

Design aspects of MEM-resonator based LF reference oscillators

MEMSLand

Cost Effective MEMS to Develop a Sustainable High Tech Business

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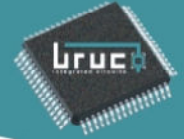
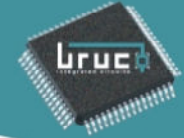


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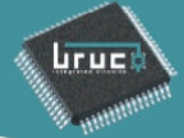
Bruco + MEMSland

The company Bruco employs two activities:

- **Integrated Circuits:**
offers development service on design, verification, test and qualification of Application Specific Integrated Circuits (ASIC's).
and
Research
- **Components:**
offers logistic service on wafer manufacturing, assembly and test and offers storage service for wafers and products.

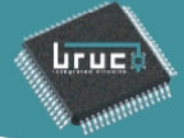
MEMSland consortium:

- **MEMS project:**
Project is partly funded by the Dutch government via MEMSland consortium.
- **Consortium objective:**
The objective of the MEMSland project, is to develop and integrate all key competencies and technologies needed for the development of a comprehensive MEMS packaging solution. The project will enhance the education of highly qualified experts in this complex field in the Netherlands.



MEM resonator basics

- MEMS = Micro Electro Mechanical System
- MEM resonator = damped mass-spring system
 - Small mechanical structures can be constructed in silicon. Preferably in a SOI process.
 - Resonator is actuated by means of a time varying electrostatic force between capacitor plates (“electrostatic actuation”).
 - Vibrating mass is observed in electrical domain by means of a time-varying capacitance.
- Potential advantage w.r.t. traditional resonators:
 - Replacement of an external component (i.e. Quartz resonator)



MEM resonator

- Fundamental mode vibration can be described by 2nd order non-linear differential equation (z = displacement):

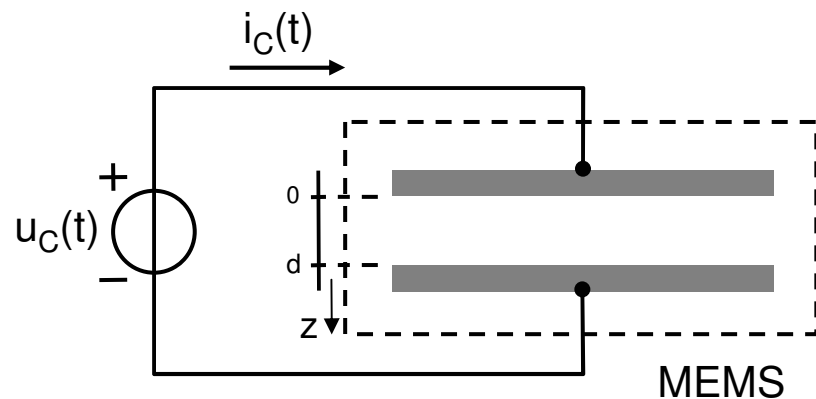
$$m \cdot \frac{d^2 z(t)}{dt^2} + \xi \cdot \frac{dz(t)}{dt} + k(z(t)) = F_{ext}(t)$$

- F_{ext} is generated by means of electrostatic actuation:
 - Apply a voltage $u_C(t)$ between capacitor plates → electric field
→ mechanical force between the capacitor plates.

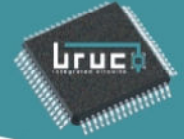
$$F_{ext}(t) = \frac{1}{2} \cdot \frac{dC(z)}{dz} \cdot u_C^2(t)$$

Electrical current into MEM

- What is the electrical current into de MEM resonator?
When a voltage $u_C(t)$ is applied to the resonator, then $i_C(t)$ is:



$$\begin{aligned}
 i_C(t) &= \frac{dq(t)}{dt} = \frac{d\{C(z(t))u_C(t)\}}{dt} \\
 &= \underbrace{C(t) \frac{du_C(t)}{dt}}_{i_{\text{capacitor}}} + u_C(t) \underbrace{\frac{dC(z(t))}{dz} \frac{dz(t)}{dt}}_{i_{\text{mechanical}}}
 \end{aligned}$$

