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Precision Analog Rectifiers With Current Input-Current Output Topologies: A Comprehensive Study

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WHAT IS ALREADY KNOWN ON THIS TOPIC?

- *Traditional rectifiers are widely used in low-frequency and high-power applications but suffer from accuracy and efficiency limitations in small-signal and high-frequency scenarios.*
- *Precision rectifiers use active components to enable accurate signal processing, especially in analog instrumentation and low-amplitude signal applications.*
- *The Current Input–Current Output (CI-CO) architecture offers significant advantages in terms of bandwidth, speed, and low distortion due to its current-mode operation*

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ABSTRACT

Precision rectifiers play a crucial role in modern electronics, providing accurate signal processing and energy conversion for a wide range of applications. Current Input-Current Output (CI-CO) rectifiers have emerged as pivotal components in modern electronic systems, offering precise signal processing, high-speed operation, and compatibility with integrated circuit technologies. These circuits, characterized by their ability to process signals entirely in the current domain, minimize power losses and enhance system efficiency. This study provides a comprehensive analysis of CI-CO rectifier circuits, focusing on their design principles, operational advantages, and application areas. Recent advancements, including resistor-less and diode-less designs, highlight the potential of CI-CO rectifiers to address challenges in high-frequency and low-voltage applications. Particular attention is given to their role in critical fields such as biomedical instrumentation, renewable energy systems, telecommunications, and smart IoT devices, where precise current regulation and energy efficiency are paramount. By presenting a detailed chronological review and comparative analysis of existing designs, this study underscores the versatility and adaptability of CI-CO rectifiers. Additionally, key performance metrics such as power consumption, bandwidth, and harmonic distortion are evaluated to guide future research and development efforts. The findings contribute to the growing body of knowledge in analog electronics and provide practical insights for engineers and researchers seeking energy-efficient, compact, and reliable rectification solutions for next-generation applications.
***Index Terms*—**Current-conveyors, current-mode circuits, operational amplifiers, precision rectifiers

I. INTRODUCTION

Rectifiers are crucial components used in nearly all electrical devices in various fields such as communication, healthcare, measurement, and computing. Full-wave and half-wave rectifier circuits are frequently employed in biomedical sensors and implants, wireless communication devices, energy harvesting systems, radio and television receivers, frequency identification applications, as well as instrumentation and measurement systems. This study provides a review of precision rectifiers constructed using Complementary Metal-Oxide-Semiconductor (CMOS) transistors, which are widely utilized in daily life, and whose absence could lead to significant disruptions.

Full-wave rectifiers are widely utilized in biomedical sensors, wireless communication systems, energy harvesting circuits, and radio frequency (RF) identification systems. These circuits are essential in analog signal processing and measurement applications, where they enable high-precision rectification for a variety of critical tasks. Beyond these applications, rectifier circuits play a fundamental role in power electronics, particularly in the efficient conversion of energy from renewable sources such as solar panels and wind turbines. They are also integral to electric vehicle charging stations and battery management systems, ensuring effective energy distribution and storage.

In industrial environments, rectifiers are essential for providing continuous Direct Current (DC) power in motor drives, welding machines, and other heavy-duty electrical applications. They are also employed in communication systems for signal demodulation in microwave and RF

WHAT THIS STUDY ADDS ON THIS TOPIC?

- *Provides a comparative analysis of CI-CO rectifier designs in the literature, organized around key performance metrics such as power consumption, bandwidth, and harmonic distortion.*
- *It highlights the advantages of CI-CO circuits in high-frequency, low-voltage, and low-power scenarios, demonstrating their suitability for next-generation applications.*
- *The study details the performance and contributions of CI-CO rectifiers in specific application areas such as biomedical systems, industrial motor control, and communication infrastructures*

receivers, as well as in satellite communication systems where low-noise rectification is vital. Furthermore, rectifiers are frequently found in medical electronics, where they support critical functions such as signal processing in electrocardiograms (ECGs) and electroencephalograms, as well as echo signal processing in ultrasound devices.

Precision rectifiers are predominantly used in applications where high precision is vital, such as analog signal processing, instrumentation, and measurement systems. Their active-component-based design also makes them highly compatible with integrated circuits (ICs), facilitating seamless integration into modern electronic systems [1]. On the other hand, traditional rectifiers are more commonly employed in power supply systems where the primary objective is to convert Alternating Current (AC) to DC power. These circuits are well-suited for scenarios where precision is not a critical requirement [2].

Precision rectifiers and traditional rectifiers differ significantly in design, performance, and applications, each serving distinct roles in electronics. Precision rectifiers are designed to handle low-level signals with exceptional accuracy and minimal distortion, making them indispensable in high-precision applications such as analog signal processing and instrumentation. In contrast, traditional rectifiers are primarily utilized in power conversion tasks, focusing on efficiency and simplicity rather than precision. Precision rectifiers rely on active components like operational amplifiers, current conveyors, and Metal-Oxide Semiconductor (MOS) transistors, enabling highly accurate signal processing. These designs often eliminate the need for passive components like resistors and diodes, resulting in compact, integrable circuits suitable for modern technologies. For example, configurations such as those using Current Follower Differential Input Transconductance Amplifiers (CFDITA) [3] achieve high precision with minimal components, facilitating seamless integration into ICs [2, 4]. Traditional rectifiers, on the other hand, are built predominantly with passive components like diodes and resistors. While these designs are straightforward and cost-effective, they are prone to non-linearities and inaccuracies, particularly when processing low-amplitude signals. This makes traditional rectifiers less suitable for applications requiring fine-grained precision. Precision rectifiers excel in handling small signal levels and high-frequency operations with minimal distortion. They can rectify signals as small as a few millivolts at frequencies up to 1 MHz, providing both inverting and non-inverting outputs when required [5, 6]. This high accuracy and bandwidth make them invaluable in advanced signal-processing tasks. Conversely, traditional rectifiers face limitations due to diode voltage drops and restricted frequency response. These factors reduce their suitability for precision applications, though they remain effective in basic AC-to-DC conversion tasks where accuracy is less critical [5, 7]. Precision rectifiers are versatile, and capable of performing multiple rectification tasks—including positive, negative, and full-wave rectifications—within a single circuit configuration [1]. This adaptability makes them ideal for complex analog signal processing and measurement systems. Traditional rectifiers, while less versatile, are robust solutions for power supply systems, focusing on converting AC to DC for various electrical and electronic devices. Their simplicity and cost-effectiveness make them a practical choice for applications where precision is secondary.

