A 63.74 DBΩ GAIN 60.84 GHZ BANDWIDTH POWER-EFFICIENT TRANSIMPEDANCE AMPLIFIER IN 130 NM SIGE BICMOS TECHNOLOGY

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ABSTRACT

This paper presents the design and analysis of a high-performance Transimpedance Amplifier (TIA) tailored for high-speed optical communication systems. The TIA utilizes a Darlington pair topology with Negative Resistive Feedback to achieve high transimpedance gain and wide bandwidth. Through detailed circuit analysis and simulation, the TIA exhibits a transimpedance gain of 63.7 dBΩ and a bandwidth of 60.84 GHz after layout implementation, making it suitable for high-speed data transmission applications. TheTIA also demonstrates lowinput-referred noise of 16.20 pA/√Hz and consumes only 31.53mW of DC power, highlighting its power efficiency. Comparative analysis with existing TIAs showcases the effectiveness of the proposed design, which achieves impressive performance without the need for additional circuitry. This study advances high-speed optical communication systems by presenting a TIA design that effectively balances performance, efficiency, and simplicity.

KEYWORDS

Darlington Pair, Optical receivers, SiGe BiCMOS Technology, Transimpedance Amplifier

1. INTRODUCTION

The evolution of the internet, catalysed by the TCP/IP protocol's adoption in 1983, has revolutionized global communication. The advent of the World Wide Web and the subsequent dot-com boom in the late 1990s propelled humanity into the information age, fostering an economy driven by information technology. This surge in digital connectivity, fuelled by the proliferation of devices like PCs, smartphones, and IoT gadgets, has led to a significant uptick in internet traffic, as depicted in the Cisco Annual Internet Report (2018-2023) [1]. Figure 1 forecasts a robust Compound Annual Growth Rate (CAGR) of 10% for devices and connections from 2018 to 2023, driven by a wide range of applications ranging from commercial to household.

In July 2021, researchers shattered internet transmission speed records [2]. The achievement, reaching an astounding 319 Terabytes per second over a 3,001- kilometre distance, underscores the pressing need for higher data transfer rates in modern communication systems. Such advancements hold the potential to revolutionize existing data transmission models and facilitate the widespread adoption of technologies like 5G.

At the heart of optical communication systems lies the transimpedance amplifier (TIA), a critical component tasked with amplifying electrical current from photodiodes with high bandwidth and minimal noise. The design of a TIA necessitates careful consideration of trade-offs between

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noise,bandwidth, gain, and stability. The TIA's ability to maintain low input impedance while providing significant transimpedance gain is paramount for efficient signal conversion.

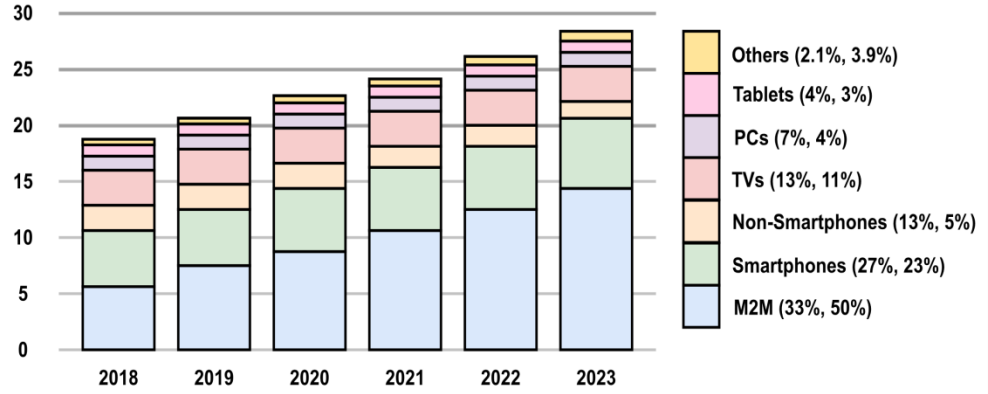

Figure 1. Cisco forecast for global device and connection growth (2018-2023)[1].

