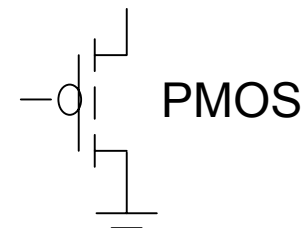
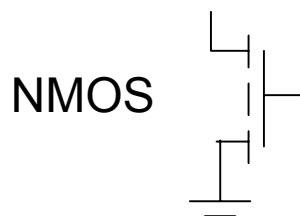


3D Range Sensor using time of flight method

By Martin Krämer



Motivation

- proof of concept of an 3D Range Sensor
- finding the difficulties

There was no prior knowledge of the light source and the characteristic of the Photo Diode



3D Range Sensor

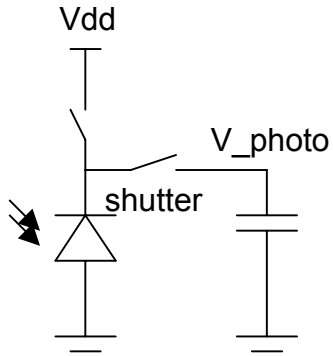
1. Concept of Time of Flight (ToF) method
 - Handling of background light
2. Concept of the Sensor and its building blocks
 - Photo PN-Diode
 - Source Follower
 - CDS Stage
3. One Readout Cycle
 - Timing of the different Clocks
4. Multiply Readout
5. Layout
6. Conclusion

Concept of Time of Flight method (1)

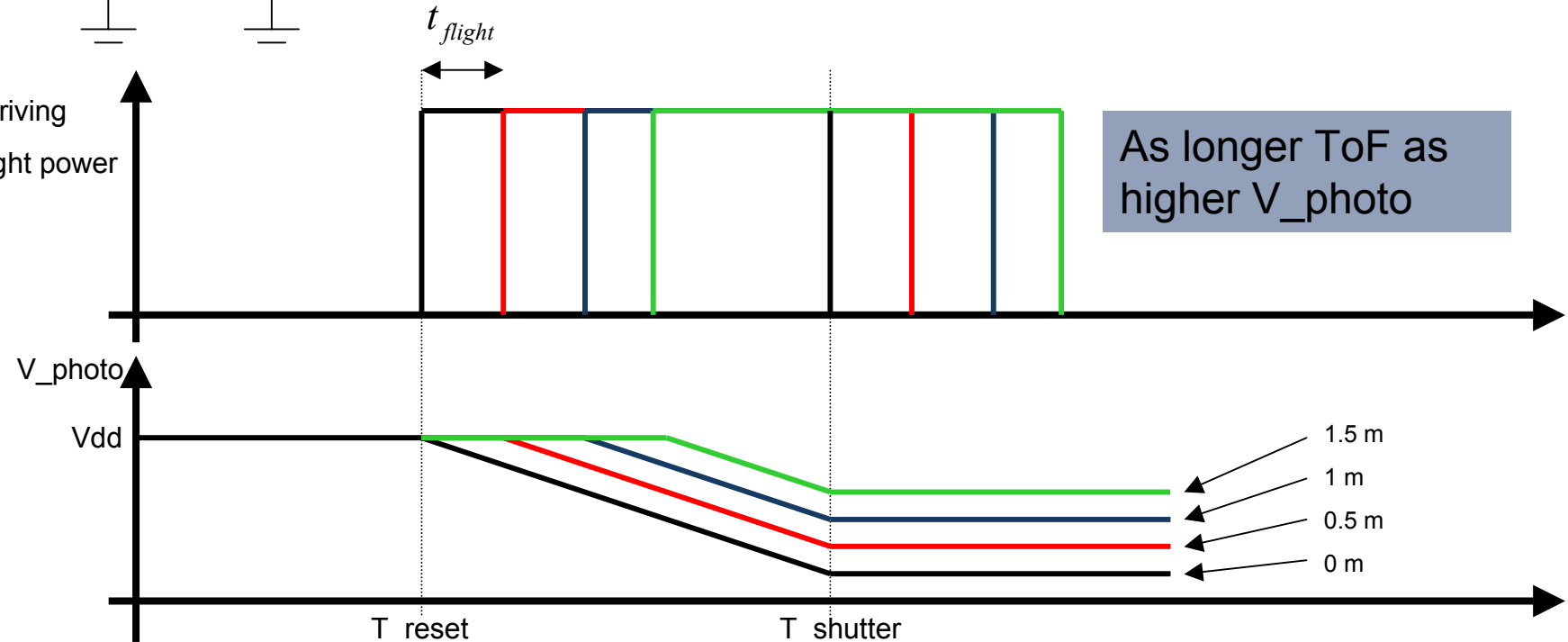
Basic Idea: Measure the time of flight of an light pulse and calculating the distance

Challenge : Speed of light is very fast, for example in 3.33 ns the light traveled 1m. We must detect ns !

Concept of Time of Flight method (2)



The photo current discharge the capacitance until the shutter close. The background light is ignored.



based on: "Entwicklung von optischen 3D CMOS-Bildsensoren auf der Basis der Pulslaufzeitmessung" by Elkhaili, O. (PhD thesis)



Concept of Time of Flight method (3)

What about the background light?

Background light causes also a photo current, thus discharge also the capacitor.

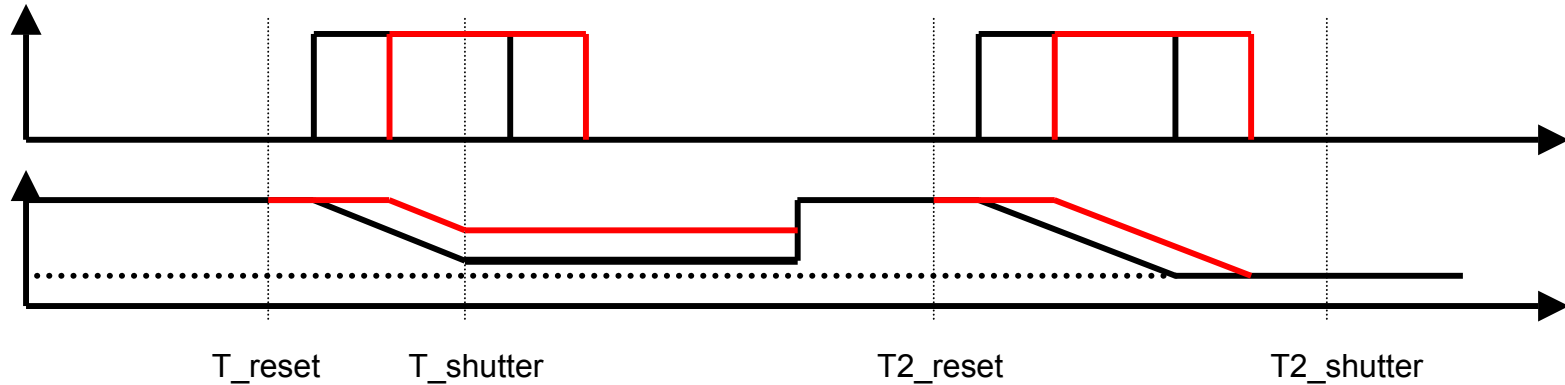
Making two measurements, one with the light source and one with only the background light. Assuming that the measurements are fast, thus the background light is constant.

Now we can subtract them and we get the correct output voltage.



Concept of Time of Flight method (3)

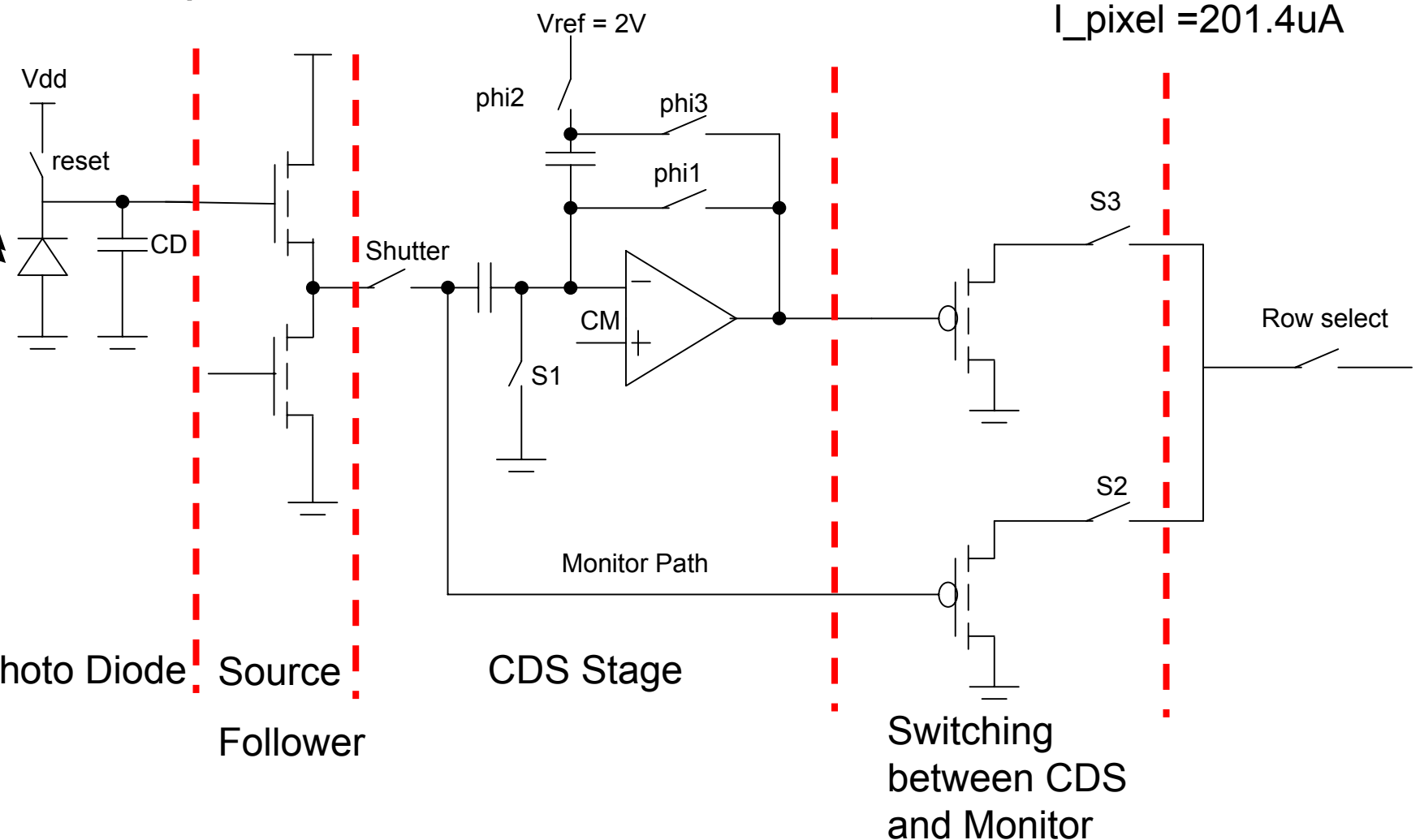
What about intensity variation of the light pulse?



