

A 2/3-inch Low Noise HDTV FT CCD-Imager for 1080i180, 1080p90 and 720p120 Scanning at Constant Image Diagonal

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- **The sensor was developed as part of a MEDEA+ project (2A206) lead by Albert Theuwissen.**

Agenda

- **Introduction**
- **4320 an important number**
 - Constant Image Diagonal
 - Scanning formats
- **Local oxide thinning**
 - Capacitance
 - Increase bandwidth
 - Reduce noise

Introduction: My World

In cooperation with DALSA we added functionality to the CCD-imager, that was not found in imagers of the competition. HD-DPM gave a competitive edge



Super slow motion: 3x



Introduction

- **The HDTV standard.....**
 - 18 possible scanning formats
 - Main 1080p, 1080i and 720p...counted vertically
 - P:progressive; i:interlaced
 - The problem: to have **ONE** camera that supports 1080p, 1080i, 720p same horizontal angle of view.
 - In High end **2/3"**, Pro-AV **1/2"** and **1/3"**
 - Lens determined
- **1080p30 and 1080i60 and 720p60**
 - 74 MHz masterclock and 30 MHz video bandwidth
- **Triple speed**
 - 3x, sports applications (Olympics, soccer)
 - 1080p90 and **1080i180** and 720p180
 - 222 MHz masterclock and 90 MHz video bandwidth

The importance of 4320 pixels per column

Mathematics to arrive at the sweet spot

Scanning Format	Prime decomposition	Log-prime notation
1080P	$2^3 \cdot 3^3 \cdot 5$	[3,3,1,0,0,0]LP6
1080I	$2^2 \cdot 3^3 \cdot 5$	[2,3,1,0,0,0]LP6
720P	$2^4 \cdot 3^2 \cdot 5$	[4,2,1,0,0,0]LP6
480P	$2^5 \cdot 3 \cdot 5$	[5,1,1,0,0,0]LP6
480I	$2^4 \cdot 3 \cdot 5$	[4,1,1,0,0,0]LP6

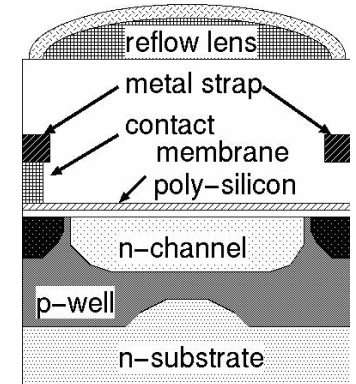
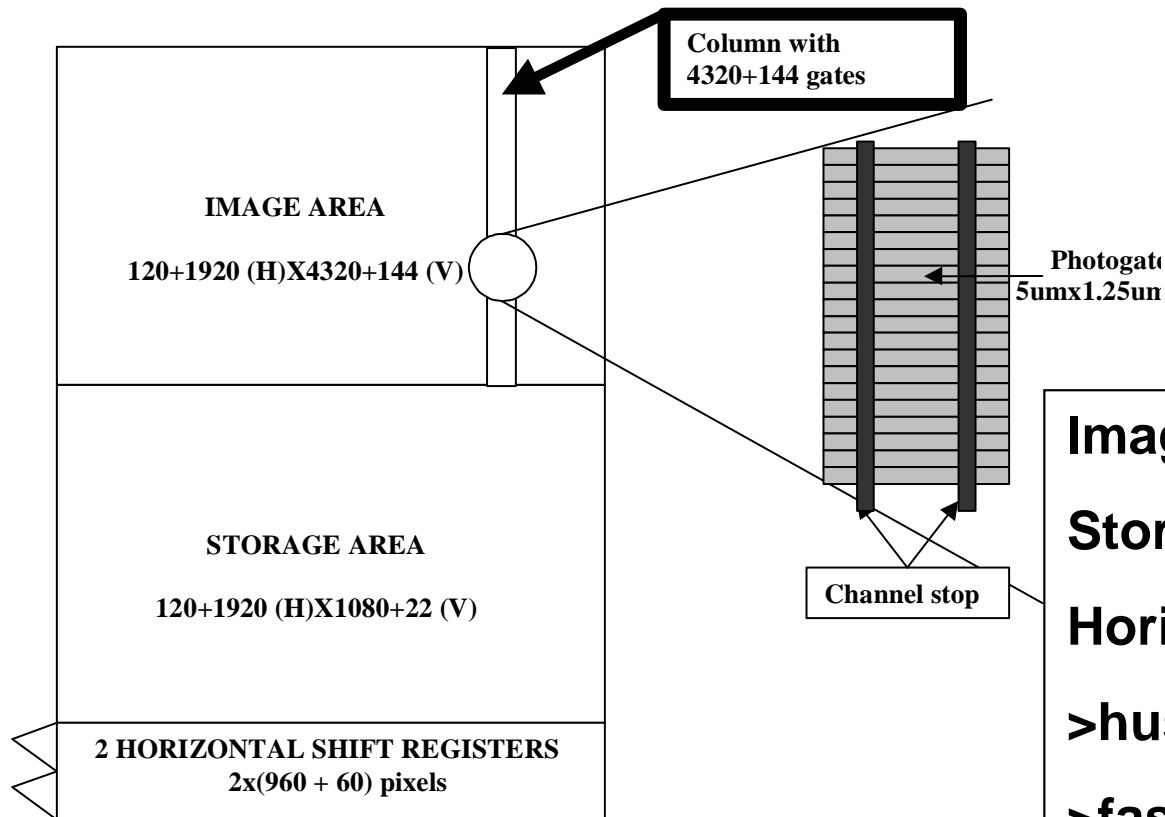
Least Common Multiple : $2^5 \cdot 3^3 \cdot 5 = 4320$