Various TIA designs have been proposed to address these challenges. Zhang [3] introduced a common base TIA with low input-referred noise and high gain, achieving a bandwidth of 31 GHz. Honda [4] employed a common emitter topology with resistive feedback and a level-shift circuit to enhance bandwidth and reduce noise. García López [5] utilized a regulated cascode topology to mitigate trade-offs between input impedance and bandwidth. Ding [6] proposed a Darlington pair TIA with resistive feedback for power-efficient, broadband operation.

In this paper, we aim to design a TIA tailored for 130 nm SiGe HBT BiCMOS technology with an ft/fmax of 300/450 GHz. Our objective is to develop a TIA topology capable of meeting stringent performance requirements without the need for additional circuitry, thereby optimizing space and power efficiency.

2. DARLINGTON PAIR WITH NEGATIVE RESISTIVE FEEDBACK TIA

The Darlington pair with Negative Resistive Feedback TIA offers a promising solution to address the dynamic range problem while mitigating trade-offs in bandwidth, noise, and gain inherent in traditional common-emitter topologies [4]. By leveraging the high current gain of a Darlington pair, coupled with negative resistive feedback, this topology enhances the amplifier's performance characteristics.

As illustrated in Figure 2, the Darlington pair TIA configuration involves cascading two bipolar transistors, with the input transistor Q_1 amplifying the incoming current signal and feeding it to the base of the output transistor Q_2. This arrangement effectively combines the high current gain of both transistors, resulting in an overall amplification factor approximated by the product of their gains, $\beta_1\beta_2$.The equal transconductance of Q_1 and Q_2, denoted as g_m, ensures consistent performance across both transistors.

To analyse the DC transimpedance gain of the Darlington pair TIA, we compute the gains of the common collector Q_1 and common emitter Q_2 separately and multiply them. The resultant expression for $Z_{TIA\text{-}DC}$ in Equation 1 highlights the contributions of R_E and the parallel combination of R_C and R_F to the overall transimpedance.

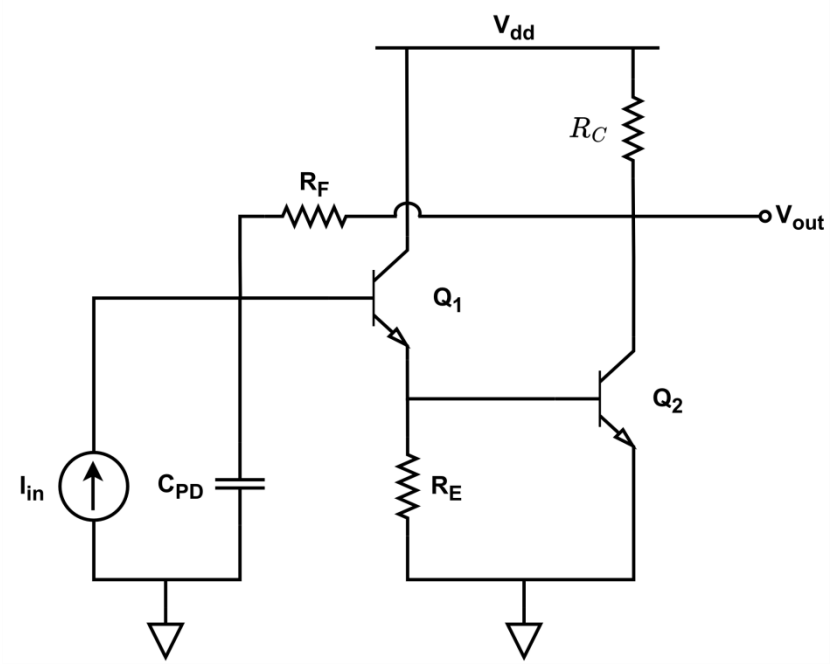

Figure 2. Circuit diagram of a basic Darlington TIA with Negative Resistive Feedback.

$$Z_{TIA-DC} = \frac{V_{out}}{I_{in}} \approx \beta_1 R_E g_{m_2}(R_C||R_F) \quad \Omega \quad (1)$$