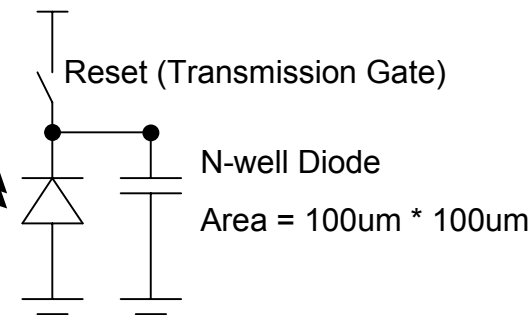
Making two measurements, one with normal short shutter Time (T_{pulse}) and one with a long shutter time.

The arriving light power is canceled. We need for the distance measurement 4 measurements.

Concept of Sensor

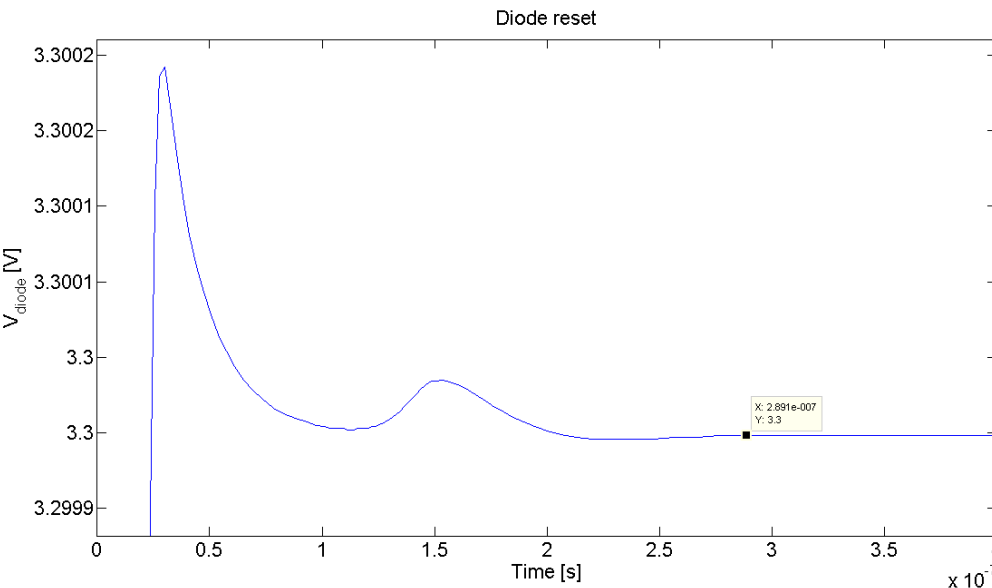


PN Diode



Using a LASER with a wave length around 900 nm as light source. Because this light is not visible for the human eye.

The NWD is deeper in the substrate, thus 900nm can reach this better then shorter wave lengths, because of absorption.



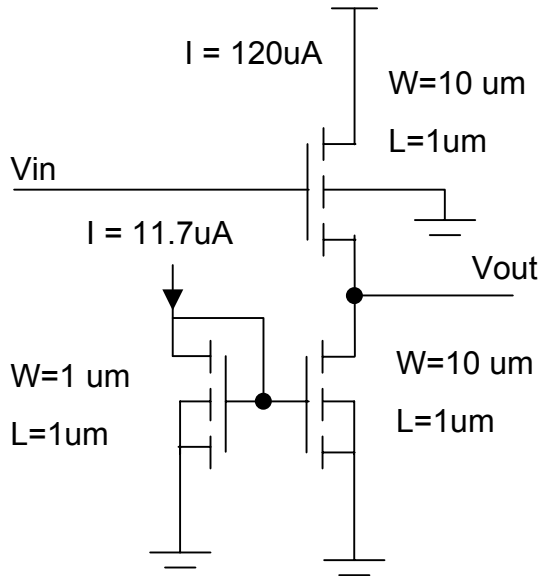
Reset time from 0V to $V_{dd}=3.3$ V is 298 ns. I gave 2 us reset time

Assumptions:

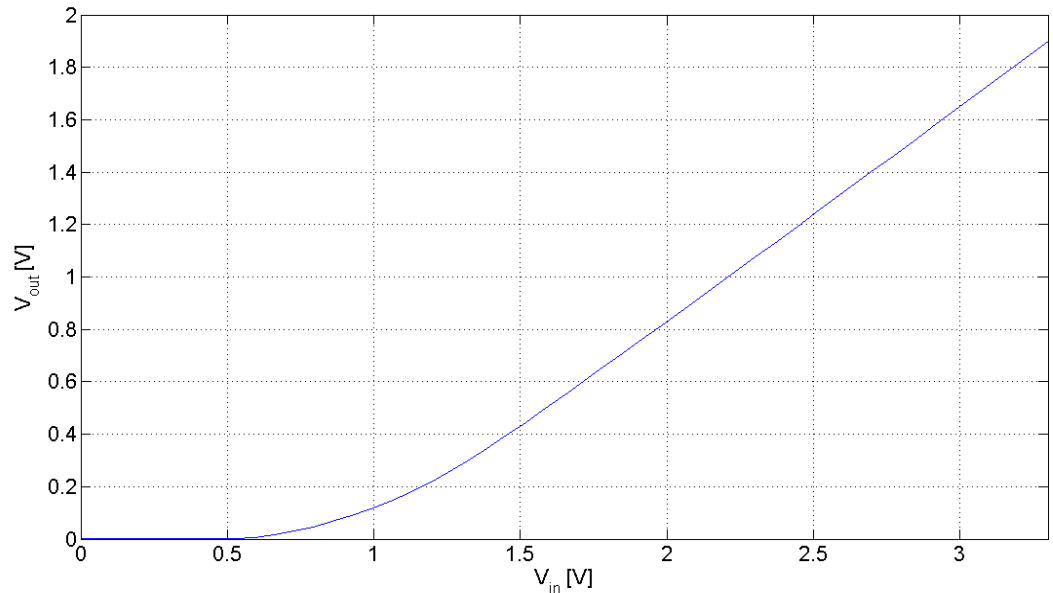
$I_{LASER} = 2$ nA

$I_{background} = 300$ pA

NMOS Source Follower

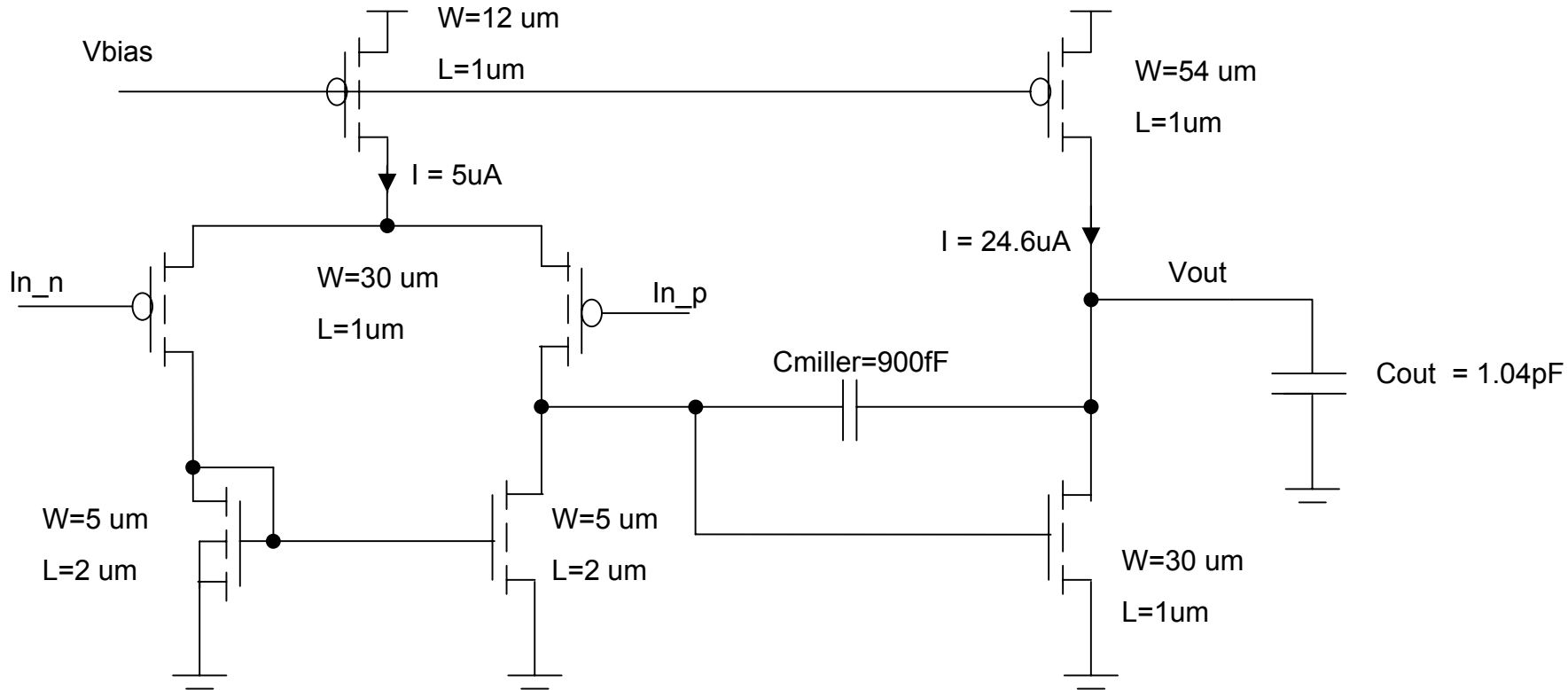


V_{bs} is not zero for the input transistor, this leads to a higher V_{th} and this gives us this big Voltage drop of 1.4 V. Also we have a Voltage gain of 0.8.