Constant Image Diagonal 1/3

=> **SAME ANGLE OF VIEW** for all scanning formats

=> **1920 (H) x 4320 (V)** and **16:9** aspect ratio

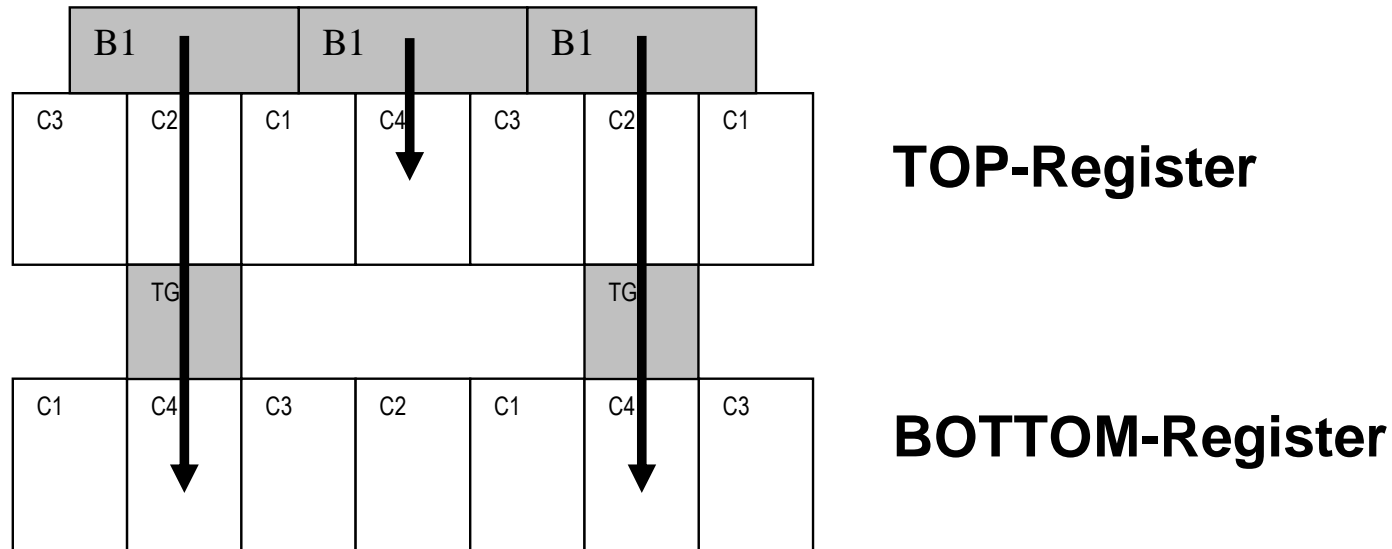
2/3" => **5 um x 1.25 um** per photogate



Pixel cross-section

Imager area: 12-phase (9MHz)
Storage area: 4-phase (9MHz)
Horizontal register: 4-phase
>hustle 4 independent voltages
>fast quasi 2-phase transport
(2x111MHz)

Close up storage horizontal register



pixels perfect aligned in time

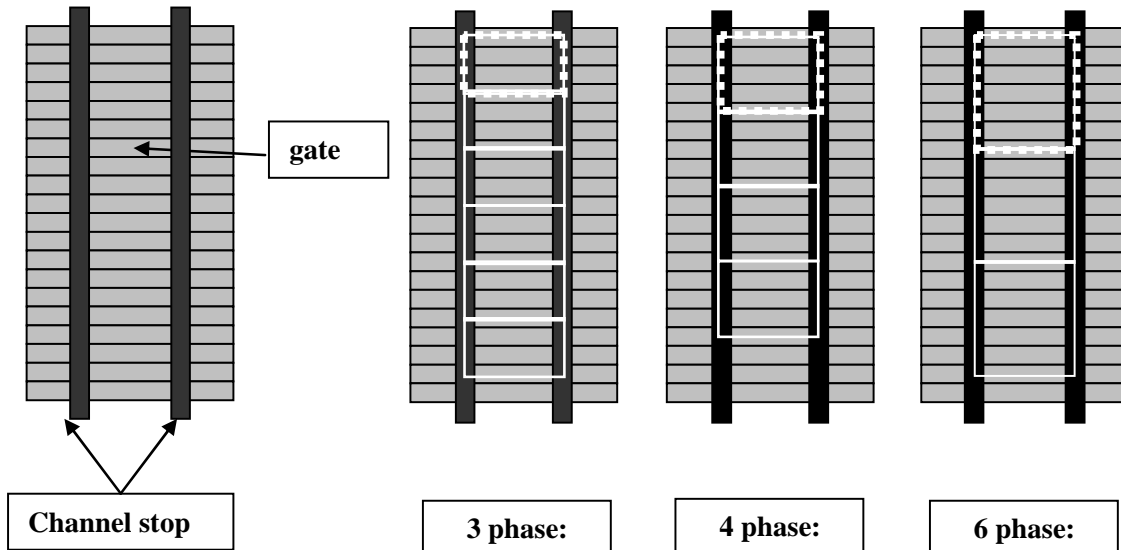
Constant Image Diagonal 2/3

- What it is *designed* to do versus what it *can* do

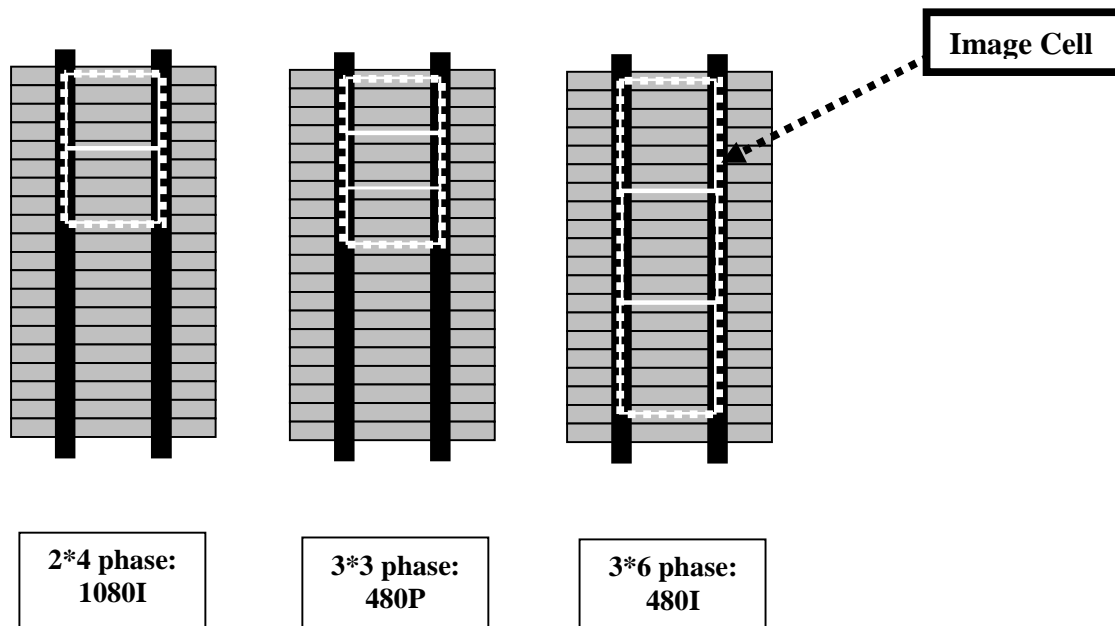
16:9 scanning formats	#GATES/Pixel	In 12-phase clocking schema
1080p	4 (= 4320 / 1080)	4-phase clocking 1 pixel
720p	6 (= 4320 / 720)	6-phase clocking 1 pixel
1080i	8 (= 4320 / (1080/2))	4-phase clocking 2 sub-pixels
480p	9 (= 4320 / 480)	3-phase clocking 3 sub-pixels
576i	15 (= 4320 / (576/2))	3-phase clocking 5 sub-pixels
480i	18 (= 4320 / (480/2))	6-phase clocking 3 sub-pixels
1080p in 2.37:1 aspect ratio	3 (= 4320*(3/4) / 1080)	3-phase clocking 1 pixel

