A monolithic, standard CMOS, fully differential optical receiver with an integrated MSM photodetector*

Yu Changliang(余长亮)†, Mao Luhong(毛陆虹), Xiao Xindong(肖新东), Xie Sheng(谢生), and Zhang Shilin(张世林)

(School of Electronic Information Engineering, Tianjin University, Tianjin 300072, China)

Abstract: This paper presents a realization of a silicon-based standard CMOS, fully differential optoelectronic integrated receiver based on a metal–semiconductor–metal light detector (MSM photodetector). In the optical receiver, two MSM photodetectors are integrated to convert the incident light signal into a pair of fully differential photogenerated currents. The optoelectronic integrated receiver was designed and implemented in a chartered 0.35 μm, 3.3 V standard CMOS process. For 850 nm wavelength, it achieves a 1 GHz 3 dB bandwidth due to the MSM photodetector's low capacitance and high intrinsic bandwidth. In addition, it has a transimpedance gain of 98.75 dBΩ, and an equivalent input integrated referred noise current of 283 nA from 1 Hz up to –3 dB frequency.

Key words: optical receiver; standard CMOS; fully differential; MSM photodetector
DOI: 10.1088/1674-4926/30/10/105010 **PACC:** 4230Q **EEACC:** 1205

1. Introduction

In high-speed fiber communication systems, monolithic optoelectronic integrated receivers and their implementation in standard CMOS processes have been mainstream research focuses. Though much progress has been made in recent years[1–4], completely applicable, silicon-based standard CMOS optoelectronic integrated receivers have not been reported yet because of the low responsivity and inadequate bandwidth of standard CMOS photodetectors.

It is well known that a Schottky diode has a much better high-frequency characteristic than a p–n junction diode because it is a majority-carrier only device, and an MSM photodetector based on the Schottky diode has fundamental advantages of a much lower capacitance per unit area to allow a large collection area without significant speed degradation, planarity, and simplicity of fabrication compared with a p–n junction photodetector[5–7]. Hence, MSM photodetectors may be more appropriate for high-speed optical receivers.

In this paper, we propose a fully differential optical receiver with an integrated MSM photodetector. A corresponding monolithic, fully differential optoelectronic integrated receiver is designed and implemented in a chartered 0.35 μm, 3.3 V standard CMOS process.

2. Concept of a fully differential optical receiver with integrated MSM photodetector

Figure 1 shows a block diagram of the proposed fully differential optical receiver with integrated MSM photodetector (MSM PD), where TIA is a differential transimpedance amplifier, LMA is a differential limiting amplifier, and DFSO is a differential to single-ended output buffer. In the optical receiver, two identical MSM photodetectors are utilized to generate a pair of fully differential photo currents for TIA under incident light illumination, which are connected between VDD and one input port of TIA and between GND and the other input port of TIA, respectively. Because an MSM photodetector has a higher intrinsic bandwidth and a much smaller capacitance (usually in the magnitude of several tens of fF) than that of a p–n junction photodetector (usually in the magnitude of pF)[7, 8] with an identical area, an optical receiver based on an MSM photodetector can reach a high bandwidth.

3. Monolithic integration design in silicon-based standard CMOS process

The monolithic integration of MSM photodetectors with metal–oxide–semiconductor field effect transistors

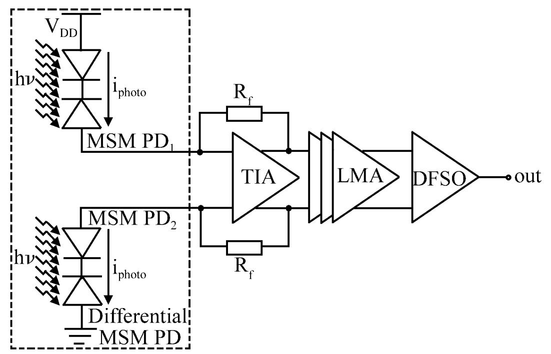

Fig. 1. A fully differential optical receiver with integrated MSM photodetector.