After the follower comes a capacitor, the big current is for speed

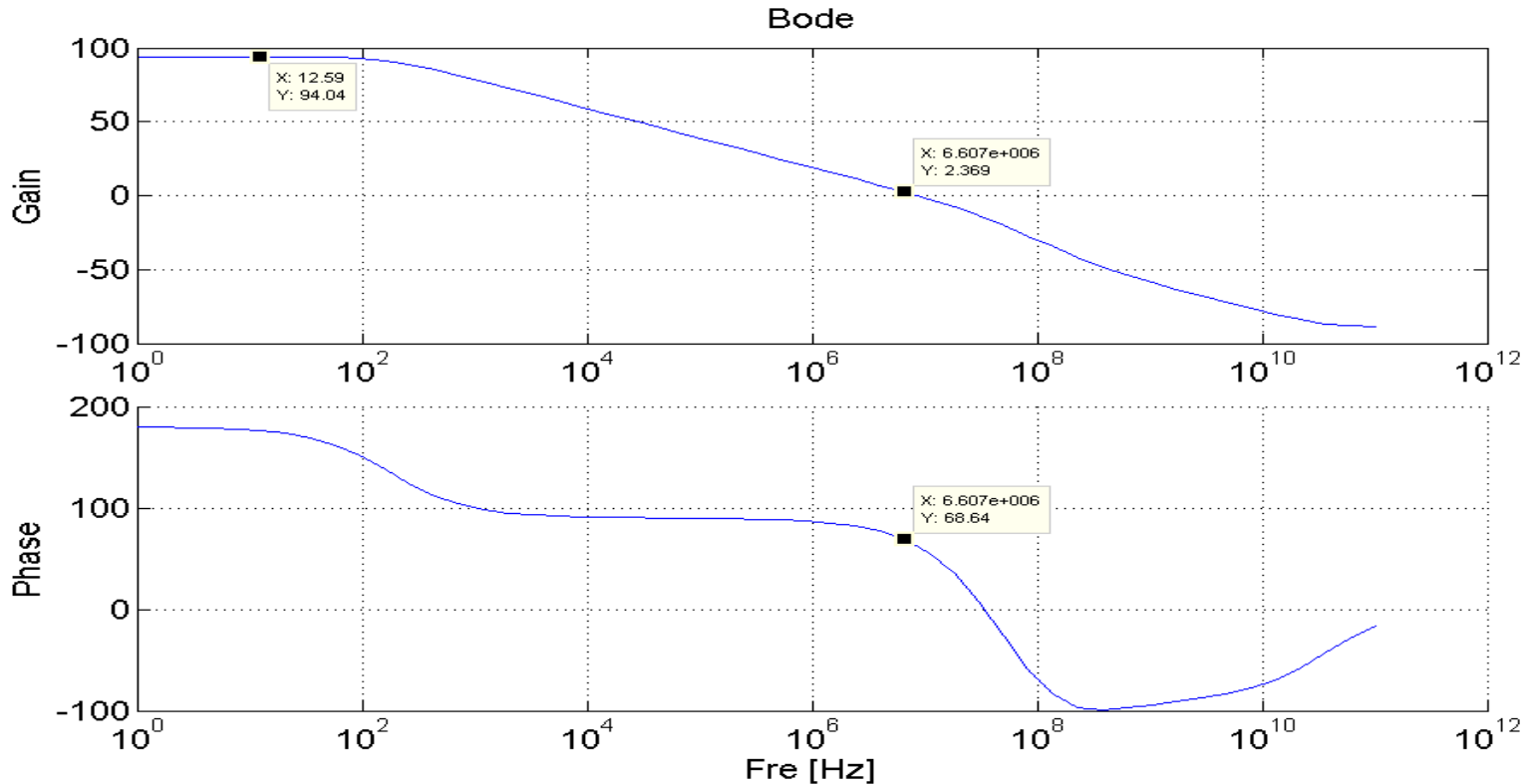
CDS Stage (Miller OTA)



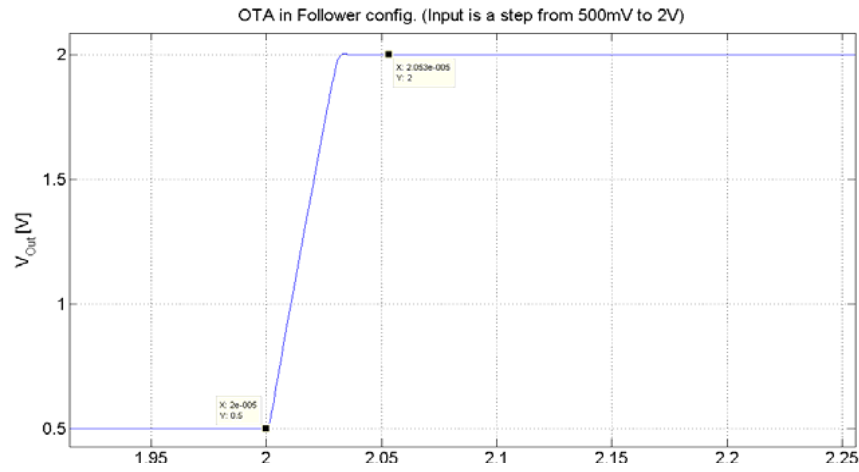
All PMOS Bulks connected to VDD and all NMOS Bulks connected to GND

CDS Stage (Miller OTA)

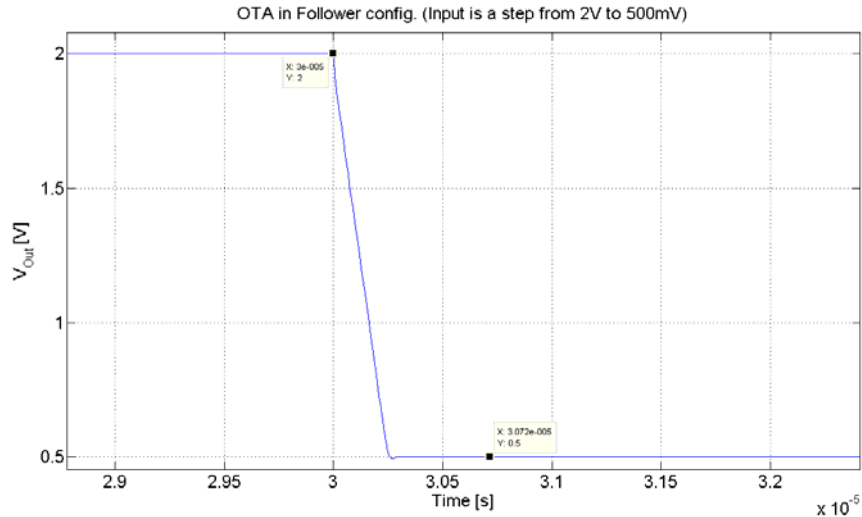
Gain = 94 dB, PM = 62° (1.4 pF at output), GBW = 9.05MHz and I_{all} = 33.7uA



CDS Stage (Miller OTA)

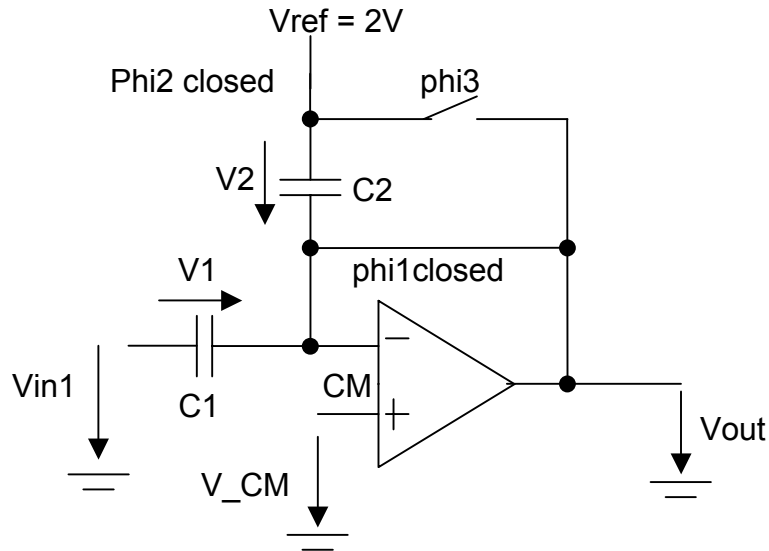


Settling time up = 530ns



Settling time down = 720ns

CDS Stage (Phase 1)

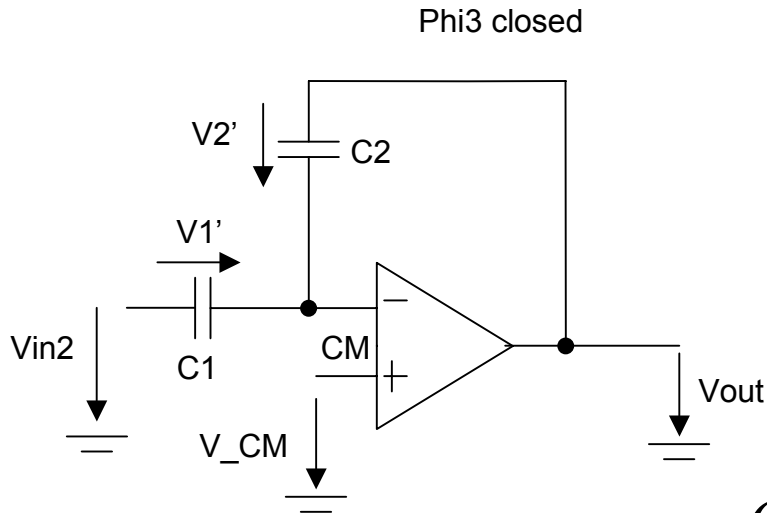


All switches are transmission gates, with $w=1.3\mu\text{m}$ and $l=0.35\mu\text{m}$

$$V_1 = V_{in} - V_{CM} \Rightarrow Q_1 = C_1 (V_{in1} - V_{CM})$$

$$V_2 = V_{ref} - V_{CM} \Rightarrow Q_2 = C_2 (V_{ref} - V_{CM})$$

CDS Stage (Phase 2)



$$V_{1'} = V_{in2} - V_{CM} \Rightarrow Q_{1'} = C_1(V_{in2} - V_{CM})$$

$$\Delta Q_1 = Q_{1'} - Q_1 = C_1(V_{in2} - V_{in})$$

$$Q_{2'} = Q_2 - \Delta Q = C_2(V_{ref} - V_{CM}) - C_1(V_{in2} - V_{in})$$

$$V_{2'} = \frac{Q_{2'}}{C_2} = V_{ref} - V_{CM} - \frac{C_1}{C_2}(V_{in2} - V_{in})$$

