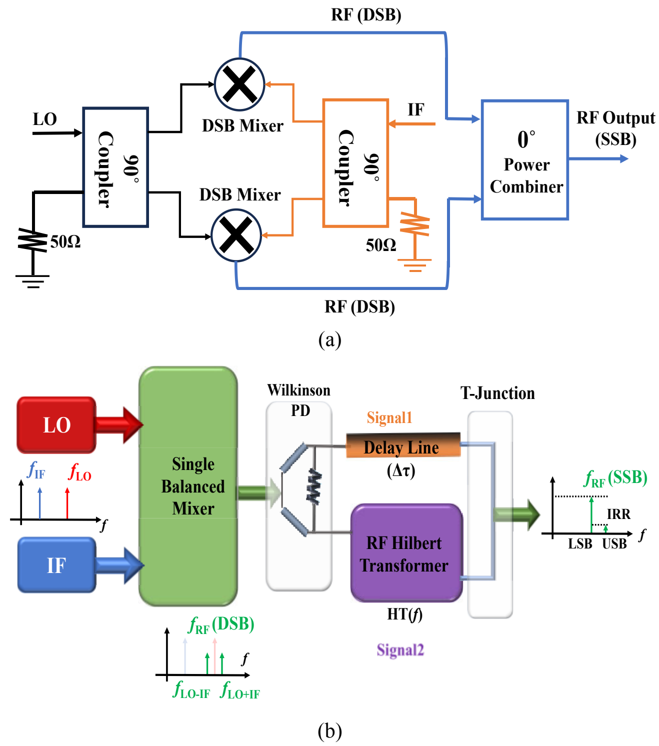

Fig.1. (a) conventional SSB mixer topology; (b) proposed RF Hilbert transformer SSB mixer topology.

matched I/Q mixers and bulky low frequency IF coupler is required to suppress LO feedthrough and spurious frequencies etc. The paper is organized as: section II provides design theory of proposed RF Hilbert transformer SSB mixer, and section III carries out experiment to validate proposed novel mixer circuit topology. Finally, the conclusion and future work are discussed in Section IV.

II. DESIGN OF RF HILBERT TRANSFORMER SSB MIXER

The proposed RF Hilbert transformer SSB mixer topology is shown in Fig. 1 (b). A single balanced mixer converts IF to RF by mixing with LO, and its output signal is divided into two paths through Wilkinson power divider. One passes along a transmission line delay, while the other signal is processed by RF Hilbert transformer. A sharp 180° phase rotation will be happened to the signal passing through RF Hilbert transformer without magnitude change at design frequency LO. It is found that LO+IF upper sideband undergoes 180° phase rotation while LO-IF lower sideband remains unaffected. After two path signals combined again through 0° power combiner, one sideband signal will be cancelled out due to 180° phase offset.

2024 IEEE/MTT-S International Microwave Symposium - IMS 2024 | 979-8-3503-7504-6/24/$31.00 ©2024 IEEE | DOI: 10.1109/IMS40175.2024.10600187

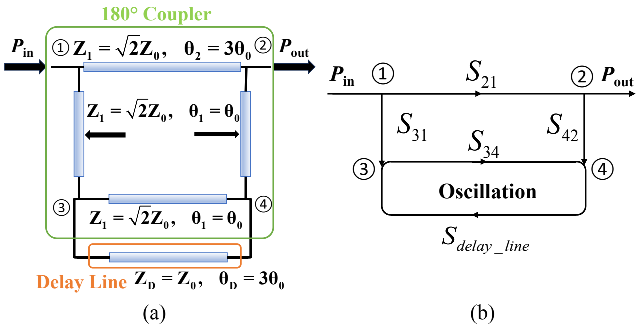

Fig.2. (a) transmission line RF Hilbert transformer circuit; (b) signal flow chart analysis of RF Hilbert transformer.

