P2-13

Use of Switched Capacitors in timing-based SPAD Image Sensors

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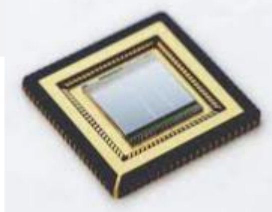
The Challenge



- Mega-pixel SPAD array,
- Using the Time of Arrival of all photons,
- Sub-nano second precision and accuracy of images,
- Low power, simple implementation.

State of the art compromises

- Low pixel resolution,
- Skipping a lot of (valuable) photon triggers,
- Pile-up due to system dead-time,
- Data- and processing congestion, power dissipation.

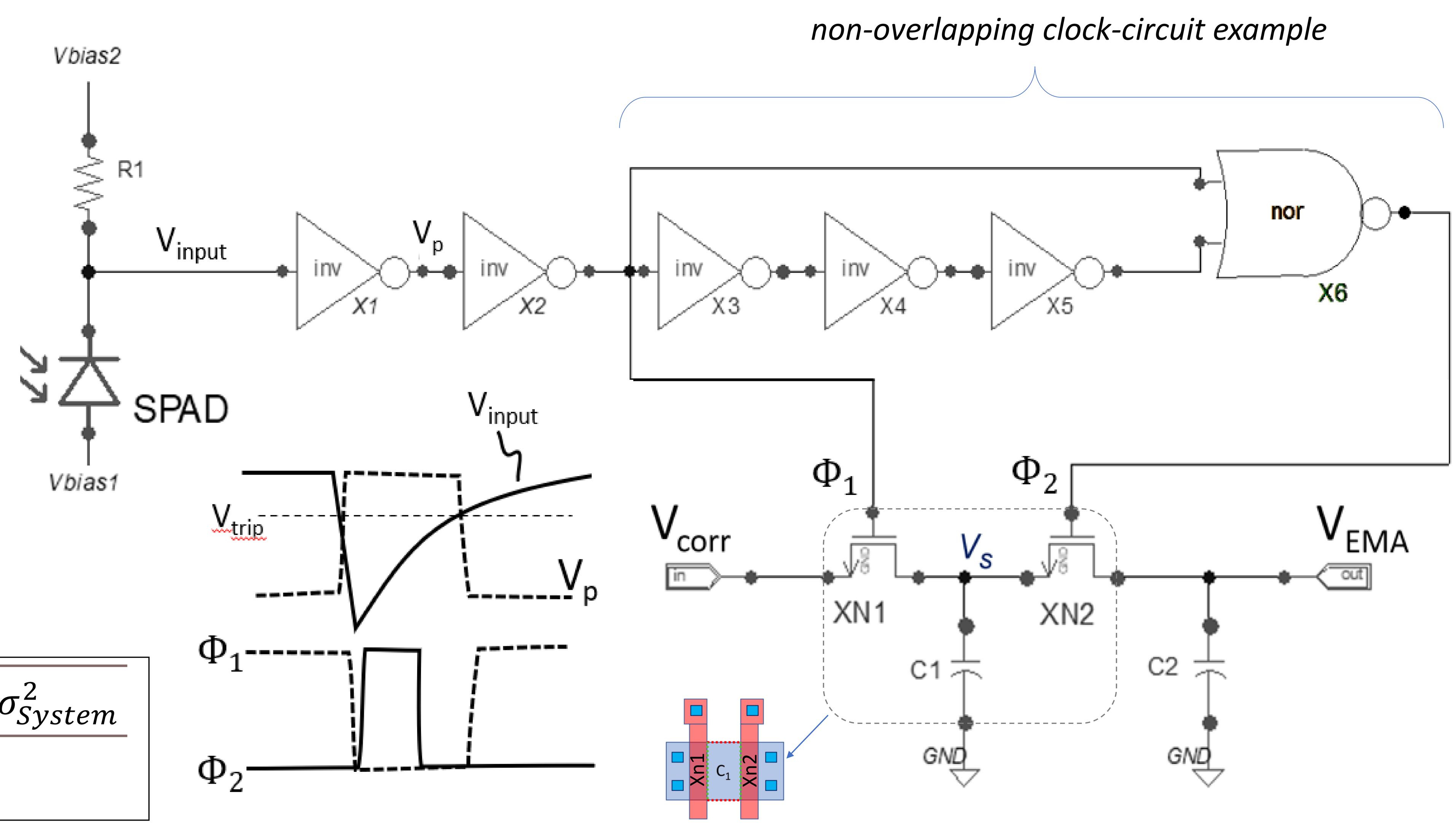
The proposal: Use of Switched Capacitors