Half-wave and full-wave rectifier circuits built with diodes have some important limitations. The voltage drops across the diodes during conduction cause efficiency loss, especially in low-voltage applications, while high currents and voltages can lead to heating and energy losses. While half-wave rectifiers are inefficient in terms of energy efficiency, the complex design of full-wave rectifiers can increase cost and circuit complexity. Furthermore, these circuits suffer from harmonic distortion and high ripple, which adversely affect energy quality and require additional filtering. To overcome these limitations, active elements such as op-amps are used for rectification [8]. Active rectifier circuits make the rectification process more precise and efficient by minimizing the voltage drop, while at the same time providing lower ripple and higher accuracy. This approach offers significant advantages, especially in low-signal and sensitive applications.

Low-power and low-voltage precision rectifier circuits are becoming increasingly important due to the growing demand for energy-efficient and compact electronic systems. Applications such as wearable devices, biomedical equipment, wireless sensor networks, and IoT-based solutions require low power consumption while maintaining reliable performance. These circuits are essential for accurately processing low-level signals, ensuring the efficiency of next-generation electronic systems. As devices become smaller, more portable, and battery-powered, advancements in rectifier design will play a crucial role in meeting evolving technological demands.

Current Input-Current Output circuits stand out for their versatility, accommodating various load types, including resistive, capacitive, and inductive loads. This adaptability makes them ideal for laboratory power supplies, industrial robotics, and modular energy management systems. For example, a laboratory power supply equipped with a CI-CO circuit can operate within a voltage range of 0–30V and deliver a constant current of 0-5A, enabling precise testing of different devices.

Beyond their adaptability, CI-CO circuits enhance system reliability through integrated protective mechanisms such as overcurrent protection. In industrial motor control, these circuits detect overloads or short circuits and disconnect the motor to prevent damage, improving operational safety. Additionally, they effectively suppress Electromagnetic Interference (EMI) and manage ripple, reducing harmonic distortion to below 1%. This ensures a stable and clean power supply, making them particularly valuable in telecommunications and medical applications. In ECG systems, CI-CO circuits maintain a low-noise environment for accurate measurements, while in telecommunications base stations, they prevent signal degradation and enhance stability.

This study expands on previous research by providing a comprehensive review of CI-CO circuits, with a particular emphasis on their current-mode operational characteristics. It presents a detailed examination of CI-CO designs found in the literature, outlining their key features, performance metrics, and diverse applications. To facilitate understanding, the findings are organized into a comparative table, offering a clear reference for researchers and engineers. Renowned for their ability to deliver precise current regulation, wide bandwidth, and high-speed performance, these circuits play a crucial role in modern electronics. By analyzing their design principles, advantages, and practical implementations, this study provides valuable insights for designers striving to develop efficient and reliable solutions in analog and low-power electronics. Ultimately, it serves as a comprehensive resource for advancing knowledge in these fields.

II. CURRENT MODE FULL-WAVE RECTIFIERS

Current-mode full-wave rectifiers are essential components in signal processing, particularly in applications requiring precise rectification of AC signals into DC. These rectifiers are designed to operate in the current domain, offering advantages such as high-speed operation, reduced power consumption, and compatibility with modern IC technologies. Recent advancements in current-mode full-wave rectifiers focus on minimizing component count, enhancing frequency response, and improving linearity and accuracy. Below are key aspects of current-mode full-wave rectifiers based on recent research.

- **Resistor-less and Diode-less Designs**: Some designs eliminate the need for diodes and passive components, using active elements like CFDITA and MOS transistors [3]. This approach simplifies the circuit and enhances integration capabilities, as seen in designs that achieve a wide input current dynamic range and high-frequency operation up to 30 MHz.
- **Low Power Consumption**: Designs using Dynamic Threshold MOS (DTMOS) transistors focus on low-voltage and low-power operation, consuming minimal power while providing full-wave rectification. These designs are efficient for applications requiring low power consumption [9].
- **Electronic Tunability**: Some rectifiers offer electronic tunability by adjusting bias voltages, allowing for control over the output waveform. This feature is beneficial for applications requiring adaptable signal-processing capabilities [10].
- **IC Suitability**: Many current-mode rectifiers are designed with IC integration in mind, using minimal active components and avoiding passive elements to reduce parasitic effects. This makes them highly suitable for modern IC technologies [3, 7].
- **Simulation and Validation**: The performance of these rectifiers is often validated through simulations using advanced CMOS technology, ensuring that theoretical predictions align with practical outcomes. This includes testing for robustness through Monte Carlo simulations and corner analysis [10, 11].

III. PRECISION RECTIFICATION USING OP-AMPS AND CURRENT-MODE TECHNIQUES

In conventional rectification processes utilizing diodes, the design requires a shared common terminal with the highest or lowest power supply source, which significantly limits flexibility. To address these constraints, MOS transistors configured as diode equivalents, with their drain and gate terminals connected, have been widely adopted [12, 13]. However, this approach is ineffective for rectifying signals with amplitudes smaller than the threshold voltage of the MOS transistors [12]. Consequently, precision rectification circuits leveraging operational amplifiers (op-amps) have been extensively developed to overcome this limitation. An example of such a circuit, combining op-amps, diodes, and resistors, is well-documented in the literature [14, 15].

One of the earliest contributions to precision rectification was the full-wave rectifier circuit proposed by Wang [13], which could operate at frequencies up to 5 kHz. Despite its voltage-based input and output signals, Wang described the rectification process as a current-mode, employing an op-amp, two current mirrors, and six MOS transistors. Further advancements include Toumazou et al. [16], who highlighted the advantages of replacing diode grounding points with DC power supplies, significantly improving performance.

Khan et al. [17] proposed a full-wave rectifier employing two current conveyors, effectively addressing the limitations associated with diode threshold voltages. Monpapassorn et al. [18] introduced a Second-Generation Current Conveyor (CCII)-based rectifier utilizing current mirrors, achieving improved performance in low-voltage applications. In subsequent refinements, Monpapassorn [19] proposed a low-impedance dual-output design to enhance dynamic performance. Yüce et al. [20] introduced a full-wave rectifier using CCII+ elements and CMOS transistors, achieving a -3 dB bandwidth for a current gain of 912 MHz and a voltage gain of 22.2 MHz. Maheshwari [21] presented a design employing a second-order controllable current conveyor (CCCII) and MOSFETs, while Djukic [22], focused on small-amplitude signal rectification up to 100 kHz.

