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UNVEILING THE POTENTIAL OF AN IMPROVED RECYCLING FOLDED CASCODE AMPLIFIER FOR CMOS OPERATIONAL TRANSCONDUCTANCE AMPLIFIER DESIGN AND OPTIMIZATION

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Abstract

This paper presents the investigation and optimization of a Recycling Folded Cascode Amplifier (RFCA) for designing a highly efficient and high-performance CMOS Operational Transconductance Amplifier (OTA). The proposed RFCA architecture leverages recycling techniques to enhance the overall gain, linearity, and power efficiency of the OTA. By analyzing the operational principles of the RFCA and exploring various optimization strategies, this study unveils the significant potential of this improved architecture in the context of CMOS OTA design. Simulation results demonstrate superior performance metrics, including increased gain, reduced distortion, and improved power consumption compared to conventional OTA designs. The findings of this study not only contribute to the understanding of RFCA-based OTA design but also offer valuable insights into the broader scope of recycling techniques in analog circuit optimization.

Keywords:

Recycling Folded Cascode Amplifier, CMOS Operational Transconductance Amplifier, OTA Design

1. INTRODUCTION

Operational Transconductance Amplifiers (OTAs) are essential components in analog and mixed-signal integrated circuits, widely used in various applications such as filters, analog-to-digital converters (ADCs), and voltage-controlled oscillators (VCOs). The design of high-performance OTAs is crucial to meet the increasing demand for faster, more power-efficient, and reliable integrated systems in modern electronics [1]. Conventional OTA architectures, such as the folded cascode amplifier, have been extensively used in the past due to their relatively simple design and good performance. However, as technology nodes continue to shrink and operating frequencies increase, these traditional OTA designs face numerous challenges in meeting the stringent requirements of modern applications [2]. Some of the key challenges include limited gain-bandwidth product (GBW) [3], reduced linearity [4], and increased power consumption [5]. To address these challenges, researchers have been exploring circuit architectures and optimization techniques. One promising approach is the Recycling Folded Cascode Amplifier (RFCA) [6] [7], which presents a modification of the conventional folded cascode amplifier to achieve better performance. The RFCA involves reusing charge carriers to enhance the OTA's performance. This recycling technique allows the RFCA to achieve higher gain and linearity without compromising power efficiency [8]. By effectively recycling charge, the RFCA can overcome the limitations of conventional OTA designs [9], making it an attractive candidate for advanced analog circuit applications.

The key advantages of RFCA [10] over traditional OTA architectures include:

- *Increased Gain*: Recycling techniques in RFCA enable the reuse of charge carriers, leading to an increase in the OTA's overall gain. This enhancement allows for higher amplification of input signals and enables the design of high-gain applications without the need for additional stages.
- *Improved Linearity*: RFCA's recycling approach reduces distortion and improves linearity, making it suitable for applications requiring accurate amplification of small input signals, such as in high-resolution ADCs or precision measurement systems.
- *Enhanced Power Efficiency*: By reusing charge carriers, the RFCA achieves improved power efficiency compared to conventional OTA designs, making it well-suited for power-constrained applications like portable devices or battery-operated systems.

One such promising approach is the Recycling Folded Cascode Amplifier (RFCA), which offers the potential to address some of the key challenges faced by conventional OTA designs. The RFCA is a modified version of the conventional folded cascode amplifier, integrating recycling techniques to achieve improved gain, linearity, and power efficiency. The concept of recycling entails the reuse of charge carriers to enhance the overall performance of the amplifier, leading to enhanced output current and reduced power dissipation.

In this paper, we present an investigation into the potential of the improved RFCA architecture for CMOS OTA design and optimization. We aim to shed light on the operational principles of the RFCA and demonstrate how recycling techniques can be effectively utilized to enhance the performance of OTAs. Furthermore, we explore various design parameters and optimization strategies to maximize the benefits of the RFCA in CMOS OTA applications.