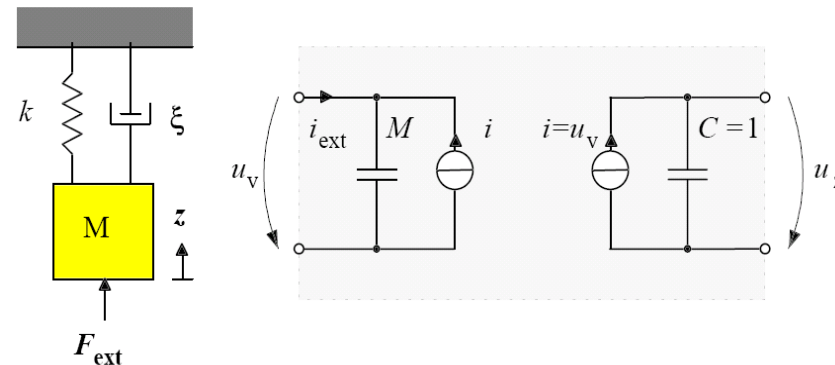


Equivalent model

- Goal: construct an equivalent electrical model which can be used in circuit simulators and that incorporates the non-linear effects:
 - Non-linear behavior of spring “constant” k_m :
 $k_m = k_0 + f(z)$, or
 $k_m = k_0 + k_1 \cdot z + k_2 \cdot z^2 + k_3 \cdot z^3 \dots\dots$
 - Non-linear capacitor $C(z)$
 $C(z)$ is MEM-geometry dependent
 - Non-linear relation between voltage and driving force:
 $F_{\text{ext}} = 0.5 \cdot dC/dz \cdot u_C(t)^2$