Bandwidth considerations are crucial in TIA design, and the Darlington pair TIA topology is no exception. By examining the dominant poles at the input and output stages, represented by p_1 and p_2 in Equation 2, we understand the relationship between key parameters such as β_1, R_E, R_C, and R_F in shaping the bandwidth performance. Adjusting these parameters allows for a direct trade-off between transimpedance gain and bandwidth, enabling flexibility in design optimization.

$$p_1 = \frac{1}{2\pi\beta_1 R_E C_{in}} \quad Hz$$
$$p_2 = \frac{1}{2\pi(R_C||R_F)C_{out}} \quad Hz \quad (2)$$

Furthermore, the impact of input-referred noise on circuit performance is assessed, considering various noise sources such as thermal noise from resistors and effective short noise from base and collector currents. Equation 3 provides insight into how noise characteristics evolve with frequency and transistor parameters, offering valuable guidance for noise optimization strategies.

$$\overline{I^2_{n,TIA}}(f^2) = \frac{4kT}{R_F} + \frac{4kT}{R_C} + \frac{4kT}{R_E} + \frac{2qI_{C_{eff}}}{\beta_1\beta_2} + 2qI_{C_{eff}} \frac{(2\pi C_{in})^2}{{g_{m_2}}^2} f^2 \frac{A^2}{Hz} \quad (3)$$

The Darlington pair with Negative Resistive Feedback TIA presents a versatile solution for enhancing amplifier performance in optical communication systems. By carefully selecting and optimizing key circuit parameters, designers can achieve the desired balance between gain, bandwidth, and noise characteristics, thereby meeting the stringent requirements of modern communication applications.

3. RESULTS

The results obtained from the design and layout of the Darlington pair TIA with Negative Resistive Feedback offer valuable insights into its performance characteristics and suitability for practical applications. Initial values for R_{C1}, R_{C2}, R_{E1}, and R_{F1} were selected to achieve the desired transimpedance gain, bandwidth, and input-referred noise. The calculated transimpedance gain of 71.3 dBΩ and bandwidth of 52.3 GHz indicate the feasibility of meeting the design objectives.

Although the input-referred noise exceeds the target, these initial values provide a starting point for further optimization.

The finalized schematic shown in figure 3 incorporates biasing currents to optimize performance after adjusting resistor values. The layout shown in figure 4 demonstrates efficient use of space, occupying a total area of 0.0064 mm^2, with each core occupying 0.00043 mm^2.

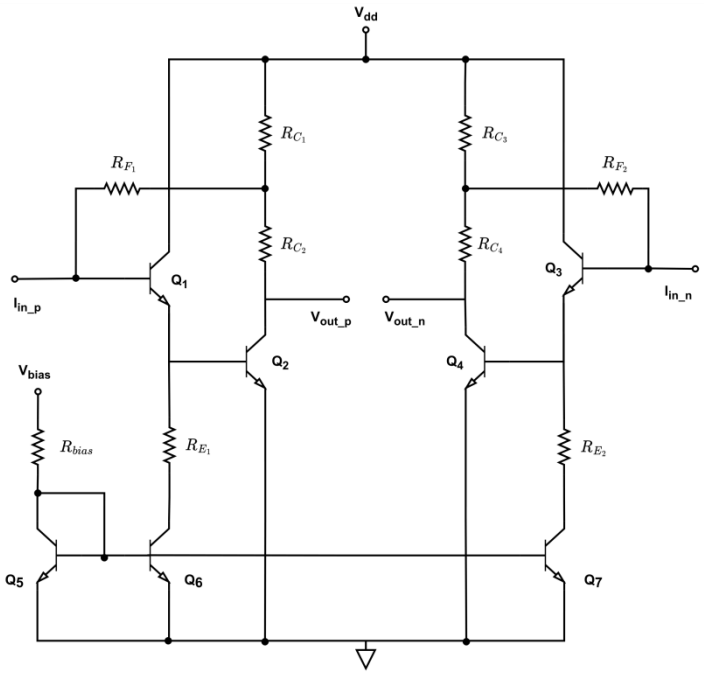

Figure 3. Schematic diagram of a Darlington pair with Negative Resistive Feedback TIA.