=>2.37:1 is used for cinemascope

Constant Image Diagonal 3/3



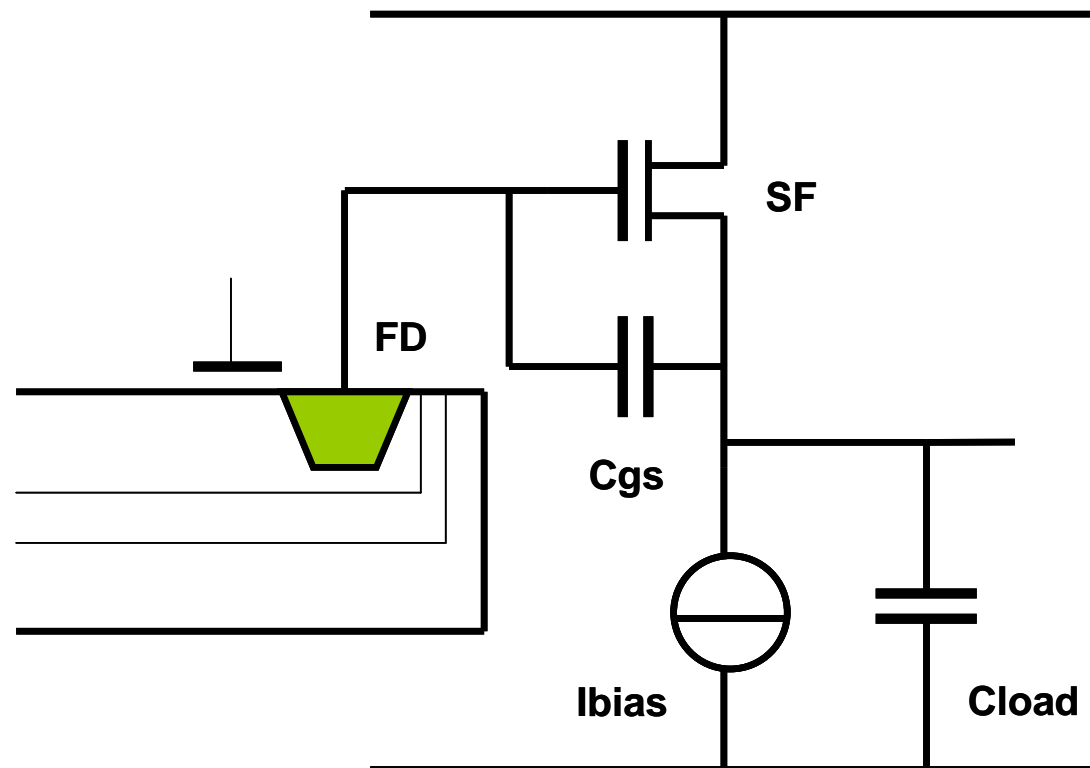
2/3" => HxV
 5 um x 1.25 um
 per photogate



