Switched 4-to-1 Transimpedance Combining Amplifier for Receiver Front-End Circuit of Static Unitary Detector-Based LADAR System

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Abstract: Laser detection and ranging (LADAR) systems are commonly used to acquire real-time three-dimensional (3D) images using the time-of-flight of a short laser pulse. A static unitary detector (STUD)-based LADAR system is a simple method for obtaining real-time high-resolution 3D images. In this study, a switched 4-to-1 transimpedance combining amplifier (TCA) is implemented as a receiver front-end readout integrated circuit for the STUD-based LADAR system. The 4-to-1 TCA is fabricated using a standard 0.18 µm complementary metal-oxide-semiconductor (CMOS) technology, and it consists of four independent current buffers, a two-stage signal combiner, a balun, and an output buffer in one single integrated chip. In addition, there is a switch on each input current path to expand the region of interest with multiple photodetectors. The core of the TCA occupies an area of 92 µm × 68 µm, and the die size including I/O pads is 1000 µm × 840 µm. The power consumption of the fabricated chip is 17.8 mW for a supplied voltage of 1.8 V and a transimpedance gain of 67.5 dBΩ. The simulated bandwidth is 353 MHz in the presence of a 1 pF photodiode parasitic capacitance for each photosensitive cell.

Keywords: LADAR; STUD; switched-TCA; optical receiver

1. Introduction

Laser detection and ranging (LADAR) systems are commonly used to acquire real-time three-dimensional (3D) images using the time-of-flight (TOF) of a short laser pulse. As LADAR technology has become more diverse, it has been utilized in various applications, such as autonomous vehicles, robots, remote sensing, reconnaissance, and motion detection, where high 3D resolution is important [1–10]. For the real-time acquisition of 3D images, a LADAR system must process all reflected TOF laser signals from every direction for a region-of-interest (ROI) in real time.

There are different methods of implementing LADAR systems. The static unitary detector (STUD)-based technique [11] has some unique advantages compared with other techniques, such as the rotational motion-based technique [12] or the focal plane array (FPA)-based technique [13]. Because the STUD-based technique has only one signal processing chain and does not need micro-lenses to increase the signal-to-noise ratio (SNR), it is cost effective. In addition, the required power level of the transmitted laser pulse is not as high as for the FPA-based technique because the STUD-based technique illuminates one collimated laser pulse at a time in a specific direction. Figure 1 shows the block diagram of a STUD-based LADAR system. In the STUD-based LADAR system, the transmitter emits laser pulses over the entire ROI with two high-speed optical scanners and the receiver detects the returned optical pulses to a static-unitary large-area photodetector.
However, an increase in the area of the photodetector results in a decrease in the bandwidth of the receiver due to the large parasitic capacitance of the large-area photodetector. To overcome this problem, the STUD-based LADAR receiver has multiple partitioned photosensitive cells, as shown in Figure 2. Each of the partitioned cells has its own transimpedance amplifier (TIA) to receive and amplify the optical current from each partitioned cell independently, and then a signal combiner sums all the outputs of each TIA into a single output signal STOP, which indicates the arrival of the return signal. A time-to-digital converter (TDC) calculates the TOF between the START and STOP signals. Since each partitioned cell with its own cascading TIA operates independently without affecting any of the other cells, its bandwidth remains unchanged. In addition, since the STUD-based LADAR receiver does not need to determine which cell detects the arriving laser pulse, inter-channel-interference is not a problem, unlike in the FPA-based LADAR receiver.