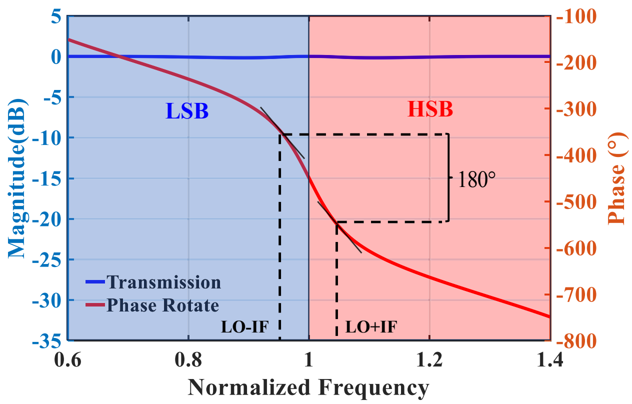

Fig. 3. Magnitude and phase response of proposed RF Hilbert transformer.

A. Transmission Line Real-Time RF Hilbert Transformer Design

The key building block in proposed mixer, RF Hilbert transformer, is composed of a 180 ˚rat-race coupler and a delay line, and the transmission line circuit is shown in Fig. 2 (a), where $Z_1 = \sqrt{2}Z_0$, $Z_D = Z_0$, $\theta_1 = \theta_0$, $\theta_2 = 3\theta_0$, and $Z_0 = 50\Omega$ and $\theta_0 = 90^\circ$. The feedback transmission line between port ③ and ④ follows $\theta_D + \theta_1 = 360^\circ$ forming a 360˚ resonator. To analyze the proposed circuit, signal flow method shown in Fig. 2(b) is applied to characterize its transfer function, which is derived as:

$$HT(f) = S_{21} + \frac{S_{31}\cdot S_{delay\_line}\cdot S_{42}}{1 - S_{34}\cdot S_{delay\_line}} \tag{1}$$

Here S_{21} is the transmission from the input port ① to output port ②. S_{31} and S_{42} are the coupling from ③ to ① and ④ to ②, respectively. S_{34} is the transmission from ③ to ④. S_{delay_line} is feedback delay line connecting port ③ and ④ to maintain the resonance. The magnitude and phase response of ideal RF Hilbert transformer is shown Fig. 3, where 180° phase rotation can be clearly observed at central LO frequency without magnitude change.

B. RF Hilbert Transformer SSB Mixer Design

The single balanced mixer is designed using two Schottky diodes connected in antipolar configuration and one rat-race coupler. The LO signal is applied to delta port of rat-race coupler, and the IF signal is fed to anti-polar diode pair via low pass filter. Due to the non-linearity of diode, the two signal LO and IF are mixed and up converted to a double sideband (DSB) output, which can be derived as [22]:

$$V_{DSB} = I_{diode}\cdot Z_0 = V_{LO-IF} + V_{LO+IF} \tag{2}$$

$$V_{LO-IF} = Z_0\cdot\frac{1}{2}V_{LO}V_{IF}\cdot\cos\left((\omega_{LO}-\omega_{IF})\right)t \tag{3}$$

$$V_{LO+IF} = Z_0\cdot\frac{1}{2}V_{LO}V_{IF}\cdot\cos\left((\omega_{LO}+\omega_{IF})\right)t \tag{4}$$

The output from the single balanced mixer including LO+IF and LO-IF frequency components is equally divided into two paths via Wilkinson power divider. One is through simple transmission line delay providing phase offset, and the other path is transferred by RF Hilbert transformer. The signal passes through transmission line delay can be derived as:

$$V_{Signal1} = \frac{1}{\sqrt{2}}(V_{LO+IF} + V_{LO-IF})\cdot e^{j\cdot\omega\Delta\tau} \tag{5}$$