Koton et al. [22], and Koton et al. [23] demonstrated low-noise rectification up to 500 kHz. Anuntahirunrat et al. [24] proposed designs using multiple CCIIs to achieve versatile and efficient rectification. Gift [25] introduced a precision full-wave rectifier operating up to 100 kHz by integrating a First-Generation Current Conveyor (CCI)

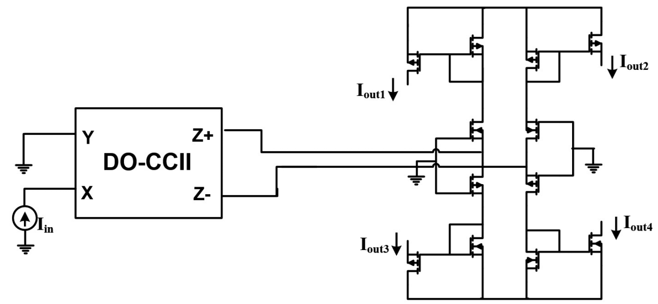

Fig. 1. Current mode MOS-only versatile precision rectifier circuit proposed by Safari et al. [26].

with traditional op-amp circuits. This design featured two operational amplifiers, one current conveyor, three resistors, and two diodes. In subsequent works, Gift refined the design to extend the frequency range to 1 MHz, incorporating two operational amplifiers, two first-generation current conveyors, four diodes, and two resistors to improve linearity and dynamic range [14]. Safari et al. [26] and Srivastava et al. [27] proposed precision rectifiers based on advanced current mirror configurations. Safari's design utilized class-AB current mirrors and a Dual-Output Second-Generation Current Conveyor (DO-CCII), emphasizing simplicity and efficiency, while Srivastava's approach addressed traditional limitations through Low Voltage Cascode Current Mirrors. The circuit proposed by Safari et al. is illustrated in Fig. 1, while the design by Srivastava et al. is depicted in Fig. 2.

A. Modern Designs Using Current Conveyors

The Differential Extra-X Current Conveyor (DXCCII) represents a significant advancement in current-mode rectification. This configuration utilizes dual-X terminals, three MOS switches, and two resistors, effectively eliminating the need for diodes. Minaei & Yuce [28] demonstrated the practicality of this approach using CMOS transistors, while Kumar & Chaturvedi [29] validated the design through HSPICE simulations, showcasing its suitability for modern electronic systems. As highlighted by Jagga et al. [30] the architecture offers simplicity, low power consumption, and resilience against variations in process, voltage, and temperature.

Two full-wave rectifiers, ingeniously designed using plus-type current conveyors from the second generation, incorporate two diodes and a pair of grounded resistors that serve crucial functions in the circuitry. These designs demonstrate remarkable resilience against variations in bias voltages or currents, thereby eliminating the necessity for additional circuitry components. They also offer high input impedance and impressive gain capabilities, as noted by Yücehan et al. [31].

Kumari and Nand [11] introduced a rectifier using a Differential Difference Current Conveyor (DDCC) block alongside MOSFET-based diodes and grounded resistors. The design achieves high-frequency operation up to 200 MHz with efficient positive and negative rectification capabilities.

Current-mode rectifiers designed with advanced current conveyors offer a range of significant advantages over traditional methods. These designs eliminate the need for diodes, overcoming threshold voltage constraints and thereby enhancing energy efficiency [19, 31]. Additionally, they meet high-frequency signal processing requirements with minimal distortion, delivering superior performance in high-speed applications [11, 26]. With reduced component usage, these designs provide a suitable foundation for semiconductor integration, enabling cost-effective solutions in fields such as telecommunications, renewable energy systems, and medical devices [26]. These findings demonstrate that current conveyor-based rectifiers are a powerful alternative for modern electronic systems in terms of both performance and integration.

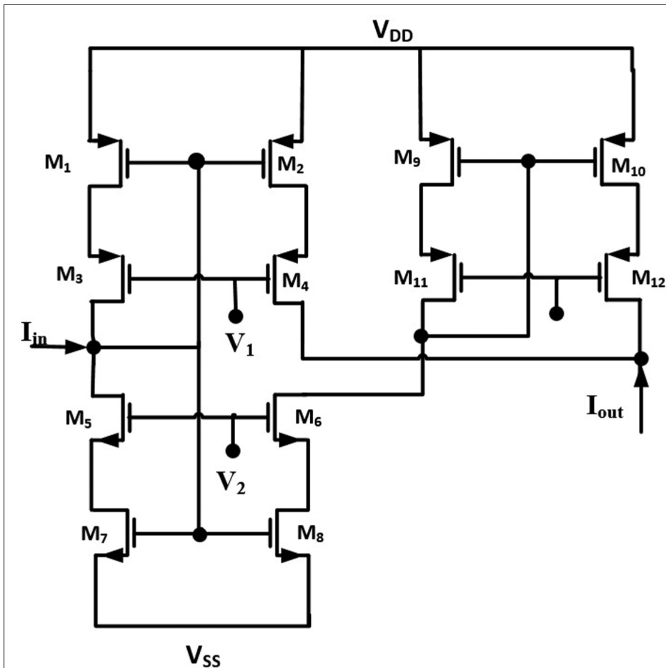

Fig. 2. Low voltage cascode current mirrors current mode full-wave rectifier [27].

In applications like telecommunications, medical devices, and renewable energy systems, designs such as those proposed by Petrović [7] and Kumngern [32, 33] demonstrate the adaptability of current-mode rectifiers in addressing diverse signal processing needs. Nonthaputha [32] and Kumngern [32, 33] highlighted programmable full-wave rectification using current-controlled analog switches, enhancing versatility in both voltage and current modes.

IV. PRECISION RECTIFIERS USING TRANSCONDUCTANCE AMPLIFIERS

The demand for precision in modern electronic systems has driven significant advancements in rectifier circuit design, particularly those leveraging active components such as Operational Transconductance Amplifiers (OTAs) and Current Differencing Transconductance Amplifiers (CDTAs). These components offer unique advantages, including high input impedance, tunable transconductance, and exceptional linearity, making them indispensable in applications requiring precise signal processing. As the need for low-power, high-speed, and compact solutions continues to grow, OTA- and CDTA-based rectifiers have emerged as key innovations in current-mode electronics. Their versatility and efficiency in handling low-level signals, along with their compatibility with ICs, have positioned these amplifiers at the forefront of rectifier technology, paving the way for both theoretical advancements and practical applications.

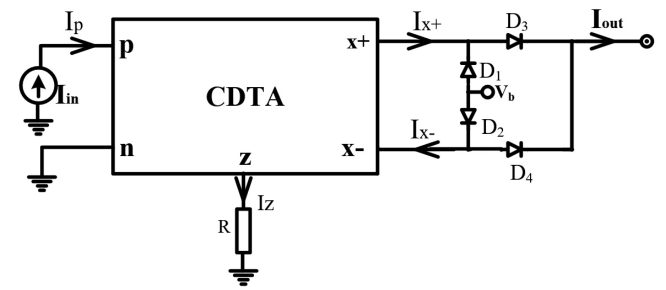

Fig. 3. Full-wave rectifier example circuit obtained using CDTA [37].

