Optical wireless communication with monolithic avalanche photodiode receivers

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***Abstract*—Receivers in 0.35 µm BiCMOS with highly efficient integrated 200 µm and 400 µm diameter avalanche photodiodes will be introduced. Results of optical wireless communication up to 12 m at 2 Gbit/s and 20 m at 1 Gbit/s in presence of 2000 lux lighting are presented. Possibilities of further improvement will be discussed.**

Keywords*—*avalanche photodiodes, optical receivers, wireless optical communication

I. Introduction

Optical wireless communication (OWC) is a promising technology for the upcoming omni-connected wireless era. The need for compact highly sensitive optical receivers pushed the research into direction of optoelectronic integrated circuits (OEIC) with special focus on avalanche photodiodes (APD) due to their inherent gain. Section II presents the high-speed OWC system with integrated linear APD receivers developed in a standard 0.35 µm BiCMOS technology with large area photodiodes. Section III presents line of sight (LOS) link with low-speed non-linear APD receiver where the APD was biased beyond breakdown voltage making it highly sensitive.

II. High-speed OWC

A. High-speed APD OEIC receivers

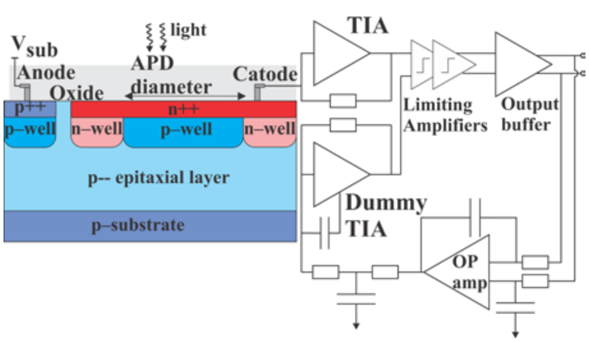

Fig. 1. Optical receiver block diagram

The structure of the produced APDs is shown in Fig. 1 together with the receiver circuit block diagram. The APDs have a multiplication zone (n++/p-well) and an absorption zone (p-- epi). The n++ layer serves as cathode and it is connected to the input of the transimpedance amplifier, whereas the substrate serves as anode. The topology of the receiver is pseudo differential (the dummy TIA is not fully balanced) with single-ended shunt-shunt feedback TIA with a common emitter input stage as front-end and differential post amplification. The offset compensation and biasing of the replica TIA was done with an operational amplifier and RC filtering. For a bit-error rate BER=10^{-9} the 200 µm diameter APD (200APD) receiver reached -35.5 dBm sensitivity at 1 Gbit/s (-32.2 dBm at 2 Gbit/s); whereas the 400 µm diameter APD (400APD) receiver reached -34.6 dBm at 1 Gbit/s (-30.6 dBm at 2 Gbit/s) [1].

B. OWC setup and experiments

The free-space optical communication was performed under normal ambient lighting (500 lux) with the system setup like in [2]. For the transmitter design we used a vertical cavity surface emitting laser (VCSEL) with a wavelength of 680 nm modulated by a laser driver MAX3740A. The laser beam divergence was equal to 0.06° full-width at half maximum (FWHM) whereas in [2] the divergence angle was 0.15°. The collimated beam could be steered using a MEMS mirror [2]. The extinction ratio (ER) was set to 8 while the output power of VCSEL was adjusted to 0.85 mW. The transmitter was modulated with a pseudorandom binary sequence (PRBS) having a length of 2^{31}-1. At the receiver side one of the differential outputs was connected to a bit error analyzer and the other was terminated with 50 Ω.

1) Maximum error free transmission distances

Due to the highly sensitive APD receivers and large collection areas of the photodiodes large transmission distances could be accommodated without using any optics at the receiver side. The 200APD receiver reached 11 m error free transmission distance (BER<10^{-9}) at 1 Gbit/s and 6.5 m at 2 Gbit/s. The 400APD receiver reached 20 m at 1 Gbit/s and 12 m at 2 Gbit/s [3]; therefore by increasing the collection area by a factor of 4 the working distance increased 1.81 times for 1 Gbit/s and 1.84 times for 2 Gbit/s. The transmission distance increased 2.8 times compared to the 200 µm diameter

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HV CMOS APD receiver which operated at 1 Gbit/s [4]. The absence of any kind of optics increased the allowable receiver's incidence angle to 20±1° compared to a receiver's incidence angle of 9° in [2] where an imaging optics was used to increase the collection area.