* Project supported by the National Natural Science Foundation of China (Nos. 60536030, 60676038) and the National High Technology Research and Development Program of China (No. 2009AA03Z415).
† Corresponding author. Email: yuchl@tju.edu.cn
Received 4 May 2009, revised manuscript received 11 May 2009

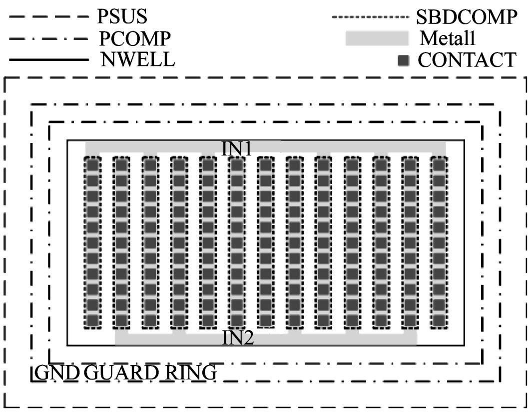

Fig. 2. A standard CMOS MSM photodetector based on the Metal1-NWELL Schottky diode.

(MOS FETs) in standard CMOS processes is very simple[5]. This is because the electrodes of an MSM photodetector and the gate fingers of a MOSFET can be defined with the same photolithographic step and the same metallization step. This section presents an MSM photodetector and a corresponding fully differential optoelectronic integrated receiver based on silicon-based standard CMOS processes.

3.1. A standard CMOS MSM photodetector

This part describes a standard CMOS MSM photodetector, shown in Fig. 2, where PSUB represents p-type substrate, PCOMP represents p-type high-concentration ion implantation region, SBDCOMP represents Schottky diode's high-concentration ion implantation region, and NWELL represents n-type well. The MSM photodetector consists of two sets of interdigitated Metal1-NWELL Schottky contacts in a rectangular NWELL, and IN1 and IN2 are two interdigitated electrodes. In addition, a rectangular-annular PCOMP region connected to GND (GND GUARD RING), surrounding the rectangular NWELL, is added to form a reverse-biased PSUB/NWELL diode for eliminating slow photo-generated carriers deep in PSUB. Since the two electrodes (IN1 and IN2) are connected serially and back to back, they form two Schottky diodes. Hence, an MSM photodetector comprising two back-to-back, interdigitated Metal1-NWELL Schottky diodes is constituted.

It is easily seen that the two electrodes of an MSM photodetector have no difference in anode and cathode, while a p–n junction photodetector usually works at a reverse bias to acquire a wide depletion region for sensitivity improvement. When the MSM photodetector is given a bias between IN1 and IN2, and is also under incident light illumination, photo-generated electrons in NWELL will diffuse and drift to the high-potential electrode; photo-generated holes to the low-potential electrode. Consequently, a photo-generated current is formed, flowing from the high-potential electrode to the low-potential electrode.

For a selected, silicon-based standard CMOS process, the power voltage, NWELL depth and doping concentration, Metal1-NWELL Schottky contact potential difference, and carrier mean free path are all constant, and finger spacing and finger width are the only optional parameters to adjust the MSM photodetector's bandwidth and sensitivity.

3.2. A standard CMOS, fully differential optoelectronic integrated receiver with MSM photodetector

Figure 3 shows the schematic of a standard CMOS, fully differential optoelectronic integrated receiver based on the MSM photodetector of Fig. 2. It utilizes two MSM photodetectors of Fig. 2 to generate a pair of fully differential photo currents for TIA. These two MSM photodetectors are completely identical, and placed symmetrically in a square illumination region to receive incident lights from only one fiber. The LMA is the cascade of five stages of a low-gain, high-bandwidth, fully differential amplifier. In the design of TIA and LMA, NMOS-diode loads and active inductors[9] are both applied to enhance bandwidth, such as M_{N3} and M_{P1}, M_{N4} and M_{P2}, and so forth.