The development of OTA- and CDTA-based rectifiers has been a significant focus in the field of electronic circuit design. In 2008, Biolek, Hancioglu, and Keskin [34] demonstrated that CDTAs offer high input impedance and excellent linearity, making them highly effective in current-mode circuits. Their foundational work provided the theoretical basis for leveraging CDTAs in sensitive applications, paving the way for future advancements. Building on this foundation, Khateb, Vavra, and Biolek [35] proposed a simplified design in 2010, using a single CDTA and two diodes to construct a full-wave rectifier. This innovative approach delivered high accuracy over a wide bandwidth, proving the practical potential of CDTAs for rectification tasks. The study described in [36] introduces a current-mode precision full-wave rectifier utilizing CCCIIs and OTAs. This innovative design ensures the rectification of current signals with a controllable output magnitude that remains unaffected by temperature variations. The circuit employs two CCCIIs and two OTAs operating in saturation mode as current-switching devices, effectively rectifying input currents ranging from -100 μA to 100 μA under ±1.5V power supplies.

In 2011, Koton, Herencsar, and Vrba [35] addressed the limitations of earlier designs, achieving improved accuracy and extending the operational frequency range in their full-wave rectifier design. This work further reinforced the role of CDTAs in rectification circuits. These advancements were followed by the innovative work of Kaçar and Başak [37] in 2014, who proposed a mixed-mode design combining current- and voltage-mode operations. Their flexible approach highlighted the versatility of CDTAs and offered significant advantages in energy efficiency and adaptability to different circuit environments. The circuit diagram of this design is shown in Fig. 3. In 2016, Sagbaş, Minaei, and Ayten [38] proposed a design that utilized minimal active components (a single OTA, diodes, and resistors) to achieve full-wave rectification. This design featured electronically controlled current gain through the transconductance of the OTA and was validated through simulations and experimental testing. The circuit schematic of this rectifier is shown in Fig. 4.

Başak and Kaçar [4] advanced the field further in 2017 by introducing OTA-based rectifiers compatible with CMOS processes. These designs, requiring minimal components, demonstrated high performance in high-frequency applications and were optimized for monolithic IC integration. The graph illustrating how diodes are formed in the MOSFET structure is presented in Fig. 5. Progress continued in 2023 with Petrović's [7] groundbreaking design, which utilized only OTAs, eliminating the need for passive components. This design achieved exceptional accuracy and zero-crossing performance for input frequencies up to 1 MHz, with a current range of ±270 μA.

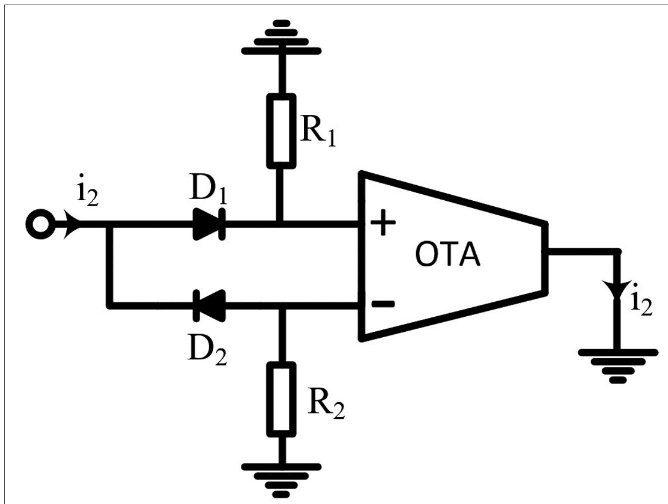

Fig. 4. Full-wave rectifier circuit using an OTA proposed by [38].

That same year, Bisariya and Afzal [39] presented a design employing transconductance-boosted Bulk-Driven Current Differencing Transconductance Amplifiers (BDCDTAs). Their low-power design, operating with a ±0.6 V supply and consuming only 143 μW, offered significant potential for practical applications. By increasing the number of transistors in the split network, the design demonstrated tunability and enhanced output current. Finally, Kumar [3] in 2024 introduced a compact full-wave rectifier design that combined CFDITA and MOS transistors. This design achieved both high accuracy and energy efficiency, setting a new benchmark in rectification circuits.

Some designs utilize OTAs exclusively, which simplifies the circuit and enhances its linearity and zero-crossing performance. These designs are effective for frequencies up to 1 MHz and are highly suitable for modern IC technologies [7]. The half/full-wave rectifier proposed by Petrovic [7] operates in Current Mode and is depicted in Fig. 6. The use of transconductance-boosted BDCDTA allows for low-voltage and low-power applications, making these designs ideal for energy-efficient systems [39].

Certain designs, such as those using a CFDITA, eliminate the need for diodes and resistors, further simplifying the circuit and enhancing its integration potential [3]. Fig. 7a and b circuits represent different approaches to rectifier design. Fig. 7a utilizes a CFDITA and two MOS transistors (PMOS and NMOS) to perform the rectification process. In this design, two input currents (I_{in1} and I_{in2}) are required to be equal ($I_{in1} = I_{in2} = I_{in}$) and are used to control the gate voltages of the MOS transistors. Depending on the polarity of the input current, the voltage at terminal Z, which is a high-impedance connection, saturates to either V_{DD} or V_{SS}. As a result, the output current (I_{out}) is determined based on the polarity of the input current. However, this design requires the input currents to be equal, necessitating additional arrangements, which may complicate the implementation. On the other hand, Fig. 7b is a modified version of Fig. 7a with the inclusion of a current inverter. This modification eliminates the need for equal input currents. Instead, a single input current (I_{in}) is used and directly connected to the low-impedance terminal F. The current inverter enhances the circuit's functionality by removing the input current matching requirement, while the output current remains determined by the input current's polarity, like Fig. 6a. In conclusion,

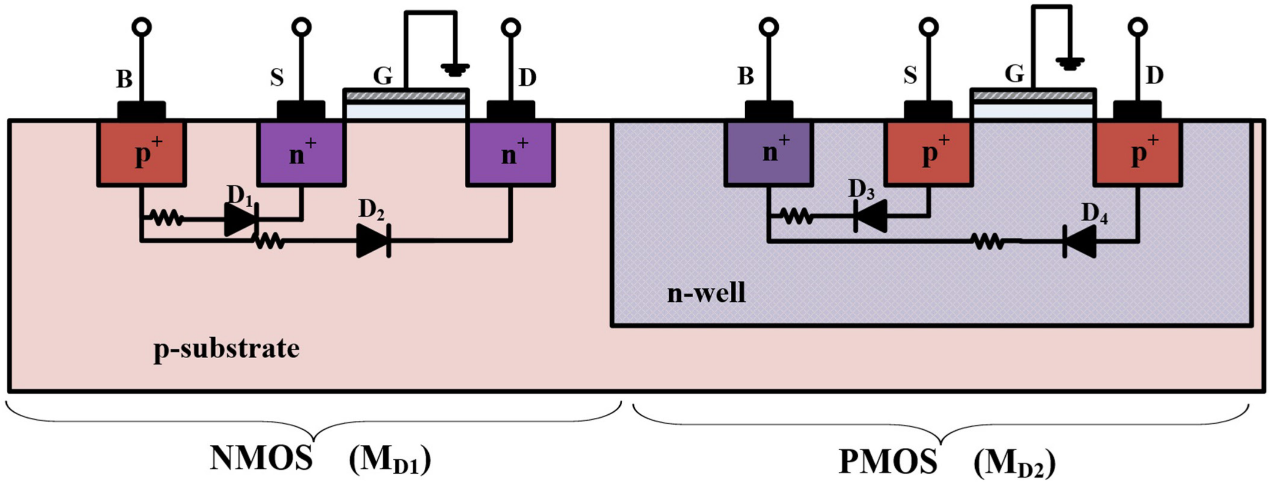

Fig. 5. The process illustrating the formation of diodes within the MOSFET structure [4].

while Fig. 7a offers a simpler structure, it requires equal input currents, which introduces additional implementation challenges. In contrast, Fig. 7b improves practicality by eliminating the need for input current matching with the inclusion of a current inverter to enhance functionality. The choice between these designs depends on the specific requirements of the application and the desired balance between simplicity and functionality.

