32x32 SPAD+TDC camera

SPAD lab

Features

- Multi-modality: photon-counting, 2D imaging, 3D time-of-flight ranging, TCSPC (time-correlated single-photon counting)
- Image dimension: 32x32 (1024) pixels
- In-pixel counter: 6 bit (photon-counting)
- In-pixel TDC: 10 bit (photon-timing)
- Max frame rate: 100,000 fps (burst) and 10,000 fps (continuous)
- Timing resolution: 312 ps – 0.9 ns
- Full scale range: 320 ns – 0.92 µs
- Hardware interface: USB 2.0
- Software interface: Matlab

Fig. 1: SPAD camera for 2D imaging, 3D ranging and TCSPC photon-counting.

Applications

- Single-photon counting, timing and imaging
- Medium- and Long-distance LIDAR
- Medical imaging, FLIM, FRET
- Time-resolved Spectroscopy
- Diffuse Optical Tomography
- Looking around the corner
- Advanced 3D Gesture user interface
- Safety and Security

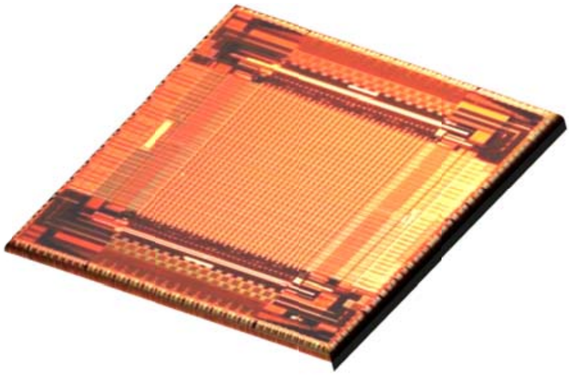

Fig. 2: Array chip containing the 32x32 pixels with 1024 SPAD detectors and 1024 TDCs.

General Description

The TCSPC (Time-Correlated Single-Photon Counting) camera (Fig. 1) is based on 32x32 smart-pixels, each containing a SPAD (Single-Photon Avalanche Diode) detector and a Time-to-Digital Converter (TDC). The chip (Fig. 2) is fabricated in a CMOS technology [1].

Each one of the 1024 pixels provides single-photon detection sensitivity (Fig. 3) and directly measures the time delay between a synch pulse (e.g. triggering a laser shining the sample under test) and the detection of a return single photon. The time delay can be either the photon time-of-flight in 3D-ranging/LIDAR applications, or the fluorescence photon emission in FLIM/FRET imaging, or the time-resolved waveform of very fast optical signals. The 1024 fully independent pixels operate in parallel, with no multiplexing during either detection or TDC conversion, in a global shutter mode. The pixel noise is the best-in-class (Fig. 4) among CMOS SPAD detectors.

In 2D/intensity mode, at every frame the SPAD array provides 1024 word of 6 bits each (i.e. single-frame photon-counting dynamics up to 64 photons). In 3D depth-resolved/timing mode, at every frame the SPAD array provides 1024 words of 10 bits each (i.e. single-frame time-bin down to 312 ps and 320 ns full-scale range).

The frame rate tops at 100 kfps (i.e. a minimum integration frame-time of 10 µs) in burst mode, and 10 kfps in continuous mode.

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Electrical Characteristics *with V_{EX} = 5 V*

Parameter	Notes	Min	Typ	Max	Units
Resolution	number of pixels		32 x 32		pixels
SPAD diameter	diameter of the SPAD into each pixel		30		µm
Pixel pitch	size of each pixel		150		µm
Pixel fill-factor	with no microlens		3.14		%
Photon Detection Efficiency (PDE) of SPAD detectors	@ 420 nm		50		%
	@ 300 nm and @ 650 nm		20		%
	@ 800 nm		5		%
Dark count rate (DCR)	with V_{EX} = 5 V		100		cps
Afterpulsing	with 20 ns hold-off time		2.6		%
Optical cross-talk	between nearest pixels		0.01		%
Photon-counting dynamics	number of bits of the in-pixel counter		6		bit
Photon-timing dynamics	number of bits of the in-pixel TDC		10		bit
On-board clock (f_{clock})	adjustable through the GUI interface	70		200	MHz
TDC least significant bit (LSB) [1]	with f_{clock} = 200 MHz		312		ps
	with f_{clock} = 160 MHz		390		ps
	with f_{clock} = 70 MHz		900		ps
TDC full-scale range (FSR) [1]	with f_{clock} = 200 MHz		320		ns
	with f_{clock} = 160 MHz		400		ns
	with f_{clock} = 70 MHz		920		ns
Full-scale depth range	max scene depth, around the target distance (even kilometers from the camera, depending on the optical setup)	48	60	138	m
TDC single-shot precision (FWHM)	with f_{clock} = 160 MHz (all 32x32 TDC working in parallel)		660		ps
Frame-rate	Burst mode (limited by FPGA read-out)	no limit		100,000	fps
	Continuous mode (limited by USB 2.0 link)	no limit		10,000	fps
Camera power supply			+5		V
Lens connector			12 mm – F/1.4 C-Mount		