The signal passes through RF Hilbert transformer can be derived as:

$$\begin{aligned} V_{Signal2} &= \frac{1}{\sqrt{2}}(V_{LO+IF} + V_{LO-IF})\cdot HT(f) \\ &= \frac{1}{\sqrt{2}}(V_{LO+IF}\cdot e^{j\cdot\pi} + V_{LO-IF}) \end{aligned} \tag{6}$$

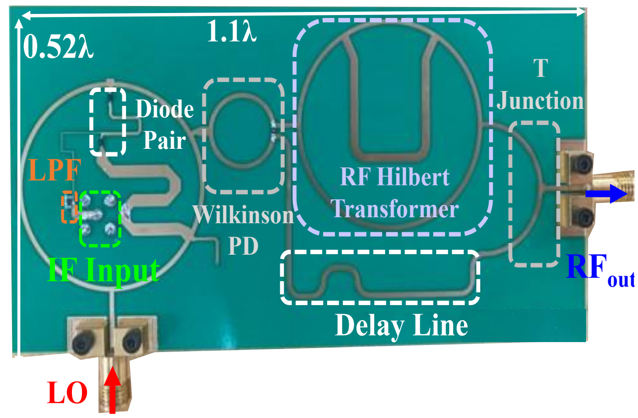

Fig. 4. Prototype of proposed RF Hilbert transformer SSB mixer.

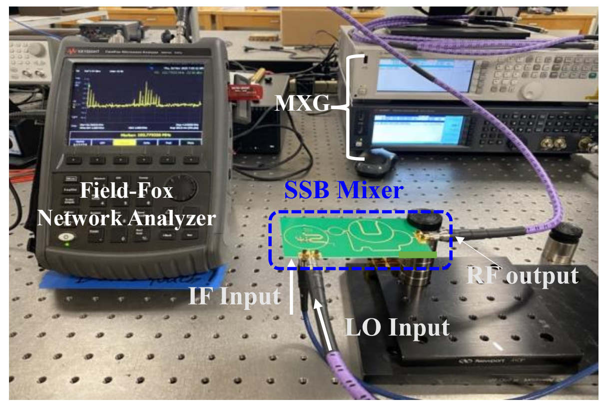

Fig. 5. Experiment setup for validating proposed RF Hilbert transformer SSB mixer.

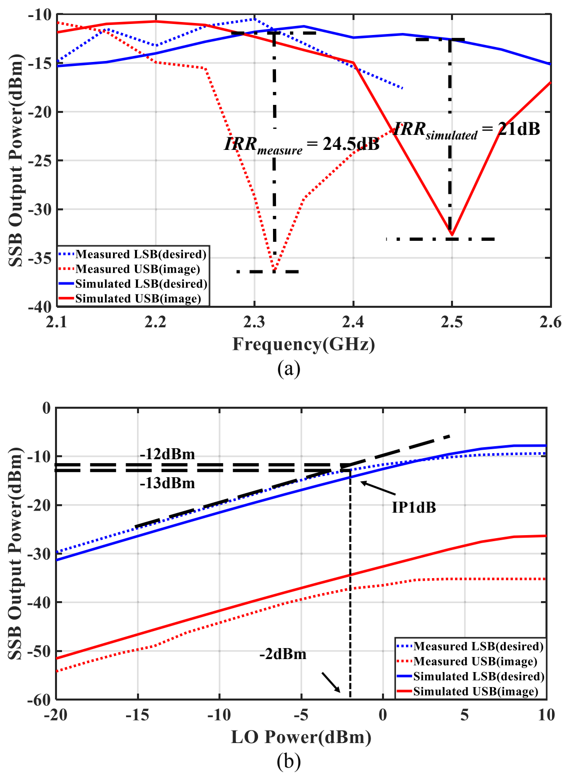

Fig. 6. Experimental results of proposed SSB modulator: (a) upper sideband cancellation; (b) SSB mixer response with LO sweep. The solid line is the simulated result, and the dot line is the measurement data.