To implement a STUD-based LADAR receiver, the same number of TIAs as partitioned photosensitive cells is needed, and they are assembled on a single board. The pad pitch in the partitioned photodetector is totally different from the pad interval of the TIAs. In case the lengths of the interconnection lines between each photosensitive cell and the corresponding TIA is different, accurate time information cannot be obtained because the time delay varies depending on which photosensitive cell receives the return signal. Therefore, the electrical length of the interconnection lines between each photosensitive cell and the corresponding TIA should be designed equal on the test fixture. This limits the number of cells for higher-resolution 3D images over a large ROI due to the interconnection problem between a partitioned photodetector and multiple TIAs [14,15]. To resolve this problem, a 4-to-1 transimpedance combining amplifier (TCA) was proposed in our previous work [14] as the...
In this study, we propose a switched 4-to-1 TCA. The switched 4-to-1 TCA has a switch on each input current path, as shown in Figure 3. The photodetector in this work has four photosensitive cells. The target size of a single photosensitive cell is 350 μm × 100 μm and the parasitic capacitance of the single cell is assumed to be 1 pF. In the STUD-based LADAR receiver, it is necessary to increase the photosensitive area of the photodetector in order to enlarge the ROI in the STUD-based LADAR receiver. Meanwhile, this increases the noise of the receiver due to the large-area photodetector. The proposed switched 4-to-1 TCA can be used, as shown in Figure 4, in the STUD-based LADAR receiver front-end. According to the position where the returned laser pulse arrives, one of the TCAs is switched on to receive the optical current and the others are not connected to the photodetector. Therefore, the noise generated from the unconnected photodetector cannot affect the receiver. The switch control signal EN causes the switch to be turned on. Depending on the ROI, it is predicted which photodetector will detect the return signal, so that the EN signal is able to turn on the corresponding switch.

![Proposed switched 4-to-1 transimpedance combining amplifier (TCA) with four partitioned photodetectors.](image1)

![Operation example with the four proposed switched 4-to-1 TCAs and four multiple partitioned photodetectors.](image2)

The TCA amplifies and combines current signals generated using the photosensitive cells from incoming optical signals into one voltage signal for further processing. The switched 4-to-1 TCA is fabricated using a standard complementary metal-oxide-semiconductor (CMOS) 0.18 μm technology. It provides 3.8 pA/√Hz average noise current spectral density with a bandwidth of 353 MHz and a transimpedance gain of 67.5 dBΩ. The core of the TCA consumes 17.8 mW of power from a 1.8 V supply. The core of the TCA occupies an active area of about 92 μm × 68 μm and the die size including I/O pads is 1000 μm × 840 μm.
2. Architecture Description

The block diagram of the proposed switched 4-to-1 TCA is shown in Figure 5. It amplifies and combines the photocurrent from the four partitioned photosensitive cells into one voltage signal. The switched 4-to-1 TCA consists of four primary stages: (1) four over-current protection (OCP) circuits; (2) four switches, four current buffers; (3) a signal combiner; and (4) a post-amplifier. The OCP circuits prevent the fabricated chip from being damaged by a very high input signal. The switch is turned on when the reflected laser pulse arrives at the corresponding photodetector among the multiple detectors. The current buffer is a low impedance input stage intended to receive the optical current from a photosensitive cell. The signal combiner sums the outputs of all the current buffers. The post-amplifier is designed to preserve the bandwidth and to enhance the transimpedance gain. A balun is a differential amplifier with differential input signals biased at the same direct current (DC) level to convert the single-ended output of the signal combiner into a differential signal. The output buffer is a differential amplifier with resistor loads of 50 $\Omega$ on both the positive and negative outputs. The schematic diagram of the designed circuit is illustrated in Figure 6.

![Block diagram of the proposed switched 4-to-1 TCA with a balun and an output buffer.](image)

**Figure 5.** Block diagram of the proposed switched 4-to-1 TCA with a balun and an output buffer.

![Schematic diagram of the proposed switched 4-to-1 TCA.](image)