Current-mode active rectifiers are also applied in wireless charging systems, where they provide accurate output current regulation. These systems achieve high efficiency and are designed to operate at frequencies like 6.78 MHz, demonstrating their applicability in IoT devices [40].

The chronological development of these studies underscores the technological advancements and innovative approaches in OTA- and CDTA-based rectifiers. These designs offer distinct advantages, including low power consumption, high accuracy, and integration simplicity, making them invaluable for modern electronic systems.

V. PRECISION RECTIFIERS BASED ON CURRENT DIFFERENCING BUFFERED AMPLIFIER CIRCUITS

In the ongoing pursuit of designing efficient and precise rectifier circuits, the Current Differencing Buffered Amplifier (CDBA) has emerged as a pivotal building block in modern electronic systems. Renowned for its inherent versatility, the CDBA offers unique advantages such as low input impedance, high output impedance, and seamless integration into current-mode systems. These characteristics position it as a cornerstone in the development of rectifiers capable of addressing the complex demands of high-frequency operation, minimal harmonic distortion, and robust scalability. Beyond these technical merits, CDBA-based designs have proven instrumental in simplifying circuit topologies without compromising performance, making them ideal for cascading applications in measurement, instrumentation, and telecommunication. As the focus on compact and cost-efficient solutions intensifies, the exploration of CDBA-driven rectifiers provides critical insights into advancing the state-of-the-art in current-mode rectification.

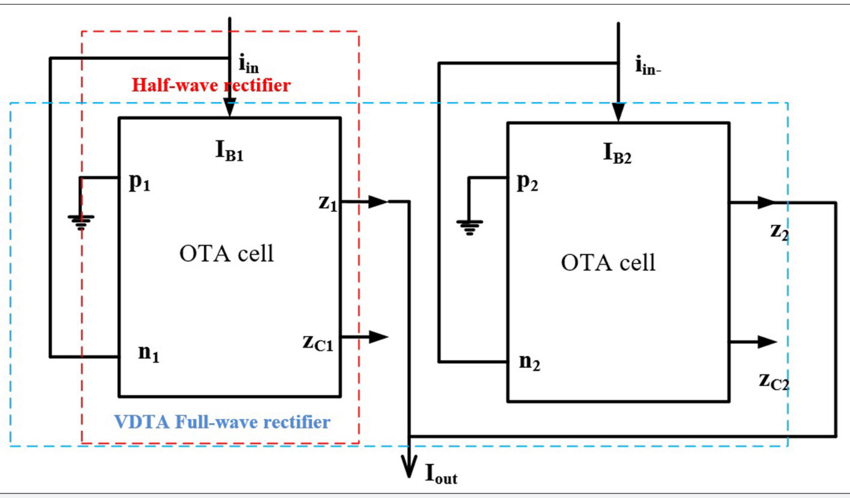

Fig. 6 Current mode half wave and FWR with OTA [7].

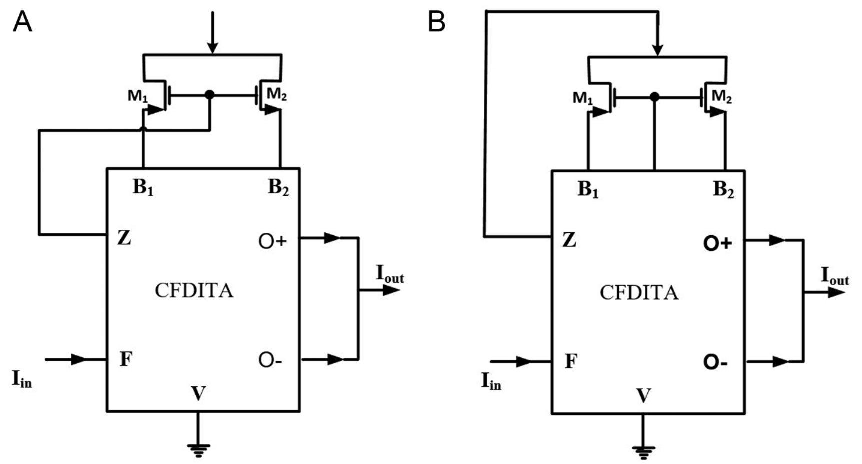

Fig. 7. CFIDTA (Current Follower Input Differencing Transconductance Amplifier) based rectifier examples [3].

The work by Erkan et al. [41] presents a novel approach to current-mode full-wave rectification using a single CDBA and two diodes. This design simplifies the circuit architecture, offering low input and high output impedances that make it ideal for cascading in current-mode systems. Two configurations are explored: CMOS-based and Current Feedback Operational Amplifier (CFOA)-based CDBA implementations. The CMOS realization is optimized for IC fabrication, while the CFOA-based implementation leverages commercially available components for cost-effective solutions. Figure 8 shows the CFOA-based rectifier implementation, redrawn based on the original design in [41].

Key advantages of the proposed rectifiers include wide-range input current handling, suitability for high-frequency applications, and minimal component matching requirements. The CFOA-based model, built with AD844 chips, demonstrates robust performance up to 100 MHz for input currents of 10 mA. Simulation results indicate that deviations in output accuracy occur at extremely high frequencies due to diode limitations, which can be mitigated by using high-speed diodes or biasing techniques.

The proposed circuits emphasize the efficiency and scalability of CDBA-based designs in current-mode signal processing. This work contributes to the field by providing a versatile and economical alternative for precise rectification in applications such as measurement, instrumentation, and telecommunication.