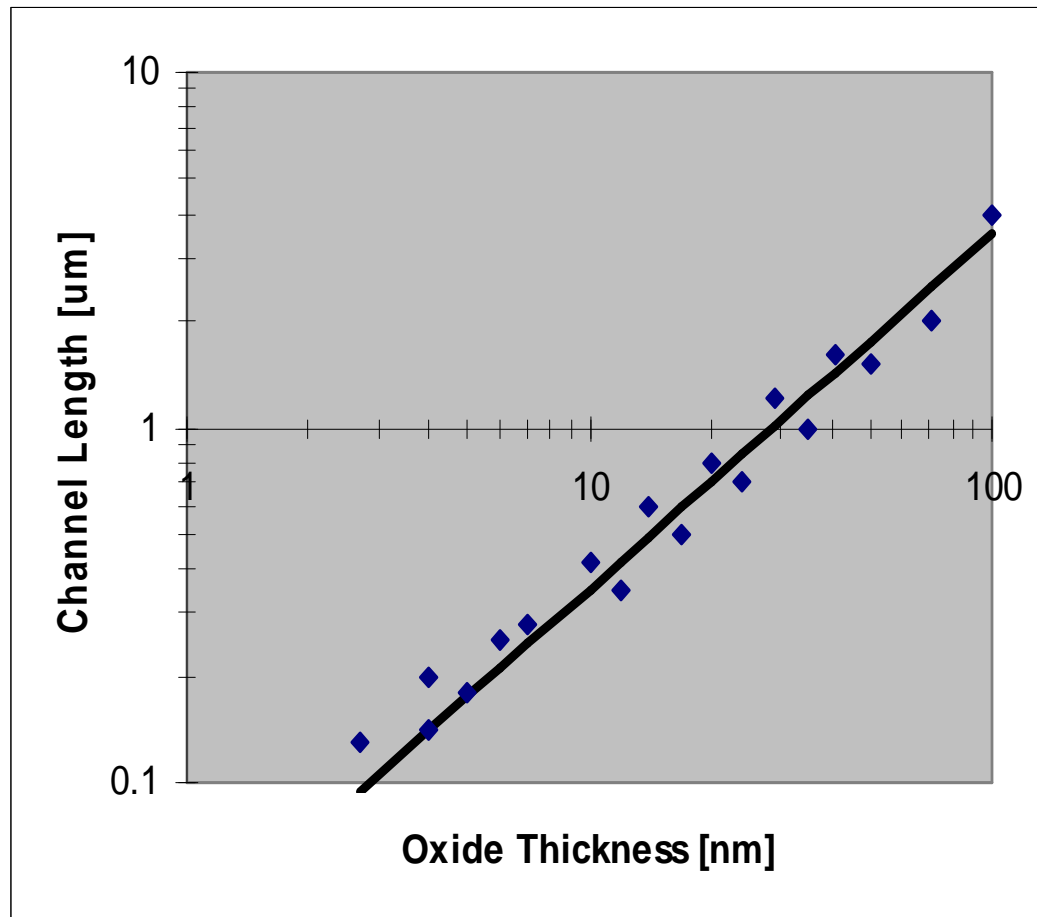
Noise and bandwidth

High bandwidth low noise

- **Using local oxide thinning for the MOST to optimize noise and bandwidth performance**
 - “Pixel” oxide thickness determines CCD performance decouple it!



Channel Length and Oxide Thickness



**Minimum
channel length**

$$L_{\min} \approx 35 * d_{ox}$$

**Based on Wong's data
(IEEE ED 1996)**

(equal units)

MOST Gate capacitance scaling

$$C_g = W * L * C_{ox} = W * L * \frac{\epsilon}{d_{ox}}$$

- **Based on Wong's data (equal units)**

$$L_{\min} \approx 35 * d_{ox}$$

- **The gate capacitance only proportional to W**

$$C_g \approx W$$

Bandwidth

- **Given a load capacitance and MOST transconductance the 3dB frequency is**

$$F_{3dB} = \frac{g_m}{2 * \pi * C_{load}} \qquad I_{ds} = W * J_x$$

$$g_m = \sqrt{2 * \frac{W}{L} * \frac{\epsilon}{d_{ox}} * u_n * I_{ds}} \approx \frac{W}{d_{ox}} \approx \frac{1}{d_{ox}}$$

Halving the oxide thickness and channel length doubles the bandwidth.

***While having same input capacitance Cg
....important for 3-stage amp***

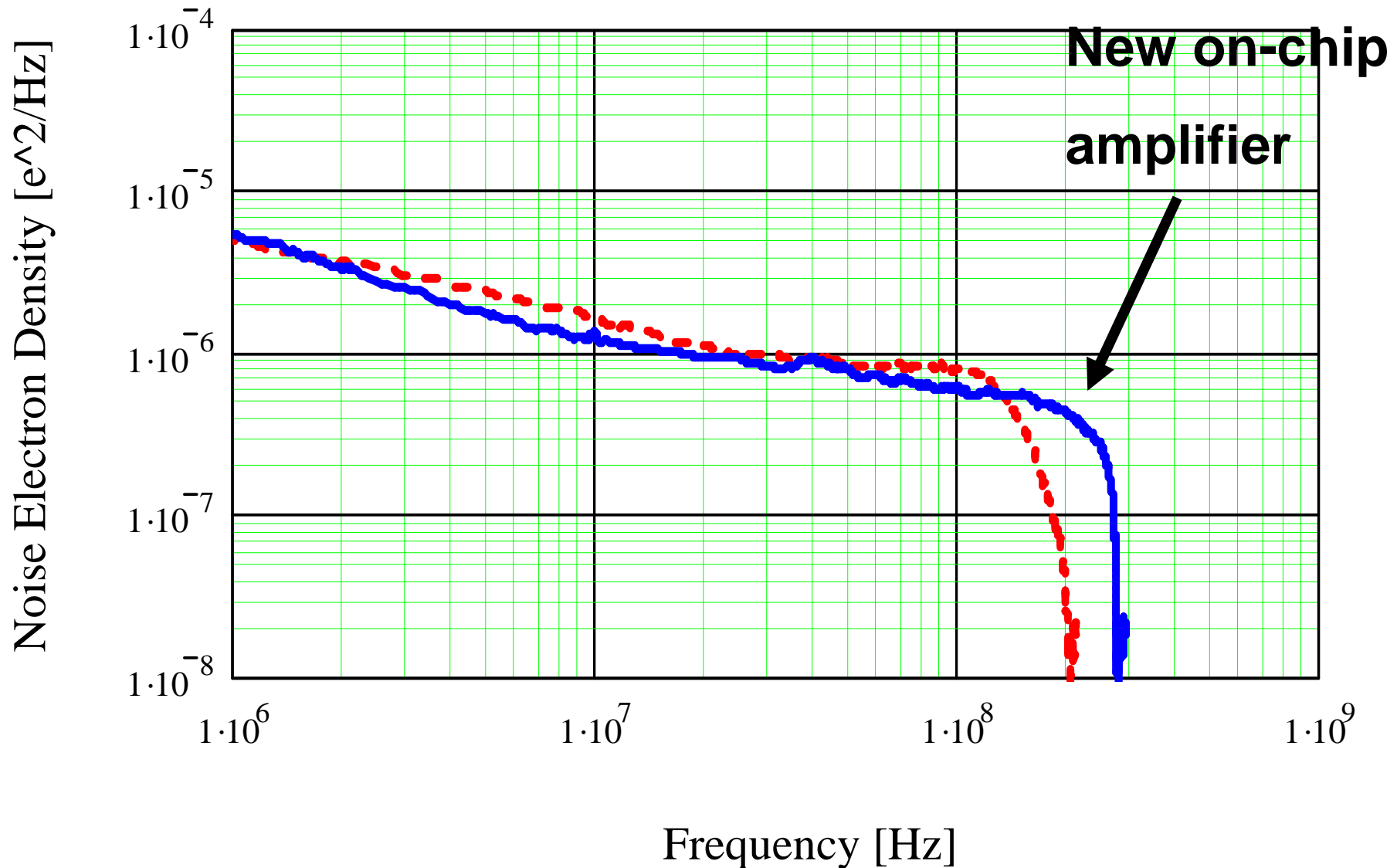
Noise

$$NED = \frac{4kT}{g_m} * \left(\frac{C_{tot}}{q} \right)^2$$

- Optimal gate capacitance approx. the MOST dimensions independent capacitance, and thus a given
- Minimizing the noise electron density...only gm left.
- But W is fixed.....capacitance determined

$$g_m = \sqrt{2 * \frac{W}{L} * \frac{\epsilon}{d_{ox}} * u_n * I_{ds}} \approx \frac{W}{d_{ox}} \approx \frac{1}{d_{ox}}$$