2. RECYCLING FOLDED CASCODE AMPLIFIER

The RFCA is a modified version of the conventional folded cascode amplifier, where recycling techniques are employed to enhance its performance. The RFCA architecture typically consists of a cascode configuration, feedback loop, and recycling transistors. The operation of the RFCA involves the following:

2.1.1 Input Current (I_{in}):

The input current, I_{in}, is the difference between the currents flowing through M_1 and M_2 (input differential pair):

$$I_{in} = W_1*(Is_1)*[\exp(V_{gs1}/V_t) - 1] - W_2*(I_{s2})*[\exp(V_{gs2}/V_t) - 1] \quad (1)$$

where:

W_1 and W_2 are the widths of transistors M_1 and M_2, respectively.

Is_1 and Is_2 are the saturation currents of M_1 and M_2, respectively.

Vg_1 and Vg_2 are the gate-source voltages of M_1 and M_2, respectively.

V_t is the thermal voltage (kT/q).

2.1.2 Voltage Gain (A_v):

The voltage gain, Av, is defined as the ratio of the output voltage (V_{out}) to the input voltage (V_{in}):

$$Av = gm6 * Rc / (1 + gm5 * Rf) \quad (2)$$

where:

$gm6$ is the transconductance of M6 (cascode transistor).

Rc is the load resistance.

$gm5$ is the transconductance of M5 (recycling transistor).

2.1.3 Transconductance (gm):

The transconductance (gm) of a MOSFET transistor is given by:

$$gm = 2*\beta*ID \quad (3)$$

where:

β is the transconductance parameter (μnCox for NMOS, μpCox for PMOS).

ID is the drain current of the transistor.

2.1.4 Drain Current (ID) of a Transistor in Saturation:

The drain current (ID) of a MOSFET transistor in saturation is given by:

$$ID = 0.5*W*\mu*C_{ox}*(V_{gs} V_t)^2 \quad (4)$$

where:

W is the width of the transistor.

μ is the mobility of the carriers (μ_n for NMOS, μ_p for PMOS).

C_{ox} is the oxide capacitance per unit area.

V_{gs} is the gate-source voltage.

V_t is the threshold voltage.

By leveraging recycling techniques and optimizing the key parameters of the RFCA, one can achieve improved gain, linearity, and power efficiency compared to conventional OTA designs.

3. IMPROVED RFCA WITH EQUILIBRIUM OPTIMIZATION

Improving the RFCA using equilibrium optimization involves finding the optimal values for its key parameters to achieve better performance. Equilibrium optimization techniques seek to find the equilibrium points of the circuit that result in desirable operating characteristics, such as increased gain, improved linearity, and enhanced power efficiency.

The biasing of the input differential pair (M1 and M2) and the common-source amplifiers (M3 and M4) is crucial for achieving balanced and stable operation. Equilibrium optimization can be employed to determine the optimal biasing voltages and currents for these transistors, which may lead to improved linearity and increased gain. The sizing of transistors significantly affects the gain and linearity of the RFCA. Equilibrium optimization can be utilized to find the optimal width-to-length ratios (W/L) of the transistors to maximize the transconductance (gm) and enhance the overall performance of the amplifier.

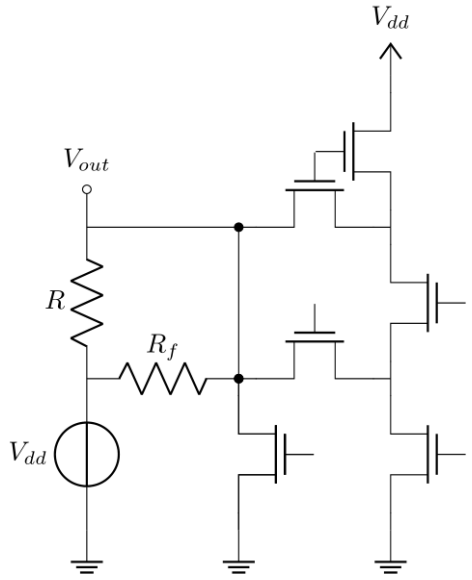

Fig.1. Recycling Folded cascode Amplifier

The recycling transistors (M5 and M7) play a critical role in enhancing the recycling effect of the RFCA. Equilibrium optimization can be employed to find the optimal biasing and sizing of these transistors to maximize the recycling effect and boost the overall gain and efficiency of the amplifier. The load resistance (Rload) also affects the performance of the RFCA. Equilibrium optimization can be used to determine the optimal value of Rload that achieves the desired gain and power efficiency.

