

# 25 Gb/s NRZ and 50 Gb/s PAM-4 Transimpedance Amplifier with Active Feedback and Equalization in 90 nm CMOS Technology

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**Keywords:** Transimpedance Amplifier (TIA), Active Feedback, Equalizer, Four-level Pulse Amplitude Modulation (PAM-4).

**Abstract:** In this paper, a high-linearity transimpedance amplifier (TIA) was designed in 90 nm CMOS technology. The input stage of the TIA was a regulated cascade circuit for low input impedance. The active feedback structure was used to replace the feedback resistor and to reduce the chip size. An equalizer was also used in the TIA to compensate the high-frequency response. Within input current amplitude of 1.1 mA, the total harmonic distortion of the TIA can be below 5%. The bandwidth of the TIA was about 26 GHz and its input-referred current density was below 74 pA/ $\sqrt{\text{Hz}}$  within the bandwidth. The TIA can be applied in 25 Gb/s non-return zero (NRZ) and 50 Gb/s (25 Gbaud) four-level pulse amplitude modulation (PAM-4) optical receivers. The power dissipation of the chip is 11.6 mW and the chip area is 0.151 mm<sup>2</sup>.

## 1 INTRODUCTION

Since the advent of optical fiber transmissions, the data transmission speed is increasing in recent years and is widely used in local area networks, regional networks, and data centers. Therefore, more people have invested in the research and promotion of high-speed fiber optic circuit design. The multi-level modulation signals can reduce the channel symbol rate and the circuit bandwidth, so the high-speed circuit for optical communications can be designed easier. In the same transmission bandwidth, the data bit rate of the 4-level pulse amplitude modulation (PAM-4) signal can be doubled than the non-return to zero (NRZ) signal (Szczerba, 2012). Therefore, the PAM-4 signal is defined as a kind of the standard signal formats in the 200 and 400 Gb/s Ethernets (Bhoja, 2017; Baveja, 2018). Using eight channels that operate at 25 Gb/s NRZ or 50 Gb/s PAM-4, the 200 Gb/s or 400 Gb/s transceiver modules can be achieved.

In the optical receiver module, the transimpedance amplifier (TIA) and the main amplifier are usually used. If the nonlinear distortions can be tolerated, the limiting amplifier (LA) can become the main amplifier. However, the distortion

of the PAM-4 signal is highly dependent on the linearity of transmission and circuit. The LA can introduce nonlinear distortions and will degrade the PAM-4 signal quality. Therefore, in the PAM-4 optical receiver, the high-linearity TIA will be needed and the LA cannot be used. The 100 Gb/s PAM-4 linear TIA was designed in 16 nm FinFET CMOS process (Lakshmikumar, 2018), and the low-noise high-linearity 56 Gb/s PAM-4 optical receiver was designed in 45 nm SOI CMOS technology (Xie, 2018). Our TIA circuit was designed in 90 nm CMOS technology, so the bandwidth compensation skills were needed for the high-speed TIA (Salhi, 2017; Hiratsuka, 2018). Therefore, an equalizer (EQ) circuit was added in our inductor-less TIA. In this paper, a high-linearity TIA with an EQ is designed in 90 nm CMOS technology for 25 Gb/s NRZ and 50 Gb/s PAM-4 transmissions.

## 2 CIRCUIT ARCHITECTURE

Figure 1 shows the block diagram of our TIA circuit. The TIA was designed as a fully differential circuit structure. A differential circuit can effectively reduce the noise interference from the power supply or the

substrate, and can increase the voltage swing. In addition, the nonlinear distortion and even-order harmonics can be also reduced. The input stage of the TIA used a regulated cascade (RGC) circuit (Seng, 2013). The RGC circuit has a low input resistance to suitable to be an input stage for current signals. In the TIA, the active negative feedback was used to replace the feedback resistor, and the voltage output of the TIA is not resistively load by the feedback device.

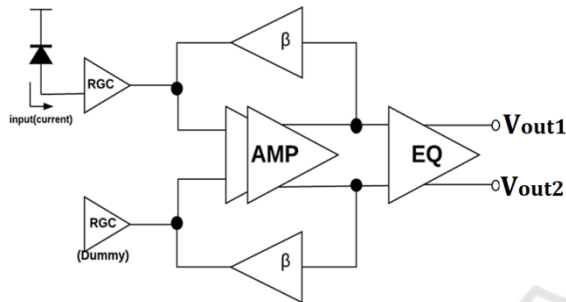


Figure 1: Block diagram of our TIA with active feedback and equalization.