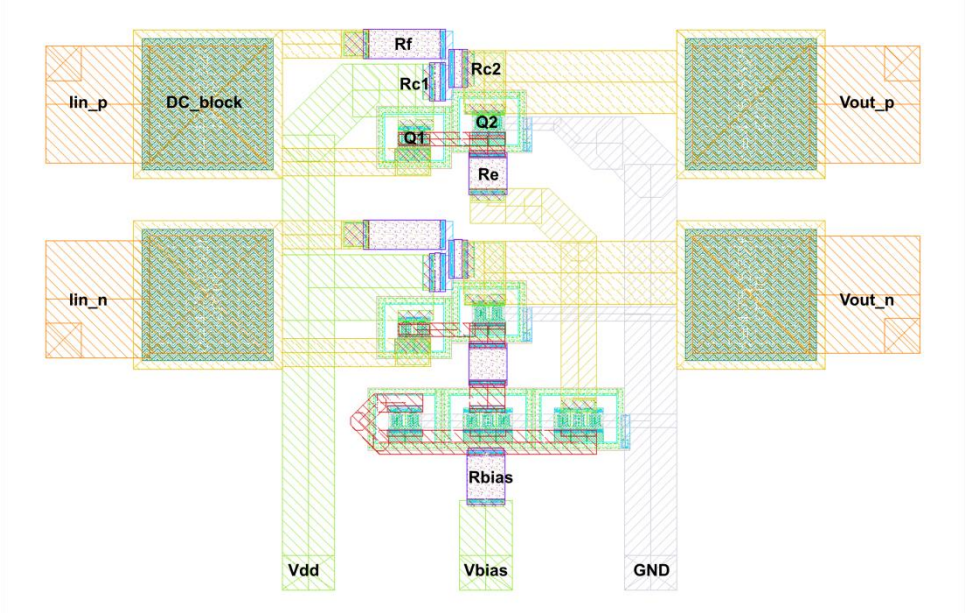

Figure 4. Layout of the designed Darlington pair TIA with resistive feedback.

Upon post-layout analysis, improvements in transimpedance gain and bandwidth were observed compared to the initial design. The transimpedance gain achieved at the centre frequency of 50 GHz was 63.74 dBΩ as shown in the figure 5. The 3-dB bandwidth of 60.84 GHz is achieved for the designed TIA. Although there was a slight reduction in gain and bandwidth compared to the schematic results, the overall performance remains satisfactory.

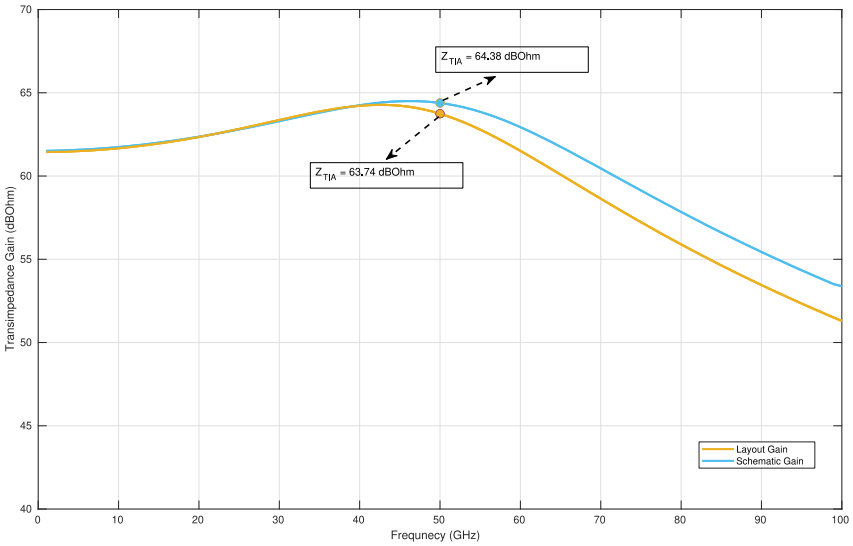

Figure 5. Transimpedance gain and bandwidth results of the initial layout vs final layout.