2) BER vs. Background-light immunity

For verifying the performance of the receiver under different ambient light levels we used a variable cold light source and placed the 200APD and 400APD receivers at the distances of 6 m and 11 m respectively. Fig. 2 shows the illuminance levels up to which BER<10^{-9} could be reached for both APD OEICs; the respective maximum illuminance levels were 6000 lux (200APD) and 2000 lux (400APD) at 2 Gbit/s. The difference is on account of different amount of background light induced photocurrent which is proportional to the photodiode area [3].

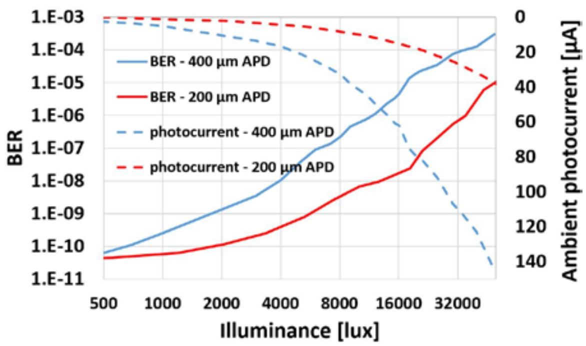

Fig. 2. BER vs. ambient light illuminance

III. High-Sensitivity Low-speed OWC

The low-speed LOS communication operated at 50 Mbit/s. The transmitter was a 635 nm laser with an external modulator (ER=26) modulated with a non-return to zero (NRZ) PRBS 2^7-1 sequence. The laser output was coupled into a single-mode fiber and collimated with the Thorlabs F280FC-B collimator giving the divergence angle of 0.01°. The integrated receiver was a 200 µm APD divided into four quadrants (fill factor FF=53%) and operated in Geiger mode as a single-photon avalanche photodiode (SPAD). Each of the four channels had a quenching circuit whose output was fed into a buffer which delivered a digital signal into a 4-channel oscilloscope where the data was stored and sampled for the BER postprocessing in MATLAB. The transmitter was placed at the distance of 2 m from the black box shielding the integrated SPAD receiver from light. The box had only a small opening for a Thorlabs laser line filter FL635-10 to allow the free space link and prevent saturation of the SPAD receiver. Fig. 3 shows the results at the distance of 2 m; for a BER limit of 2×10^{-3} (red line) the needed output optical power is a little below 1 µW thanks to the good sensitivity of the receiver. If the output power of the laser would be increased to maximum allowable 1 mW for class 1 lasers the transmission distance could be increased considerably. SPAD receivers have only recently been used for communication due to their parasitic effects, which are worse in a wireless environment. The results comparable to ours are 200 Mbit/s visible light communication (VLC) at very short distance [5] with a receiver containing 60 SPADs, and 60 Mbit/s at 2 m VLC [6] divided into three different RGB channels, requiring three 128×32 array SPAD receiver chips receiving 20 Mbit/s each, with dedicated filters.

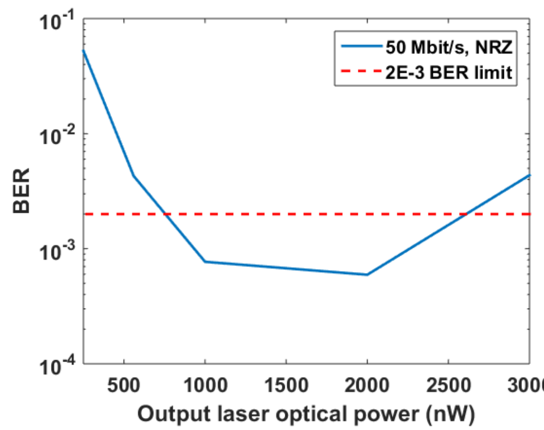

Fig. 3. BER vs. output laser power at distance of 2 m

IV. Conclusion

The recent progress within our group in the area of APD OEICs has been presented. The high-speed linear APD receivers allowed progress in terms of transmission distance and receiver acceptance angle and their high immunity to background light makes them a suitable choice for the receiver side of OWC systems. Although the SPAD receiver represents an important step forward with respect to improved sensitivity, speed and transmission distance a long and challenging way lies ahead towards the Gbit/s range.

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