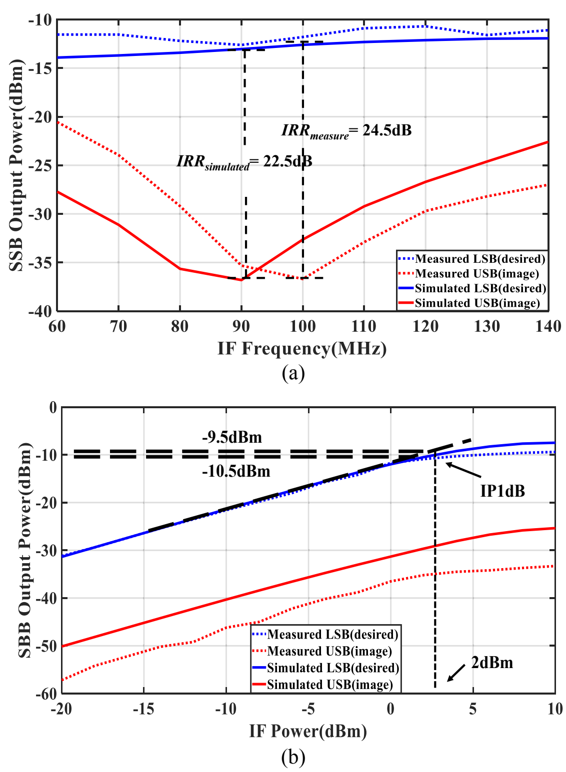

Fig. 7. Experimental results of proposed SSB modulator compared with the result of simulation: (a) IF frequency sweep; (b) IF power sweep. The solid line is the simulated result, and the dot line is the measurement data.

Two transformed signals are combined through T combiner, and the output is derived as:

$$\begin{aligned} V_{SSB} &= V_{Signal1} + V_{Signal2} \\ &= \frac{1}{\sqrt{2}}(V_{LO+IF} \cdot e^{j \cdot \pi} + V_{LO+IF} \cdot e^{j \cdot \omega \Delta \tau}) \\ &+ \frac{1}{\sqrt{2}}(V_{LO-IF} + V_{LO-IF} \cdot e^{j \cdot \omega \Delta \tau}) \end{aligned} \tag{7}$$

From equation (7), it is found that one of the sideband signals can be cancelled out, and the delay line $\Delta\tau$ determines either lower sideband or upper sideband to be suppressed after the combiner.

III. Implementation of Proposed SSB Mixer

To prove our design concept, a RF Hilbert transformer SSB mixer is designed and fabricated using RO4350B with a thickness of 0.76mm, ε_r = 3.48, and tanδ = 0.0037. The prototype is shown in Fig. 4, and its size is around $0.52\lambda \times 1.1\lambda$. The LO frequency f_{LO} is selected at 2.5 GHz, and IF frequency is 100 MHz. The circuit is designed based on the selected LO frequency. Here, IF signal is fed from the back side of PCB, and two Schottky diodes (SMS7621) are connected to a lumped element based low pass filter. Microstrip lines are applied to design Wilkinson power divider, Hilbert transformer, phase delay line, and T-junction power combiner. Electrical length of delay is $n{\cdot}\lambda$ $\{n \in N \mid n \geq 0\}$, and $n = 1$ is applied to minimize the insertion loss and simultaneously cancel out the upper sideband. It should be noticed that T-junction used at the output for combining Signal1 and Signal2 can achieve the optimized image rejection. The circuit simulation and layout are carried out using Keysight ADS. The experiment set up for proposed SSB mixer is shown in Fig. 5, where IF and LO sources are generated from two signal generators (MXG). The sideband cancelled RF output is measured using Keysight Field-Fox network analyzer. The simulation and measured results are depicted in Fig. 6 and Fig. 7. To be specific, in Fig. 6 (a), it shows that the upper sideband is cancelled, and the ratio is >24.5 dB in simulation as plotted in dotted lines and >21 dB in experiment as in solid lines. Fig. 6 (b) shows the output power of proposed SSB mixer when the LO power is swept from -20 dBm to 10 dBm. It finds that measured 1 dB compression is around -2 dBm with output power around -13 dBm. IF frequency sweep measurement is shown in Fig.7 (a) that 20 dB image rejection ratio bandwidth is 20 MHz in frequency range 2.49-2.51 GHz in simulation and 30 MHz in frequency range 2.31-2.34 GHz in measurement. In Fig. 7 (b), it shows the power response of IF input. Comparing with the LO power, it shows a better linearity where the IP1dB is measured around 2 dBm with output power around - 10.5 dBm. Overall, the simulation results align well with experiment measurement, and there is slight frequency offset between simulation and measurement are caused from modelling of diode, PCB fabrication tolerance, and assembling process. The size of proposed RF Hilbert transformer SSB mixer can be further reduced by applying miniaturized couplers, power dividers, and lumped elements for delay line.