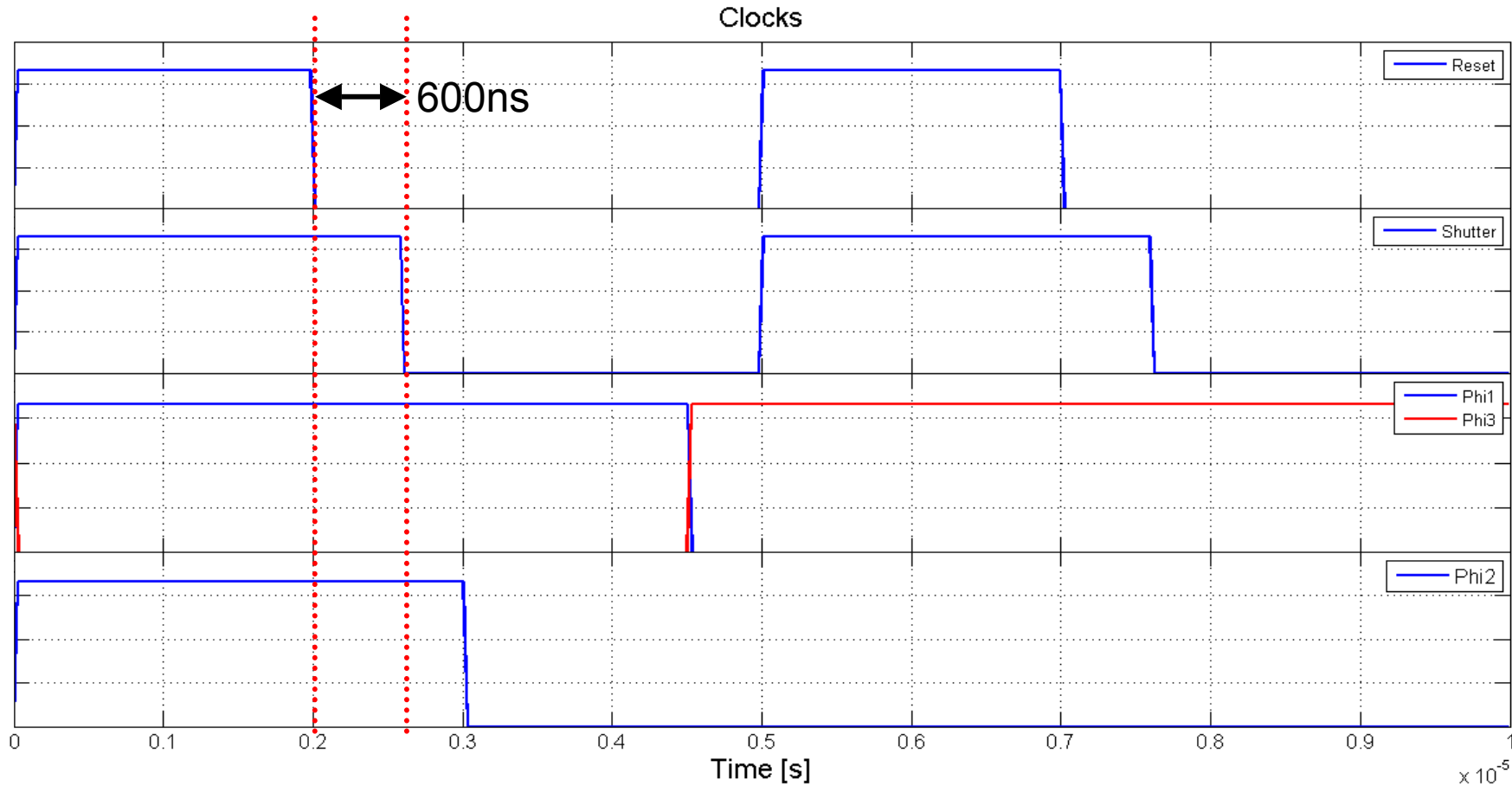
$$V_{out} = V_{2'} + V_{CM} = \underline{\underline{V_{ref} - \frac{C_1}{C_2}(V_{in2} - V_{in})}}$$