The DFSO is a new, high bandwidth, differential to single-ended converter proposed to reduce its influence on the optical receiver's whole frequency characteristic. Unlike a conventional differential to single-ended converter[10], it adds two additional NMOS diodes (M_{N32} and M_{N33}) parallel with the two PMOSs (M_{P7} and M_{P8}) of the active current mirror load for output resistance reduction, and it also deletes the current bias MOSFET for better impedance matching.

Finally, a wide-swing and constant-transconductance bias current source[11] was chosen for the optical receiver to achieve a relatively stable circuit performance. The output port of the bias current source is directly connected to the node V_{BIAS}.

4. Experimental results

To avoid the possibility of the output voltage signal amplitude being too low to make testing feasible, the proposed optoelectronic integrated receiver was designed with a 98.75 dBΩ high-transimpedance gain. Additionally, it was also designed with a 1.069 GHz 3 dB bandwidth, and a 283 nA total equivalent input integrated referred noise current from 1 Hz up to –3 dB frequency, that is, a –16 dBm sensitivity could be reached at a 10^{-12} BER if the MSM photodetector's responsivity is assumed to be 80.4 mA/W[12] (the calculation of optical sensitivity is described in detail in Ref. [13]).

Then, the optical receiver was implemented in a chartered 0.35 μm, 3.3 V standard CMOS process. Figure 4 shows the die photograph. In Fig. 4, the region surrounded by a black rectangle is the differential MSM photodetector of Fig. 3 with an area of 80×80 μm^2.

Figure 5 gives the measured results after die bonding on a PCB board acquired by a 10 Gbit/s, 850 nm VCSEL of New Focus, a 3 GHz network analyzer and a wide-bandwidth oscilloscope of Agilent Technologies. Figures 5(a) and 5(b) are the measured optic frequency response and measured transient response at 1 GHz for 850 nm wavelength with –10 dBm optical power, respectively. They demonstrate that the optical receiver

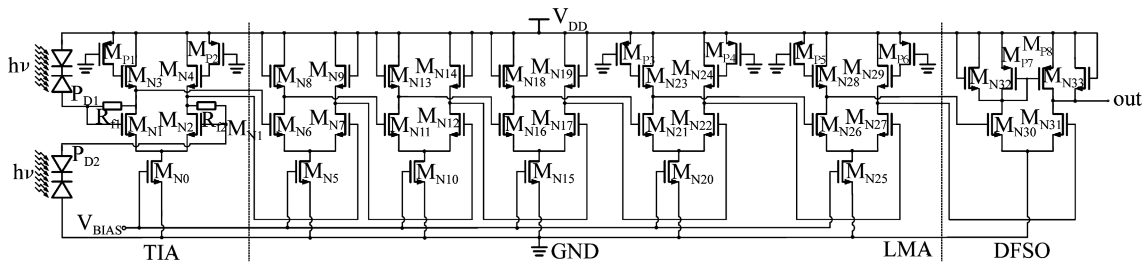

Fig. 3. A standard CMOS, fully differential optoelectronic integrated receiver with MSM photodetector.

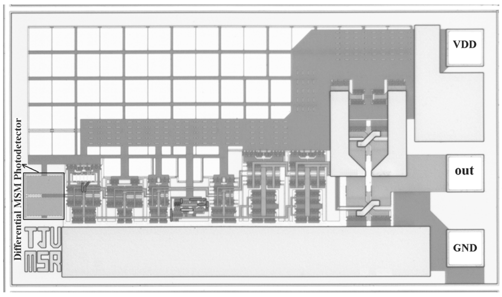

Fig. 4. Die photograph of the optoelectronic integrated receiver in a chartered 0.35 μm, 3.3 V standard CMOS process.