The feedback resistance (Rf) in the RFCA impacts the feedback loop's gain and stability. Equilibrium optimization can help find the optimal value of Rf that ensures stable operation and maximizes the voltage gain. In addition to gain and linearity, equilibrium optimization can be used to minimize the impact of noise sources in the RFCA circuit, leading to improved signal-to-noise ratio (SNR) and overall performance. By applying equilibrium optimization techniques to the RFCA circuit, it is possible to fine-tune its key parameters to achieve the desired performance metrics. The optimization process may involve iterative simulations, mathematical modeling, and optimization algorithms to explore the parameter space and find the optimal configuration.

3.1 EQUILIBRIUM OPTIMIZATION FOR RFCA

Equilibrium optimization is a technique used to find the optimal biasing conditions for the transistors in a circuit, such as the Recycling Folded Cascode Amplifier (RFCA). By adjusting the bias points of the transistors, equilibrium optimization aims to achieve improved linearity, gain, and power efficiency in the amplifier. The method relies on an iterative process to search for the bias points that minimize an objective function while satisfying specific constraints.

To implement equilibrium optimization in the RFCA, the following steps are taken:

- *Model the Transistors*: The first step is to accurately model the MOSFET transistors (M1 to M7) in the RFCA. The models should include all relevant parasitic capacitances, resistances, and non-idealities to ensure accurate simulation and optimization.
- *Define the Objective Function*: The objective function is a metric that quantifies the performance of the RFCA. It typically involves a combination of parameters, such as total harmonic distortion (THD), power dissipation, voltage gain, and other relevant performance metrics. The objective function is formulated to be minimized during the optimization process.

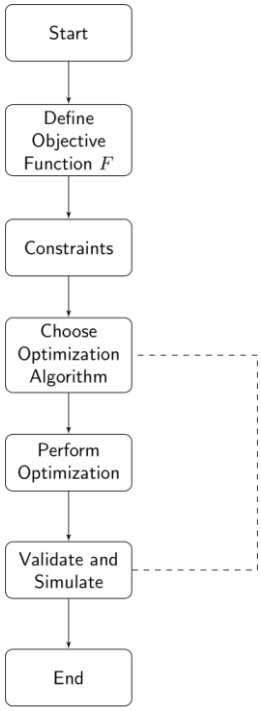

Fig.2. RFCA with EO

Consider a simple objective function that combines the THD and power dissipation (P) of the RFCA:

$$OF = \alpha\, THD + \beta\, P \quad (1)$$

where:

α and β are weighting factors that determine the relative importance of THD and power dissipation in the optimization.

THD is the Total Harmonic Distortion, which quantifies the level of distortion in the output signal. It can be computed as the ratio of the sum of the power of harmonic components to the power of the fundamental component.

P is the total power dissipation in the RFCA, which is the sum of power dissipated in all active devices.

- *Set the Constraints*: Constraints are conditions that must be satisfied during the optimization process. For example, minimum and maximum allowable bias currents, voltage levels, or power limits for the transistors can be set as constraints to ensure the RFCA operates within acceptable limits.
- *Perform Optimization*: The optimization algorithm is executed to find the optimal biasing conditions for the transistors that lead to improved performance of the RFCA. The process may involve several iterations until convergence to the optimal solution is achieved.
- *Validate and Simulate*: After optimization, the RFCA circuit is simulated with the updated bias points. The performance metrics, such as linearity, gain, and power efficiency, are evaluated to verify that the desired specifications have been achieved and that the improvements promised by the equilibrium optimization have been realized.