[1] LSB and FSR are adjustable through the GUI by changing the on-board clock frequency (f_{CLOCK}).
1 LSB = $1/(f_{CLOCK} \cdot 16)$ n = 10 bit FSR = $2^n \cdot$ LSB = $1024 \cdot$ LSB

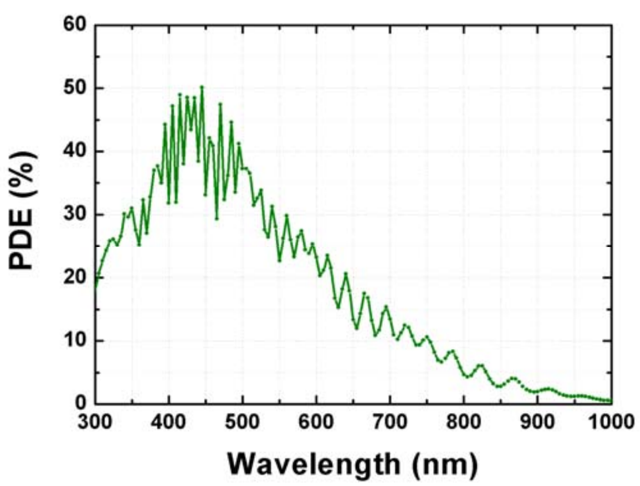

Fig. 3: Photon Detection Efficiency at V_{EX} = 5 V of the CMOS SPADs.

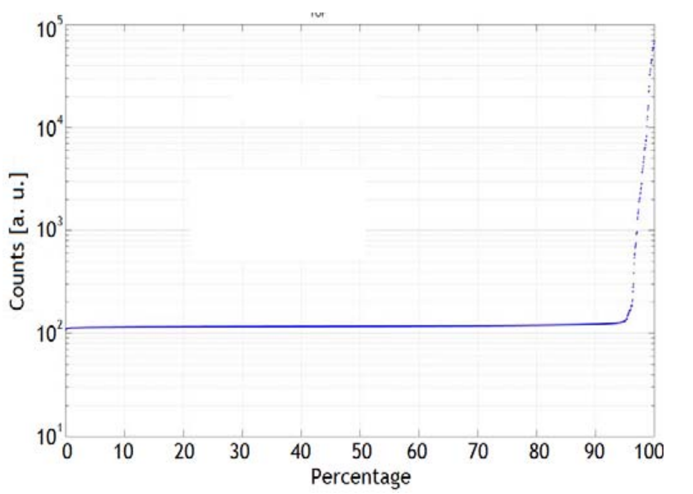

Fig. 4: Dark Count Rate distribution at V_{EX} = 5 V and at room temperature of the CMOS SPADs.

[1] F. Villa, D. Bronzi, Y. Zou, C. Scarcella, G. Boso, S. Tisa, A. Tosi, F. Zappa, D. Durini, S. Weyers, U. Paschen, and W. Brockherde, "CMOS SPADs with up to 500 µm diameter and 55% detection efficiency at 420 nm," *J. Mod. Opt.*, pp. 1–14, Jan. 2014.

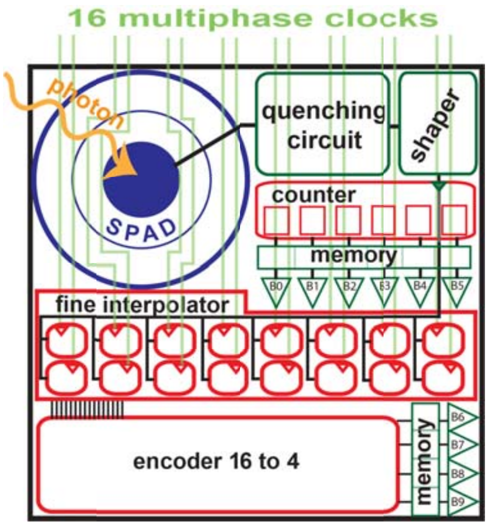

Fig. 5: Pixel block diagram with 30 µm SPAD and 10 bit TDC.