Controlled current source modeling

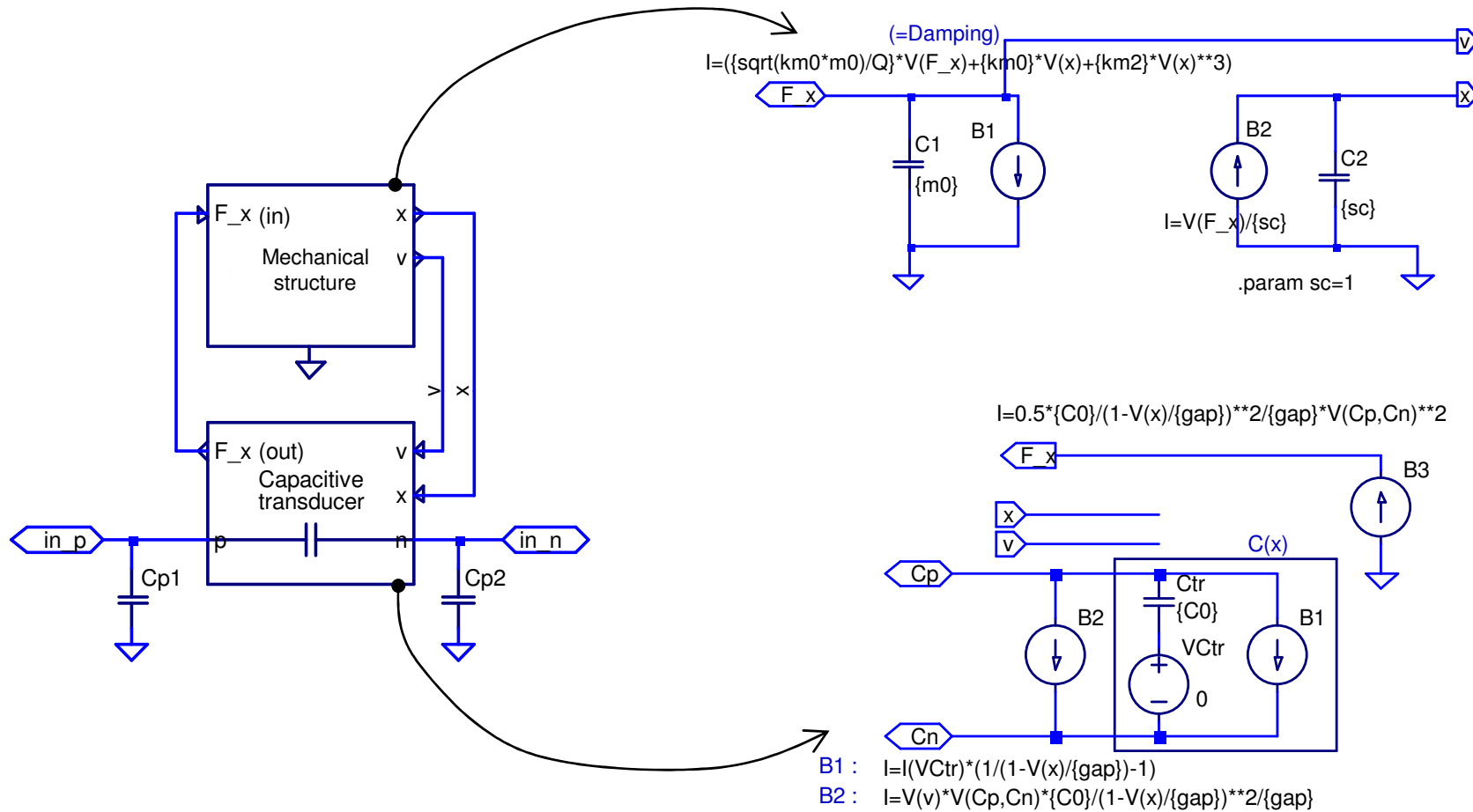
Circuit) Component	Mechanical equation	Electrical equation
a) Displacement	$v = \frac{\partial z}{\partial t}$	$u_v = \frac{\partial u_z}{\partial t}$
b) Force	$F = F_{\text{ext}}$	$i = i_{\text{ext}}$
c) Spring	$F = -kz$	$i = -ku_z$
d) Damper	$F = -\xi v$	$i = -\xi u_v$
e) Mass	$F = -M \frac{\partial v}{\partial t}$	$i = -C \frac{\partial u_v}{\partial t}$

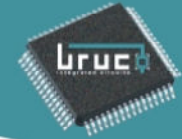


$$M \frac{\partial^2 z}{\partial t^2} + \xi \frac{\partial z}{\partial t} + kz + k_3 z^3 = F_{\text{ext}}$$

