Design And Implementation Of Inductor-Less Low Power Variable Gain Amplifier Using NCFET For 5G Applications

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ABSTRACT

This paper introduces a straightforward yet powerful method for designing Variable Gain Amplifiers (VGAs) using Negative Capacitance Field Effect Transistor (NCFET). To maximize bandwidth while minimizing size, the design employs an inductor-less approach. Additionally, a novel technique utilizing a self-compensated transistor is proposed to correct gain errors. As a result, the VGA exhibits an inherently accurate linear characteristic without requiring additional exponential generators for gain control. The concept was validated by fabricating the VGA using NCFET technology. Experimental results demonstrate that the VGA's voltage gain can be adjusted from -20 dB to 25 dB. Furthermore, a bandwidth exceeding 80 GHz is maintained across the entire gain range. The VGA consumes 0.350 mW of power, including the output buffer.

Key words: NCFET, Variable Gain Amplifier, Fixed Gain amplifier, Buffer.

I. INTRODUCTION

5G technology is revolutionizing the industries with its high-speed, low-latency, and reliable connectivity. It enhances Mobile Broadband (eMBB) for faster internet access, seamless streaming, and immersive Virtual Reality and Argument Reality (VR/AR) experiences. The massive Internet of Things (mIoT) connects vast networks of devices, enabling smart cities, connected vehicles, and industrial IoT applications. The development of 5G technology has driven the need for advanced RF front-end components, especially Variable Gain Amplifiers (VGAs) [1,2]. VGAs are essential for maintaining signal integrity by adjusting the signal amplitude to match the dynamic range of later stages. However, traditional VGAs struggle to meet 5G's requirements [7], particularly at millimeter-wave frequencies [9], where achieving high gain, low noise, and power efficiency is crucial.

High-band frequencies, known as millimeter wave (mm Wave), operate between 24 GHz and 300 GHz and deliver extremely high data speeds and ultra-low latency. However, mm Wave signals have a limited range and easily obstructed by physical barriers. Operating across different frequency bands, including millimetre wave (mm Wave) and sub-6 GHz [13], 5G receivers must manage challenges such as interference, power consumption, and thermal management, especially as they handle the demanding data rates of 5G [10].

To address the challenges posed by mm Wave frequencies, 5G systems Develops “Beamforming technology”. Beamforming is a method of directing radio signals in a specific direction rather than broadcasting them in all directions, as in traditional antennas [15]. In a 5G network, beamformers are used to focus the signal towards the intended user or device, effectively creating a "beam" of concentrated radio waves. This directional control is crucial for overcoming the limitations of mm Wave frequencies [16]. By dynamically steering the beam as the user moves, beamformers help maintain a strong and focused connection, ensuring that the high-frequency signals reach the user with minimal interference and loss. This technology not only enhances signal strength and quality but also reduces interference with other signals, which is essential in densely populated areas where many devices are operating simultaneously.

The 5G receiver, a key component in any 5G-enabled device plays a critical role in capturing and processing the signals transmitted through these focused beams. The receiver must be capable of handling the high frequencies associated with mm Wave signals [14,15], as well as processing large amounts of data with minimal latency. The beamforming capabilities embedded within the receiver allow it to effectively capture the incoming signal, even as the user moves or as the environment changes. Within the 5G receiver, Variable Gain Amplifiers (VGAs) are essential for managing the variability in signal strength that occurs due to the challenging nature of mm Wave communications [3,4]. In a typical 5G environment, the strength of the received signal can fluctuate significantly depending on factors such as distance from the base station, the presence of obstacles, and interference from other signals. VGAs address this issue by dynamically adjusting the amplitude of the received signals to ensure they fall within an optimal range for further processing. For instance, if a signal is too weak due to distance or obstruction, the VGA increases the gain, amplifying the signal to a usable level. Conversely, if the signal is too strong—perhaps due to proximity to the base station or reflection off nearby surfaces—the VGA reduces the gain to prevent distortion and potential signal overload. This dynamic adjustment is crucial for maintaining the integrity of the signal, ensuring that it can be processed accurately and without error. By managing the signal's dynamic range, VGAs help to optimize the overall performance of the 5G receiver, contributing to clearer, more reliable communication.