In my circuit $C_2=320.952\text{fF}$

and $C_1=1.047\text{pF}$. The gain of the stage is $A=3.26$

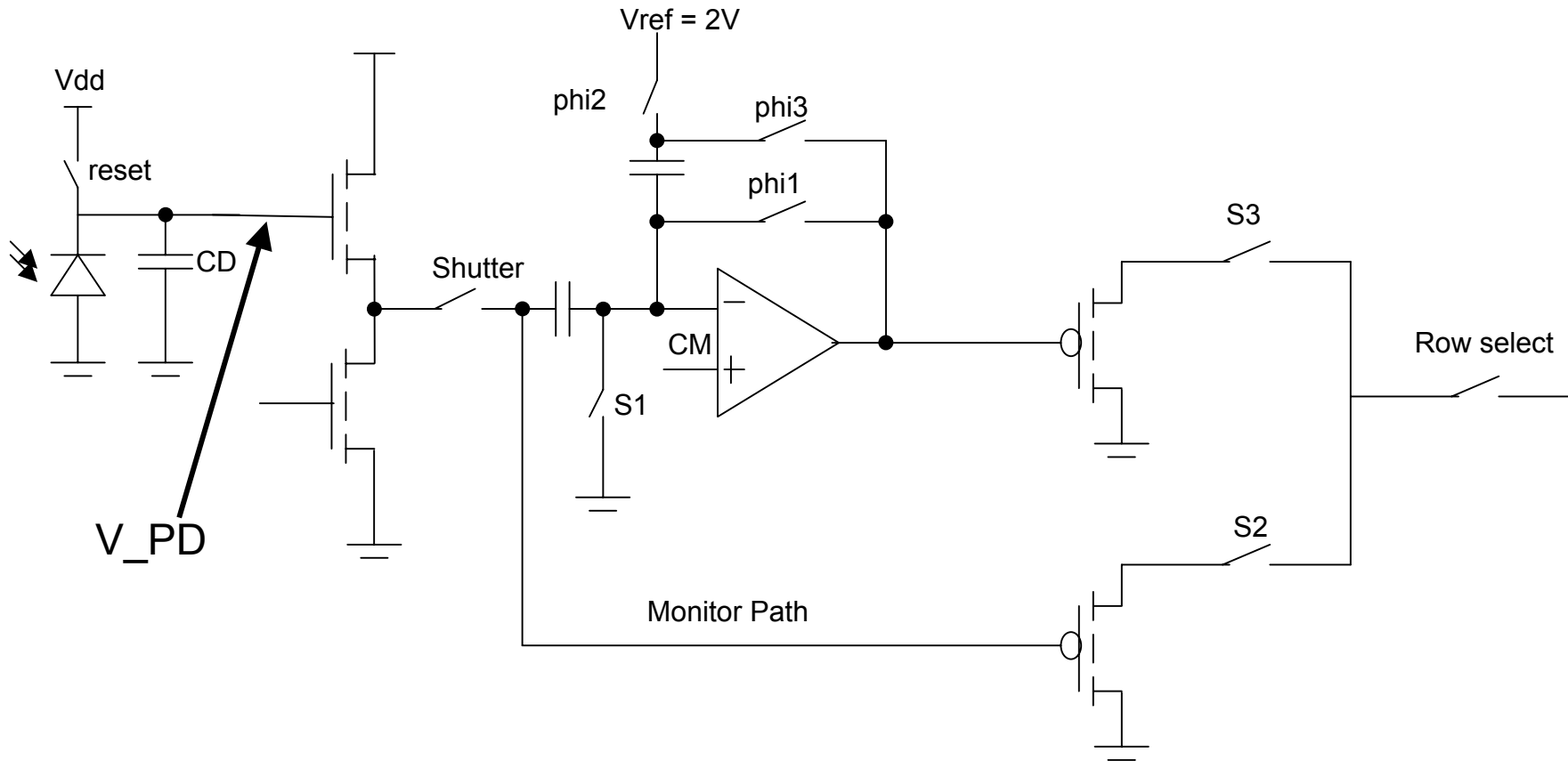
One measurement cycle

Clock timing



One measurement cycle

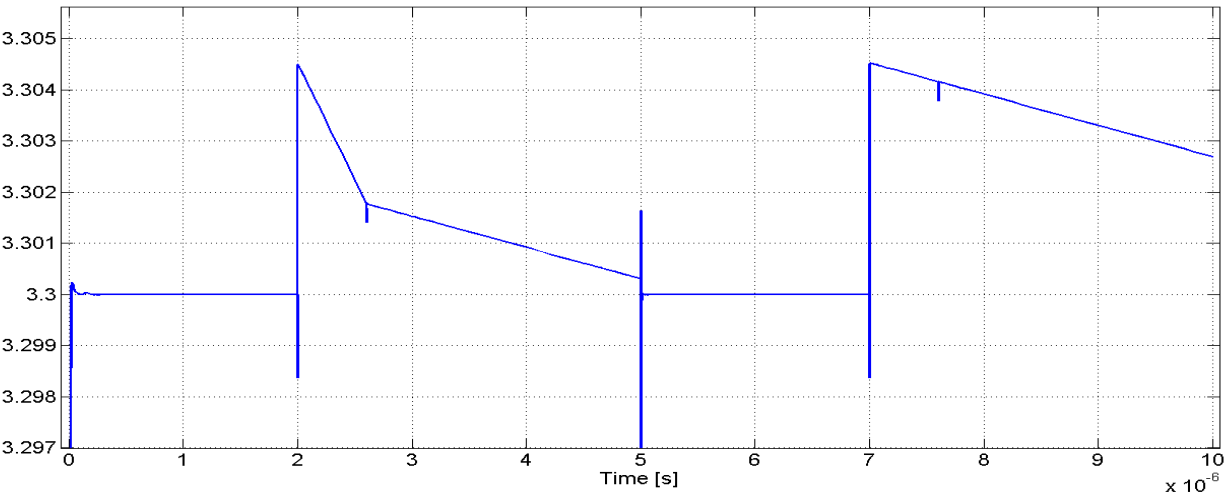
PD Voltage



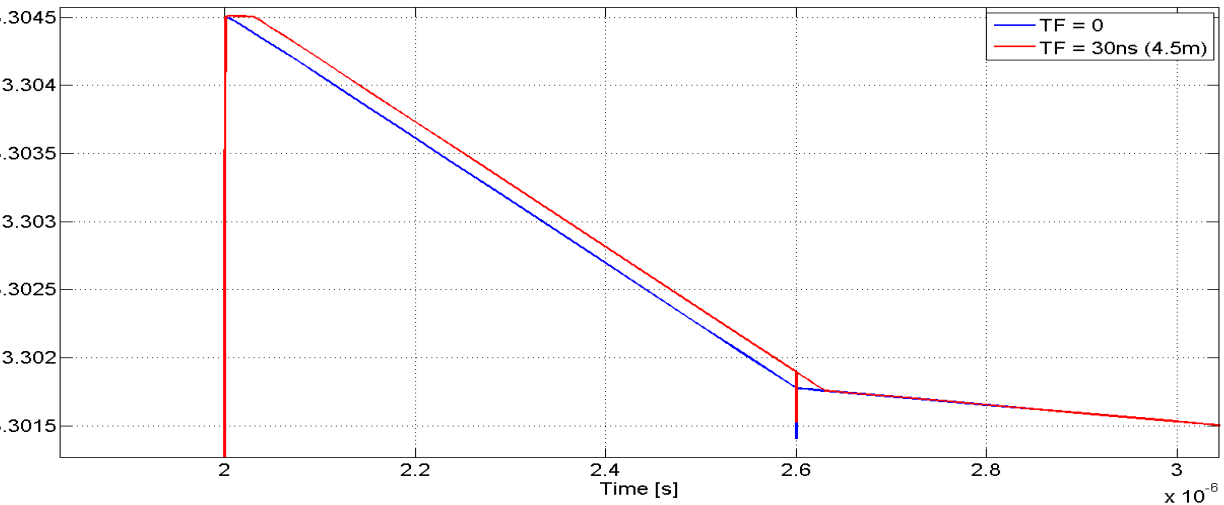
3D Range Sensor

One measurement cycle

PD Voltage



40mV step at 2us caused by charge injection and clock feed through

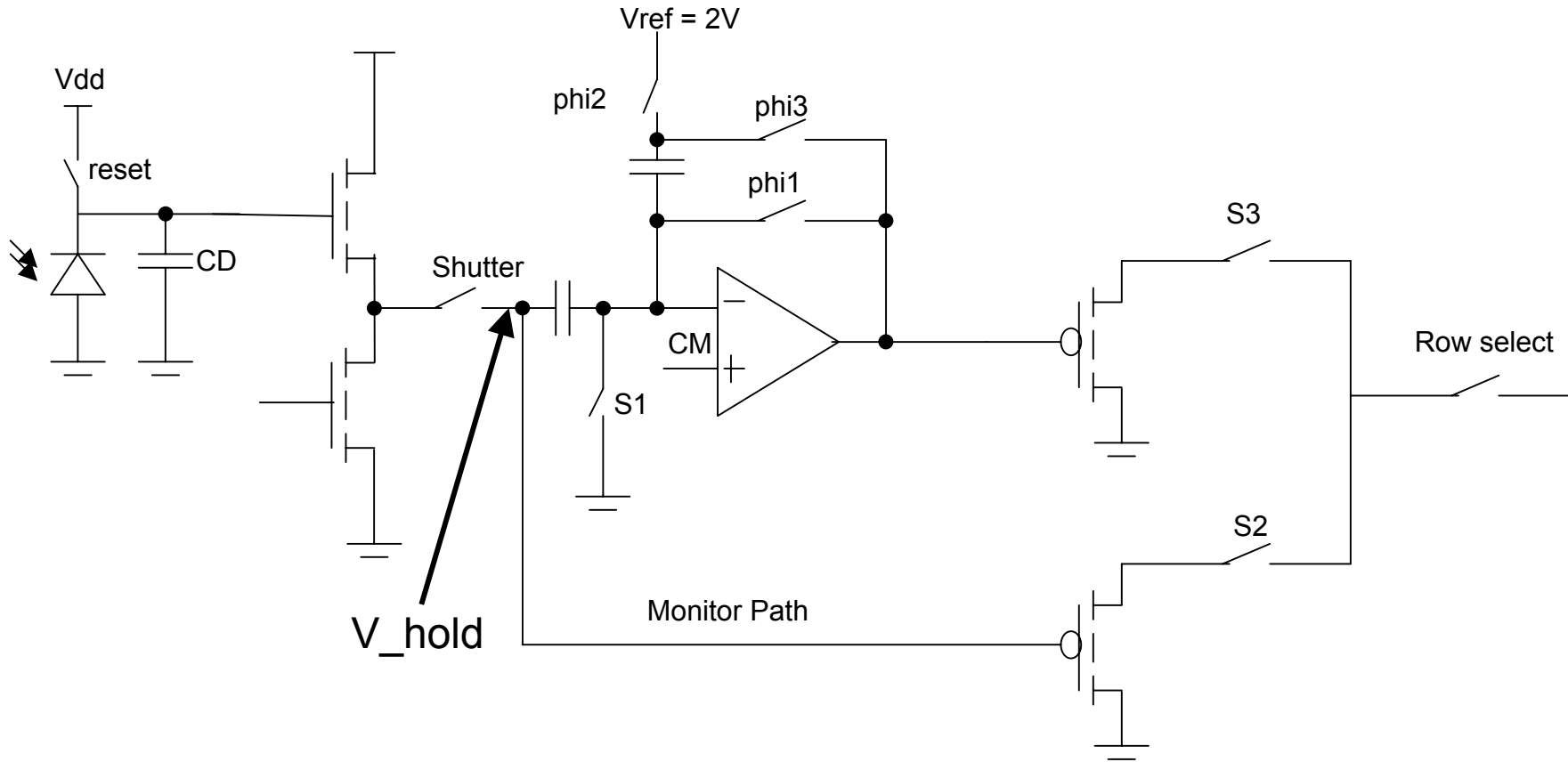


TF=0 to TF=30ns is the measurement borders



One measurement cycle

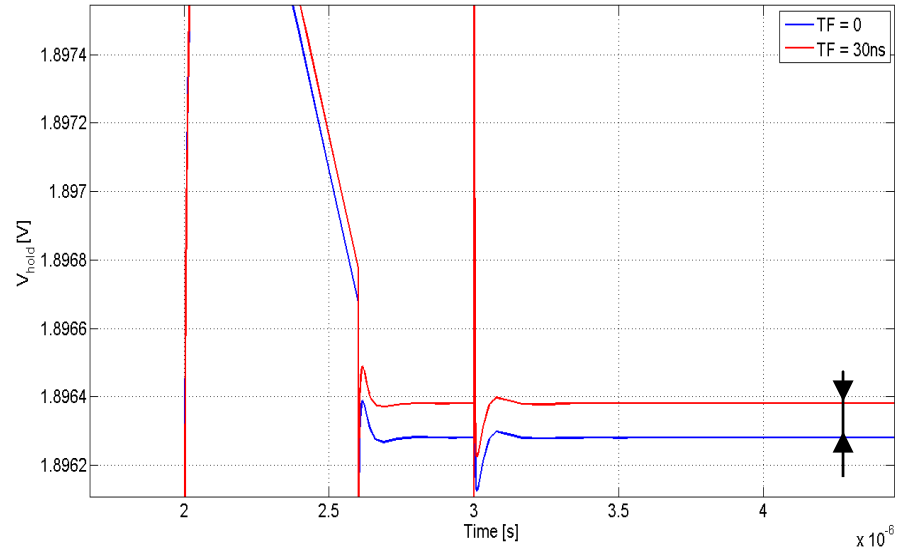
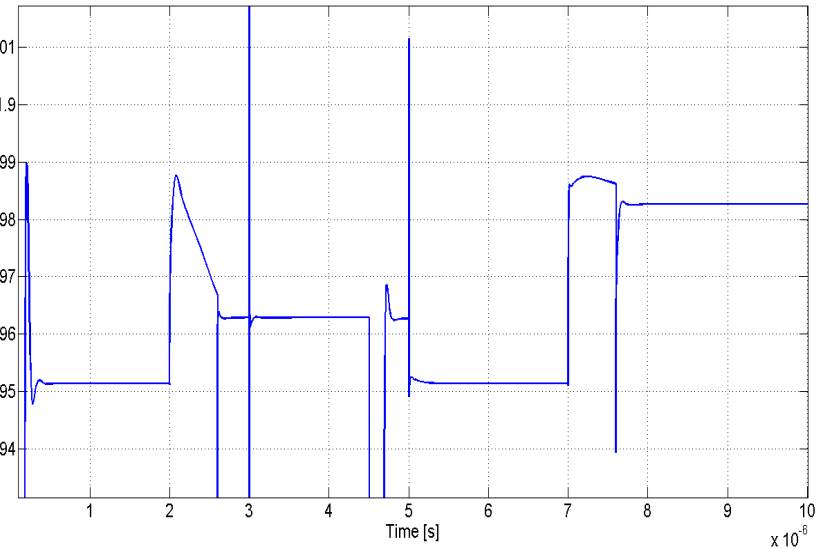
V_hold