Noise Spectrum.....a first result



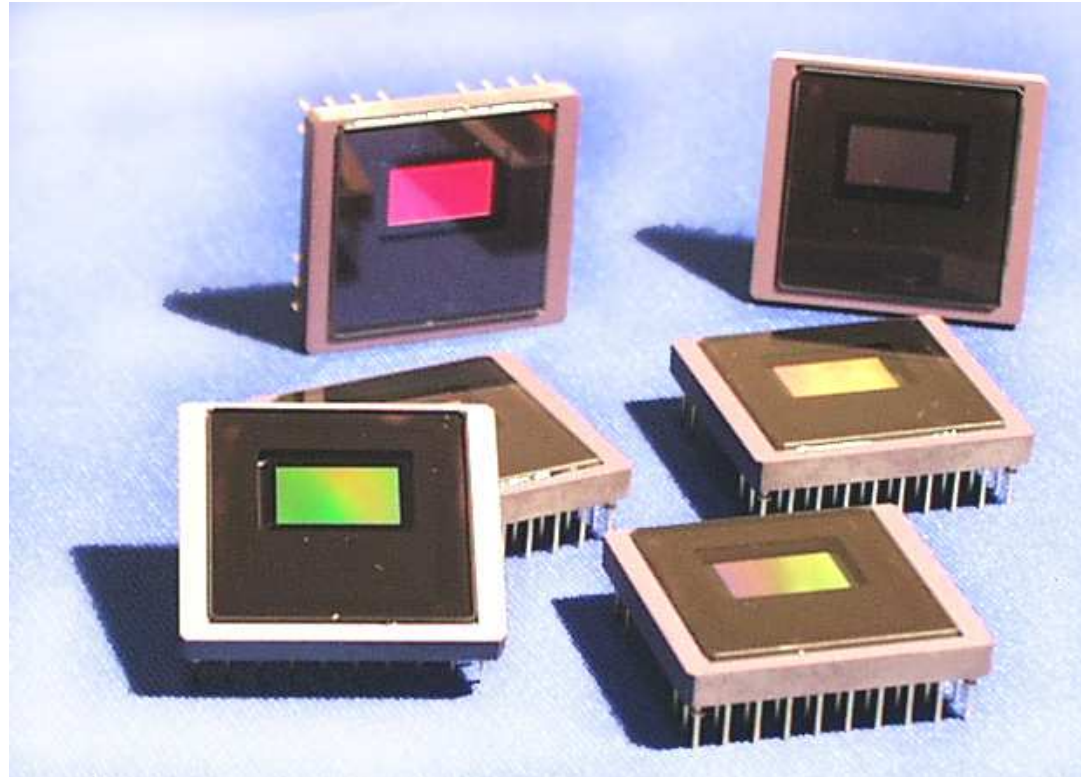
Benchmarking

Type	Ref	Reset Frequency	Ampl. Type	Conversion gain	Noise after CDS/ $\sqrt{\text{Resetfrequency}}$
FF-CCD	ED1997 Burke	100 kHz	Source Follower	20 $\mu\text{V}/\text{e}$	6.3 $\text{e}/\sqrt{\text{MHz}}$
CMOS	AIS2003 Krymski	50 kHz	Source Follower +Gain	60 $\mu\text{V}/\text{e}$	6.3 $\text{e}/\sqrt{\text{MHz}}$
FF-CCD	AIS2005 Draijer	25 MHz	Source Follower	40 $\mu\text{V}/\text{e}$	2.8 $\text{e}/\sqrt{\text{MHz}}$
CMOS	ISSCC2005 Kozlowski	104 kHz	Source Follower +Gain	? $\mu\text{V}/\text{e}$	46 $\text{e}/\sqrt{\text{MHz}}$
CMOS	ISSCC2006 Yoshihara	156 kHz	Source Follower +Gain	40 $\mu\text{V}/\text{e}$	17.7 $\text{e}/\sqrt{\text{MHz}}$
CMOS	ISSCC2007 Takahashi	156 kHz	Source Follower +Gain	75 $\mu\text{V}/\text{e}$	11.6 $\text{e}/\sqrt{\text{MHz}}$
CMOS	ISSCC2007 Cho	625 kHz	Source Follower +Gain	101 $\mu\text{V}/\text{e}$	10.4 $\text{e}/\sqrt{\text{MHz}}$
FT-CCD	This paper	111MHz	Source Follower	18 $\mu\text{V}/\text{e}$	1.3 $\text{e}/\sqrt{\text{MHz}}$

Table

Technology	Tungsten, thin transparent membrane Frame Transfer CCD		Number of horizontal registers	2
Chip Size	12.0(H) x 12.7(V) mm ²		Number of horizontal clock phases During fast horizontal transport	4 Quasi 2-phase operation
Aspect Ratio	16:9		Number of on-chip amplifiers	2
Storage number of clock phases	4		Measured bandwidth of on-chip amplifier	>241MHz
Storage number of columns x lines	2040(H) x 1102(V)		Conversion gain	18 μ V /e
Image number of clock phases	12		Max frame rate, pixel rate	180 fld/sec, 223Mpixel/sec
Image number of columnsxgates	2040(H) x 4464(V)		Horizontal transport frequency	2x112MHz
Pixel size in 1920x1080p90	5.0 μ m x 5.0 μ m (HxV)		Vertical transport frequency	10MHz
Pixel size in 1920x1080i180	5.0 μ m x 5.0 μ m x 2 (HxV)		Noise Electron Density (NED) of the on-chip amplifier	0.75 e^2 /MHz@37.125MHz 0.59 e^2 /MHz@112MHz
Pixel size in 1920x720p120	5.0 μ m x 7.5 μ m (HxV)		Temporal Noise After CDS in 30MHz	8e or 2.1 e^2 /MHz
Pixel size in 1920x1080p90 @ 2.37:1	5.0 μ m x 3.75 μ m (HxV)		Sensitivity in Green	820 electrons/lux/sec/ μ m ²
			Qmax	680 electrons/ μ m ²