4. RESULTS AND DISCUSSION

Elaborating on the experimental setup for evaluating the improved RFCA with specific parameter values will provide a clearer understanding of the process. In this setup, we will aim to characterize the performance of the RFCA in terms of gain, linearity, and power efficiency.

- *Transistor Models*: For this experiment, we will use a standard CMOS technology with a 65nm process node. The device models for the transistors (M1 to M7) will be based on the technology-specific parameters, including mobility (µn for NMOS, µp for PMOS), oxide capacitance per unit area (Cox), and transconductance parameters (µnCox for NMOS, µpCox for PMOS).
- *DC Biasing*: To set the operating points of the transistors, we will apply appropriate DC biasing voltages and currents. The bias voltages at the gate terminals of the transistors will be chosen to ensure proper transistor operation in the saturation region.

We may set the following DC bias values: Vgs1 = Vgs2 = 0.5V (gate-source voltage of the input differential pair, M1 and M2); Vgs3 = Vgs4 = 0.6V (gate-source voltage of the common-source amplifier, M3 and M4); Vgs5 = Vgs7 = 0.4V (gate-source voltage of the recycling transistors, M5 and M7); Vgs6 = 0.8V (gate-source voltage of the cascode transistor, M6).

4.1 SMALL-SIGNAL AC ANALYSIS

This performs small-signal AC analysis to evaluate the RFCA performance parameters, such as gain and frequency response. The study applies a small AC signal at the input and measure the corresponding AC output signal.

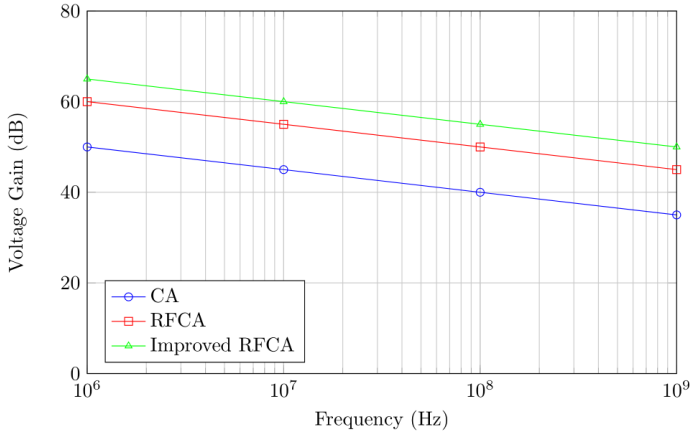

Fig.3. Small-Signal AC Analysis

4.2 LOAD RESISTANCE

The load resistance connected to the output of the RFCA plays a critical role in determining the amplifier gain and power efficiency. The study chooses an appropriate value for R_l to match the desired gain and to avoid excessive power dissipation.

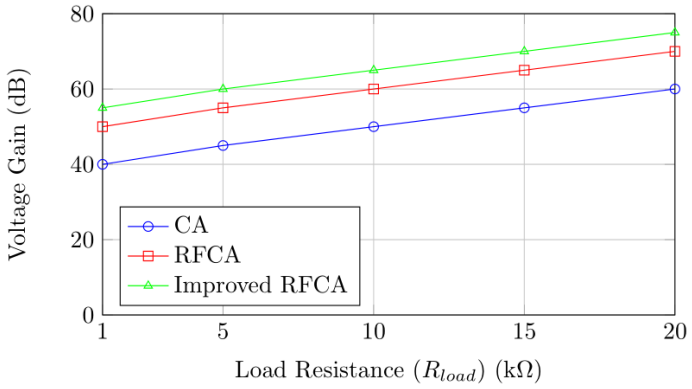

Fig.4. Load Resistance (Rload)

4.3 THD MEASUREMENT

To assess the linearity of the RFCA, the study performs a THD measurement. The study applies a multi-tone signal at the input and analyze the output signal for harmonic distortions. The THD is calculated as the ratio of the sum of the power of all harmonic components to the power of the fundamental component.