An inductor-less, four-stage wideband VGA is designed and implemented by using NCFET technology [5,7]. High amplification is provided by fixed-gain components in the initial and third stages, while variable gain elements are incorporated into the second and last stages. The latter stages employ self-compensated transistors to achieve exceptional dB-linear gain control without the need for a pseudo-exponential generator. The paper is coordinated as follows: The proposed VGA design methodology is explained in Section II, the advantages of NCFET over CMOS technology are outlined in Section III, and Section IV covers the design of FGA, VGA, and buffer using NCFET technology, along with the overall VGA architecture [1]. A summary of the comparison and results for the proposed VGA is presented in Section V. The paper concludes with Section VI.

II. PROPOSED METHODOLOGY

The variable gain amplifier employs a four-stage configuration, with fixed-gain amplifiers in the first and third stages providing substantial amplification, while variable gain amplifiers occupy the second and fourth stages. This arrangement enables efficient gain regulation across a broad spectrum. To maximize bandwidth while minimizing size, the amplifier utilizes an inductor-free design strategy. This approach enables the device to attain a bandwidth exceeding 80 GHz, which is essential for applications in 5G technology. Modern applications like 5G benefit greatly from the use of Inductor-less Variable Gain Amplifiers (VGAs) due to their numerous advantages. The elimination of inductors, which are typically large components, results in a more compact and integrated circuit design. This size reduction is crucial for space-constrained applications such as mobile devices and 5G transceivers. Furthermore, these inductor-less designs are more energy-efficient, utilizing active components and capacitors that can be optimized to minimize power consumption. When integrated with cutting-edge technologies like Negative-Capacitance Field Effect Transistors (NCFETs), these amplifiers can achieve high performance while consuming less power, making them well-suited for battery-powered devices. Another key benefit is their superior wideband performance. Unlike inductor-based designs, which often face limitations in bandwidth and frequency range, inductor-less VGAs are better equipped to handle high-frequency operations, including the millimeter-wave bands employed in 5G technology. The circuit schematic includes a source-coupled differential pair operating in the triode region, which is essential for achieving the desired performance characteristics. The power consumption of the VGA, including the buffer, is reported to be 0.350mW. This compact design is advantageous for integration into various applications.

III NCFET

Over the last ten years, decreasing operational voltages has become progressively challenging with each new technological advancement. The scaling of CMOS is nearing its limits due to challenges in managing chip power density, primarily because of the Boltzmann distribution of charge carriers. This distribution principally restricts the subthreshold swing from falling below 60mV/decade at room temperature. Consequently, further voltage scaling in smaller nodes has been reduced.

To address this issue, the negative capacitance effect observed in ferroelectric materials such as HfO2 can be utilized. The Negative Capacitance Field Effect Transistor (NCFET) is comparable to the Metal Oxide Semiconductor Field Effect Transistor (MOSFET), with the key distinction being the incorporation of an additional ferroelectric layer within the transistor's gate stack. We know that, $C=\frac{dQ}{dV}$ In conventional capacitors, a positive increase in charge (dQ > 0) corresponds to a positive increase in voltage (dV > 0), and the reverse holds true as well. However, for negative capacitance (NC), an increase in charge (dQ > 0) results in a decrease in voltage (dV < 0), and vice versa. Ferroelectric (FE) materials are characterized by their non-centrosymmetric crystal structure, which makes them non-linear components. These materials demonstrate spontaneous polarization, meaning they exhibit polarization even without an applied electric field. FE materials have two stable polarization states when the electric field is zero, which can be switched by applying an electric field that exceeds the coercive field Ec.

$$\varepsilon_0\varepsilon_f = \frac{dP}{dE} = \varepsilon_0 + \frac{dP}{dE} \approx \frac{dP}{dE}$$

FE's instability causes polarization in the direction opposite to the applied electric field, with $\frac{dP}{dE} < 0$. The free energy per unit volume for FE can be described using the Landau mode:

$$W(P)= \alpha P^2 + \beta P^4 + \gamma P^6 - E_P$$

In this case, the anisotropy constants α, β, and γ are Landau coefficients. Upon differentiating W with respect to P, we obtain: The unstable polarization state takes place at the highest energy point (Q = 0).

$$E = 2\alpha P + 4Bp^3 + 6\gamma P^5$$

Differentiating E with regard to P yields the reciprocal of permittivity.