HD-DPM Imager



Conclusion

- **A 2/3” multi-format HDTV imager was developed**
 - With equal angle of view in 1080p, 1080i and 720p
 - Running at 1920x1080i180
 - 180 fields/second
 - Horizontal transport at 2x111MHz
 - Vertical transport at 9.25MHz
- **Low noise ($0.59 \text{ e}^2/\text{MHz}@111\text{MHz}$) and high bandwidth ($>240\text{MHz}$) can be reached simultaneously when use is made of local oxide thinning as an additional optimization parameter for MOS transistors in the on-chip amplifier**
- **The triple speed HDTV camera, applying this imager, was used during the 2008 Olympics in Beijing and the 2008 European soccer games**

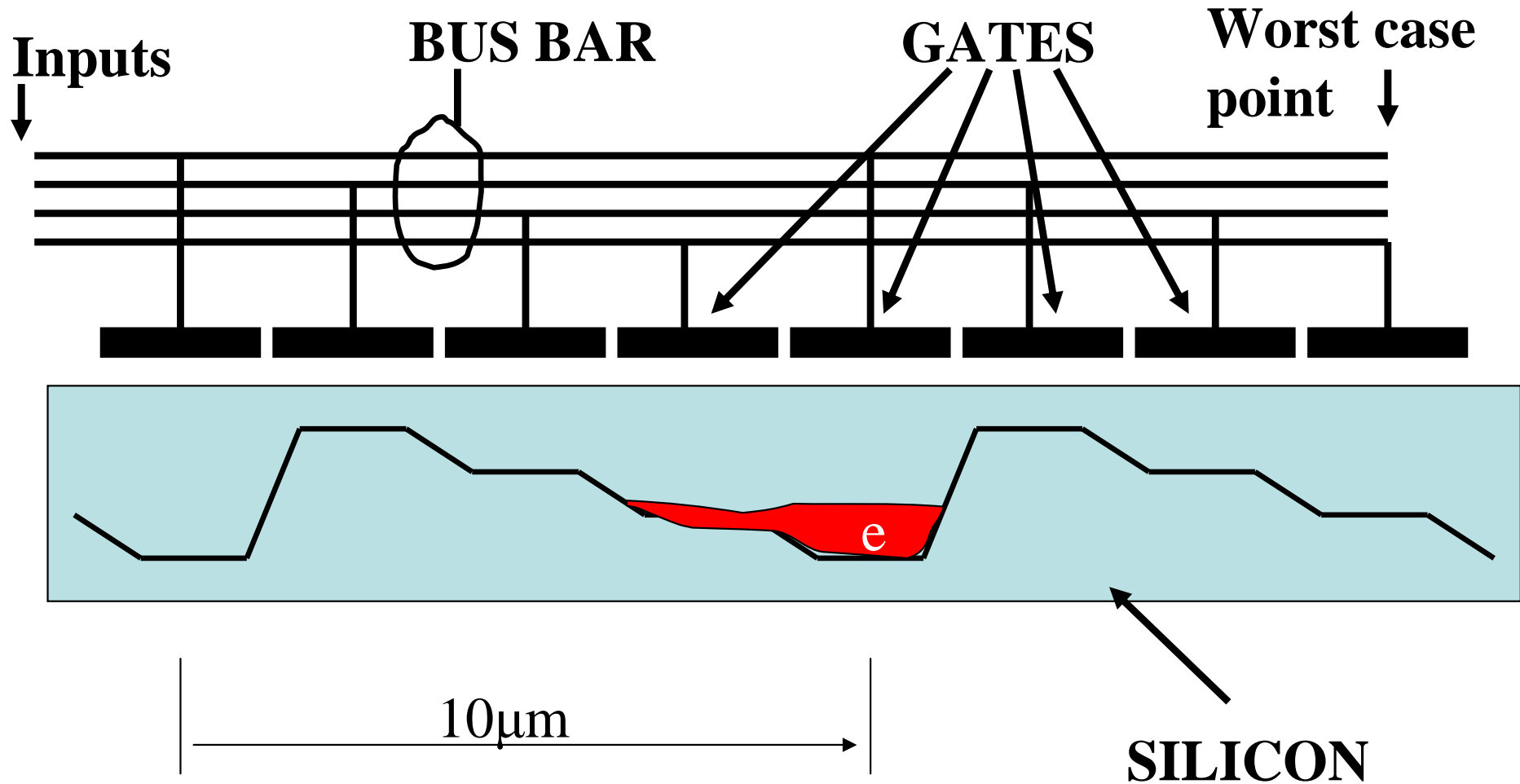
Q&A

Bonus material

An analytical approach

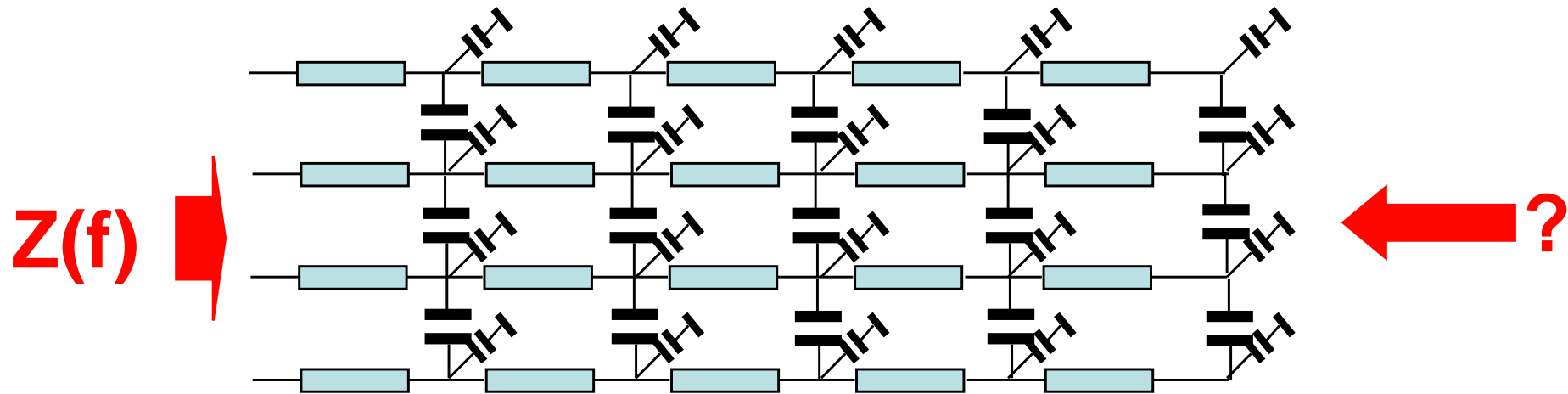
for the imager internal clock distribution