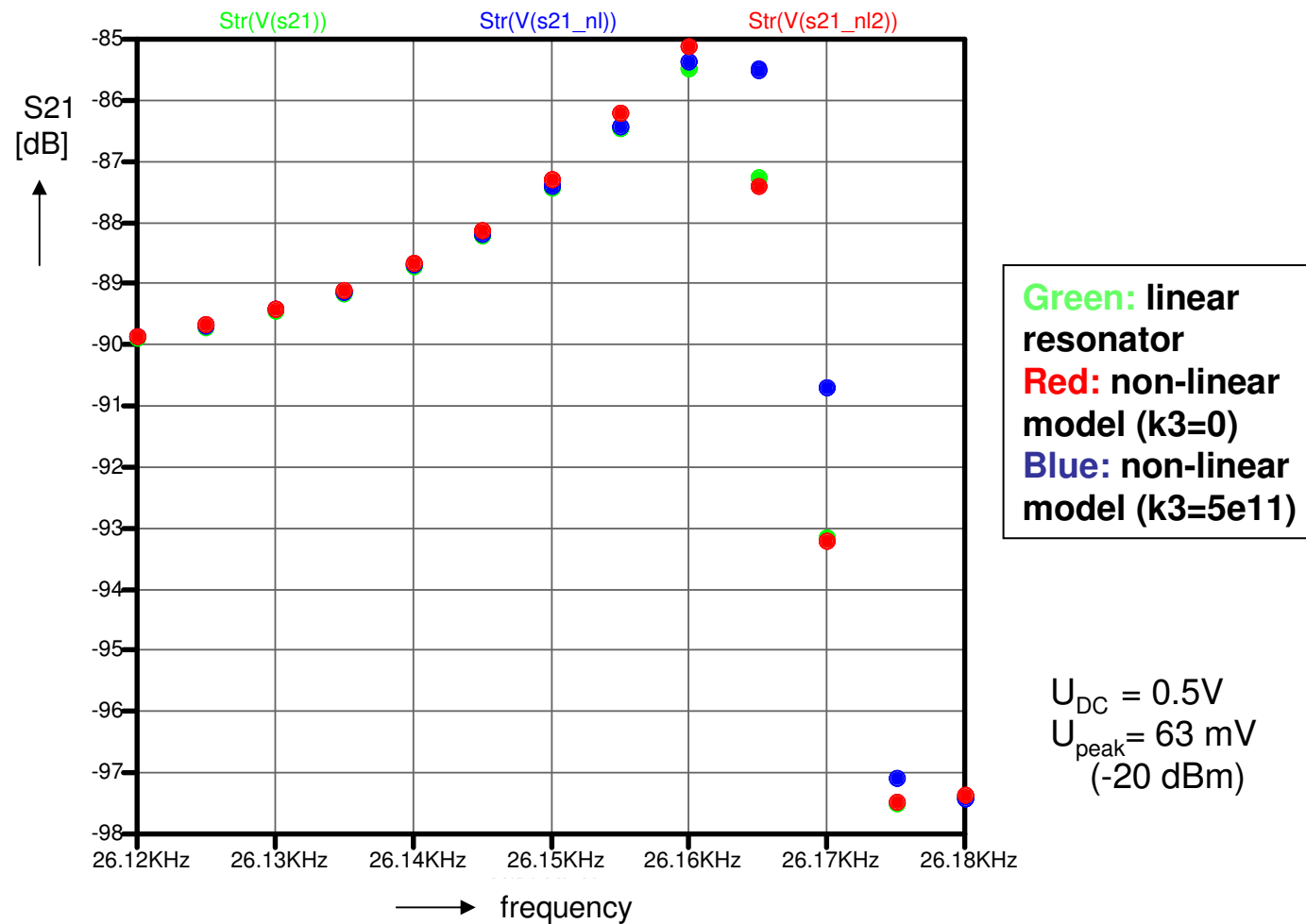
Reference: [T. Veijola]