$$(\varepsilon_0\varepsilon_f)^{-1} = 2\alpha + 12\beta P^2 + 30\gamma P^4$$

The application of the negative permittivity effect in NC devices faces obstacles due to the nullification of the depolarization effect. Nevertheless, by employing an external electric field that surpasses the coercive field, it becomes feasible to alter the polarization state of the ferroelectric material and induce negative capacitance. This negative capacitance effect leads to a decrease in the subthreshold swing below the Boltzmann threshold. The subthreshold swing (SS) can be represented mathematically

$$SS = \frac{\partial V_G}{\partial log_{10}(I_{DS})} = \frac{\partial V_G}{\partial \varphi_s}\frac{\partial \varphi_s}{\partial log_{10}(I_{DS})} \cong \frac{\partial V_G}{\partial \varphi_s} 2.3(kT/q)$$

The term ∂VG/∂ψs refers to the bulk-charge factor (m), while ψs stands for the surface potential.

$$m = \left(1 + \frac{C_s}{C_{ins}}\right)$$

SS below 60 mV/dec can be attained in NCFET when (Cins < 0) with (Cs > 0) results m less than 1. To ensure stable operation without hysteresis in NCFET, to ensure that the overall gate capacitance remains positive.

The $C_s(Q)$ and $-C_{ins}(Q)$ must be closely matched in order to provide low SS. The baseline MOSFET provides the dielectric medium through oxide layer which stabilizes the negative capacitance state in the ferro electric. This addition modifies the capacitance characteristics of the device that includes the Gate capacitance and ferro electric capacitance. the equivalent capacitance model for the conventional FET and NCFET is shown in Fig 1.a) and Fig 1.b) respectively.

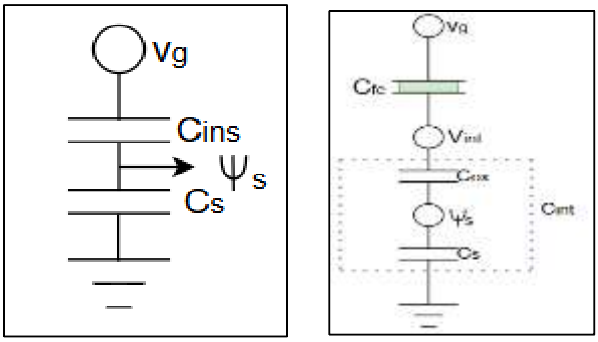


Fig 1. a) Equivalent capacitance model of FET. b) Equivalent capacitance model of NCFET

Due to this addition of the ferro electric layer, there will be internal voltage amplification, which will in turn results in steeper sub-threshold swing (SS) often less than 60mV/dec. this property makes NCFET special by reducing power consumption while maintaining the faster switching speeds.

$$A_V = \frac{|C_{fe}|}{|C_{fe}| - C_{int}}$$

In order to provide a negative capacitance, we need to have C_{fe} greater than the C_g. This leads to the internal voltage amplification responsible for the improved device performance, specifically higher ON current and lower leakage current.

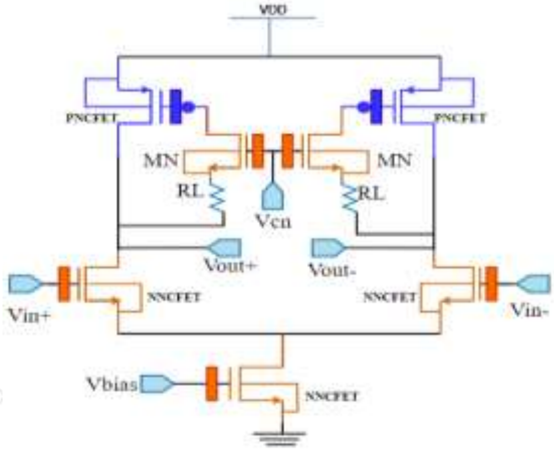
$$C_g = \frac{|C_{fe}|.C_{int}}{|C_{fe}| - C_{int}, |C_{fe}| > 0}$$

IV. PROPOSED ARCHITETURE USING NCFET

A) VARIABLE GAIN AMPLIFIER UNIT DESIGN

Variable Gain Amplifier (VGA) using a Negative Capacitance Field-Effect Transistor (NCFET) involves utilizing the negative capacitance effect inherent in NCFETs to dynamically control signal amplification. The NCFET's gate stack includes a ferroelectric material that exhibits a negative capacitance region, which reduces the gate capacitance and lowers the subthreshold swing (SS), leading to higher transconductance (G_m). This allows the NCFET to operate more efficiently at lower voltages, enabling the VGA to achieve higher gain with less power consumption. In this design, the gain is controlled by varying the gate voltage, which adjusts the negative capacitance effect and, in turn, the transconductance. As a result, small changes in the control voltage can produce significant variations in the output signal's amplitude, making the NCFET-based VGA highly effective for applications that require precise and wide-ranging gain control.