3D Range Sensor

One measurement cycle

Hold Voltage

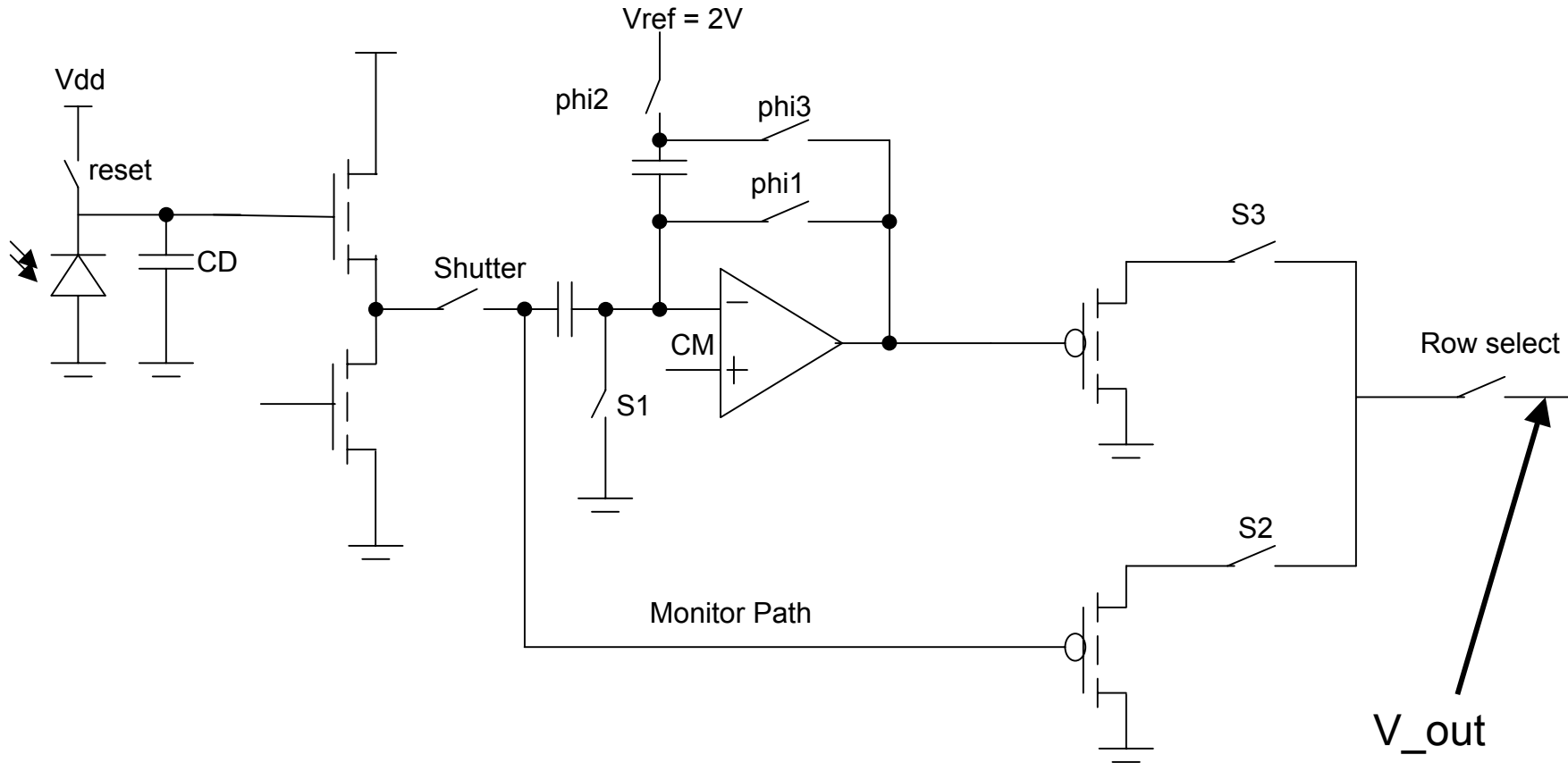


The difference between the Hold Voltages is 96 μ V. This is really small. The range is from 0 to 4.5m (TF=30ns)



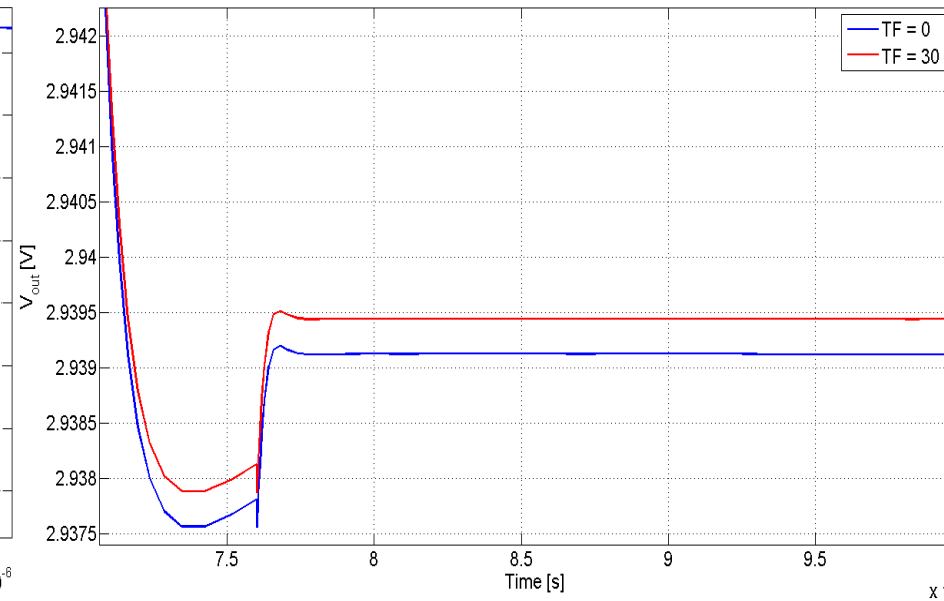
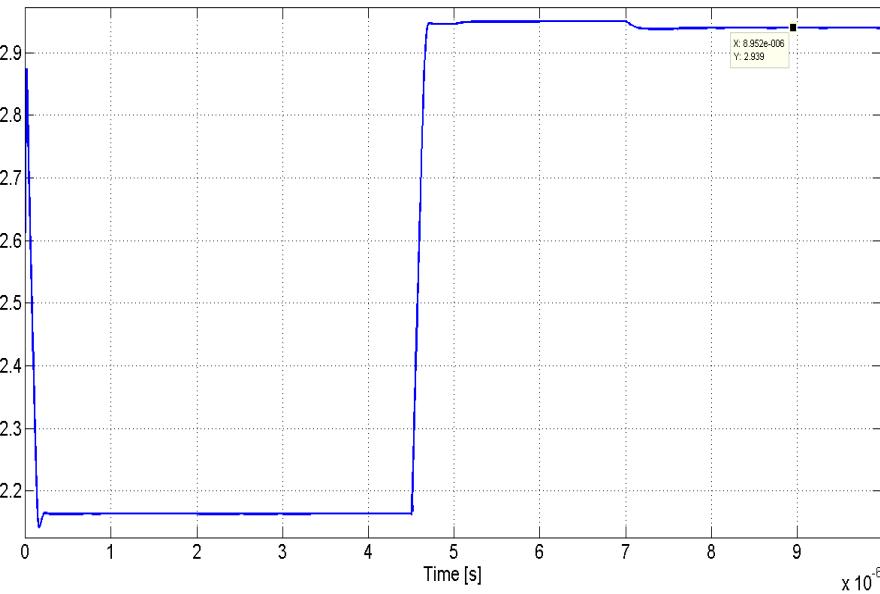
One measurement cycle

V_{out}



One measurement cycle

Hold Voltage



After the CDS stage, the difference between the Output Voltages is 321 μ V.
This is a gain of 3.343 (from calculation 3.26)



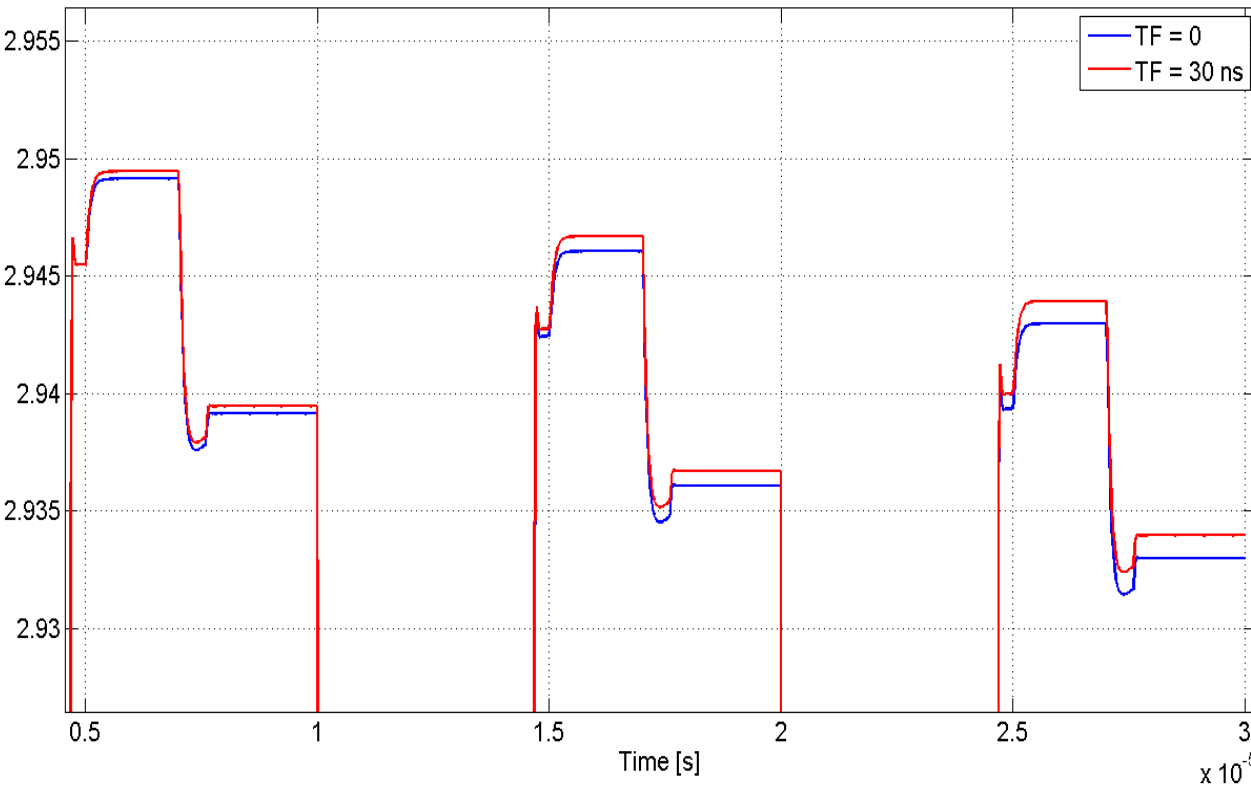
Multiple Readout

321 μV is not much for a range from 0 to 4.5m

But there is a possibility in the CDS stage for more gain. The Output Voltage is stored on C2, this output voltage can be used as new reference Voltage. Thus we can subtract often, we only have to make sure that the distance and the light situation doesn't change.