Equivalent large-signal model

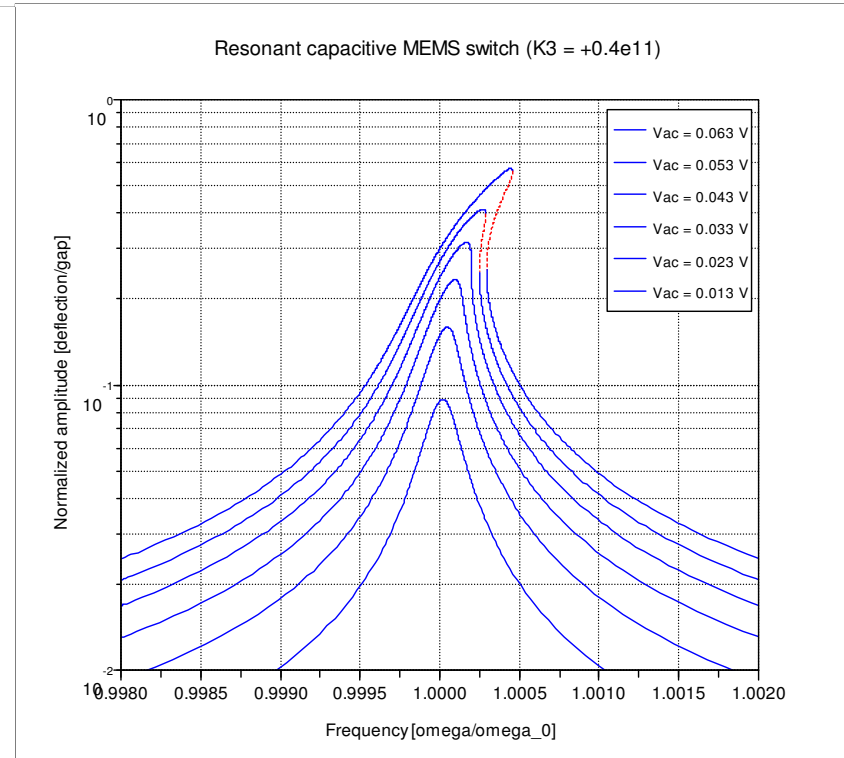
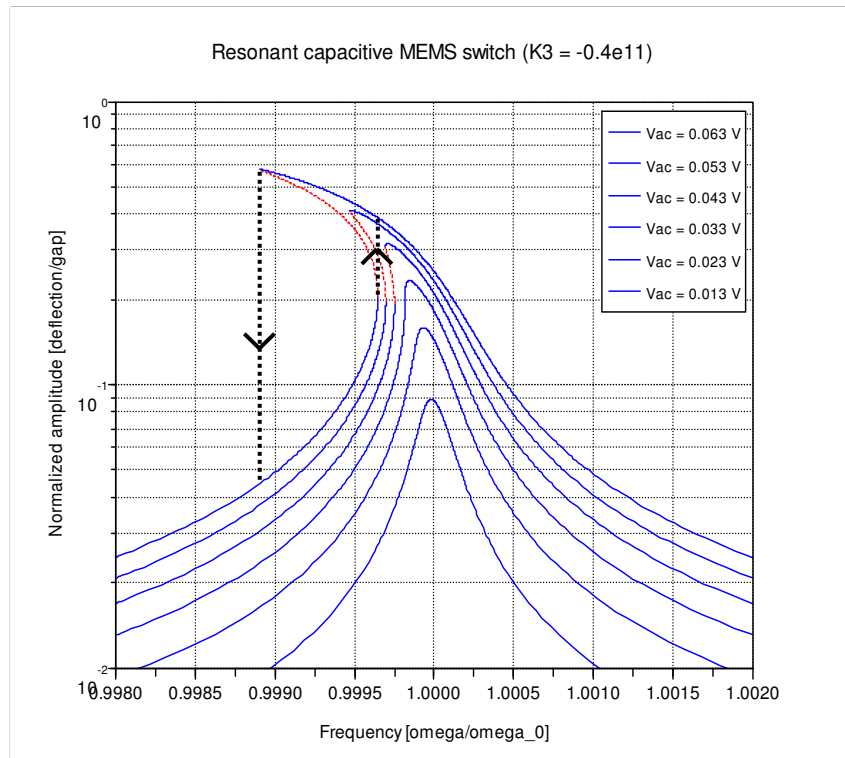




Example of simulation results



Resonance curves of a MEM resonator



Resonator curves for various signal amplitudes when $U_{DC} = 0.5V$.
 (Only mechanical behavior and created with "AUTO"-software)

