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Gigacount/second Photon Detection Module Based on an 8 × 8 Single-Photon Avalanche Diode Array

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Abstract

In this letter we present a compact photon detection module, based on an 8×8 array of single-photon avalanche diodes (SPADs). The use of a dedicated silicon technology for the fabrication of the sensors allows us to combine large active areas (50-μm diameter), high photon detection efficiency (49% at 550-nm wavelength) and low dark count rate. Thanks to a fully parallel architecture, the module provides voltage pulses synchronous to each photon detection for a maximum global count rate exceeding 1 Gcps. These properties makes the system suitable for operation in two different free-running modes. The first, suitable to acquire faint signals, allows multi-spot acquisitions and can be used to considerably reduce the measurement time in applications like single-molecule analysis. With the second it is possible to use all the pixels in a combined mode, to extend and move the dynamic range of the module to very high count rates and to attain number resolving capabilities.

Keywords

Array detectors; single-photon avalanche diodes (SPADs); photon counting; photon number resolving; gigacount rate

I. INTRODUCTION

RECENT years have seen the rise of single-photon avalanche diodes (SPADs) as a valid alternative to photomultiplier tubes (PMTs) in many single-photon counting and time-correlated single-photon counting applications: high photon detection efficiency (PDE), small size, high reliability and the possibility to fabricate detector arrays are the main advantages of SPADs [1]. In addition to this, silicon custom technologies have widely contributed to obtain large-area devices, with remarkable performance in terms of dark count rate (DCR), afterpulsing probability, timing resolution and PDE over the visible range up to 1-μm wavelength [1], [2]. At the same time gigacount applications have emerged in many

areas, such as astronomy [3] or quantum cryptography [4], demanding for high count rate single-photon detectors.

In this paper we present a compact detection module featuring an 8×8 SPAD array fabricated in custom silicon technology. A fully parallel architecture, combined with fast active quenching circuits (AQC), makes the module especially suited for applications requiring free-running operation at high count rate and/or high dynamic range. In particular, we envision its use in two different operation modes. On one hand, the module can be used in a multi-spot configuration in which each pixel, thanks to a suitable optics, collects the light from a different point in the sample. This allows to perform 64 simultaneous acquisitions, therefore reducing the overall measurement time of the same factor. Such a configuration is today adopted for example in high-throughput single-molecule fluorescence spectroscopy [5]. On the other hand, the module can be used in a combined-pixels configuration in which the light coming from a single source is randomly spread across the array. In this case, the availability of 8×8 independent detectors allows to increase the maximum detectable photon flux of a factor 64, reaching a remarkable maximum count rate of 1 Gcps (for a maximum tolerable linearity error of 6 dB), and/or to resolve the number of photons impinging simultaneously on the array. Of course in this operation mode a penalty is paid in terms of noise, since the DCR of all pixels adds up. On the contrary, only a small penalty in terms of system detection efficiency is paid if a suitable array of microlenses is used to focus the light on detectors active areas (thus avoiding losing photons in dead space between them). According to these features, the module can be proposed as a valid alternative to gigahertz photon counting solutions based on superconducting detectors [6], multiplexed detector arrays [7] or silicon photomultipliers (SiPM) [8].

In Section II we will describe the architecture of the photon detection module, while in Section III we will present an experimental characterization of its main parameters.

II. DESCRIPTION OF THE MODULE

The detection module presented in this letter is based on the array of 8×8 silicon SPADs depicted in Fig. 1. Each detector has a circular active area with a diameter of $50\text{ }\mu\text{m}$ and center-to-center spacing between adjacent pixels (pitch) is $250\text{ }\mu\text{m}$. This array has been fabricated in collaboration with the Institute for Microelectronics and Microsystems of the Italian National Council of Research (IMM-CNR sez. Bologna). A custom silicon technology has been used for the fabrication in order to optimize the detectors performance [1], [9]. A common cathode configuration has been adopted for the array, i.e. the same bias voltage is applied to all the cathodes through a common terminal while each anode is routed to an individual bonding pad for connection to an external AQC through wire-bonding. The AQCs have been fabricated by using a $0.18\text{-}\mu\text{m}$ High-Voltage CMOS technology and arranged in two chips each of them containing 32 fully independent channels. Placing the SPADs and the AQCs on separate chips allows us to use different technologies for the fabrication of the detectors and of the quenching electronics, in order to obtain the best performance for each of them [1]. However, this has a price: the amount of connections physically achievable between separate chips limits the maximum number of pixels to some tens.