CCD charge transport



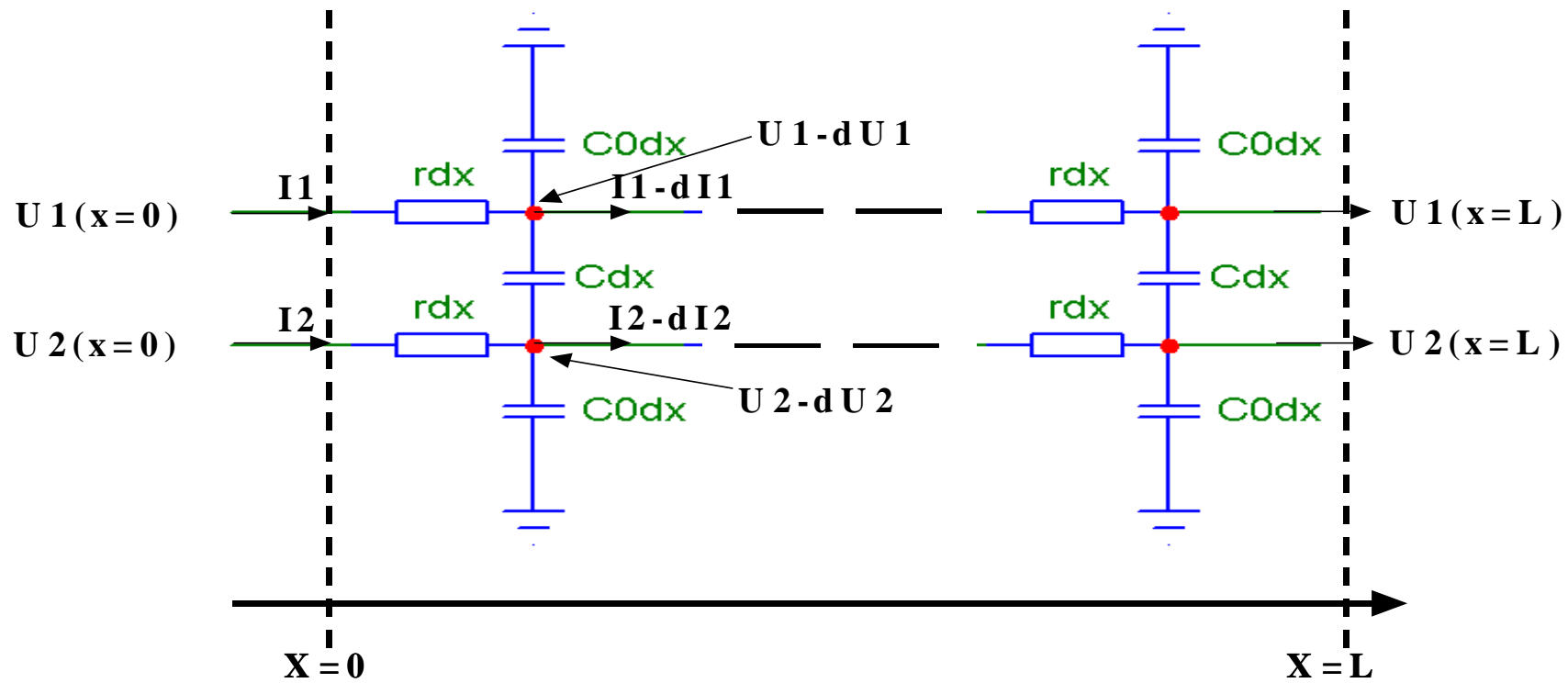
The general question

- Use the fact that a lumped model with over 4000 discrete elements can be approximated very well with a few coupled partial differential equation



- Solving them resulted in a closed form equation with the series resistance, parallel capacitance per unit length, cross capacitance and length of transportregister as a parameter.

Quasi 2-phase



The equations

Measurable

$$Z(f) := \frac{2 \cdot r}{\lambda(f) \cdot \tanh(\lambda(f) \cdot L) + \mu(f) \cdot \tanh(\mu(f) \cdot L)}$$

$$H(f) := \frac{U(L, f)}{U(0, f)}$$

Predictable

$$H(f) := e^{-\lambda(f) \cdot L} \cdot (1 + \tanh(\lambda(f) \cdot L))$$

SOLUTION

$$\frac{d}{dx} U(L, t) := 0 \quad U(0, t) := V$$

$$\lambda(f) := \sqrt{1j \cdot 2 \cdot \pi \cdot f \cdot r \cdot (C0 + 2 \cdot C)}$$

$$\mu(f) := \sqrt{1j \cdot 2 \cdot \pi \cdot f \cdot r \cdot C0}$$

BOUNDARY CONDITIONS

$$\frac{d}{dx} \frac{d}{dx} I(x, t) := (C0 + 2 \cdot C) \cdot r \cdot \frac{d}{dt} I(x, t)$$

PARAMETERS

$$\frac{d}{dx} \frac{d}{dx} U(x, t) := (C0 + 2 \cdot C) \cdot r \cdot \frac{d}{dt} U(x, t)$$