- A SPAD trigger generates two non-overlapping clocks driving two NMOS switches X_{N1} and X_{N2}.
- V_s samples voltage $\mathbf{V_{corr}}$ at the falling edge of Φ_1, and,
- Output V_{EMA} integrates the average sampled voltages over multiple samples:

$$V_S \, . C_1 + V_{EMA}^{previous} . C_2 = V_{EMA}^{new} \left(C_1 + C_2 \right)$$

$$\Rightarrow \quad V_{EMA}^{new} = \left(1 - \frac{1}{n_{ema}}\right) V_{EMA}^{previous} + \frac{1}{n_{ema}} V_S$$

- Averaging Number: $n_{ema} = 1 + \left(\frac{C_2}{C_1}\right)$
- Exponential Moving Average: $\sigma_{EMA} = \sqrt{\frac{\sigma_{laser}^2 + \sigma_{SPAD}^2 + \sigma_{System}^2}{2 \, . n_{ema}}}$

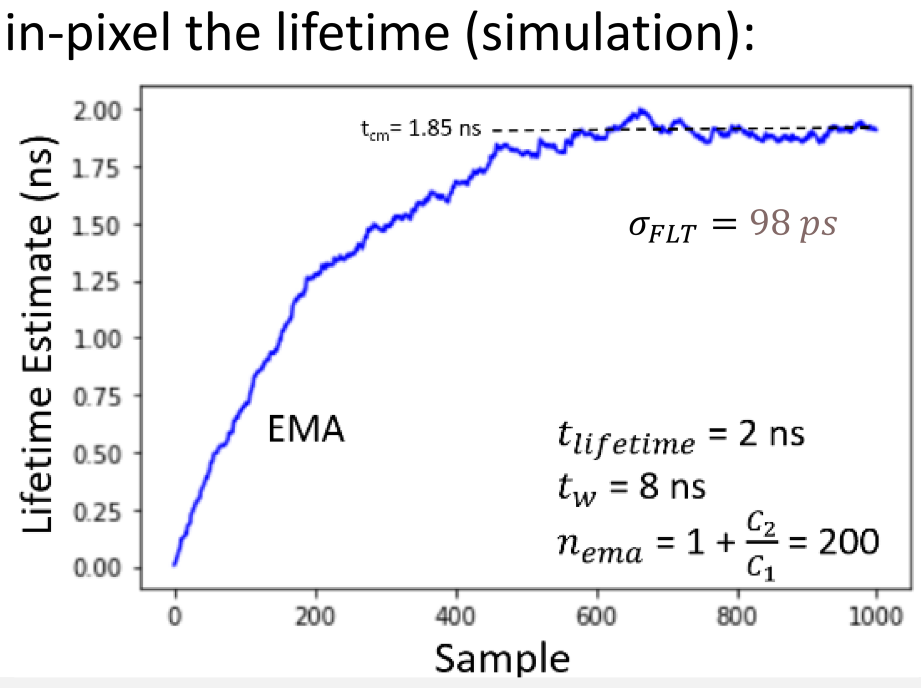


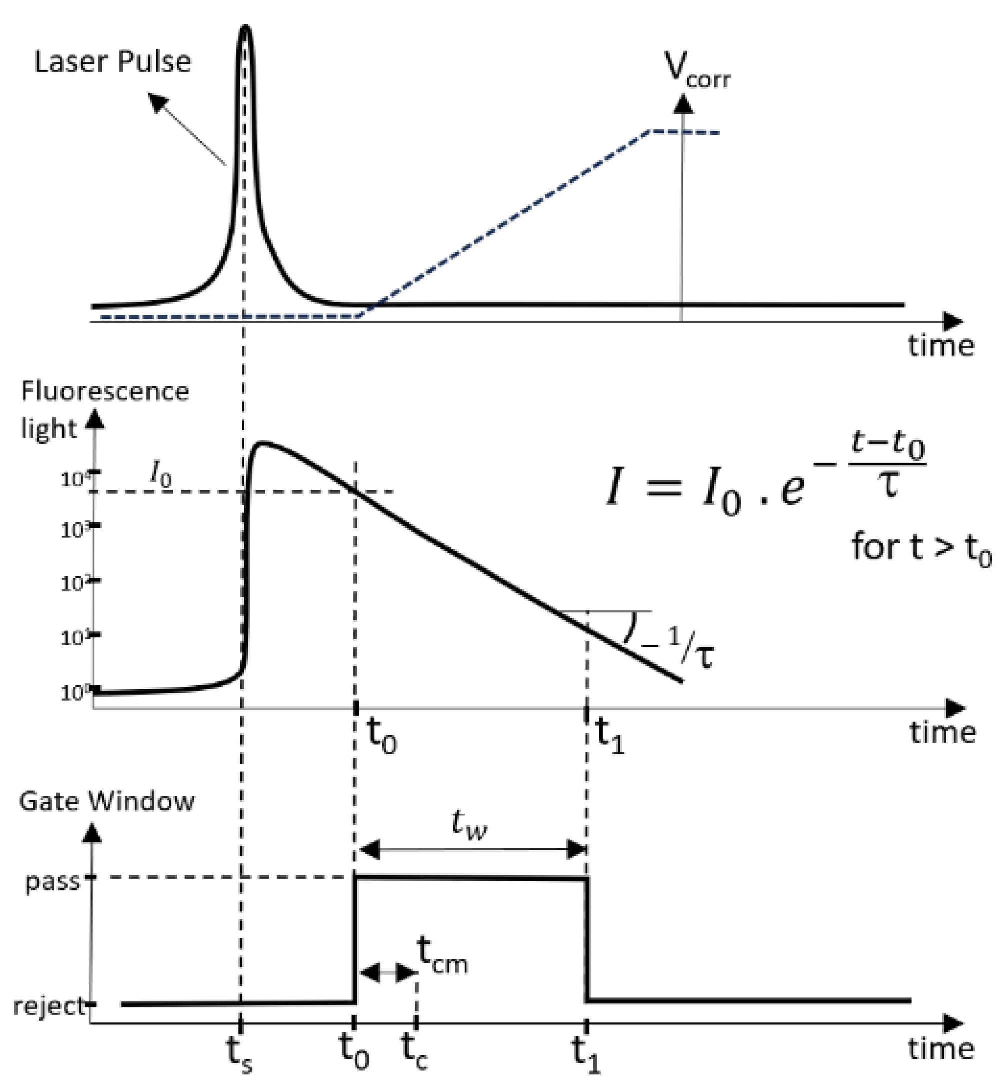
Use in Fluorescence Lifetime Imaging

- The center of mass in a time window is indicative for the fluorescence lifetime:

$$t_{cm} = t_c - t_0 = \frac{\int_{t_0}^{t_1} t . I . dt}{\int_{t_0}^{t_1} I . dt}$$

- Using a voltage ramp as $\mathbf{V_{corr}}$ computes in-pixel the lifetime (simulation):