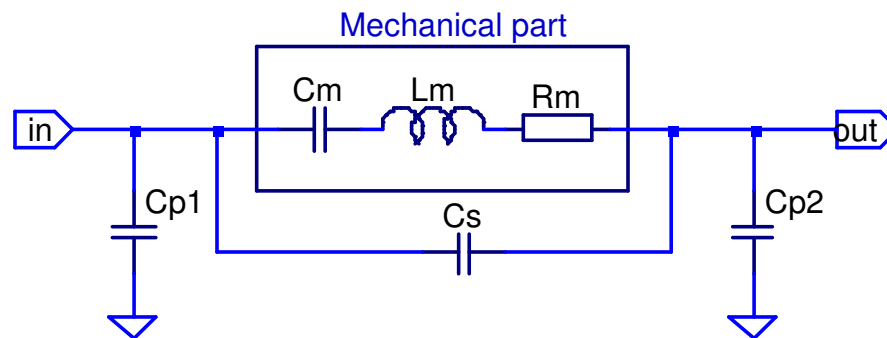
Equivalent linear circuit elements

- When $U_{DC} \gg |u(t)| \rightarrow$ linear behavior \rightarrow linear equivalent electrical circuit:

$$Q = \frac{\sqrt{m \cdot k_{eq}}}{\xi}$$

$$\omega_o = \sqrt{\frac{k_{eq}}{m}}$$

$$\eta = U_{DC} \frac{dC_s(z)}{dz}$$

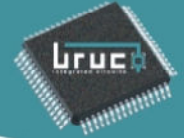


$$R_m = \frac{\xi}{\eta^2}$$

$$C_m = \frac{\eta^2}{k_{eq}}$$

$$L_m = \frac{m}{\eta^2}$$

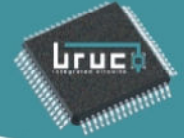
(m = mass, k_{eq} = equivalent spring constant, ξ = damping factor and η = electromechanical coupling coefficient)



Equivalent spring constant

- Contributions to the spring “constant”: (= those contributions which are proportional to the displacement)
 - Mechanical contribution: k_0
 - Electrical force contribution: k_e .
 - Total equivalent spring constant: $k_{eq} = k_0 + k_e$
- Example: the resonance frequency of a parallel plate MEM resonator with a capacitance C_s , having small excitation-signals compared with its bias voltage (U_{DC}) is: ($k_e \approx -C_s/d^2 \cdot U_{DC}^2$)

$$\omega_o = \sqrt{\frac{k_{eq}}{m}} = \sqrt{\frac{k_0 - \frac{C_s}{d^2} U_{DC}^2}{m}}$$

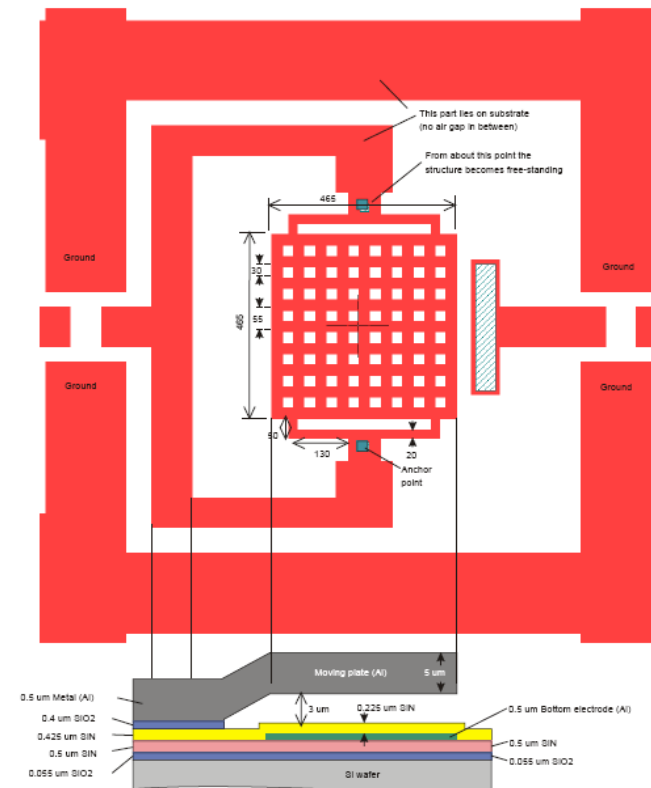


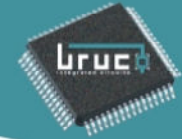
Oscillator implementation (Test-chip)