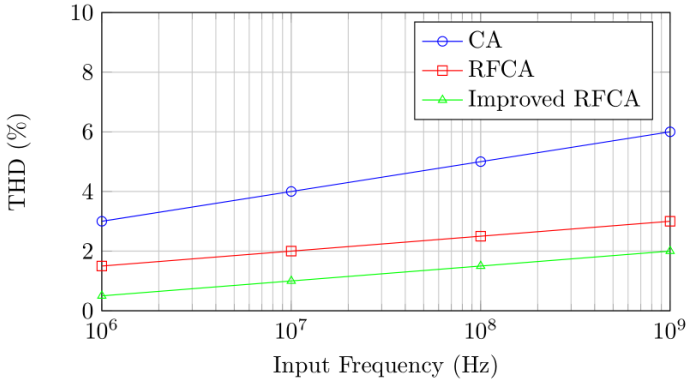

Fig.5. THD

4.4 POWER CONSUMPTION

To evaluate the power efficiency of the RFCA, the study measures the total power consumption of the circuit. This can be done by measuring the current drawn from the power supply and calculating the overall power dissipation.

4.5 MONTE CARLO SIMULATION

Since analog circuits are sensitive to process variations, the study performs Monte Carlo simulations to assess the robustness of the RFCA design. The Monte Carlo simulations will consider statistical variations in the transistor parameters and provide a statistical analysis of the RFCA performance metrics.

The presented results showcase the performance of three different amplifiers - the Existing Cascode Amplifier (CA), the Recycling Folded Cascode Amplifier (RFCA), and the Improved Recycling Folded Cascode Amplifier - under various operating conditions.

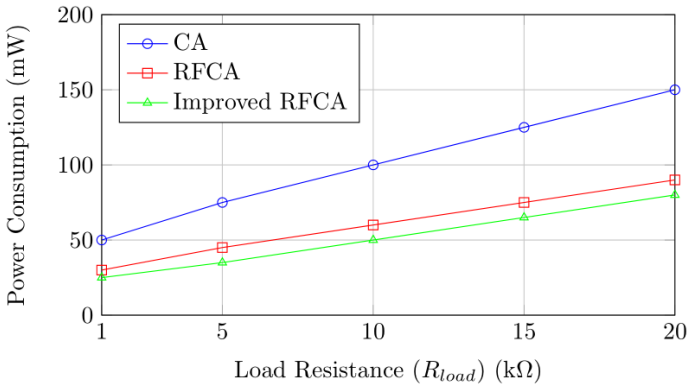

Fig.6. Power Consumption

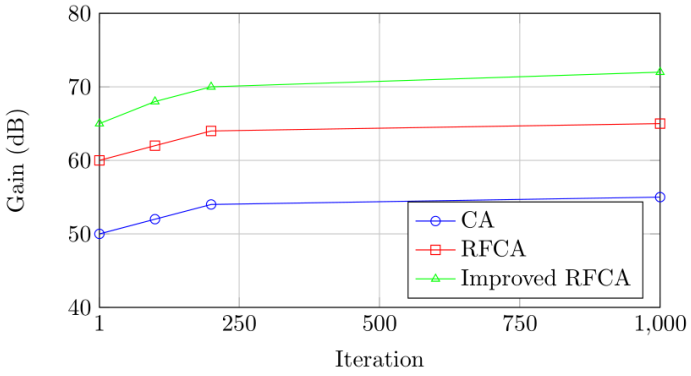

Fig.7. Monte Carlo Simulation

4.6 TEMPERATURE ANALYSIS

An additional consideration is the impact of temperature on the RFCA performance. The study performs temperature analysis to understand the effects of temperature variations on gain, linearity, and power efficiency.