Fig 2. VGA using NCFET



The circuit schematic of variable gain unit using NCFET as shown in Fig 2, which is same as the VGA using CMOS technology, the MOS transistors are replaced with the NCFET. The supply voltage V_{dd}=500mV, V_{in}=70mV, V_{cn}=10mV - 50mV, V_{bias}=500mV, R_L=2KΩ.

B) FIXED GAIN AMPLIFIER UNIT DESIGN

A Fixed Gain Amplifier using NCFET works by utilizing the NCFET's negative capacitance effect to achieve stable, efficient signal amplification. The ferroelectric material in the NCFET's gate reduces gate capacitance and lowers the subthreshold swing (SS), resulting in higher transconductance (gm). The amplifier's gain is fixed by setting a constant gate voltage, which establishes a stable operating point for the NCFET. This setup ensures a consistent amplification factor for the input signal, offering high gain with low power consumption, improved linearity, and reduced noise, making it ideal for applications needing reliable, steady amplification. The topology of fixed gain unit using NCFET is shown in Fig 3, which is similar to Fixed gain unit using CMOS technology except that the supply voltage is low.

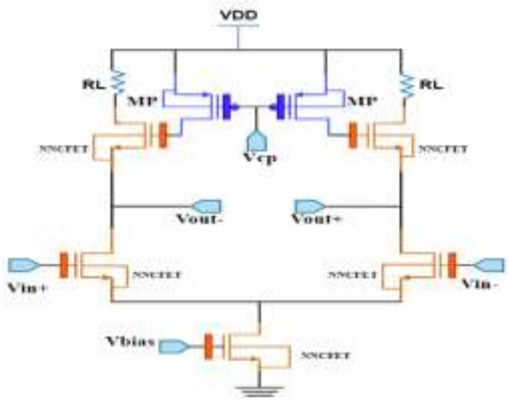


Fig 3.

FGA using NCFET

The supply voltage V_{dd}=500mV, V_{in}=70mV, V_{cp}=10mV – 50mV, V_{bias}=500mV, R_L=2KΩ

C) OUTPUT BUFFER

Using Negative Capacitance Field-Effect Transistors (NCFETs) in output buffers can make electronic devices more efficient. NCFETs use special materials that allow them to work at lower voltages, which means they use less power and generate less heat. They also help signals move faster and stay clearer, making the devices work better overall. However, adding these special materials to current technology is tricky, and getting consistent results can be challenging. Despite these challenges, NCFETs offer a promising way to improve the performance and efficiency of electronic circuits.

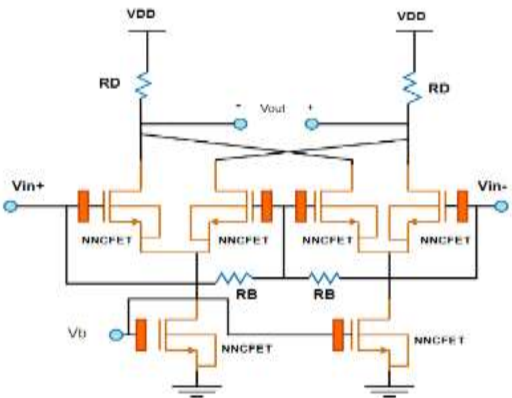


Fig 4.

Output Buffer using NCFET

D) OVERALL VGA ARCHITECTURE

A high gain can be achieved by utilizing two fixed gain units and two variable gain units. Fixed and variable gain units are cascaded together in the first level. Secondly, identical stage is cascaded with first stage. Finally, an output buffer is cascaded for testing purpose to design an overall variable gain amplifier and the characteristics are simulated. The overall variable gain amplifier architecture is shown in