Figure 2 shows the schematic diagram of the TIA with active feedback, not including the RGC input stages. The TIA is a two-stage differential amplifier, the M3 and M4 is a differential pair, and the M1 and M2 is another differential pair. The feedback paths are from the drains of the M1 and M2 to the gates of the M3 and M4. The feedback devices use the voltage-controlled current sources, Mf1 and Mf2. For reducing the chip size, the drain loads of the two-stage differential amplifier use active loads, MP1, MP2, MP3, and MP4.

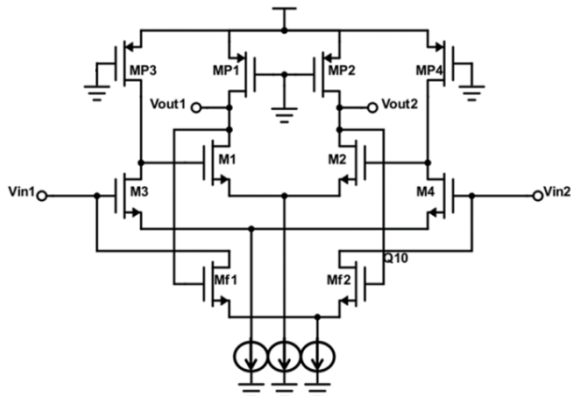


Figure 2: Schematic of our TIA with active feedback.

Figure 3 shows the schematic diagram of the equalizer in the TIA. The equalizer was designed in the differential configuration with source and

capacitive degenerations (Talluri, 2015). The equalizer was also the output stage in the TIA, so the R1 and R2 were set as 50 Ω matching resistors. Figure 4 shows the half circuit of the equalizer, its transfer function can be written as

$$EQ(s) = \frac{G_m R_L}{1 + \frac{G_m R_e}{2}} \times \frac{1 + \frac{s}{\omega_z}}{(1 + \frac{s}{\omega_{p1}})(1 + \frac{s}{\omega_{p2}})} \quad (1)$$

where  $\omega_z = 1/(R_e C_e)$ ,  $\omega_{p1} = (1 + G_m R_e / 2) / (R_e C_e)$ , and  $\omega_{p2} = 1 / (R_L C_L)$ . The Bode's plot of the equalizer is also shown in Figure 4. The values of R3 and C1 can be set carefully to compensate for the high-frequency response of the TIA and to extend the bandwidth.

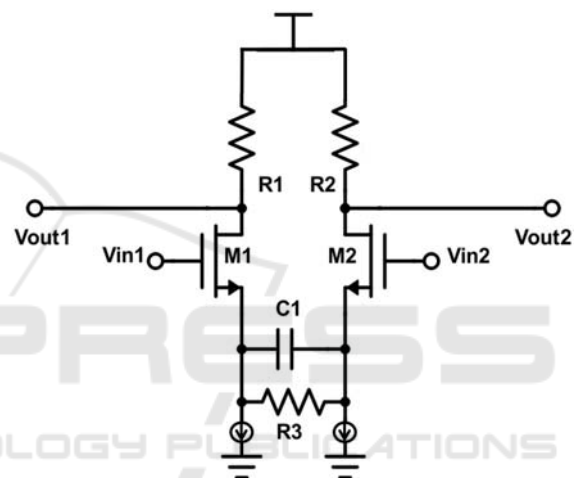


Figure 3: Schematic of the equalizer.

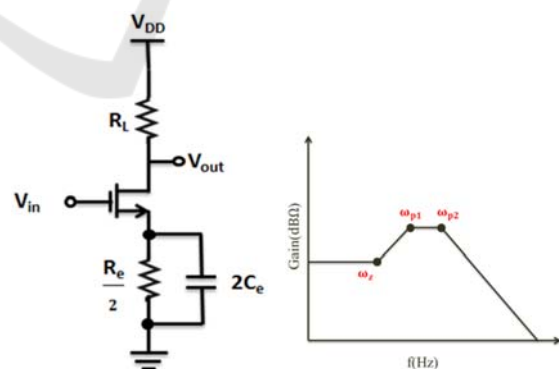


Figure 4: Half circuit and frequency response of the equalizer.