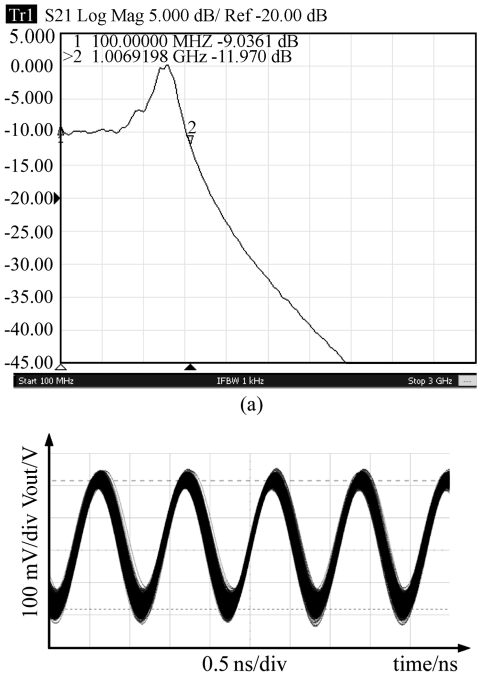

Fig. 5. Measured results: (a) Optic frequency response for 850 nm wavelength with –10 dBm optical power; (b) Transient response at 1 GHz for 850 nm wavelength with –10 dBm optical power.

achieves a 1 GHz 3dB bandwidth, and the output voltage signal amplitude is about 400 mV. It is seen that these tested results are basically consistent with the designed performance.

5. Conclusion

A fully differential optical receiver with integrated MSM photodetector is proposed in this paper. A corresponding silicon-based, fully differential optoelectronic integrated receiver based on the MSM photodetector consisting of Metal1-NWELL Schottky diodes was designed and implemented in a chartered 0.35 μm, 3.3 V standard CMOS process. It achieves a 1 GHz 3dB bandwidth for 850 nm wavelength. However, there are still some MSM photodetector manufacturing issues that need to be overcome, especially the reliability of metal–semiconductor Schottky contacts.

References

[1] Tavernier F, Steyaert M. A high-speed fully integrated optical receiver in standard 130 nm CMOS. 15th IEEE International Conference on Electronics, Circuits and Systems, 2008: 806

[2] Grözing M, Jutzi M, Nanz W, et al. A 2 Gbit/s 0.18 μm CMOS front-end amplifier for integrated differential photodiodes. Topical Meeting on Silicon Monolithic Integrated Circuits in RF Systems, Dig Papers, 2006: 361

[3] Hermans C, Tavernier F, Steyaert M. A gigabit optical receiver with monolithically integrated photodiode in 0.18 μm CMOS. Proc Eur Solid-State Circuit Conf, 2006: 476

[4] Chen W Z, Huang S H, Wu G W, et al. A 3.125 Gbps CMOS fully integrated optical receiver with adaptive analog equalizer. IEEE Asian Solid-State Circuits Conference, 2007: 396

[5] Berger P R. MSM photodiodes. IEEE Potentials, 1996, 15(2): 25

[6] Hurm V, Bronner W, Benz W, et al. Large area MSM photodiode array for 0.85 μm wavelength 10 Gbit/s per channel parallel optical links. Electron Lett, 2002, 38(18): 1051

[7] Zhu S, Lo G Q, Kwong D L. Low-cost and high-speed SOI waveguide-based silicide Schottky-barrier MSM photodetectors for broadband optical communications. IEEE Photonics Technol Lett, 2008, 20(6): 1396

[8] Liu M Y, Chou S Y, Alexandrou S, et al. 110 GHz Si MSM photodetectors. IEEE Trans Electron Devices, 1993, 40(11): 2145

[9] Yu Changliang, Mao Luhong, Song Ruiliang, et al. Design and implementation of an optoelectronic integrated receiver in standard CMOS process. Chinese Journal of Semiconductors, 2007, 28(8): 1198

[10] Razavi B. Design of analog CMOS integrated circuits. New York: The McGraw-Hill Companies, Inc, 2001

[11] Johns D A, Martin K. Analog integrated circuit design. New York: John Wiley & Sons, Inc, 1997

[12] Li M, Anderson W A. Si-based metal–semiconductor–metal photodetectors with various design modifications. Solid-State Electron, 2007, 51(1): 94

[13] Das M B, Chen J W, Eugene J. Designing optoelectronic integrated circuit (OEIC) receivers for high sensitivity and maximally flat frequency response. IEEE J Lightwave Technol, 1995, 13(9): 1876