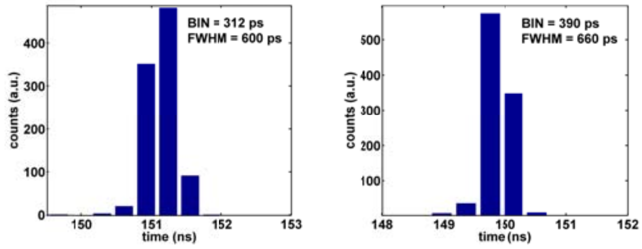

Fig. 6: Single-shot precision with 312 ps bin (left), and 390 ps bin (right). The FWHM precision is 600 ps and 660 ps, respectively.

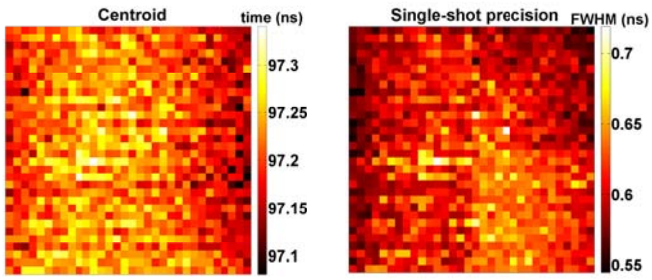

Fig. 7: Centroid (left) and FWHM (right) of the arrival time histogram (about 40,000 conversions) in all the pixels of the array (bin = 312 ps).

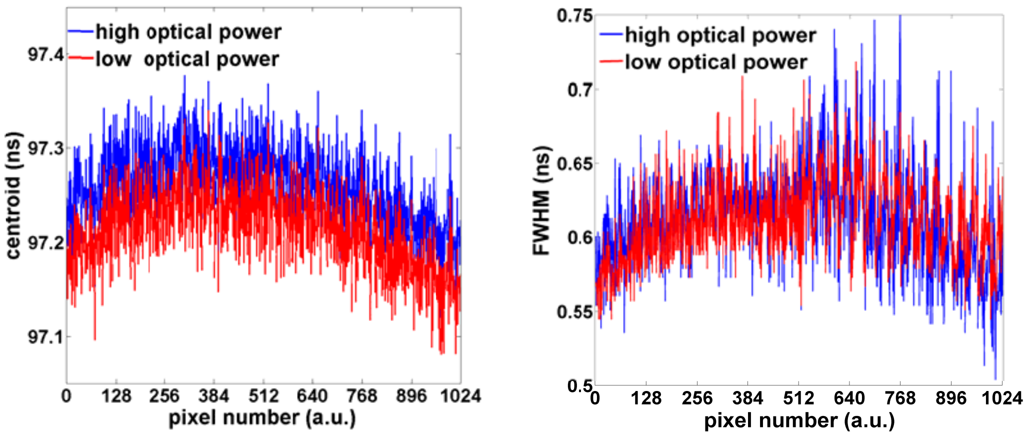

Fig. 8: Centroid (left) and FWHM (right) of arrival time histograms of each array pixel with low (red) and high (blue) optical power illuminating the 32x32 SPAD + TDC array.

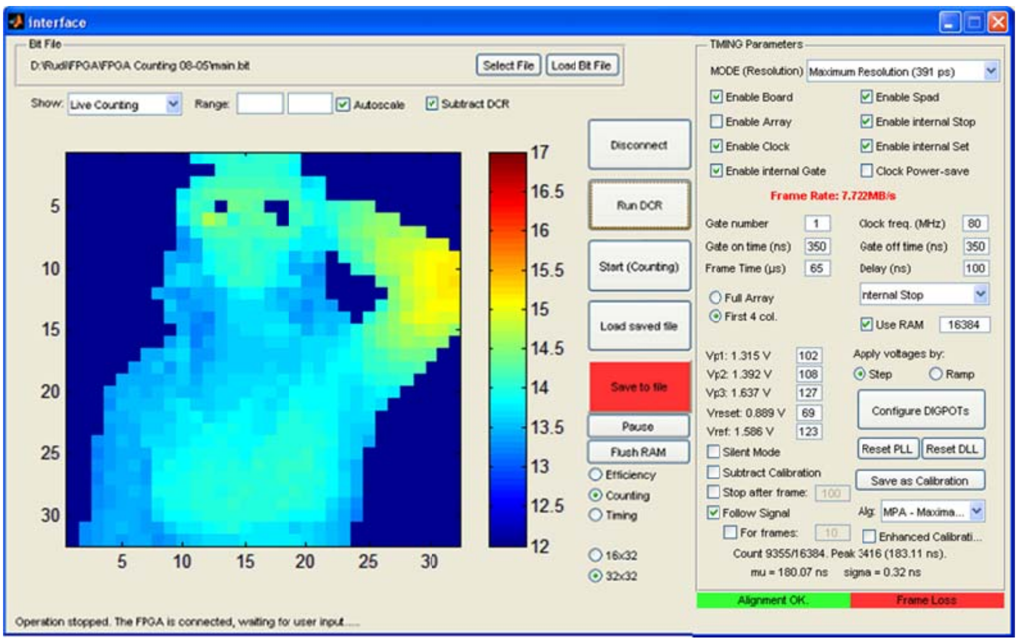

Fig. 9: SPAD + TDC camera Graphical User Interface for 2D imaging and 3D ranging.