Figure 5 shows the layout diagram of the TIA circuit with active feedback and equalization. The TIA chip was designed in TSMC 90 nm CMOS technology. The chip area including the pads is  $0.343 \times 0.44 \text{ mm}^2$ . The input pad can be connected

with a photodiode, the Vout1 and Vout2 pads are the differential output ends, and the Vbias pad can adjust the currents of the current source circuits. There are two voltage source pads, Vdd, and four ground pads, Gnd, in the TIA chip.

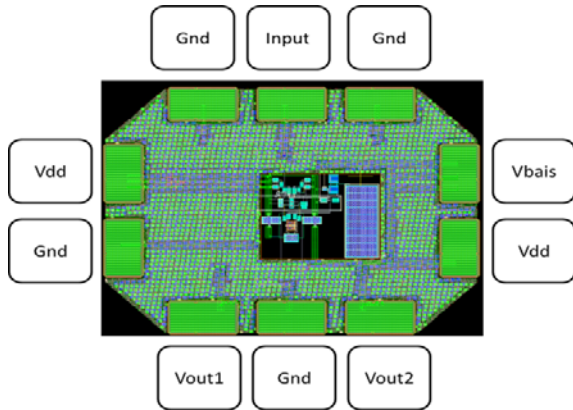


Figure 5: Layout diagram of the TIA chip.

### 3 RESULTS AND DISCUSSION

#### 3.1 Simulated Results

Figure 6 shows the post-simulated DC transfer curve of the TIA. By the curve, the transimpedance gain of 34 dBΩ is estimated. For the linear operation, the peak-to-peak input current must be below 1.1 mA, while the output swing reaches 80% of the fully limited value of the TIA. The maximum output voltage amplitude is about 55 mV.

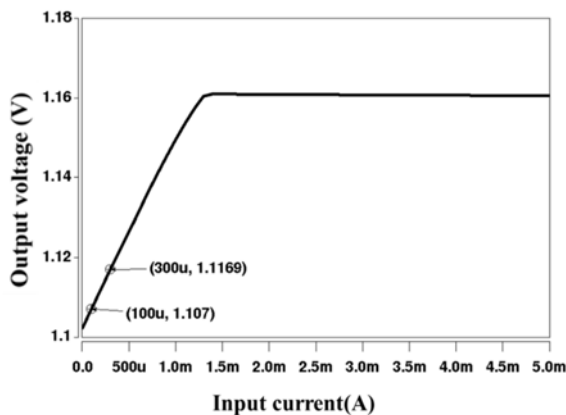


Figure 6: Post-simulated DC transfer curve of the TIA.

Figure 7 shows the post-simulated frequency response of the TIA. In the simulations, an equivalent photodiode circuit was added and the capacitance and resistance of the equivalent

photodiode were 0.3 pF and 2 kΩ, respectively. For the lower frequency range, the gain was about 34 dBΩ and correspondent with the estimation for the DC analysis. There was a peak response at about 12 GHz, and the peak response was caused by the equalizer. The 3-dB bandwidth of the TIA was about 26 GHz, so the TIA can be suitable for the 25 Gb/s NRZ and 50 Gb/s PAM-4 operations.

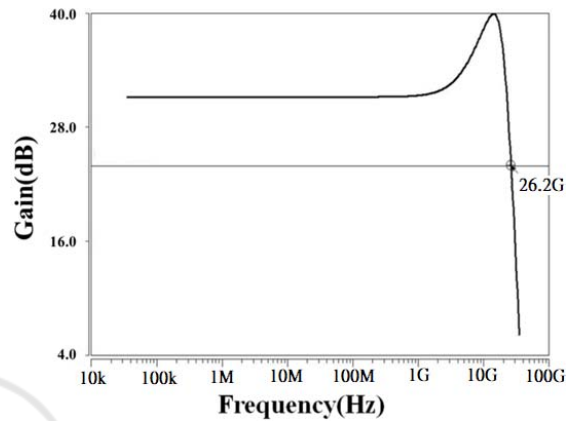


Figure 7: Post-simulated frequency response of the TIA.