**Figure 6.** Schematic diagram of the proposed switched 4-to-1 TCA.

2.1. OCP and Input Switch

The OCP circuit, as shown in Figure 6, is designed to protect the 4-to-1 TCA from being damaged by a very high input current [16]. The transistor $M_5$ turns on when its source voltage is larger than 1.04 V. As shown in Figure 7, when the input current is approximately 400 $\mu$A, the source voltage of $M_5$ reaches 1.043 V. When the input current is larger than 400 $\mu$A, the increase in the input voltage is suppressed and the sink current to the OCP circuit increases. Therefore, the effective range of the input voltage is from the DC bias voltage of the input current buffer, approximately 610 mV to 1.043 V, before the OCP circuit turns on.
To expand the ROI with multiple partitioned photodetectors, a switch is added on each input current path. Several types of switches, such as n-channel metal-oxide-semiconductor field effect transistor (NMOSFET or NMOS), p-channel MOSFET (PMOSFET or PMOS), and CMOS transmission gates, are available. In this study, NMOS switches $M_6$ are used on all input current paths, as shown in Figure 6. A high output will be degraded by the NMOS switch, since the NMOS switch turns off when the input becomes $EN - V_{th}$, where $EN$ is a control signal of the switch and $V_{th}$ is the threshold voltage of the switch transistor $M_6$. The maximum input value of the NMOS switch without signal degradation is approximately 1.175 V when the $V_{th}$ of $M_6$ is about 625 mV, and the available maximum input voltage dependent on the input photocurrent is 1.043 V. Therefore, an NMOS switch on the input path is capable of passing an input signal having a value from 610 mV to 1.043 V. A PMOS switch is not a viable solution, since the threshold voltage is larger than 610 mV and a low input signal cannot be passed through a PMOS switch.

![Figure 7. Simulated input voltage and sink current to OCP (over-current protection) circuit according to the input current.](image)

2.2. 4-to-1 TCA, Post-Amplifier, Balun, and Output Buffer

Four copies of the regulated cascode (RGC) topology are selected as current buffers because of their low input impedance and wide bandwidth characteristics, as compared to other topologies such as the inverter, common-source, and common-gate topologies [17]. The RGC structure reduces the input impedance significantly by using the $M_2$ and $R_2$ stage as a local feedback to boost the transconductance of $M_1$. The small-signal impedance of the RGC structure ($Z_{in}$) is given by (1):

$$Z_{in} \approx \frac{1}{g_{m1}(1+g_{m2}R_2)},$$

where $g_{m1}$ and $g_{m2}$ are the transconductances of $M_1$ and $M_2$, respectively.

The signals from the current buffers combine through two stages, as shown in Figure 6. In the first stage, two inputs are summed through the output load resistor $R_1$ of the RGC TIA. In the second stage, common-source amplifiers are used at the outputs of the two first-combining stages, and their currents are summed through a single resistive load $R_3$. There is a common-source amplifier between the first and second combining stages that functions as a buffer and a bias shifter.

To analyze the effect of the noise introduced by partitioned photosensitive cells and the TCA, the simplified circuit is illustrated in Figure 8 with noise factors [15]. The equivalent total input referred noise of the TCA is approximately given by (2):

$$\overline{i_{n,\text{in}}}^2 \approx \frac{v_{n,\text{OUT}}^2}{Z_{T,TCA}} = 4 \left( \frac{i_{n,\text{PD}}^2 + i_{n,\text{CE}}^2}{2} + \frac{i_{n,R1}^2}{2} \right) \cdot R_1 + \frac{2i_{n,C2}^2 + i_{n,R3}^2}{Z_{T,TCA}} \cdot R_3^2$$

(2)
where $i_{n,PD}^2$ is the noise from a single photosensitive cell, $i_{n,CB}^2$ is the generated noise in the current buffer stage, $i_{n,C2}^2$ is the generated noise in the second combining stage, and $i_{n,K1}^2$ and $i_{n,R3}^2$ are the thermal noise from $R_1$ and $R_3$, respectively. In this analysis, we assume that:

$$
\begin{align*}
 i_{n,PD}^2 &= i_{n,PD1}^2 = i_{n,PD2}^2 = i_{n,PD3}^2 = i_{n,PD4}^2 \\
 i_{n,CB}^2 &= i_{n,CB1}^2 = i_{n,CB2}^2 = i_{n,CB3}^2 = i_{n,CB4}^2 \\
 v_{n,C1}^2 &= v_{n,C2,1}^2 = v_{n,C1,2}^2 \\
 i_{n,c}^2 &= i_{n,c2,1}^2 = i_{n,c2,2}^2.
\end{align*}
$$

In (2), the receiver noise with a large-area photodetector, even though it is partitioned, is increased in the developed TCA. The noise generated in the first combining stage with the current buffer is also the dominant factor of the equivalent total noise.