Paul et al. [42] proposed a low-voltage class AB CMOS current mirror functioning as a precision rectifier, designed to handle bidirectional current signals significantly larger than the bias current. The circuit used a Schmitt-trigger-controlled current switch to direct positive and negative currents to NMOS and PMOS mirrors, achieving high linearity with minimal distortion. Simulations conducted in 180nm CMOS technology with a ±0.5V supply demonstrated its capability to process 200μA peak-to-peak currents with a 1μA bias current and a 115 MHz bandwidth. This design was particularly suited for high-frequency, low-power applications, including biomedical devices and wireless power systems. Roy et al. [6] proposed a current-mode precision full-wave rectifier employing a single Inverted Z-Copy CDBA (IZC-CDBA) and two MOSFETs. This innovative design generates both inverting and non-inverting rectified outputs without requiring any topology modifications. The circuit features low input impedance, high output impedance, and full cascadability, making it suitable for high-frequency operations and IC implementation. Simulations demonstrated its efficient operation up to 200 MHz with low power consumption, high dynamic range, and minimal total harmonic distortion, highlighting its potential for high-frequency signal processing and low-power systems [6]. Figure 9 presents the IZC-CDBA-based precision full-wave rectifier as proposed in [6], which provides both inverting and non-inverting outputs in a current-mode configuration.

VI. INNOVATIVE APPLICATIONS OF CURRENT-MODE RECTIFIERS

The swift advancement of electronic systems has prompted the necessity for the creation of novel rectifier configurations that surpass traditional methodologies to satisfy the requirements of contemporary applications. Accuracy, efficiency, and scalability have emerged as critical factors, especially in current-mode circuits where precise signal processing and minimal energy dissipation are essential. Recent developments have unveiled pioneering methodologies, harnessing innovative architectures and atypical active components to transform the functionalities of rectification systems. These advancements tackle enduring obstacles such as harmonic distortion, high-frequency performance, and component intricacy, thereby facilitating revolutionary applications across a myriad of disciplines. The subsequent sections elucidate some of the most innovative contributions to the discipline, highlighting designs that epitomize the amalgamation of theoretical creativity and practical applicability. By incorporating advanced elements such as Winner-Takes-All (WTA) circuits and memristive technologies, these investigations provide persuasive insights into the potential of current-mode rectifiers in confronting emerging challenges within signal processing, secure communications, and high-speed instrumentation.

The study by Koton et al. [43] introduces a current-mode precision full-wave rectifier leveraging a two-cell WTA circuit. Unlike traditional designs that require phase-inverted signals or complex active building blocks, the proposed circuit demonstrates a compact and efficient architecture utilizing CMOS technology. This design eliminates the need for signal inversion and offers complementary phase outputs with high impedance, making it suitable for high-frequency applications. The integration of the WTA circuit provides a robust mechanism for precise rectification by directly comparing input currents and dynamically steering them to generate absolute current values. This approach not only simplifies the design but also enhances performance at frequencies exceeding 70 MHz, as verified through SPICE simulations. Such attributes make the proposed design a compelling choice for current-mode rectifiers used in instrumentation, signal processing, and high-speed analog systems. By focusing on minimalism and efficiency, the proposed design aligns with the demands of modern analog signal processing, offering a pathway for further exploration in high-frequency and low-power applications.

Memristive circuits, such as the full-wave diode bridge rectifier analyzed by Sadecki and Marszalek [44], offer a novel perspective for current-mode systems. Their unique current-voltage hysteresis characteristics, high sensitivity to parameter variations, and ability to transition between periodic and chaotic responses present valuable opportunities for precise current signal processing and nonlinear control in current-mode rectifiers. The bifurcation analysis conducted in the study highlights how these circuits can be optimized for stable or chaotic operation, providing a versatile approach for applications in current-mode design, including chaotic cryptography and secure communications.

The continuous evolution of analog circuit design has led to significant improvements in current-mode rectifiers, particularly through the integration of Floating Gate MOS (FGMOS) and DTMOS technologies. These innovations offer substantial advantages in low-power, high-linearity, and high-frequency applications, addressing the limitations of conventional rectification methods.

The FGMOS transistors, characterized by their tunable threshold voltage and enhanced charge storage capability, provide precise current manipulation, making them highly effective in rectifier designs tailored for low-power and high-speed analog signal processing. The work by Moradinezhad et al. [45] introduces a high-linearity full-wave rectifier based on a current squarer cell utilizing FGMOS transistors. By implementing a dual translinear loop approach, this current-mode rectifier achieves robust performance with a -3 dB bandwidth of 148.4 MHz and low power consumption of 44 μW, making it highly suitable for energy-efficient analog signal processing applications. Its wide bandwidth and precision characteristics enable applications in instrumentation, communication systems, and portable measurement devices, where efficient AC to DC conversion and signal detection are critical. Additionally, it plays a key role in peak detection, amplitude modulation, and signal polarity detection, ensuring accurate signal processing in various electronic systems.

Similarly, Chhabra et al. [46] present a low-voltage squarer/divider circuit using FGMOS transistors, which has been further adapted for full-wave rectification. By leveraging the MOS Translinear Loop principle, the proposed rectifier achieves superior linearity and an extended input dynamic range while operating at a supply voltage as low as 0.7V. With a -3dB bandwidth of 17.37 MHz and a maximum power consumption of only 115.4 μW, this design is particularly well-suited for low-power Very Large Scale Integration (VLSI) applications and portable electronic systems.

In addition to FGMOS-based rectifiers, DTMOS technology has emerged as a promising alternative for ultra-low voltage and high-efficiency rectification circuits. DTMOS transistors leverage threshold voltage modulation, allowing for improved conduction properties, particularly in sub-threshold regions. Unlike FGMOS transistors, which offer a programmable threshold voltage, DTMOS devices exhibit dynamic threshold voltage reduction, making them highly efficient in energy-harvesting and low-power IoT applications.

A comparative analysis of FGMOS and DTMOS-based rectifiers reveals key distinctions in performance characteristics. FGMOS-based designs excel in high-frequency applications, offering broader bandwidths and better linearity due to their charge storage capabilities. These attributes make them ideal for high-speed signal processing, secure communications, and biomedical instrumentation. On the other hand, DTMOS-based rectifiers are particularly effective in ultra-low power designs, as their low leakage current and efficient body-biasing mechanisms minimize energy consumption, making them suitable for wearable electronics and self-powered systems.

While FGMOS rectifiers require additional charge-balancing techniques to prevent long-term charge-trapping effects, DTMOS-based circuits face potential scalability issues in deep-submicron technologies, where process variations in body-biasing effects may impact performance consistency. Despite these trade-offs, both technologies play a crucial role in advancing rectification techniques, with FGMOS-based designs favoring high-performance applications and DTMOS-based designs excelling in energy-constrained environments.

VII. DISCUSSION

This study provides a comprehensive analysis of CI-CO rectifiers, showcasing their significant advantages over traditional rectifier designs. The chronological review in Table I highlights the steady evolution of CI-CO rectifiers, reflecting their growing relevance in modern electronics. By leveraging advanced active components such as CFDITAs, CDTAs, and CCCIIs, CI-CO rectifiers effectively address challenges inherent in traditional designs, including diode voltage drops, harmonic distortion, and inefficiencies in low-signal-level applications.