The input referred current noise density of the TIA was simulated, as shown in Figure 8. Within the bandwidth, the input referred current noise density was below 74 pA/√Hz. The noise performance of the TIA is not very excellent. Generally, active feedback tends to result in more noise than shunt resistance feedback.

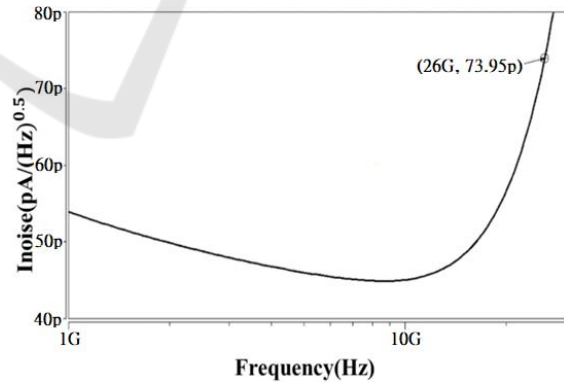


Figure 8: Post-simulated input referred current noise density of the TIA.

For PAM-4 signals, the linearity of the circuit or transmission system seriously influences the signal quality. Therefore, using a 5 GHz input sine-wave signal, the total harmonic distortion of the TIA versus the peak-to-peak input current was simulated, as shown in Figure 9. When the peak-to-peak input

current is below 1.1 mA, the total harmonic distortion can be below 5%. The linearity of the TIA is good. The condition for the linear operation was also correspondent with the evaluation from the DC transfer curve.

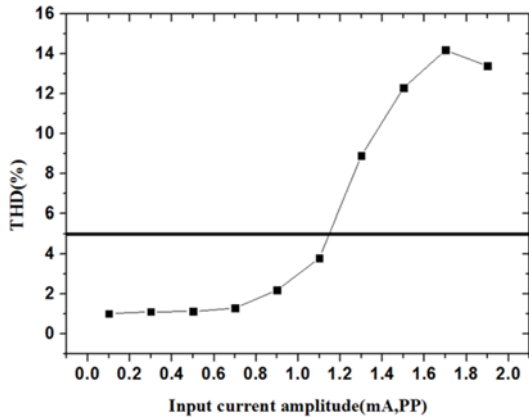


Figure 9: Post-simulated total harmonic distortion of the TIA.

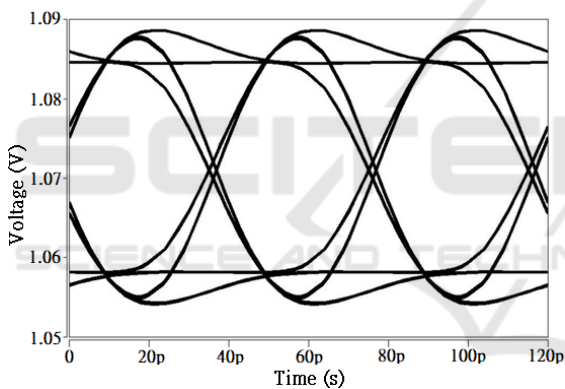


Figure 10: Post-simulated 25 Gb/s NRZ output voltage eye diagram of the TIA.

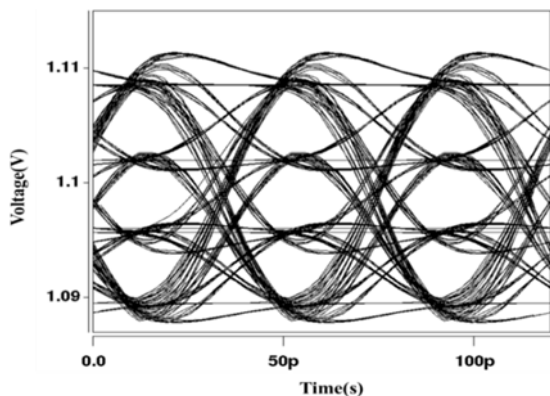


Figure 11: Post-simulated 50 Gb/s PAM-4 output voltage eye diagram of the TIA.