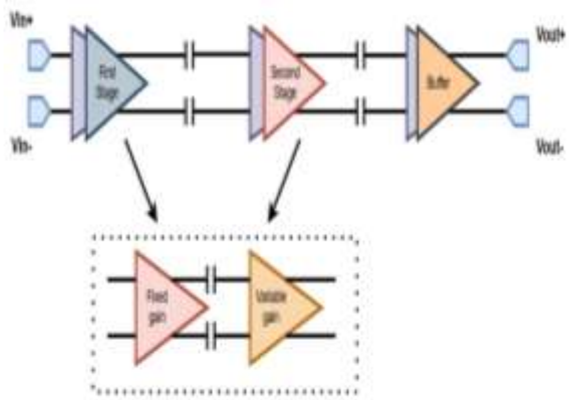


Fig 5. Overall VGA using NCFET

V.COMPARSION AND RESULTS

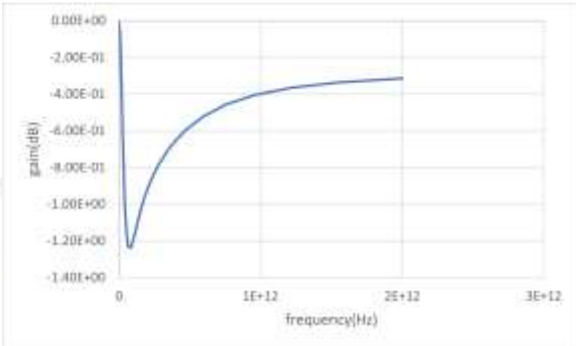


Fig 6. S11-parameter analysis

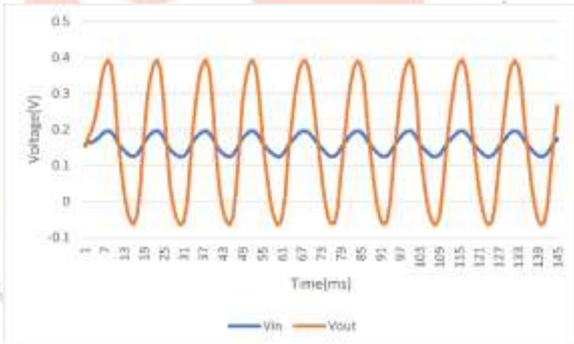


Fig 7. Voltage gain

The Variable Gain Amplifier (VGA) operates with a control voltage range from 10 mV to 50 mV, achieving a dB-linear gain variation of 45dB, ranging from -21dB to 24dB. This VGA operates at a frequency of 80 GHz. Fig 6 presents the S11-Parameter analysis, where gain is plotted against frequency, clearly indicating that the VGA achieves operating frequency of 80 GHz. Fig 7 illustrates the input and output voltage characteristics of the VGA, showing an input voltage of 70 mV and an output voltage of 390 mV. From these values, the VGA achieves a gain of 24dB.

Table 1. Comparison Table

PARAMETERS	BASE PAPER	PROPOSED DESIGN
Control Method	Analog	Analog
Band Width (GHz)	4	80
Gain Range (dB)	40(-19 – 21)	45(-21 – 24)
Power(mW)	3.5	0.350
Technology	CMOS	NCFET
Delay	NA	50ps

Table 1 presents a comparison between this work and the reference base paper. Compared to previous works, the designed VGA significantly extends the bandwidth and achieves a much wider voltage gain variation range. Additionally, the power consumption of the designed VGA is lower compared to prior designs. The results of this work demonstrate strong alignment between simulation and measurement data. Consequently, it can be said that the suggested method for creating VGAs is efficient and successful, especially for applications that emphasize high-speed signal processing.

VI. CONCLUSIONS

The research findings indicate that integrating negative-capacitance field-effect transistors (NCFETs) into Variable Gain Amplifiers (VGAs) yields considerable benefits in terms of energy efficiency, gain management, and signal quality. This investigation highlights the critical role of dynamic gain adjustment in preserving signal integrity for high-frequency applications, such as 5G networks, and emphasizes the advantages of inductor-less VGAs in achieving broad bandwidth performance. The negative capacitance phenomenon allows VGAs to function efficiently at reduced voltages, resulting in an enhanced gain with decreased power usage, making them ideal for energy-conscious applications and battery-operated devices. This research highlights the importance of cutting-edge RF front-end components, such as VGAs, in fulfilling the rigorous demands of 5G technology, especially at millimeter-wave frequencies, where high amplification, minimal noise, and energy efficiency are essential.