IV. Conclusion

A novel SSB mixer topology is proposed in this paper, where single balanced mixer, power divider, RF Hilbert transformer, delay line, and combiner are applied to suppress the one sideband signal. Different from conventional SSB mixer, it is first time a RF Hilbert transformer is applied to modulate the sideband overcoming the issues from I/Q mixers mismatch and bulky IF coupler. To verify the design concept, a prototype is designed and fabricated using RO4350B, and the measured results align with simulation results and theory prediction. In our future work, we will further investigate the design with compact size and larger operating bandwidth to support emerging wideband spectrum management applications, especially at mmWave leveraging chip design.

Acknowledgement

This work was supported in part by NSF CCF-2124525 and NSF ECCS-2124531. The authors appreciate the kindness and assistance of the stuffs from FAMU-FSU College of Engineering.

References

[1] H. Zhang, H. Ren, Y. Gu, B. Arigong, “A Fully Symmetrical Uni-Planar Microstrip Line Comparator Network for Monopulse Antenna,” *IEEE Microw. Wireless Techn. Lett.,* vol. 33, no. 5, pp. 611-614, Jan. 2023.

[2] H. Zhang, P. Liu, J. Casamayor, S. Z. Pour, M. Plaisir and B. Arigong, "A Planar Monopulse Comparator Network Design from Port-Transformation Rat-Race Coupler," *2024 IEEE Radio and Wireless Symposium (RWS)*, San Antonio, TX, USA, pp. 64-67, Jan. 2024.

[3] H. Zhang, P. Liu and B. Arigong, "A Novel Direction of Arrival Estimation Planar Monopulse Receiver," *IEEE Texas Symposium on Wireless and Microwave Circuits and Systems* (*WMCS*), Waco, TX, pp. 1-3, April 2023.

[4] R. V. L. Hartley, “Transmission of Information,” *Bell System Technical Journal*, vol. 7, no.3, pp. 535-563, Jul. 1928.

[5] Y. -W. Wang and J. -H. Tsai, “A 19-GHz High Sideband Suppression Single Sideband Up-Conversion Mixer,” *2022 Asia-Pacific Microwave Conference (APMC)*, pp. 378-380, Japan, Nov. 2022.

[6] Y. Liu, B. Zhang, Z. Niu, Y. Feng and Y. Fan, “A Novel 180-210 GHz Single Sideband Mixer Using Filtering Waveguide-Microstrip Transition Structure,” *IEEE Microw. Wireless Tech. Lett*., vol. 33, no. 6, pp. 727- 730, Jun. 2023.

[7] Y. Gao, A. Wen, W. Jiang, Y. Fan, Y. He and D. Zhou, “Fundamental/Subharmonic Photonic Microwave I/Q Up-Converter for Single Sideband and Vector Signal Generation,” *IEEE Trans. Microw. Theory Techn.,* vol. 66, no. 9, pp. 4282-4292, Sept. 2018.