The 25 Gb/s NRZ and 50 Gb/s (25 Gbaud/s) PAM-4 output voltage eye diagrams were simulated for the peak-to-peak input current of 400  $\mu$ A, as shown in Figures 10 and 11. The total output voltage amplitude was above 20 mV. For the 25 Gb/s NRZ operation, the eye diagram of the TIA output signal is very clear. For the 50 Gb/s PAM-4 operation, the top, middle, and bottom eyes of the eye diagram of the TIA output signal can obtain the same eye-height, because the linearity of the TIA was good.

### 3.2 Measured Results

The TIA chip was tested through an evaluation board. We designed the evaluation board, and the high-frequency printed circuit board (PCB) material was Rogers 4350B. The high-frequency signal traces were designed using grounded coplanar waveguides on the PCB. To avoid DC level into the wide-bandwidth oscilloscope, the DC block was used in the signal output end. In our measurements, the photodiode (PD) was not used with the TIA chip. A voltage-to-current converter including a 1 k $\Omega$  resistor and a 0.15 pF capacitor was used to convert the voltage signal from the arbitrary waveform generator into the current signal. The 0.15 pF capacitor was used as the equivalent capacitance of PD. For the TIA chip testing, the measurement architecture is shown in Figure 12.

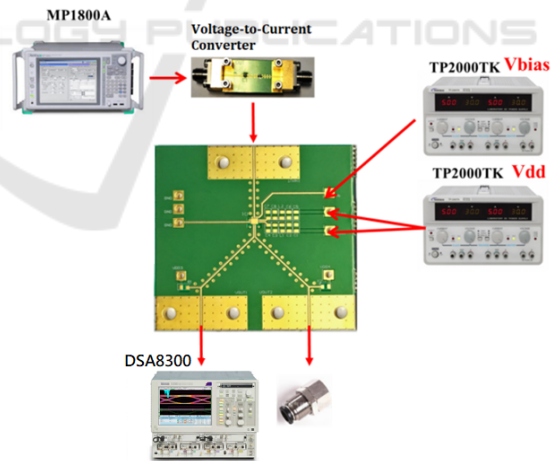


Figure 12: Measurement architecture for the TIA chip on a PCB.

A 25 Gb/s NRZ electrical eye diagram from the signal quality analyzer (Anritsu MP 1800A) was measured through the digital sampling oscilloscope (Tektronix DSA8300), as shown in Figure 13(a), the rise and fall times of the eye diagram were 18.2 ps and 15.1 ps, the peak-to-peak time jitter was 3.54 ps,

the signal-to-noise ratio (SNR) was 34.3, and the voltage amplitude was 514.5 mV. From the voltage-to-current converter, Figure 13(b) shows the 25 Gb/s NRZ eye diagram with a rise time of 14.3 ps, a fall time of 12.4 ps, a peak-to-peak time jitter of 17.1 ps, an SNR of 10.0, and an amplitude of 37.8 mV. The quality of 25 Gb/s NRZ signal was degraded through the voltage-to-current converter, and the equivalent current amplitude was about 0.76 mA. From the output of the TIA on PCB, Figure 13(c) shows the 25 Gb/s NRZ eye diagram with a rise time of 21.5 ps, a fall time of 15.6 ps, a peak-to-peak time jitter of 29.4 ps, an SNR of 7.87, and an amplitude of 30.72 mV. The transimpedance gain of the TIA was estimated at about 32 dB $\Omega$ . Although the output signal quality of the TIA chip was not very good, the TIA was still suitable for 25 Gb/s NRZ operation.

Using the TIA chip on PCB, 32 Gb/s NRZ eye diagram was also measured, as shown in Figure 14. Both rise and fall times of the eye diagram were over 18 ps, the peak-to-peak time jitter was 28.3 ps, the signal-to-noise ratio (SNR) was 6.56, and the amplitude was 26.8 mV. The output signal quality of the TIA chip was not good because the input current signal quality of the TIA was also not good. Therefore, the TIA could also be applied for 32 Gb/s NRZ operation.