One of the most prominent trends observed in the literature is the transition towards resistor-less and diode-less configurations. Designs such as those proposed by Safari et al. [26] and Kumar [3], utilizing CFDITAs and DXCCIIs, demonstrate the elimination of passive components, resulting in enhanced integration capabilities and reduced parasitic effects. These advancements are particularly beneficial for applications requiring compact and energy-efficient solutions, such as biomedical devices, IoT systems, and portable electronics. Furthermore, Complementary Metal-Oxide-Semiconductor (CMOS)-based implementations, as shown in [9], achieve minimal power consumption and high operational frequencies, further solidifying CI-CO rectifiers as an optimal choice for high-speed and low-power scenarios.

A key characteristic of CI-CO rectifiers is their ability to deliver steady and precise current regulation, particularly in applications requiring meticulous control across varying load conditions. For instance, in motor drives and battery charging systems, these circuits ensure consistent performance, prolonging device lifespan and reducing energy waste. The incorporation of feedback mechanisms enables CI-CO circuits to swiftly respond to load variations, ensuring stable

TABLE I. COMPARISON OF ALL PROPOSED CURRENT-MODE AND CURRENT INPUT AND CURRENT OUTPUT RECTIFIERS

Article	Year	Power Consumption	Frequency	Active Component (counts)	Resistor Counts	Diode Counts	Supply Voltage
[47]	1995	*NA	2 MHz	2 CCII+	2 R	4-Diodes	15V
[48]	2000	*NA	100 KHz	2 OPA+ 1 CCI	3 R	2-Diodes	–
[49]	2001	1.8 mW	100 MHz	2 CCII+	2 R	4-Diodes	±1.2V
[25]	2002		1 MHz	2 OPA+2 CCII	2 R	4-Diodes	–
[50]	2003	*NA	1 MHz	DOCF	2 R	2-Diodes	±10 V
[24]	2004	*NA	100 kHz	3 CCCII or 4 CCCII	R	0	±15 V
[36]	2006	554.8µW	1 MHz	2 CCCIIs and 2 OTAs	0	0	±1.5V
[14]	2007	*NA	1 MHz	OPA1 + OPA2	3 R	2-Diodes	± 1V
[34]	2008	6.31 mW	5 MHz	1 CDTA	0	4-Diodes	±1.8 V
[35]	2010	*NA	5 MHz	1 CDTA	1 R	2-Diodes	±5 V
[9]	2010	0.08 µW	20 MHz	12 CMOS	0	0	-0.39V and +0.37V
[51]	2010	*NA	500 kHz	CCII + UVC	0	2-Diodes	±5 V
[23]	2011	*NA	10kHz	2 CCII or CCII and UVC	R	0	*NA
[43]	2011	*NA	70 MHz	2-cell WTA- 21 transistors	0	0	±1.5 V
[23]	2011	*NA	1 MHz	CCII + UVC veya 2 CCII	0	2-Diodes	±5 V
[52]	2011	*NA	10 MHz	1 CDTA	0	4-Diodes	±5 V
[53]	2011	*NA	30 MHz	2 CDTA	0	0	±3V
[54]	2012	<15 µW	1 MHz	7 CMOS	0	0	±0.75 V
[37]	2014	1.12 mW	100 MHz	1 CDTA + 2 CMOS	1 R	0	±1.5V
[41]	2015	*NA	100 MHz	2 CFOA (AD844 based)	0	2-Diodes	±12V
[41]	2015	*NA	4.5 MHz	20 MOS + 2 Current Sources	0	2-Diodes	±1.5 V
[38]	2016	*NA	1 KHz–100 kHz–1 MHz	OTA	2R	2-Diodes	±1.5V
[4]	2017	*NA	1 GHz	2 CMOS	0	0	±0.9 V
[26]	2017	188 µW	1 MHz	1 DO-CCII and MOSFETs	0	0	±0.9 V
[27]	2017	2.1 µW	85.85 MHz153.23MHz	12 MOSFETs	0	0	±0.75 V
[27]	2017	0.16 mW	153.2 MHz	12 CMOS	3 R	0	±0.75 V
[26]	2018	188 µW	1kHz–1 MHz	34 CMOS	0	0	±0.9 V
[55]	2019	47.97µW	5kHz–200kHz	Class AB CMOS current mirrors used (FWR)	Many floating R and C	0	±0.9 V
[55]	2019	23.76µW	5kHz–200kHz	Class AB CMOS current mirrors used (HWR)	Many floating R and C	0	±0.9 V
[45]	2020	44µW	148.4 MHz	FGMOS based 8 MOSFETs	8 C	0	1V
[11]	2021	2.94 mW	200 MHz	DDCC, (16 MOSFETs)	R	0	± 0.9 V
[6]	2023	0.318 mW	200 MHz	IZC-CDBA	0	0	± 0.6 V
[7]	2023	0.54 mW	1 MHz	OTA (VDTA)	0	0	±0.9 V
[39]	2023	143 uW	500 Hz	BD-CDTA	R	2-Diodes	±0.6 V

(*Continued*)

TABLE I. COMPARISON OF ALL PROPOSED CURRENT-MODE AND CURRENT INPUT AND CURRENT OUTPUT RECTIFIERS (*Continued*)

Article	Year	Power Consumption	Frequency	Active Component (counts)	Resistor Counts	Diode Counts	Supply Voltage
[42]	2023	*NA	1MHz	2 Current mirrors and Current switch	0	0	±0.5 V
[46]	2023	44μW	190 MHz	FGMOS based 14 MOSFETs	4 C	0	0.7 V
[3]	2024	0.76 mW	30 MHz	19 MOSFETs	0	0	± 1.25V
[30]	2024	0.73 mW	5MHz	1 DXCCII and 3 MOS	0	0	±1.25 V

BD-CDTA, Bulk-Driven Current Differencing Transconductance Amplifier; CCCII, Current-Controlled Current Conveyor (Second Generation); CCI, Current Conveyor (First Generation); CCII+, Second Generation Current Conveyor (Positive Type); CDBA, Current Differencing Buffered Amplifier; CDTA, Current Differencing Transconductance Amplifier; CFOA, Current Feedback Operational Amplifier; DOCF, Differential Output Current Follower; DXCCII, Differential Extra-X Current Conveyor; FGMOS, Floating Gate MOS; FWR, Full-Wave Rectifier; HWR, Half-Wave Rectifier; IZC-CDBA, Impedance-Zero Controlled Current Differencing Buffered Amplifier; MOSFET, Metal-Oxide-Semiconductor Field-Effect Transistor; OPA, Operational Amplifier; OTA, Operational Transconductance Amplifier; UVC, Universal Voltage Conveyor; VDTA, Voltage Differencing Transconductance Amplifier; WTA, Winner-Take-All Circuit.
*NA, Not Available.

operation even under dynamic conditions. This adaptability has made them indispensable in critical applications such as Light Emitting Diode (LED) drivers, laboratory power supplies, and industrial automation systems.