The post-amplifier is realized using a two-stage common-source amplifier. The first stage has an active inductor load, consisting of a transistor $M_4$ and a resistor $R_4$, to increase the overall bandwidth [18]. The second stage controls the pulse polarity and the DC bias.

The balun converts the single-ended TCA output signal to differential signals. The balun and output buffer are illustrated in Figure 6. The balun is a differential amplifier with differential inputs biased at the same DC level. In this study, the same DC voltage as compared with the output voltage of the TCA is applied through additional DC bias port $VB$. The output buffer is also a differential amplifier, and it is designed to match the output impedances to 50 $\Omega$ on both the positive and negative outputs.

The full width at half maximum (FWHM) of the input pulse used in this work is about 2.2 ns and its rise time is ~1 ns. The bandwidth required for the designed TCA to preserve its rise time is approximated by [19,20] as:

$$
BW \simeq \frac{0.35}{t_r},
$$

where $t_r$ is the rise time of the input pulse. For a rise time of 1 ns, (3) gives a bandwidth of approximately 350 MHz. The simulated transimpedance gain of the developed TCA obtained using this balun and output buffer is shown in Figure 9. The transimpedance gain is approximately 68 dBΩ and the $-3$ dB
frequency is approximately 353 MHz with a photodetector parasitic capacitance of 1 pF. The gain and bandwidth from each circuit stage is summarized in Table 1.

![Figure 9](image-url) Simulated transimpedance gain of the proposed TCA obtained using this balun and output buffer.

<table>
<thead>
<tr>
<th>Stage</th>
<th>Gain</th>
<th>Bandwidth</th>
<th>Direct Current (DC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current buffers and first combining stages ($R_1$)</td>
<td>70 dBΩ (3 kΩ)</td>
<td>330 MHz</td>
<td>1.48 mA</td>
</tr>
<tr>
<td>Second combining stage</td>
<td>2 dB</td>
<td>310 MHz</td>
<td>0.65 mA</td>
</tr>
<tr>
<td>Post-amplifier</td>
<td>6 dB</td>
<td>415 MHz</td>
<td>2.06 mA</td>
</tr>
<tr>
<td>Balun and output buffer</td>
<td>−10 dB</td>
<td>353 MHz</td>
<td>3.78 mA</td>
</tr>
</tbody>
</table>

### 3. Measurement Results

The switched 4-to-1 TCA was implemented in a 0.18 μm CMOS technology. The core occupies an area of 92 μm × 68 μm, and the die size including I/O pads is 1000 μm × 840 μm. A microphotograph of the fabricated chip with bond wires on the test fixture is shown in Figure 10. All the biases were applied through bond wires, and short pulse response measurement was performed with a coaxial micro-receptacle (CMJ) connector.

![Figure 10](image-url) Microphotograph of the fabricated chip with bond wires on the test fixture.

The fabricated chip was mounted on a wire-bonded chip-on-board (COB) module to measure the electrical pulse response, as shown in Figure 11a. A 10-kΩ resistor acts as a voltage-to-current converter. To measure the pulse transient response of the fabricated circuit, an electrical pulse signal,
generated from an Agilent 81110A pattern generator (Keysight, Santa Clara, CA, USA), was applied to
each input channel of the implemented test fixture, as shown in Figure 11b. The OUT+ and OUT–
signals were measured using an Agilent DSO7104B oscilloscope.