From the signal quality analyzer, a 50 Gb/s (25 Gbaud) PAM-4 electrical eye diagram was measured, as shown in Figure 15(a), and the eye diagram was with a rise time of 8.0 ps, a fall time of 8.3 ps, a peak-to-peak time jitter of 16.1 ps, an SNR of 4.02, and a total amplitude of 300.4 mV. From the voltage-to-current converter, Figure 15(b) shows the 50 Gb/s PAM-4 eye diagram with a rise time of 21.4 ps, a fall time of 18.0 ps, a peak-to-peak time jitter of 40.1 ps, an SNR of 1.77, and an amplitude of 38.9 mV. From the output of the TIA chip on PCB, Figure 15(c) shows the 50 Gb/s PAM-4 eye diagram, but the signal quality was bad and the parameters of the eye diagram could not be obtained. Because the quality of the current signal from the voltage-to-current converter was not good, the output signal quality of the TIA could not become better. The amplitude between two levels of a PAM-4 signal is smaller, so the amplitude of the PAM-4 signal needs to be amplified as possible as large. If the TIA chip can be tested with a PD, the output signal of the TIA can have better quality.

According to the post simulations of the TIA, the performance of our TIA circuit and the comparison with other literatures are summarized in Table 1. The figure of merit (FOM) is defined as (2) and (3). Our TIA had a high FOM value because the TIA had

low power consumption and small chip area. However, the transimpedance gain and output amplitude of our TIA chip still need to be improved for PAM-4 applications.

$$\text{FOM1} = \frac{\text{Gain (dB}\Omega\text{)} \times \text{Bandwidth (GHz)}}{\text{Power (mW)} \times \text{Chip Area (mm}^2\text{)}} \quad (2)$$

$$\text{FOM2} = \frac{\text{Gain (dB}\Omega\text{)} \times \text{Bit rate (Gb/s)}}{\text{Power (mW)} \times \text{Chip Area (mm}^2\text{)}} \quad (3)$$

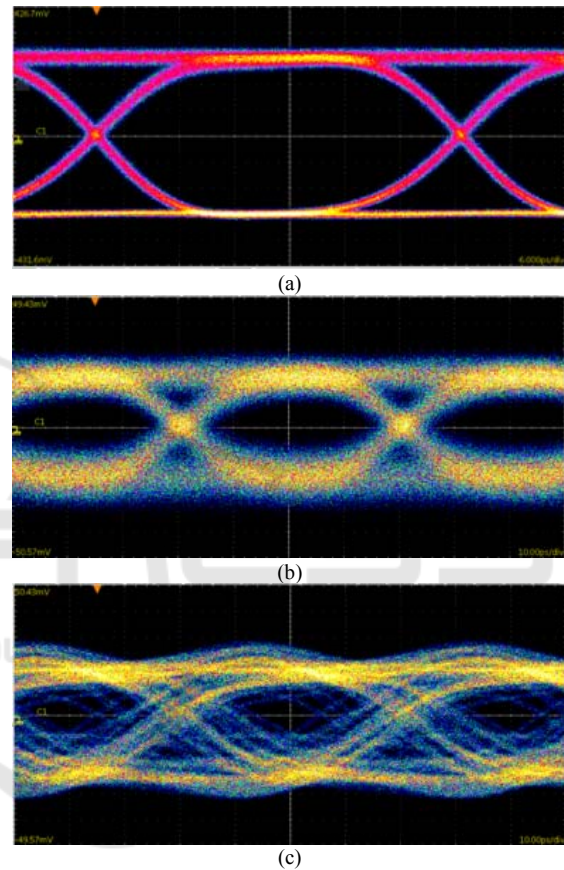


Figure 13: Measured 25 Gb/s NRZ eye diagrams from (a) the pattern generator, (b) the voltage-to-current converter, and (c) the TIA chip on a PCB.

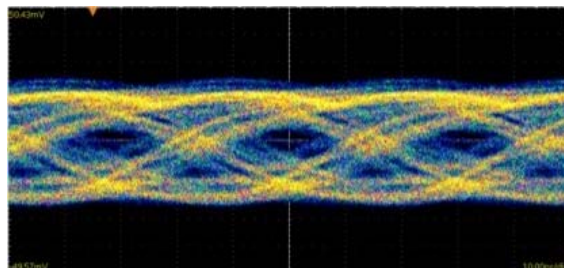


Figure 14: Measured 32 Gb/s NRZ eye diagram from the TIA chip on a PCB.