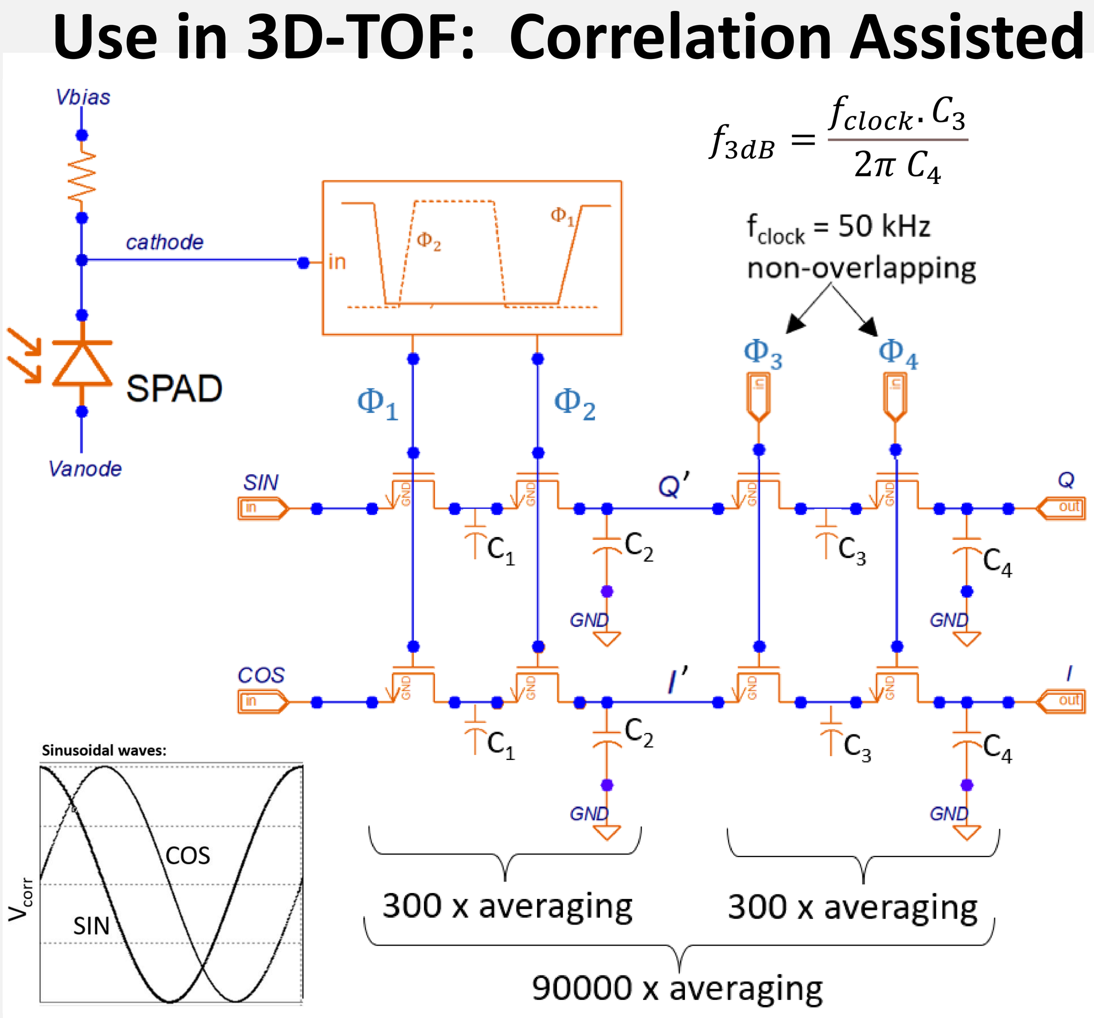


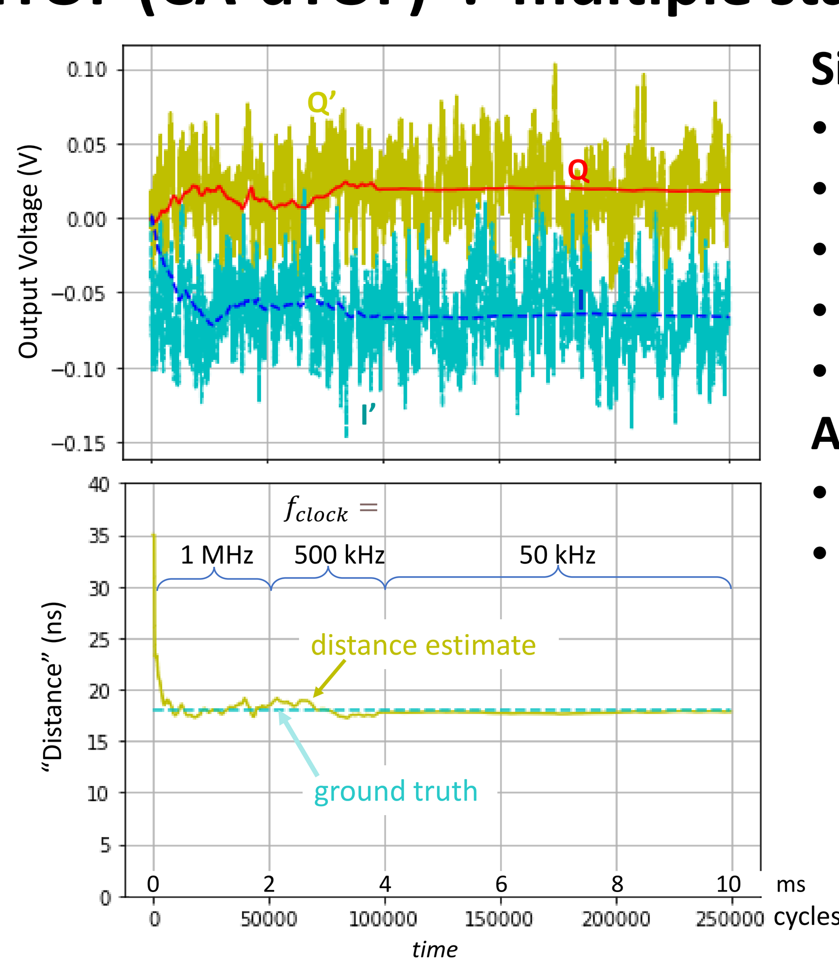


Additional Considerations:

- An AND-gate needs to be added for muting the Φ_2 clock (not shown); a Gate-Window signal to be applied over the full array.
- Output Voltage ~ Lifetime.
- Large Dynamic range: no saturation of output or change in lifetime output over several orders of magnitude, however, at (high) light input levels pile-up will degrade accuracy.
- If better precision is needed, a second stage can conveniently be added (see below).
- Only a single ADC conversion needs to be performed per pixel and per frame.
- With high ambient light, two centers of mass can be measured based on different window lengths, for cancellation.

Use in 3D-TOF: Correlation Assisted dTOF (CA-dTOF) : multiple stage approach





Simulation parameters:

- Demodulation frequency = 25 MHz
- 250.000 cycles of 40 ns = 10 ms frame.
- 4 % of cycles contain a TOF-photon.
- 40% of cycles contain an ambient photon
- Deadtime SPAD = 4 ns.

Result:

- Accuracy < 100 ps
- Precision = 0.49 %

Additional Options:

- Multiple SPADs per pixel, for example, 4 or 9.
- Multiple Frequencies: improving precision, removing ambiguity.

Conclusion

- Switched capacitor averaging can be used in timing based SPAD image sensors
- This averaging is based on the Exponential Moving Average, that requires only 1 memory element (a capacitor)
- Multiple stages can be used for extended averaging of voltages, these voltages typically providing timing information
- One example for FLIM and one for dTOF have been given
- This is a totally novel approach for in-pixel ToA processing, avoiding individual trigger events to be communicated.

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CoDaFLight – Colouring the Dark in Fluorescence Light