Moreover, the integration of sophisticated control algorithms, such as predictive control and adaptive filtering, has further enhanced the operational effectiveness of CI-CO rectifiers. These methods allow for the proactive adjustment of current output in response to anticipated load variations, thereby minimizing power losses and optimizing energy management. High-frequency switching components, frequently employed in modern designs, improve thermal performance and reduce the physical footprint of the circuits, making them particularly suitable for compact applications like electric vehicles and portable devices. Additionally, the integration of smart grid functionalities within CI-CO rectifiers presents an exciting opportunity to revolutionize power allocation and regulation, paving the way for more sustainable energy solutions.

Despite their numerous advantages, CI-CO rectifiers are not without limitations. As highlighted in Table I and the reviewed literature, high-frequency operation often introduces increased sensitivity to parasitic effects and non-idealities in active components. For instance, designs like those of Srivastava et al. and Roy et al. [6] have demonstrated remarkable performance at frequencies exceeding 100 MHz, yet they require meticulous component selection and calibration to maintain robustness. Furthermore, the cost and design complexity of CI-CO rectifiers may limit their adoption in applications where simplicity and cost-effectiveness are prioritized, such as basic AC-DC conversion.

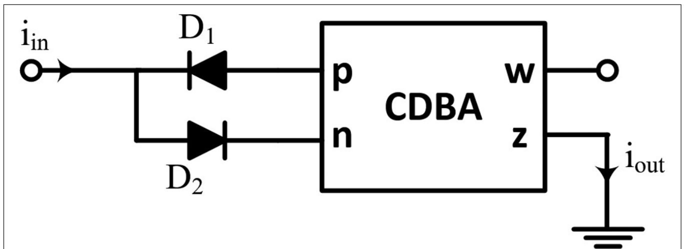

Fig. 8. Current differencing buffered amplifier-based rectifier [41].

The ability of CI-CO circuits to adapt to fluctuating energy sources is another critical advantage. For example, in renewable energy systems like photovoltaic arrays and fuel cells, input current variations are common. CI-CO rectifiers, equipped with advanced feedback systems, react quickly to these changes, maintaining a steady output current and ensuring efficient energy transfer. This flexibility not only reinforces energy stability but also improves the overall efficiency and reliability of power systems, making CI-CO circuits essential in the shift towards sustainable energy solutions.

From a practical perspective, the comparative analysis Table I underscores the versatility of CI-CO rectifiers across a wide range of applications. Configurations employing IZC-CDBAs [6] excel in high-frequency signal processing, while designs based on BD-CDTAs [39] offer high precision in low-power and low-voltage environments. These advancements enable CI-CO rectifiers to accommodate diverse load types—resistive, capacitive, and inductive—broadening their applicability in fields such as renewable energy management, telecommunications, and medical diagnostics.

Finally, CI-CO rectifiers offer critical protective features, including overcurrent protection and EMI suppression, which are vital for ensuring system reliability and longevity. For instance, in industrial motor control systems, these circuits can detect overload or short-circuit conditions and activate self-defense mechanisms to prevent damage. Similarly, their low-noise operation and resistance to EMI enhance reliability in sensitive applications like telecommunications and medical devices, where precision and stability are paramount.

In conclusion, CI-CO rectifiers represent a transformative advancement in modern electronics, bridging the gap between precision, efficiency, and scalability. However, challenges such as parasitic effects, tuning complexity, and cost remain areas for further exploration. Future research should focus on developing hybrid designs that integrate the simplicity of traditional rectifiers with the advanced features of CI-CO configurations. Additionally, the adoption of novel materials, such as graphene-based transistors and memristors, alongside the optimization of control algorithms, could unlock new opportunities for these circuits. By addressing these challenges and leveraging their inherent advantages, CI-CO rectifiers are poised to play a pivotal role in the advancement of next-generation electronic systems.

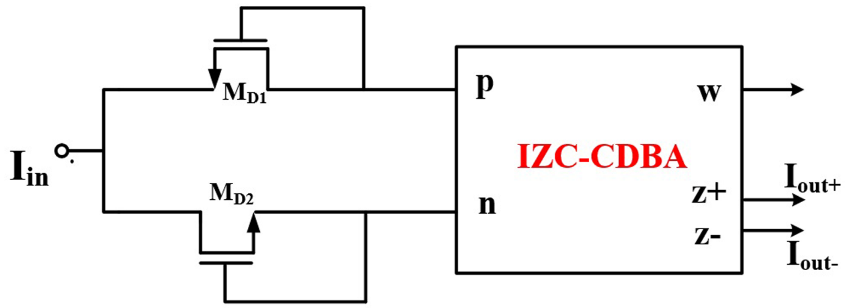

Fig. 9. Current differencing buffered amplifier-based current mode precision FWR [6].

VIII. CONCLUSION

This study has examined the evolution, design, and applications of CI-CO rectifiers, emphasizing their critical role in modern electronic systems. CI-CO rectifiers distinguish themselves from traditional designs by their precision, energy efficiency, and compatibility with ICs, making them ideal for compact and low-power applications. Through detailed analysis, it has been demonstrated that CI-CO rectifiers effectively address limitations such as voltage drops, non-linearities, and high ripple, which are common in traditional rectifiers. By leveraging advanced active elements, such as OTAs and current conveyors, these circuits minimize passive component usage, ensuring superior performance in high-frequency and low-signal environments.

The versatility of CI-CO rectifiers allows them to accommodate diverse applications, ranging from medical diagnostics and telecommunications to renewable energy systems and IoT-based devices. Their ability to handle fluctuating energy sources and varying load types with precision makes them indispensable in high-demand scenarios, such as electric vehicle charging stations and industrial automation systems. Additionally, CI-CO circuits' inherent feedback mechanisms enable robust protection features, ensuring system reliability and safety in critical applications.

While CI-CO rectifiers continue to evolve with enhanced integration and optimized circuit architectures, emerging technologies such as FGMOS and DTMOS transistors provide additional design opportunities. FGMOS-based rectifiers leverage tunable threshold voltage control, enhancing precision and frequency response, making them particularly useful in high-speed analog processing applications. Meanwhile, DTMOS-based rectifiers optimize ultra-low power consumption, offering promising solutions for energy harvesting and wearable electronics. The integration of these advanced semiconductor technologies may further refine CI-CO rectifier designs, improving their adaptability in high-frequency, low-power applications.

Future research could explore novel materials, hybrid designs, and smart control algorithms to further optimize CI-CO rectifiers for emerging applications in high-frequency, low-power electronics. The comprehensive comparative analysis presented in this study aims to serve as a reference for researchers and engineers, fostering innovation and practical solutions in the field of precision analog rectification.

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