Figure 12 shows the measured transient pulse response for the fabricated chip. The pulse magnitude
of the input voltage from the pattern generator is adjusted so that the input current becomes 20 µA and
the FWHM of the input signal is 2.2 ns with a 1.8 ns rise time, which is the minimum rise time of the
Agilent 81110A pattern generator. The input current is applied to each successive input channel from
IN1 through IN4, and 200 segment pulse responses of OUT+ and OUT– are measured. The blue lines
represent the pulse response of 200 segments, and the red line represents the average pulse response
value. The average peak-voltage of the measured output pulses is approximately 47.4 mV, and hence,
the transimpedance gain is calculated to be 67.5 dBΩ using by (4). This value is very near the simulated
results of 68 dBΩ.

\[
Z_T = 20 \times \log_{10} \left( \frac{47.4 \text{ mV}}{20 \mu \text{A}} \right)
\]  

(4)

Figure 12. Measured transient pulse response for the fabricated chip.
The integrated single-ended output noise of the switched 4-to-1 TCA was measured via the oscilloscope root-mean-square (RMS) calculation function with no input signal source, as shown in Figure 13 [21]. The standard deviation of the output was measured to be 0.524 mV. After subtracting the inherent oscilloscope noise of 0.4 mV rms, the corrected single-ended integrated output noise of the TCA was estimated to be 0.338 mV rms. The integrated input-referred noise of the differential output of the switched 4-to-1 TCA for each input channel can be calculated as in Reference [22].

\[ I_{n,in} \approx \frac{1}{4} \cdot \frac{2 \sqrt{(0.524 \text{ mV})^2 - (0.4 \text{ mV})^2}}{67.5 \text{ dB} \Omega} = 0.07 \mu A_{\text{rms}} \]  

(5)

![Figure 13. Integrated single-ended output noise of the switched 4-to-1 TCA.](image)

The average input-referred noise current density is:

\[ I_{n,in,avg} \approx \frac{I_{n,in}}{\sqrt{BW}} = 3.8 \text{ pA/} \sqrt{\text{Hz}} \]  

(6)

The switched 4-to-1 TCA used a supply voltage of 1.8 V and dissipated 17.8 mW of power. The performances of the TCA are summarized in Table 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combining Channel</td>
<td>4</td>
</tr>
<tr>
<td>(C_{PD}/\text{cell (pF)})</td>
<td>1</td>
</tr>
<tr>
<td>Effective total (C_{PD}) (pF)</td>
<td>4</td>
</tr>
<tr>
<td>Transimpedance gain (dB(\Omega))</td>
<td>67.5</td>
</tr>
<tr>
<td>Bandwidth (MHz)</td>
<td>353 (simulated)</td>
</tr>
<tr>
<td>Input-referred noise current density/(\text{cell (pA/}\sqrt{\text{Hz}}))</td>
<td>3.8</td>
</tr>
<tr>
<td>Power consumption (mW)</td>
<td>17.8</td>
</tr>
<tr>
<td>Chip size (mm(^2))</td>
<td>1.00 \times 0.84</td>
</tr>
<tr>
<td>Technology</td>
<td>Complementary metal-oxide-semiconductor (CMOS) 0.18 (\mu)m</td>
</tr>
</tbody>
</table>
4. Conclusions

A compact switched 4-to-1 TCA was implemented using 0.18 μm CMOS technology and was used as a receiver front-end ROIC for a STUD-based LADAR system. A switch was inserted on the input path of the TCA to expand the effective photosensitive area without increasing the noise from the large-area photodetector of the STUD-based LADAR system. The space between the partitioned photosensitive cells and its cascading current buffers was made smaller by about several hundred micrometers by integrating several TIAs and a signal combiner onto a single chip. The fabricated chip had a power consumption of 17.8 mW for a 1.8 V supplied voltage, an average input-referred noise current spectral density of 3.8 pA/√Hz, and a transimpedance gain of 67.5 dBΩ. The chip was operated based on the same working principle as the STUD-based LADAR receiver. Therefore, the compact switched 4-to-1 TCA is suitable for the front-end ROIC of the STUD-based LADAR system as one integrated chip.

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Conflicts of Interest: The authors declare no conflict of interest.

References