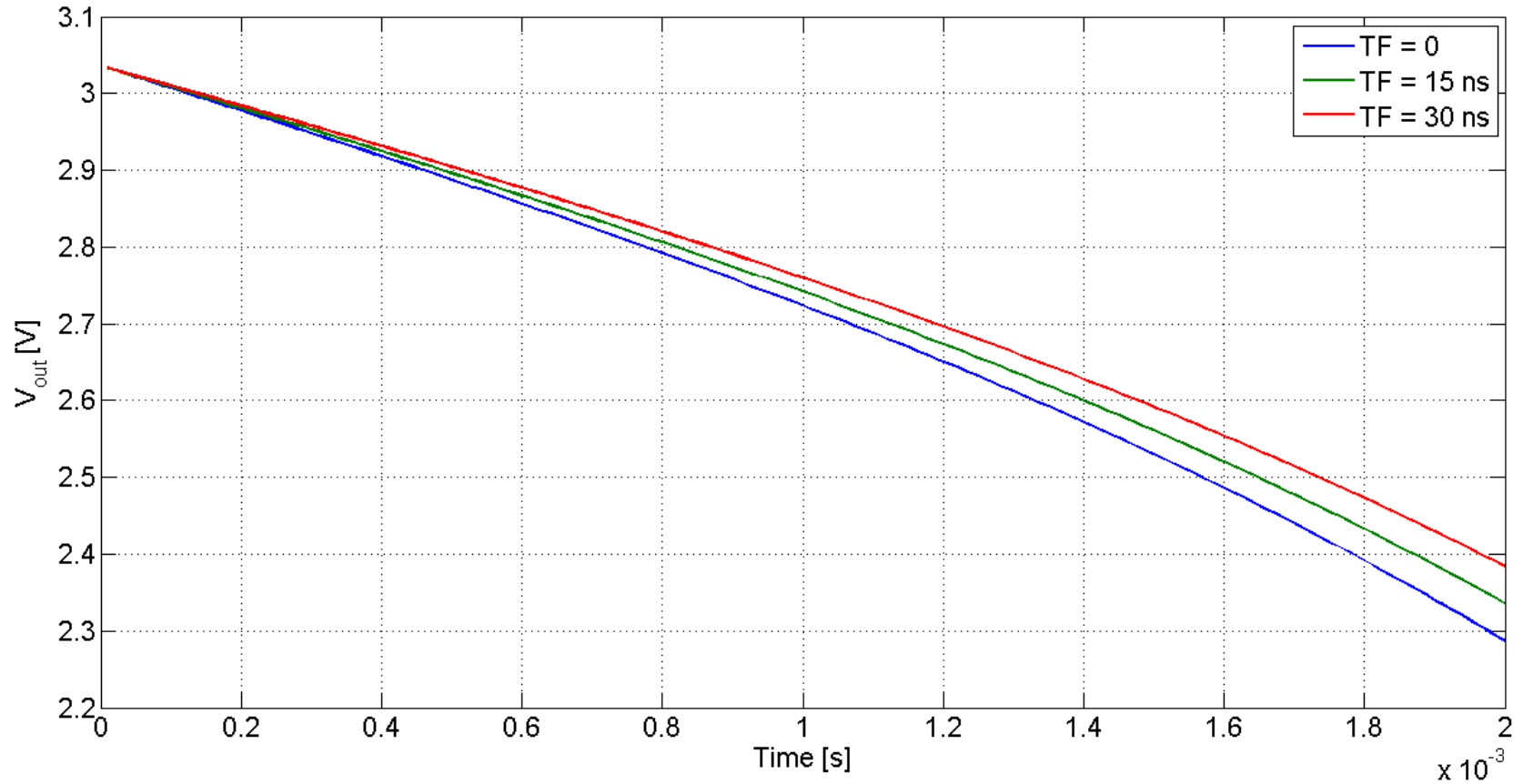
Multiple Readout

3 Cycles



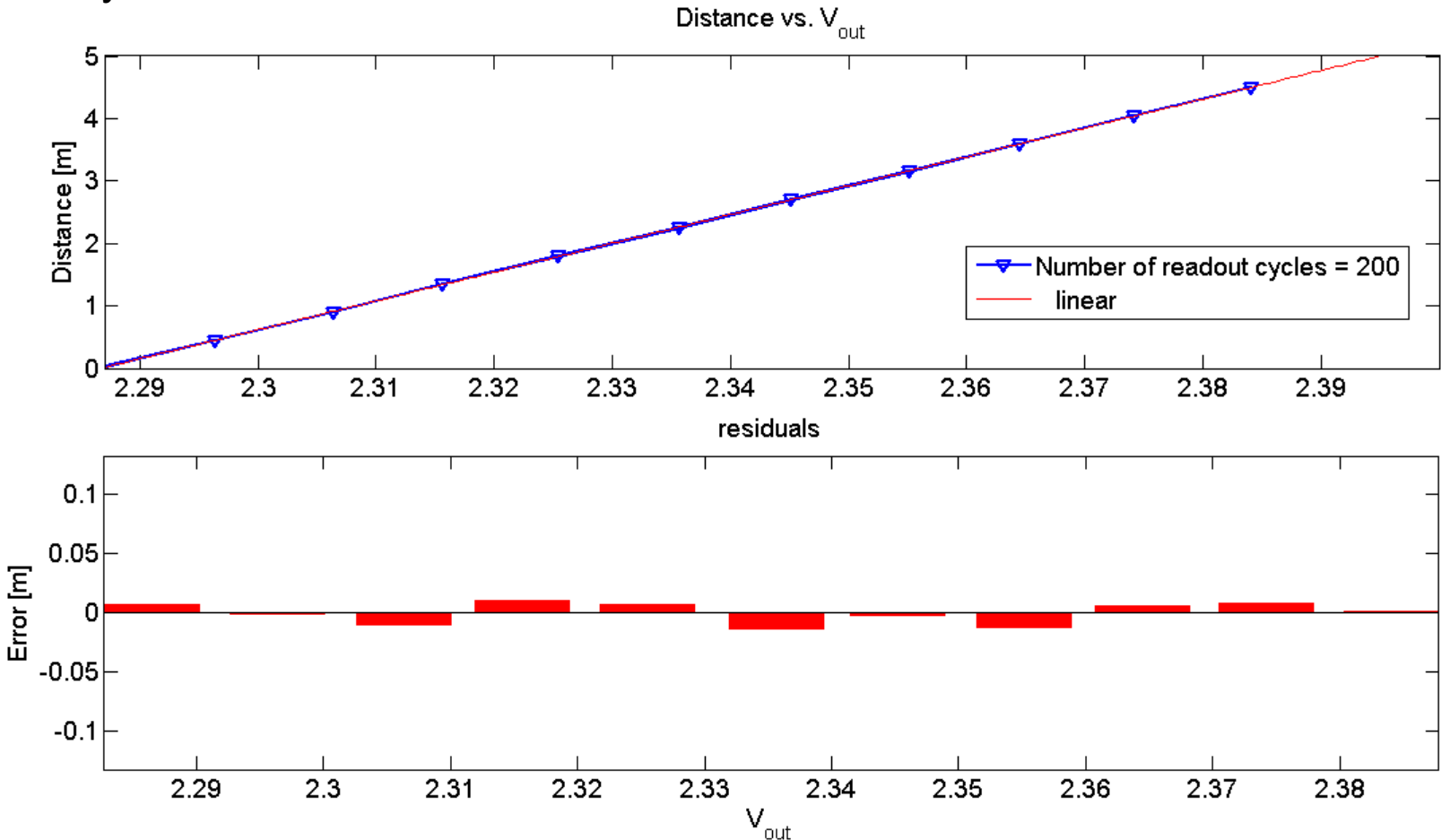
After 3 cycles we have a Voltage difference of 959uV. This is a gain of 2.987