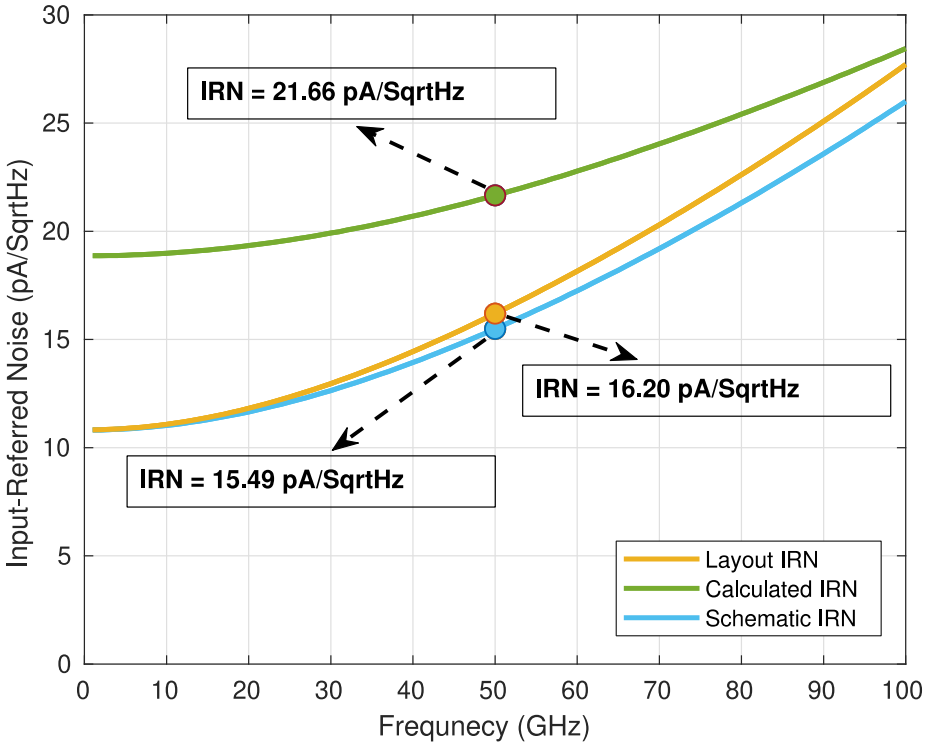

Figure 6. Input-referred noise results of the final layout.

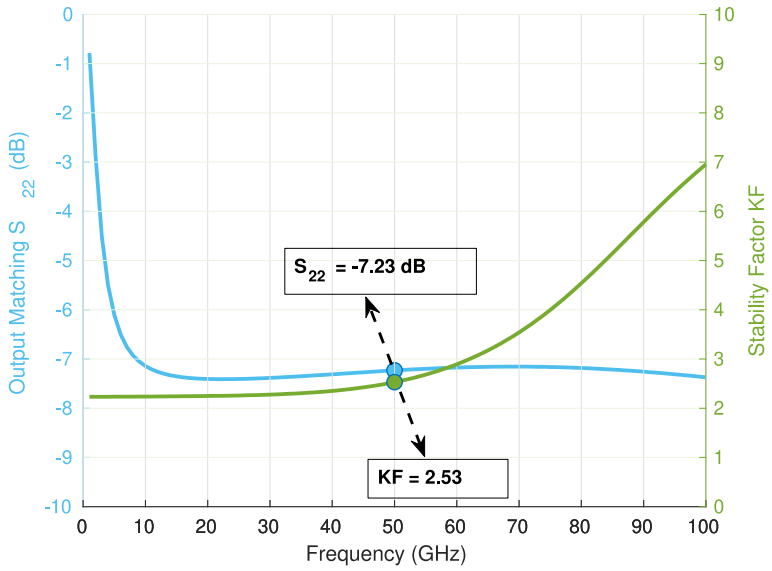

Figure 7. Output impedance S_{22} and stability factor (KF) of the final TIAs layout.