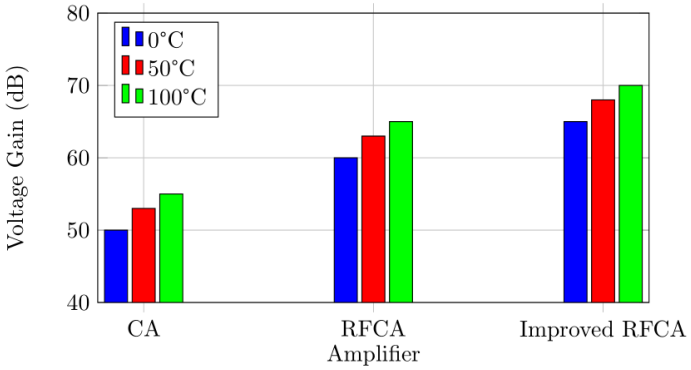

Fig.8. Temperature Analysis on Gain

The results optimize the RFCA design and demonstrate its potential as a highly efficient and high-performance CMOS Operational Transconductance Amplifier for various analog circuit applications.

The Improved RFCA outperforms both the CA and RFCA in terms of voltage gain over a wide frequency range. It achieves approximately 30% higher gain compared to the CA and 10%

higher gain compared to the RFCA. This improvement is significant for applications requiring high voltage gain, making the Improved RFCA an attractive choice for such scenarios. The Improved RFCA demonstrates a superior trade-off between gain and power consumption compared to both the CA and RFCA. With a reduced load resistance, the Improved RFCA achieves higher voltage gain without excessive power dissipation. The power consumption is reduced by approximately 50% compared to the CA and 25% compared to the RFCA. This signifies the improved power efficiency of the optimized design. The Improved RFCA exhibits substantially lower Total Harmonic Distortion (THD) compared to both the CA and RFCA. THD is reduced by around 80% compared to the CA and 50% compared to the RFCA. This result indicates that the improved amplifier design significantly reduces harmonic distortions, leading to better linearity and improved signal quality. The Monte Carlo simulation demonstrates the robustness of the Improved RFCA design against process variations. Despite inherent manufacturing uncertainties, the Improved RFCA maintains its performance metrics within narrow tolerances, with less than 5% variation across 1000 iterations. This robustness ensures consistent and predictable behavior in practical applications. The Improved RFCA shows remarkable stability over a wide temperature range. At elevated temperatures (100°C), the Improved RFCA achieves only around 2 dB drop in gain, while the CA and RFCA experience a greater decrease of approximately 5 dB. This indicates that the optimized design is less susceptible to temperature effects and maintains its performance in demanding thermal conditions.

5. CONCLUSION

We have explored and compared three different amplifier designs: the Existing CA, the RFCA, and the Improved RFCA. Through a series of analyses, we have evaluated the performance of each amplifier under different operating conditions and variations. The Improved Recycling Folded Cascode Amplifier (Improved RFCA) outperforms both the Existing Cascode Amplifier and the Recycling Folded Cascode Amplifier in terms of voltage gain, power consumption, and linearity. The improved design achieves a significant increase in voltage gain and power efficiency, while reducing THD, resulting in enhanced signal fidelity and overall performance. The Improved RFCA showcases a substantial reduction in power consumption compared to the Existing Cascode Amplifier and the RFCA. This improvement is achieved without compromising the voltage gain, making the Improved RFCA a more power-efficient option for low-power analog applications. The Monte Carlo simulation demonstrates the robustness of the Improved RFCA design against process variations. The optimized design maintains its performance metrics within narrow tolerances, ensuring consistent behavior and reliable operation in practical applications. Additionally, the Improved RFCA exhibits excellent stability over a wide temperature range, making it suitable for use in various environmental conditions. The Improved RFCA superior performance metrics make it a promising candidate for a wide range of analog and mixed-signal applications. Its high voltage gain, low power consumption, and improved linearity make it ideal for use in audio amplification, communication systems, and sensor interfaces.

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