Multiple Readout

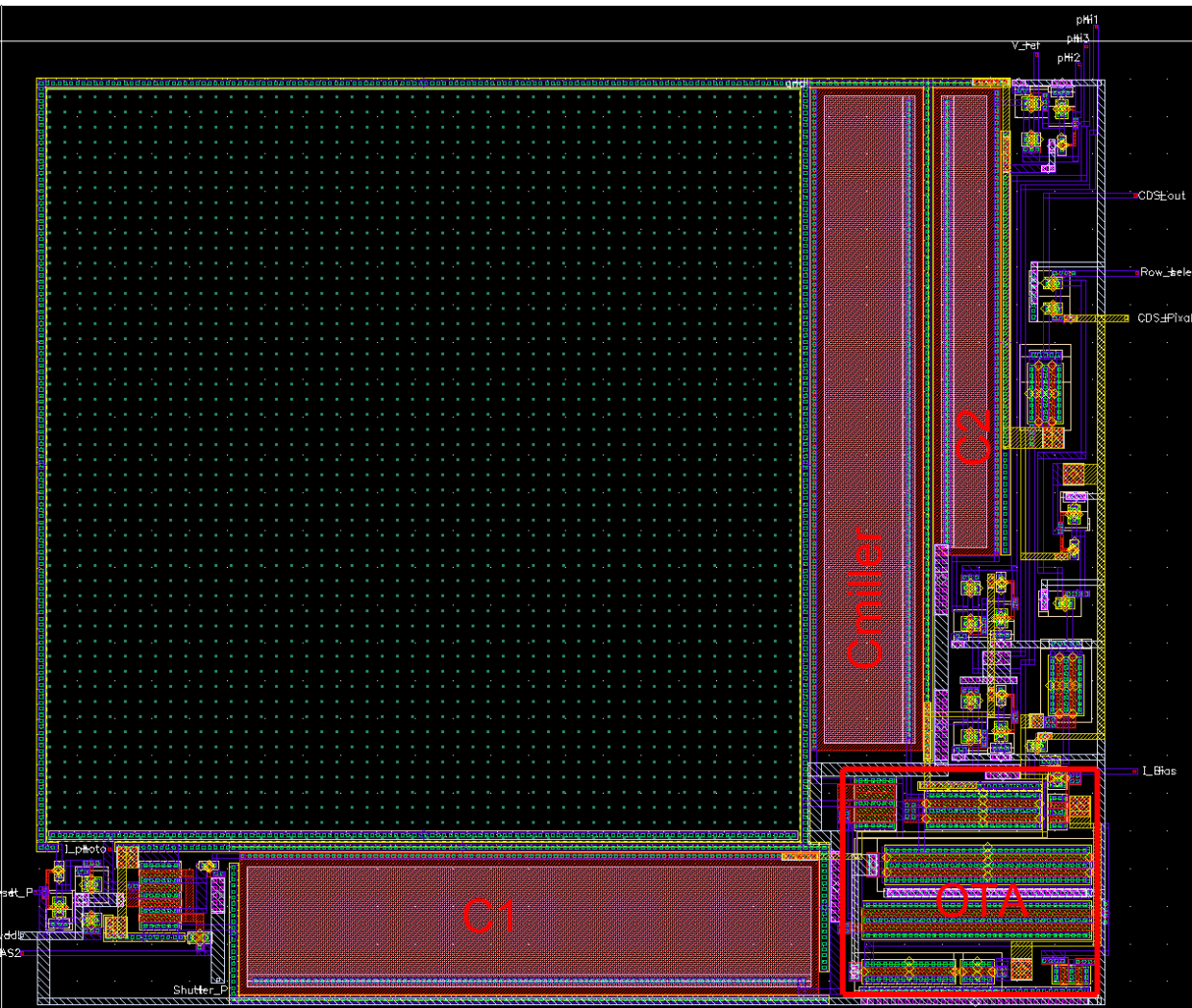


Multiple Readout

200 Cycles



Layout



W=142.5 μm

L=123.1 μm

Fill factor = 57%

Layout Pixel LVS

```
Warning: Unknown device "rpoly2" on a permuteDevice command.
Warning: Unknown device "rpoly1" on a permuteDevice command.
Warning: Unknown device "lat3" on a permuteDevice command.
Warning: Unknown device "vert15" on a permuteDevice command.
Warning: Unknown device "vert10" on a permuteDevice command.
Warning: Unknown device "vert5" on a permuteDevice command.
Warning: Unknown device "pmosm4" on a permuteDevice command.
Warning: Unknown device "rmosm4" on a permuteDevice command.
Warning: Unknown device "rmosm4" on a permuteDevice command.
Warning: Unknown device "rmosh6" on a permuteDevice command.
Warning: Unknown device "rmosh4" on a permuteDevice command.
Warning: Unknown device "ng" on a permuteDevice command.
Warning: Unknown device "cvar" on a permuteDevice command.
Warning: Unknown device "csandwt" on a permuteDevice command.
Warning: Unknown device "zd2sm24" on a permuteDevice command.
Warning: Unknown device "pd" on a permuteDevice command.
Warning: Unknown device "nd" on a permuteDevice command.

The net-lists match.

                layout schematic
                instances
Commands      un-matched      0      0
              rewired      0      0
              size errors  0      0
Run Direct   pruned      0      0
Create Net   active      51     51
              total      51     51

                nets
Libr          un-matched      0      0
Cell         merged      0      0
View        pruned      0      0
              active      33     33
              total      33     33

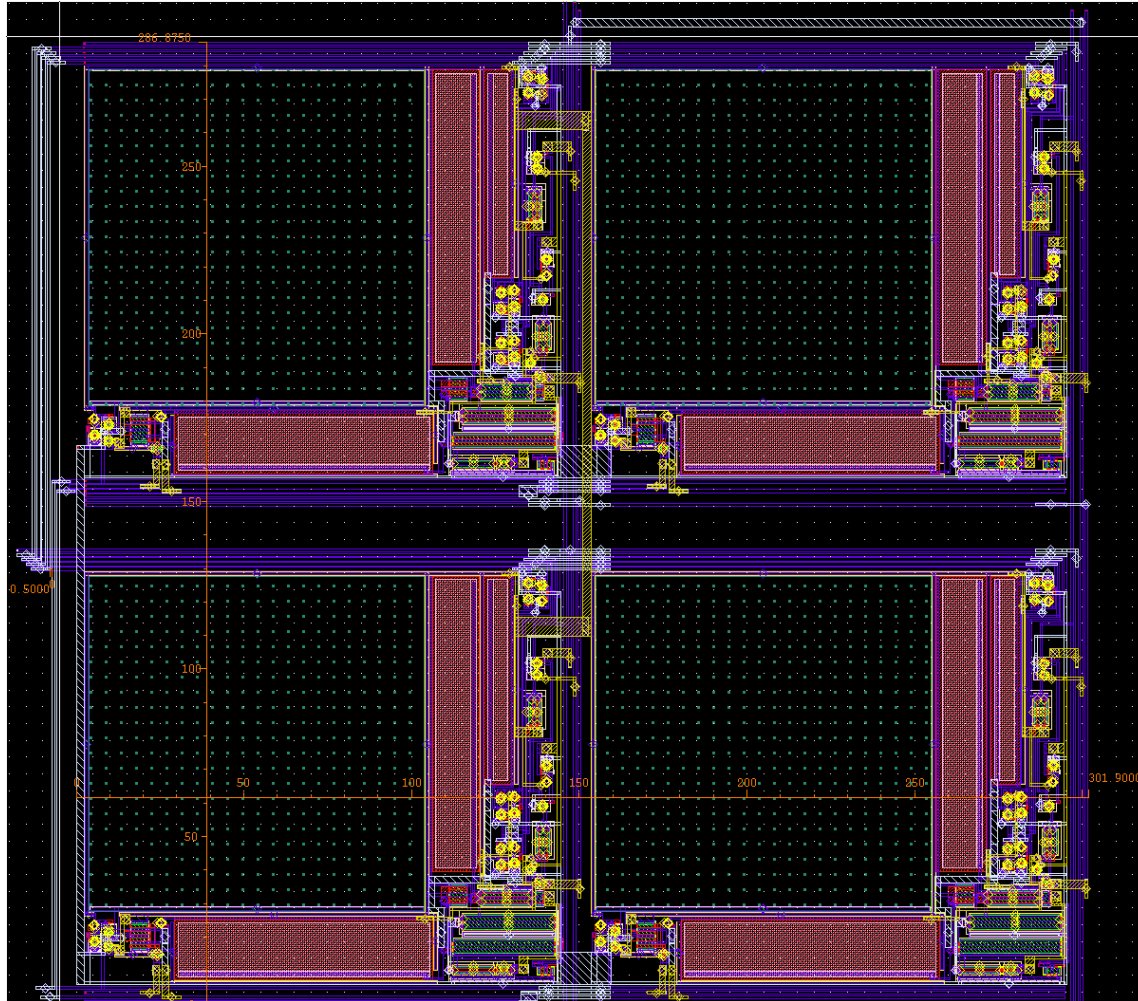
                terminals
Rules File   un-matched      0      0
Rules Libra  matched but
              different type  0      0
LVS Option   total      14     14
              End comparison:   Apr 15 19:12:49 2008

Correspond   Comparison program completed successfully.

Switch Na

Priority 0 Run local
```

Layout 2*2 matrix



Layout 2*2 matrix LVS

Warning: Unknown device "rpoly2" on a permuteDevice command.
Warning: Unknown device "rpoly1" on a permuteDevice command.
Warning: Unknown device "lat3" on a permuteDevice command.
Warning: Unknown device "vert15" on a permuteDevice command.
Warning: Unknown device "vert10" on a permuteDevice command.
Warning: Unknown device "vert5" on a permuteDevice command.
Warning: Unknown device "raosm4" on a permuteDevice command.
Warning: Unknown device "raosm4" on a permuteDevice command.
Warning: Unknown device "raosm4" on a permuteDevice command.
Warning: Unknown device "raosh5" on a permuteDevice command.
Warning: Unknown device "raosh4" on a permuteDevice command.
Warning: Unknown device "ng" on a permuteDevice command.
Warning: Unknown device "cvar" on a permuteDevice command.
Warning: Unknown device "csandvt" on a permuteDevice command.
Warning: Unknown device "zd2sm24" on a permuteDevice command.
Warning: Unknown device "pd" on a permuteDevice command.
Warning: Unknown device "nd" on a permuteDevice command.

The net-lists match.

	layout	schematic
instances		
un-matched	0	0
rewired	0	0
size errors	0	0
pruned	0	0
active	204	204
total	204	204

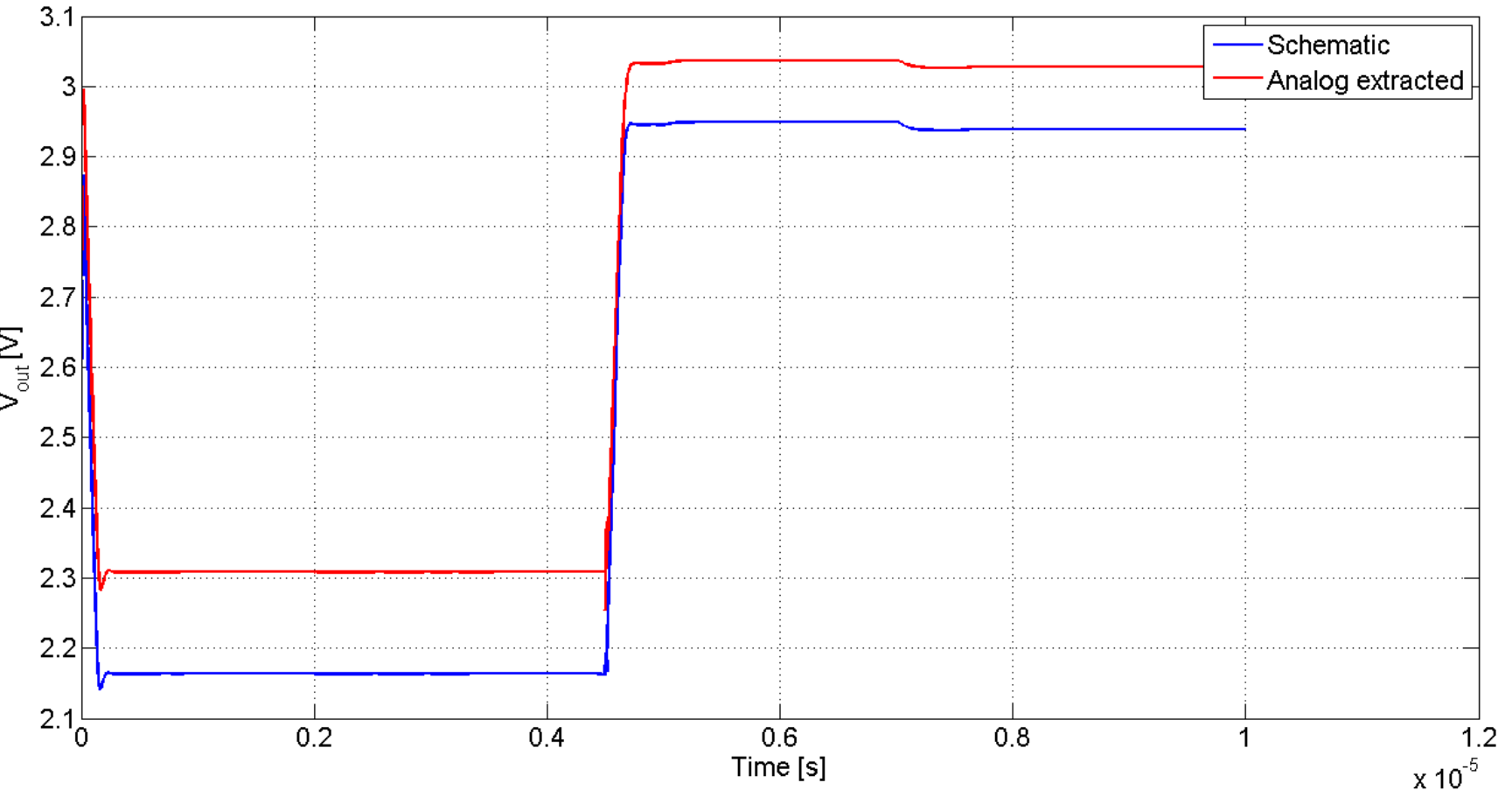
	layout	schematic
nets		
un-matched	0	0
merged	0	0
pruned	0	0
active	101	101
total	101	101

	layout	schematic
terminals		
un-matched	0	0
matched but different type	0	0
total	21	21

End comparison: Apr 15 19:24:19 2008

Comparison program completed successfully.

Analog Extracted one cycle



Conclusion

- It is possible
- But the concept needs a high precision circuit, this means it costs area and current
- It is absolutely necessary for the design to know the light source and the PD
- In this study the noise was neglected, it is also absolutely necessary to make a noise analysis. It is one of the biggest error factors because of the low voltage differences

Ref: “Entwicklung von optischen 3D CMOS-Bildsensoren auf der Basis der Pulslaufzeitmessung“ by Elkhaili, O. (PhD thesis)