[8] X. Gao, H. Li, J. Song, J. An, X. Bu and H. Liu, “Modeling and analysis of a high-Tc superconducting polarization-manipulating single-sideband mixer for terahertz communications”, *Appl. Phys. Lett*, vol. 130, no. 17, pp. 173903, Nov. 2021.

[9] Z. Tang and S. Pan, “A Filter-Free Photonic Microwave Single Sideband Mixer,” *IEEE Microw. Wireless Compon. Lett.*, vol. 26, no. 1, pp. 67-69, Jan. 2016.

[10] H. Zhang and B. Arigong, "Full 3D Coverage Beamforming Phased Array with Reduced Phase Shifters and Control 2D Tunable 3 × 3 Nolen Matrix," *2022 IEEE International Symposium on Phased Array Systems & Technology* (*PAST*), Waltham, MA, USA, pp. 1-6, Oct. 2022.

[11] H. Ren. H. Zhang. Y. Jin, Y. Gu, B. Arigong, “A Novel 2-D 3 × 3 Nolen Matrix for 2-D Beamforming Applications,” *IEEE Trans. Microw. Theory Techn*., vol. 67, no. 11, pp. 4622–4631, Jun. 2019.

[12] W. Liu et al., “A fully reconfigurable photonic integrated signal processor,” *Nat. Photon.*, vol. 10, no. 3, pp. 190–195, Mar. 2016.

[13] H. V. Nguyen and C. Caloz, “First- and second-order differentiators based on coupled-line directional couplers,” *IEEE Microw. Wireless Compon. Lett.*, vol. 18, no. 12, pp. 791–793, Dec. 2008.

[14] J. D. Schwartz, J. Azana, and D. V. Plant, “An electronic temporal imaging system for compression and reversal of arbitrary UWB waveforms,” *2008 IEEE Radio & Wireless Symposium (RWS)*, Orlando, FL, USA, pp. 487-490, Jan. 2008.

[15] M. A. G. Laso et al., “Real-time spectrum analysis in microstrip technology,” *IEEE Trans. Microw. Theory Techn.,* vol. 51, no. 3, pp. 705-717, Mar. 2003.

[16] H. Zhang and B. Arigong, “A Novel Frequency Reconfigurable Real-Time RF Edge Detector,” *2023 IEEE/MTT-S International Microwave Symposium* (*IMS*), pp. 1148-1151, San Diego, CA, USA, Jun. 2023.

[17] A. El Sayed et al., “A Hilbert Transform Equalizer Enabling 80 MHz RF Self-Interference Cancellation for Full-Duplex Receivers,” *IEEE Trans. Circuits Syst. I, Reg. Papers*, vol. 66, no. 3, pp. 1153-1165, Mar. 2019.

[18] R. Islam, M. H. Maktoomi, H. Ren and B. Arigong, “Spectrum Aggregation Dual-Band Real-Time RF/Microwave Analog Signal Processing from Microstrip Line High-Frequency Hilbert Transformer,” *IEEE Trans. Microw. Theory Techn.,* vol. 69, no. 11, pp. 4647-4657, Nov. 2021.

[19] H. P. Bazargani, M. R. Fernández-Ruiz and J. Azana, “Tunable optical filter using photonic Hilbert transformation,” *Adv. Photon*., vol. 2013, pp. 1-3, Jul. 2013.

[20] H. Zhang and B. Arigong, "A Novel Frequency Reconfigurable RF Hilbert Transformer for Real-Time Analog Signal Processing," *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 70, no. 4, pp. 1361-1365, April 2023.

[21] H. Zhang, B. Arigong, “A Real Time RF Analog Signal Processor for Time Delay Estimation,” *IEEE 22nd Annual Wireless and Microwave Technology Conference* (*WAMICON*), Clearwater, FL. USA, pp. 1-4, April 2022.

[22] Razavi, B, “*Fundamentals of Microelectronics*, *Wiley*.” 2nd Edition 2013.