# Light Monitoring in Standard Silicon Photonics with a Monolithic Transimpedance Amplifier

Monica Crico[1], Andres Martinez[1], Francesco Morichetti[1], Andrea Melloni[1], Giorgio Ferrari[2], Marco Sampietro[1],
Francesco Zanetto[1]
[1] Dipartimento di Elettronica, Informazione e Bioingegneria, Politecnico di Milano, 20133 Milano, Italy
[2] Dipartimento di Fisica, Politecnico di Milano, 20133 Milano, Italy
Email: monica.crico@polimi.it

***Abstract*—The integration of a transimpedance amplifier in standard Silicon Photonics is presented. The circuit can successfully read integrated photodiodes up to a frequency of $2\,\mathrm{MHz}$ and down to $-40\,\mathrm{dBm}$ of input optical power, demonstrating successful on-chip analog processing of electrical signals.**

## I. INTRODUCTION

The integration density enabled by Silicon Photonics (SiP) technologies allows the design of large-scale optical systems-on-chip, comprising hundreds of photonic devices able to perform complex manipulation of light beams. In addition to having excellent optical properties, silicon is an interesting photonic material because it can be processed by exploiting the same manufacturing steps of the microelectronic industry. Consequently, the cointegration of both electronic and photonic functionalities on the same die is expected to be a key enabler for the design of next-generation electro-optical systems, exploiting the unrivaled bandwidth of optical devices and the versatility of CMOS electronics. The option of integrating photonic devices into a standard microelectronic stack has been successfully pursued to design high-speed transceivers for optical communications operating at hundreds of $\mathrm{Gbit\,s^{-1}}$ [1], [2]. Recently, the opposite approach has also been demonstrated [3], with the integration of complementary metal-oxide-semiconductor (CMOS) devices and digital circuits into a standard SiP process. Here, we further extend this approach and show that analog electronic circuits can also be integrated in standard SiP technologies, opening the way to on-chip amplification and processing of electrical signals.

## II. CMOS TRANSISTORS IN SIP

CMOS transistors have been integrated into the photonic chip with a zero-change approach, achieved by using only the fabrication steps already available in the standard technological stack of Advanced Micro Foundry (AMF, Singapore) [3]. Since in SiP technologies the metal layers are relatively far from the silicon, the transistors were designed with lateral silicon gates, by exploiting the minimum waveguide-to-waveguide distance of around $200\,\mathrm{nm}$ (Figure 1a, 1b). Both nMOS and pMOS devices were realized, employing the same geometry while inverting the doping species of the diffusion regions. A reasonably low threshold voltage around $1.5\,\mathrm{V}$ has been achieved thanks to the fact that the native silicon layer of a photonic chip is naturally depleted of free carriers [4]. Both devices have been electrically characterized demonstrating successful operation (Fig. 1c, 1d) and used to integrate a transimpedance amplifier (TIA) on the photonic chip.

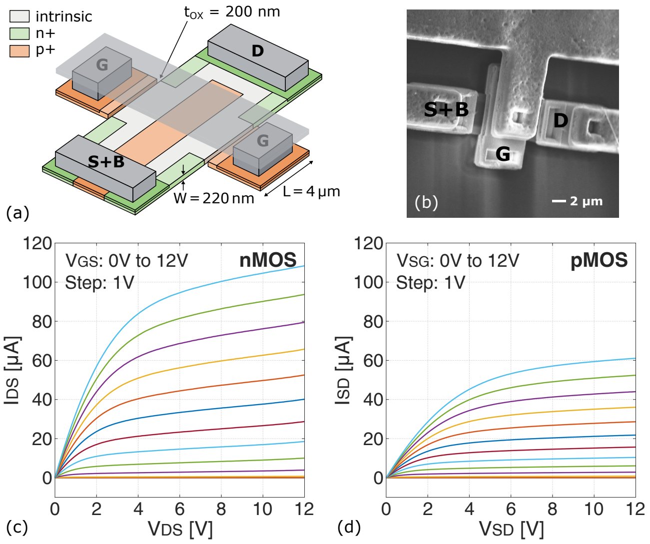

Fig. 1. Successful realization of nMOS and pMOS transistors in standard Silicon Photonics. a) 3D view of the nMOS structure and b) its microscope photograph. c), d) Measured characteristic curves of the two transistors.

## III. TRANSIMPEDANCE AMPLIFIER FOR ON-CHIP OPTICAL POWER MONITORING

To implement the TIA, a standard two-stage operational transconductance amplifier (OTA) has been designed (Figure 2a). A transdiode current generator biases the input nMOS pair and the active load. A second Miller-compensated stage provides further amplification and the desired single-pole frequency response. The circuit has a supply voltage of $5\,\mathrm{V}$ and a power consumption of $400\,\mathrm{\mu W}$. The amplifier has been connected in a transimpedance configuration with a feedback resistance of $10\,\mathrm{k\Omega}$, to read the current signal from integrated germanium photodiodes (PD) and turn it into a voltage directly on the photonic chip. In principle, a battery of TIAs could be used to read any integrated sensor and precisely monitor the optical power in the optical circuit. More in general, an OTA represents the fundamental building block of many analog electronic circuits and could be used to integrate analog-