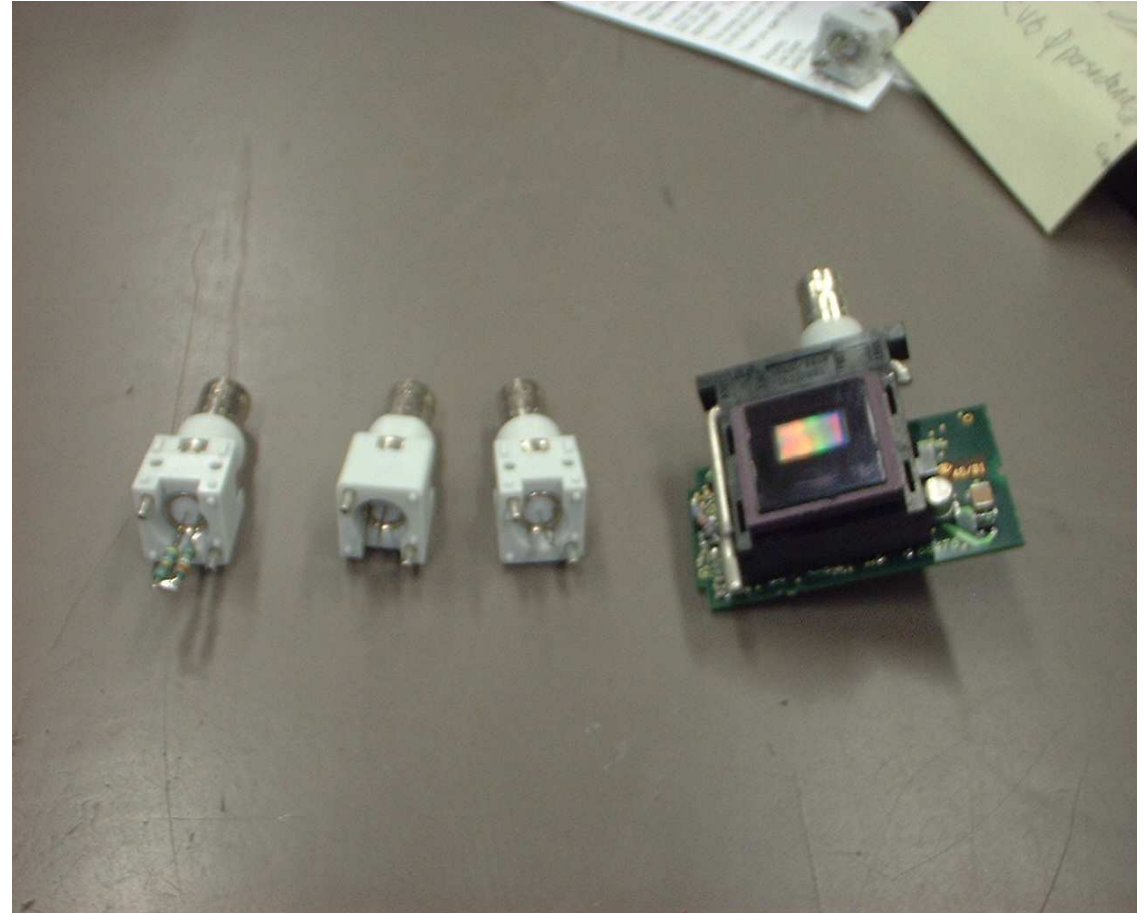
DIFFERENTIATION and SUBSTITUTION

$$\frac{d}{dx} I(x, t) := (C0 + 2 \cdot C) \cdot \frac{d}{dt} U(x, t)$$

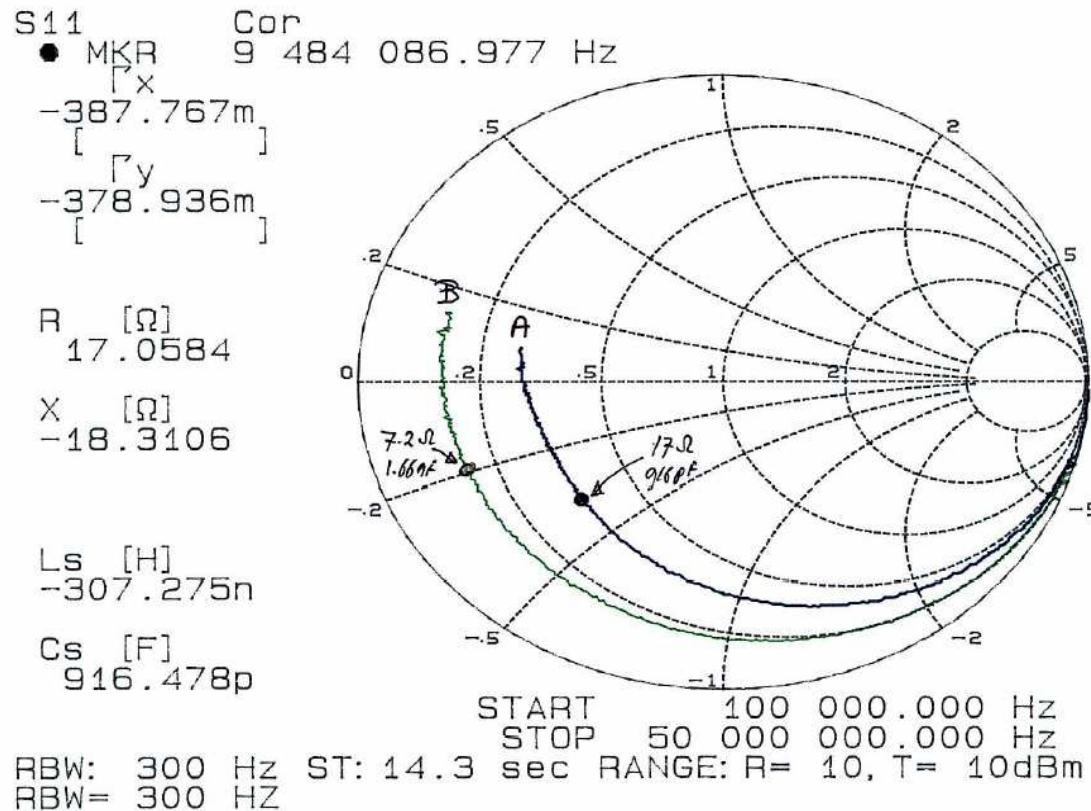
$$\frac{d}{dx} U(x, t) := r \cdot I(x, t)$$

The measurement

- Calibration of the network-analyser reflectometer setup
 - 3 kind of terminators needed
 - Open
 - Short
 - Characteristic impedance
- Measure the parameters on the PCB with imager



Smith-chart of vertical phases



Input impedance of the Image and Storage clock lines

- Horizontal axis is the real part of the impedance the vertical axis the imaginary part.
- The impedance crosses the real axis at some point showing that there is also some self-inductance in the circuit.
- Marker at 9.48MHz and is close to the 2-speed VTR.
- The series R and C at that frequency are:
 - 17 Ohm and 916 pF for the image clock and
 - 7.2 Ohm and 1.66nF for the storage clock.

Smith-chart of horizontal phases

- Impedance of the horizontal clock lines
 - Driven in quasi 2-phase.
 - The frequency sweeps from 1 MHz to 200 MHz.
 - At 74 MHz, near the driving frequency of 2-speed mode, the equivalent series resistance is 24 Ohm and capacitance is 88 pF.