The SPADs and the AQC's have been assembled into a compact detection module (Fig. 2) that ensures an optimized operation of each component and that can be easily exploited in real applications. In particular, the SPAD array has been mounted on a thermoelectric cooler (TEC) to take advantage of the reduction of the dark count rate at lower temperatures. To prevent the issues related to moisture condensation, the detection module features a sealed chamber for the housing of the 64-pixels SPAD array, of the TEC and of the two AQC arrays; the chamber can be filled with dry nitrogen through two valves. The sealed chamber is surrounded by two printed circuit boards, stacked one on top of the other. The bottom board contains the power supplies and a proportional-integral-derivative (PID) controller that guarantees a stable temperature control on the SPAD array. This has been obtained exploiting a feedback loop between the Peltier cooler and a negative temperature coefficient (NTC) thermistor that is mounted in thermal contact with the detectors. Programming conveniently this board, the user can set the SPADs temperature (down to -15°C) and the bias conditions (up to 8 V above the breakdown voltage). The top board provides a convenient interfacing of the detection module to external systems. In particular, the outputs of the 64 independent AQC's, each providing a voltage pulse synchronous with the detection of a photon by the corresponding SPAD, are routed to an FPGA. The latter in turn delivers the information to the user in two different ways: on one hand the synchronous pulses are made available on 64 pins of a SCSI connector; on the other hand the counts accumulated in adjustable time windows can be transmitted through USB interface to an external PC.

Compared to high pixel density modules, the advantages of the fully parallel architecture we adopted are clear: for example CMOS cameras like [10] or [11] can achieve photon count rates much higher than 1 Gcps, but they provide only the number of events accumulated in a specific integration time. On the other hand, cameras with an event-driven readout [12] make available a signal synchronous with the photon detection, but they can achieve only count rates of some tens of Mcps.

III. EXPERIMENTAL CHARACTERIZATION

A complete experimental characterization of the module has been carried out in order to evaluate the performance of the whole system. All the measurements have been performed in different operating conditions, with the dead time set to 30 ns, as a good trade-off between maximum count rate and afterpulsing probability (around 1% for the majority of the devices, in any case below 4%). From measurements performed on the same kind of detectors connected to the same AQC [13], in these conditions we estimate the optical crosstalk probability to be 1% for two adjacent SPADs and negligible for SPADs spaced of two or more pitches.

A. Dark Count Rate

In order to characterize the detector noise, the dark count rate has been measured for all the channels of the array at different temperatures and overvoltage values. Fig. 3 shows for example the DCR obtained by biasing the array at an overvoltage $V_{ov} = 6\text{ V}$ and by cooling the detector down to a temperature T of 5°C , -5°C and -15°C . Note that in Fig. 3 devices have been sorted in increasing order of DCR and the horizontal axis has been normalized to

100: in this way on the x-axis it is possible to read the percentage of devices having a DCR lower than the corresponding value of on y-axis, thus obtaining a sort of cumulative distribution of the DCR. DCR distribution and temperature dependence are consistent with results reported in [1].

B. Photon Detection Efficiency

A standard, fully automated setup has been used for the measurement of the PDE: a lamp coupled to a diffraction grating generates a monochromatic light and, with the help of an integrating sphere, a uniform beam of photons is obtained and directed toward the active area of the detector. A serial interface allows to sweep all the wavelengths of interest and to open/close a mechanical shutter for real-time measurement of the dark count rate. The number of photons detected by each pixel of the array is collected through the USB interface, whereas the number of impinging photons is obtained using a calibrated photodiode placed on a secondary port of the integrating sphere. The detection efficiency of each channel is thus calculated as:

$$PDE = \frac{n_{open}^* - n_{closed}^*}{n_{ph}}, \quad (1)$$

where n_{ph} is the photon rate impinging on the active area, while n_{open}^* and n_{closed}^* are the count rates recorded by the detector respectively with the shutter open and closed.

Actually, n_{open}^* and n_{closed}^* are obtained from the measured values n_{open} and n_{closed} compensating for the well-known distortion introduced by the dead time T_{dead} [14]:

$$n_{open/closed}^* = \frac{n_{open/closed}}{1 - T_{dead} n_{open/closed}}. \quad (2)$$

Results of the PDE characterization are shown in Fig. 4 and 5. In particular, Fig. 4 shows the dependence of the PDE, averaged over all the channels of the array, as a function of the wavelength. Measurements have been taken at three different values of the overvoltage V_{ov} : 4 V, 6 V and 8 V. The PDE peaks at 550 nm reaching a remarkable value of 49% at an overvoltage of 6 V. An indication of the uniformity of the PDE across the array can be obtained from Fig. 5 where the PDE at three different wavelengths (550 nm, 700 nm and 850 nm), measured at an overvoltage of 6 V, is plotted as a function of the pixel number.