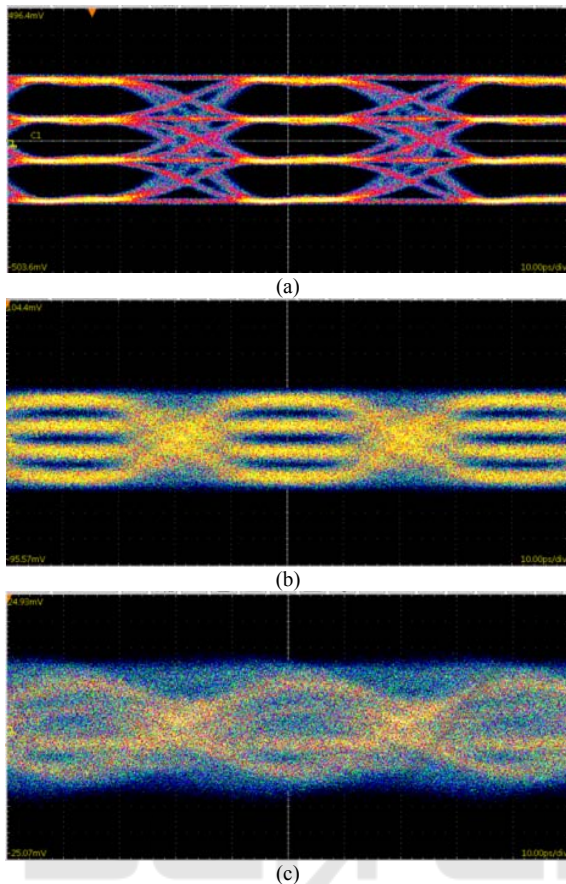


Figure 15: Measured 50 Gb/s PAM-4 eye diagrams from (a) the pattern generator, (b) the voltage-to-current converter, and (c) the TIA chip on a PCB.

Table 1: Comparison of the performance of the TIA circuits.

Ref.	Kim 2014	Liao 2007	Han 2010	Hiratsuka 2018	This work
	Post-Sim.	Measure	Post-Sim.	Measure	Post-Sim.
CMOS Tech.	65 nm	90 nm	130 nm	65 nm	90 nm
Gain (dBΩ)	52	66	60	52.3	34
BW (GHz)	50	29	12.6	12.6	26
Bit rate (Gb/s)	52	40	20	25	50
Power (mW)	49.2	75	38.3	3.96	11.6
Area (mm <sup>2</sup> )	0.48	0.15	0.22	0.63 (0.0064 Core Area)	0.15
FOM1	110.1	170.1	89.7	264.1 (26001)	508.0
FOM2	114.5	234.7	142.4	524.1 (51590)	977.0

## 4 CONCLUSIONS

We propose a wide-bandwidth and high-linearity full differential TIA circuit in CMOS 90nm technology. The TIA used the active feedback to replace the feedback resistor and to reduce the chip area. The equalizer was also used in the TIA to compensate for the high-frequency response of the TIA and to extend the bandwidth. The transimpedance gain, bandwidth, and input referred current noise density were about 34 dBΩ, 26 GHz, and 74 pA/√Hz, respectively. The power consumption of the TIA chip was about 11.6 mW, and the chip area was  $0.343 \times 0.440$  mm<sup>2</sup>. Below the peak-to-peak input of 1.1 mA, the TIA can have good linearity. The 25 Gb/s NRZ and 50 Gb/s PAM-4 eye diagrams of the TIA were simulated, and the 25 Gb/s NRZ, 32 Gb/s NRZ and 50 Gb/s PAM-4 eye diagrams of the TIA were measured. In 25 Gb/s NRZ and 50 Gb/s PAM-4 simulations, the TIA circuit had good performance. Because the input current signal was degraded by the voltage-to-current converter, the TIA output signal cannot obtain clear eye diagram for 50 Gb/s PAM-4 measurements. Our TIA chip could be used in 25 Gb/s NRZ and 50 Gb/s PAM-4 optical receivers for 200 Gb/s and 400 Gb/s high-speed optical transmissions.

## ACKNOWLEDGEMENTS

This paper is supported by the Taiwan Semiconductor Research Institute and the Taiwan Ministry of Science and Technology (MOST 107-2218-E-992-304 and MOST 107-2637-E-992-011).

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