VII. REFERENCES

[1] L. Kong et al., "Design of a Wideband Variable-Gain Amplifier with Self-Compensated Transistor for Accurate dB-Linear Characteristic in 65 nm CMOS Technology," in IEEE Transactions on Circuits and Systems I: Regular Papers, vol. 67, no. 12, pp. 4187-4198, Dec. 2020.

[2] L. Kong, "Wideband dB-linear VGA for high-speed communications," Ph. D dissertation, School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore, 2019.

[3] L. Kong, Y. Chen, H. Yu, C. C. Boon, P. -I. Mak and R. P. Martins, "Wideband Variable Gain Amplifiers Based on a Pseudo-Current-Steering Gain-Tuning Technique," in IEEE Access, vol. 9, pp. 35814-35823, 2021.

[4] C. Fan *et al.*, "Design of a Wideband dB-Linear Variable Gain Amplifier with Continuous Gain Adjusting in 90-nm CMOS Technology," in *IEEE Access*, vol. 9, pp. 152646-152656, 2021.

[5] H. Amrouch, G. Pahwa, A. D. Gaidhane, J. Henkel et al., "Negative capacitance transistor to address the fundamental limitations in technology scaling: Processor performance," IEEE Access, vol. 6, pp. 52 754–52 765, 2018.

[6] S. Salamin, M. Rapp, H. Amrouch, G. Pahwa et al., "Ncfet-aware voltage scaling," in 2019 IEEE/ACM International Symposium on Low Power Electronics and Design (ISLPED). IEEE, 2019, pp. 1–6.

[7] F. Padovan, M. Tiebout, A. Neviani and A. Bevilacqua, "A 15.5–39GHz BiCMOS VGA with phase shift compensation for 5G mobile communication transceivers," ESSCIRC Conference 2016: 42nd European Solid-State Circuits Conference, Lausanne, 2016, pp. 363-366.

[8] H. Agarwal, P. Kushwaha, J.-P. Duarte, Y. Lin, A. Sachid, M.-Y. Kao, H.-L. Chang, S. Salahuddin, and C. Hu, "Engineering Negative Differential Resistance in NCFETs for Analog Applications," IEEE Trans. Electron Devices, vol. 65, no. 5, pp. 1–7, 2018.

[9] A. Alkhateeb, O. El Ayach, G. Leus, and R. W. Heath, "Channel estimation and hybrid precoding for millimeter wave cellular systems," IEEE J. Sel. Topics Signal Process., vol. 8, no. 5, pp. 831–846, Oct 2014.

[10] T. S. Rappaport, S. Sun, R. Mayzus, H. Zhao, Y. Azar, K. Wang, G. N. Wong, J. K. Schulz, M. Samimi, and F. Gutierrez, "Millimeter wave mobile communications for 5g cellular: It will work!" IEEE Access, vol. 1, pp. 335–349, 2013.

[11] M. W. Sabri, N. A. Murad, and M. K.A. Rahim, "Bi-directional Beams Waveguide Slotted Antenna at Millimeter Wave," TELKOMNIKA, vol. 16, no. 4, pp. 1515-1521, August 2018.

[12] B. Sadhu et al., "A 28-GHz 32-Element TRX Phased-Array IC With Concurrent Dual-Polarized Operation and Orthogonal Phase and Gain Control for 5G Communications," in IEEE Journal of Solid-State Circuits, vol. 52, no. 12, pp. 3373-3391, Dec. 2017.

[13] W. Roh, J. Y. Seol, J. Park, B. Lee, J. Lee, Y. Kim, J. Cho, K. Cheun, and F.Aryanfar, "Millimeter-wave beamforming as an enabling technology for 5g cellular communications: theoretical feasibility and prototype results," IEEE Communications Magazine, vol. 52, no. 2, pp. 106–113, February 2014.

[14] Hu Wang, "5g Vision, Characteristics and Requirements", David Fritsche, Gregor Tretter, Corrado Carta, and Frank.

[15] M. W. Sabri, N. A. Murad, and M. K.A. Rahim, "Bi-directional Beams Waveguide Slotted Antenna at Millimeter Wave," TELKOMNIKA, vol. 16, no. 4, pp. 1515-1521, August 2018.

[16] Ellinger, "Millimeter-Wave Low-Noise Amplifier Design in 28-nm Low-Power Digital CMOS" IEEE Transactions on Microwave Theory and Techniques, Vol. 63, No. 6, June 2015GSA Spectrum Group, June 2016.