C. Linearity

To demonstrate the ability of this module to operate up to very high detection rates, we measured the count rate as a function of the impinging photon rate, namely the linearity curve. To this aim we used a modified version of the PDE setup, acting on the neutral density filter placed between the output window of the integrating sphere and the detector. Repeating the measurement at the same wavelength, but with filters of different transmittance, it is possible to sweep the impinging photon rate over orders of magnitude. Furthermore, it is possible to additionally extend the photon rate dynamics of the setup modifying the distance between the detector and the integrating sphere. Fig. 6 shows the

result attained by biasing the detector at $V_{ov} = 6V$ and $T = -10^\circ C$. In particular, red circles corresponds to the linearity curve of the SPAD having the lower DCR. For comparison, on the same figure, it has been plotted also (green dashed) the theoretical curve:

$$n_{open} = \frac{PDE n_{ph} + n_{closed}^*}{1 + T_{dead} (PDE n_{ph} + n_{closed}^*)}. \quad (3)$$

The diagram shown in Fig. 6 can be divided in three main regions: for low impinging photon rates the detector counts are dominated by the DCR and no dependence on the impinging light is appreciable. For intermediate rates the behavior of the detector is linear, with an angular coefficient equal to the detection efficiency. After that, in the third zone, the detected count rate reaches again a saturation value, this time equal to the inverse of the dead time, as expected for a non-paralyzable detection system [14]. The almost perfect matching between experimental and theoretical results proves that the pixel introduces no distortion except the expected ones related to the DCR and the dead time. In Fig. 6 is reported also (blue crosses) a global linearity curve obtained by summing the count rate of every pixel and plotting it against the total photon rate impinging on the devices active areas. Comparison with the corresponding theoretical curve (black dash-dot) shows that no additional distortion is introduced also when all the pixels are operated simultaneously at very high count rates, differently from what happens for example with event-driven architectures [12]. This leads to a global maximum count rate of 1 Gcps (considering a maximum tolerable linearity error of 6 dB), or a saturated global count rate of more than 2 Gcps. Furthermore also the dynamic range (DR) performance are comparable with the nowadays state of the art [15], [16], with a remarkable 141.3 dB.

So far we have always assumed that all the photons impinging on the array are focused on the active area of the detectors, i.e. fill factor losses due to dead space between pixels are negligible. Indeed, this can be achieved using a microlens array and, as a future development, the photon detection module presented will be provided with this additional feature.

IV. CONCLUSION

A new compact photon detection module has been developed and extensively characterized. Attained results suggest the use of the module in two different operating modes: a multi-spot mode, suitable for low-noise measurements coming from different sources, and a combined-pixel mode, to achieve gigacount rates and improve the dynamic range of the system. Furthermore, thanks to its fully parallel architecture, the system could be used also in applications requiring photon number resolving capabilities. A final comparison with other single-photon detectors that provide a synchronous pulse with the photon arrival is shown in Table I: commercial thin and thick SPAD modules, CMOS SPADs and other high count rate solutions based on silicon devices have been taken in account.

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Fig. 1.
Microphotograph of the 8×8 SPAD array detector. Chip size is 2.4mm × 2.4 mm.

Fig. 2.
Frontal view of the photon detection module.

Fig. 3. DCR cumulative distribution for different temperatures. Detectors have been biased with an overvoltage $V_{ov} = 6$ V.

Fig. 4.

PDE versus wavelength, measured at three overvoltages V_{ov} . Data have been averaged over all the 64 channels.

Fig. 5. PDE versus detector number, measured at three wavelengths λ . Detectors have been biased with an overvoltage $V_{ov} = 6$ V.

Fig. 6. Linearity comparison between the pixel with the lowest DCR and the combined-pixel mode. Temperature set to -10 °C and overvoltage to 6 V.

TABLE I

Comparison among the detection module presented and other commercial/state-of-the-art solutions.

Detector	Dimension (μm)		Array size	Single-pixel PDE (%)			DCR (cps)	Max count rate (Mcps)	Dynamic range (dB) ¹
	Diameter	Pitch		400 nm	550 nm	800 nm			
MPD PDM [17]	50		1	24	49	15	95^2	12	121.8
Excelitas SPCM-AQRH [18]	180		1	9	55	62	25^2	40	138.1
0.35- μm CMOS SPAD [15]	20		1	50	34	5	25	50	140
0.13- μm CMOS SPAD [16]	8		1				410	185	139.2
This work: Best SPAD	50		1	22	49	13	72^2	33	131.8
Event-driven [12]	8	45	64×48	12	20	4	1136640	80	97.5
SiPM [8]	14^3	25	40×40	75	55	16	270000	1000	125.7
This work: Combined mode	50	250	8×8	22	49	13	33470^2	2130	141.3

¹Dynamic range is expressed as $20 \log DR$.

²Thermoelectrically cooled.

³Square side length.