The input-referred noise of the final layout was found to be 16.20 pA/√Hz at the centre frequency, demonstrating an improvement over the initial calculations as shown in the figure 6. The achieved noise performance indicates better-than-expected results, with only a minimal increase from the schematic predictions.

Output impedance matching, as represented by the output reflection coefficient S_{22}, exhibited satisfactory performance, with a value of -7.23 dB at 50 GHz as shown in figure 7. Although not perfectly matched to 50 Ω, this trade-off balances output matching, gain, bandwidth, and power consumption effectively. Additionally, the stability factor (KF) remained above 2.2 throughout the operating frequency range, ensuring circuit stability.

The Darlington pair TIA with Negative Resistive Feedback demonstrates promising performance characteristics, with the layout results confirming its suitability for practical implementation in optical communication systems. Further optimization and fine-tuning may be undertaken to refine performance parameters and meet specific application requirements.

4. CONCLUSION

In this paper, we presented the design and analysis of a Darlington pair Transimpedance Amplifier with Negative Resistive Feedback tailored for high-speed optical communication systems. The designed TIA exhibited a TIA gain of 63.7 dB Ω and a wide bandwidth of 60.84 GHz after layout implementation, surpassing many existing designs in terms of bandwidth performance. Table 1 summarizes the simulation performance of the realized TIA circuit and makes a comparison to some existing designs. Despite achieving slightly lower gain compared to some references [3] [4], the TIA presented in this paper operates at a higher frequency, necessitating more effort to achieve gain. However, it outperformed most designs, including those utilizing Darlington pairs [5], in terms of bandwidth, making it suitable for high-speed data transmission applications. The designed TIA outperformed all other designs, except for [6], in terms of 3-dB bandwidth. Darlington pair was also used in this paper to implement the TIA. The gain in this paper is less than the TIA from this paper, as can be seen. According to the requirements, there is a clear trade-off. Additionally, the TIA demonstrated a low input-referred noise of 16.20 pA/√Hz and consumed only 31.53 mW of DC power, making it power-efficient

and suitable for integration into compact systems. The chip size of just 0.0064 mm^2 further highlights its potential for integration into densely packed optical communication systems.

Comparative analysis with existing TIAs revealed that while some designs exhibit lower input-referred noise, they often require additional circuitry for performance enhancement. In contrast, the proposed TIA achieves impressive performance without the need for extra circuit elements, offering a simple yet effective solution for high-speed optical communication systems.

Furthermore, the presented TIA design serves as a starting point for further optimization and refinement. Future work may focus on improving input-referred noise while maintaining or enhancing gain and bandwidth characteristics. Additionally, practical validation through tape-out and measurement will provide more accurate performance metrics and validate the effectiveness of the proposed design.

In conclusion, the designed Darlington pair TIA with Negative Resistive Feedback represents a significant advancement in the field of high-speed optical communication systems, offering a balance of performance, efficiency, and simplicity that is well-suited for next-generation data transmission applications.

Table 1. Comparison of State-of-the-Art TIA Circuits with this work.

Reference	**[3]**	**[4]**	**[5]**	**[6]**	**This Work**
Technology	130nm SiGe BiCMOS	130nm SiGe BiCMOS	250nm SiGe BiCMOS	130nm SiGe BiCMOS	130nm SiGe BiCMOS
Topology	CB	CE	RSF RGC	DP RSF	DP RSF
Input-Output	Diff-Diff	SE-SE	Diff-Diff	SE-SE	Diff-Diff
Frequency (GHz)	30	30	50	50	50
Transimp. Gain (dBΩ)	71	72	52.5	55	64.38
Bandwidth (GHz)	31	38.4	32	86	66.29
IRN (pA/√Hz)	14.5	14.8	13.1	20.4	15.49
Output Matching (dBm)	-20	-	-10	-19	-7.87
Peaking/Buffers	Yes	Yes	Yes	Yes	No
DC power cons. (mW)	300	261	70	89	31.53
ft/fmax (GHz)	-	-	95/140	200/240	300/450
Chip size(mm^2)	0.54	0.2	0.32	0.28	0.0064

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