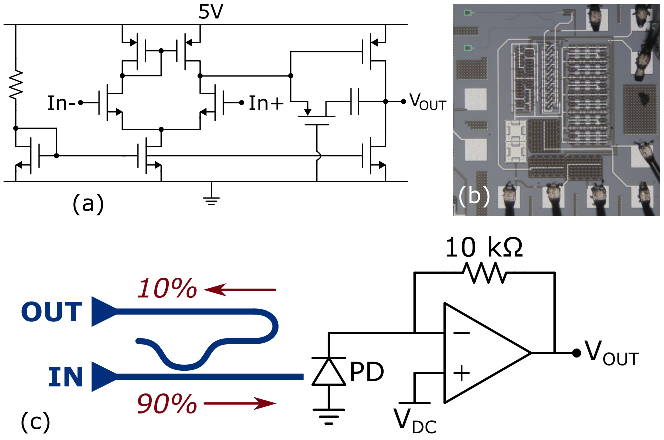

Fig. 2. a) Internal structure of the amplifier and b) its microscope photograph. c) Schematic view of the TIA connected to an on-chip power monitor.

to-digital and digital-to-analog converters or to implement local feedback loops to control and stabilize the behavior of programmable photonic circuits [5]. A microscope photograph of the fabricated chip is shown in Figure 2b.

## IV. EXPERIMENTAL RESULTS

A test structure has been designed to characterize the functionality of the TIA, as shown in Figure 2c. It is made of a straight waveguide that injects light to an integrated photodiode, that is then read by the TIA. To precisely compare the readout performed by the integrated amplifier with conventional bench-top instruments, a 90-10 splitter routes $10\%$ of the injected light signal out of the chip. TE-polarized grating couplers have been used to couple light in and out of the circuit, each introducing $4\,\mathrm{dB}$ of losses.

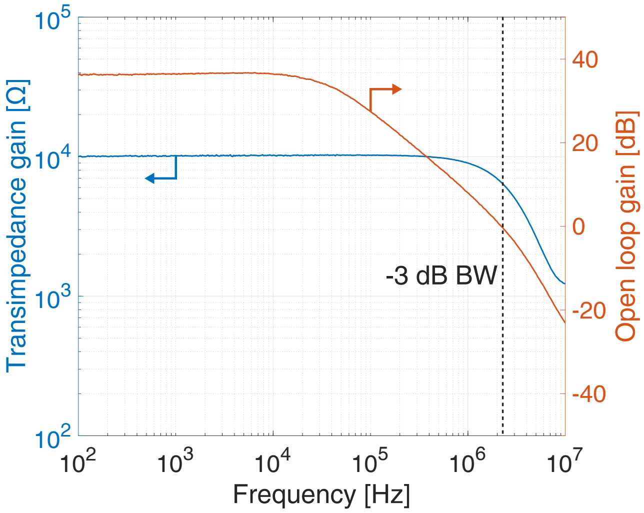

Fig. 3. Measured transimpedance gain and open loop gain of the amplifier, as a function of frequency.

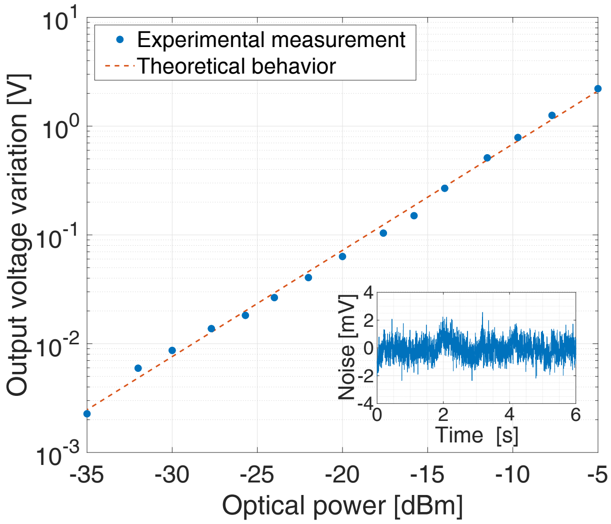

Fig. 4. Voltage variation at the output of the TIA as a function of the optical power reaching the photodiode. The inset shows the noise at the TIA output with a $1\,\mathrm{kHz}$ readout bandwidth.

First, the TIA has been electrically characterized by testing its frequency response (Figure 3), both in open-loop and in transimpedance configuration. As can be seen from the graph, the gain-bandwidth product of the open-loop gain exactly matches the $-3\,\mathrm{dB}$ bandwidth of the transimpedance gain, confirming the correct design of the circuit and the stability of the amplifier. The resulting bandwidth is about $2\,\mathrm{MHz}$, wide enough to perform effective monitoring of the optical power in the most common applications [5]. Then, optical validation has been performed, in order to assess how the circuit responds to actual current signals from the photodiode. Progressively smaller values of optical power have been injected into the chip by attenuating the input light signal and the corresponding voltage variation has been measured at the output of the TIA. The results are shown in Figure 4. The relation between optical power and output voltage is linear, in accordance with theoretical behavior. The lowest signal that can be detected by the circuit has been assessed by measuring the noise at the TIA output without light. A noise RMS value of $660\,\mu\mathrm{V}$ has been measured with a readout bandwidth of $1\,\mathrm{kHz}$, corresponding to a minimum detectable light variation of $-40\,\mathrm{dBm}$ considering the $0.8\,\mathrm{A\,W^{-1}}$ responsivity of the PDs.

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