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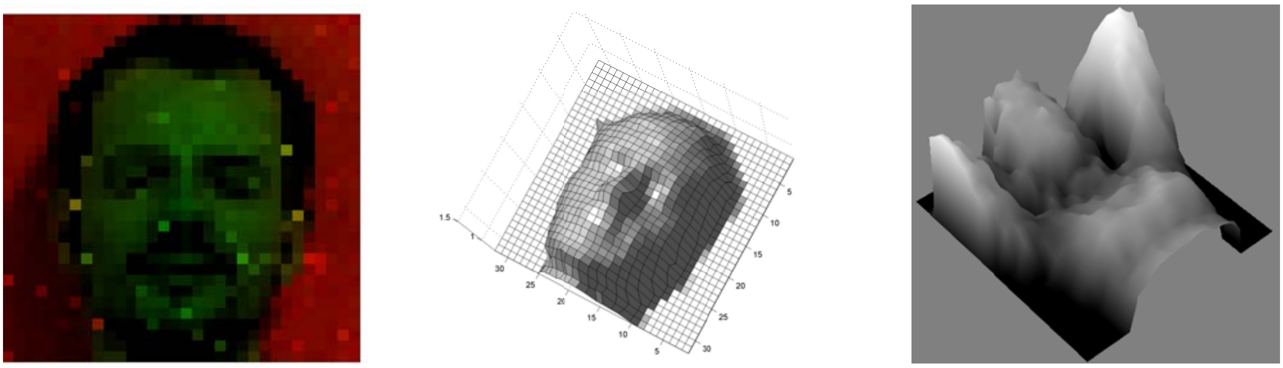

Fig. 10: 3D photon-timing ranging image acquired by the 32x32 SPAD camera at λ = 750 nm (90 mW uniformly distributed over the acquired scene) in 1 ms (dwell time). Left image at 6 m, right image at 8 m.

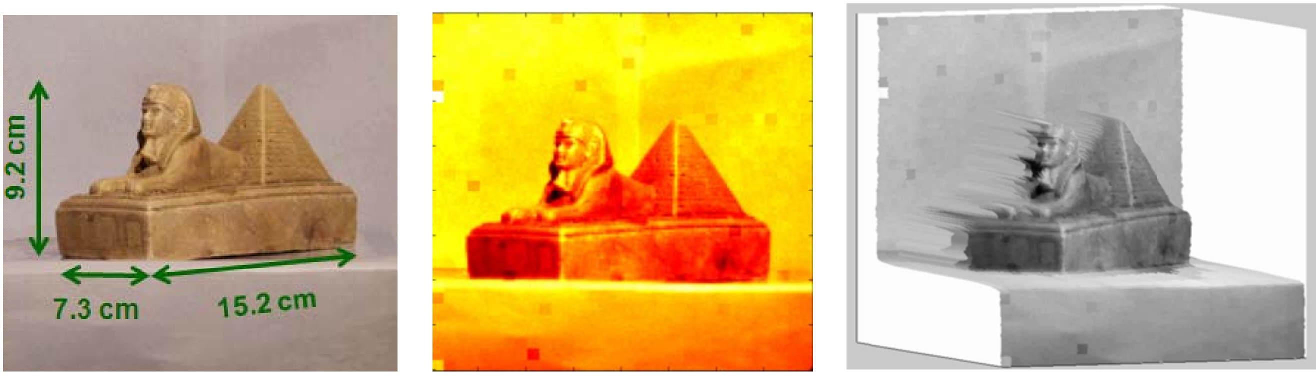

Fig. 11: Target at 8 m acquired with a standard camera (left), with the SPAD camera in 2D photon-counting mode (center) and in 3D photon-timing mode, with the reconstruction merging 2D and 3D data (right). Scene was scanned with 25 steps (i.e. reconstructed image has 160 x 160 pixels) for a total of 250 ms dwell time.

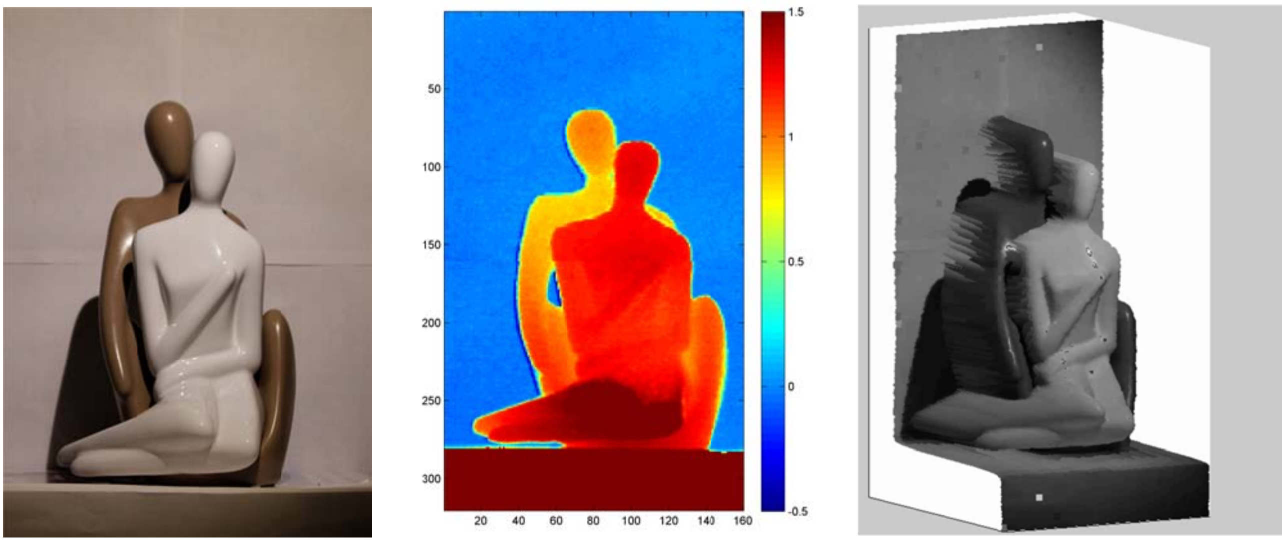

Fig. 12: Target at 8 m acquired with a standard camera (left) and reconstruction by merging 2D and 3D data (right) acquired by the SPAD camera. Scene was scanned with 50 steps (i.e. reconstructed image has 160 x 320 pixels) for a total of 250 ms dwell time.

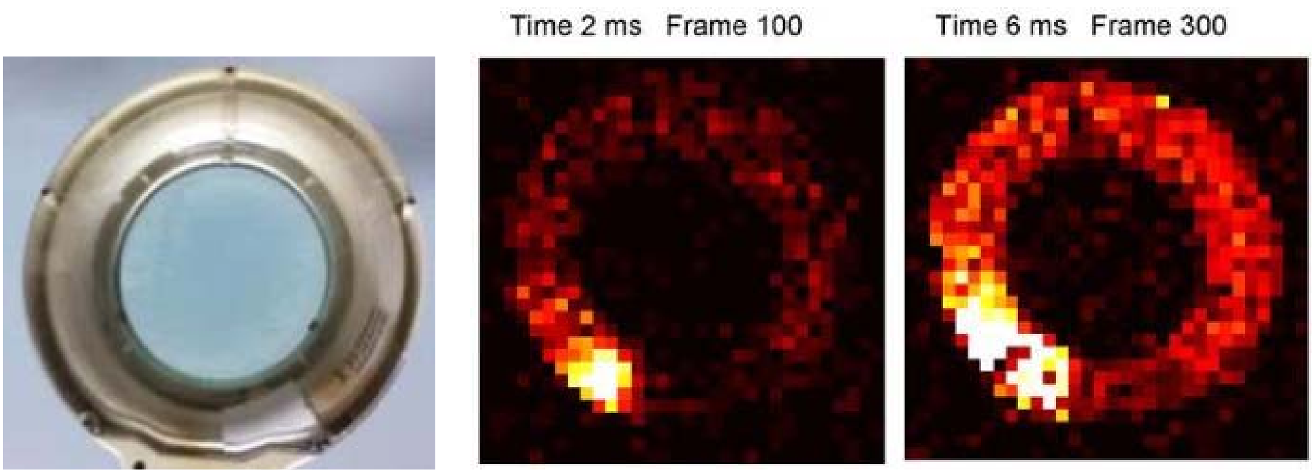

Fig. 13: Frames from a 2D movie of a circular neon lamp, acquired at 50,000 fps, showing the fast gas discharge propagation through the tube.