- MEM resonator: $f_{\text{res}} \approx 26 \text{ kHz}$ (resonant switch)
- Supply voltage: 1.8V nominal
- Process: 0.18 μm CMOS (TSMC)
- Bias voltage resonator: $U_{\text{DC}} = 0.5 \text{ V}$ (externally provided)
- Output must be able to drive a 10 pF load with a rail-to-rail swing
- Minimum power consumption required

Resonant switch (by NXP)

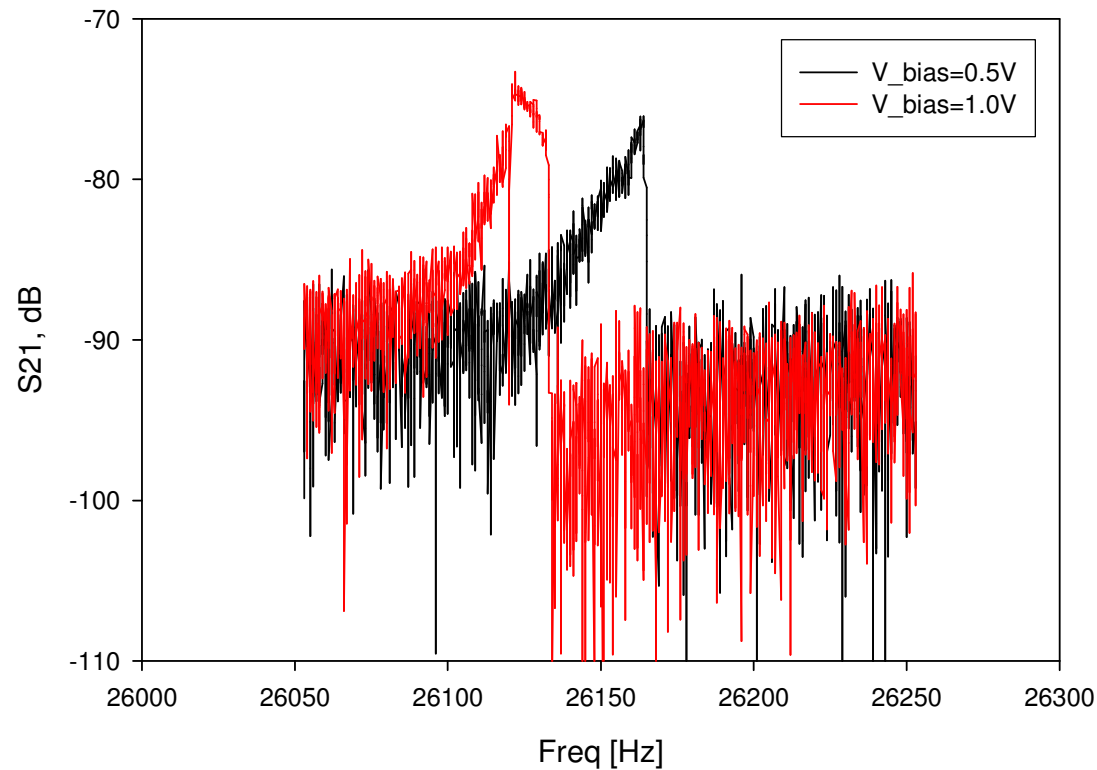
- MEM resonant switch:
26 kHz MEM “resonator” from NXP. (Originally intended to be a capacitive switch)

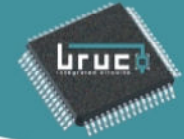




S21 measurement results:

S-para measurement, Switch
AC power=-20dBm



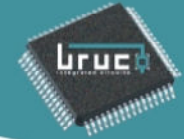


Element-values of equivalent model

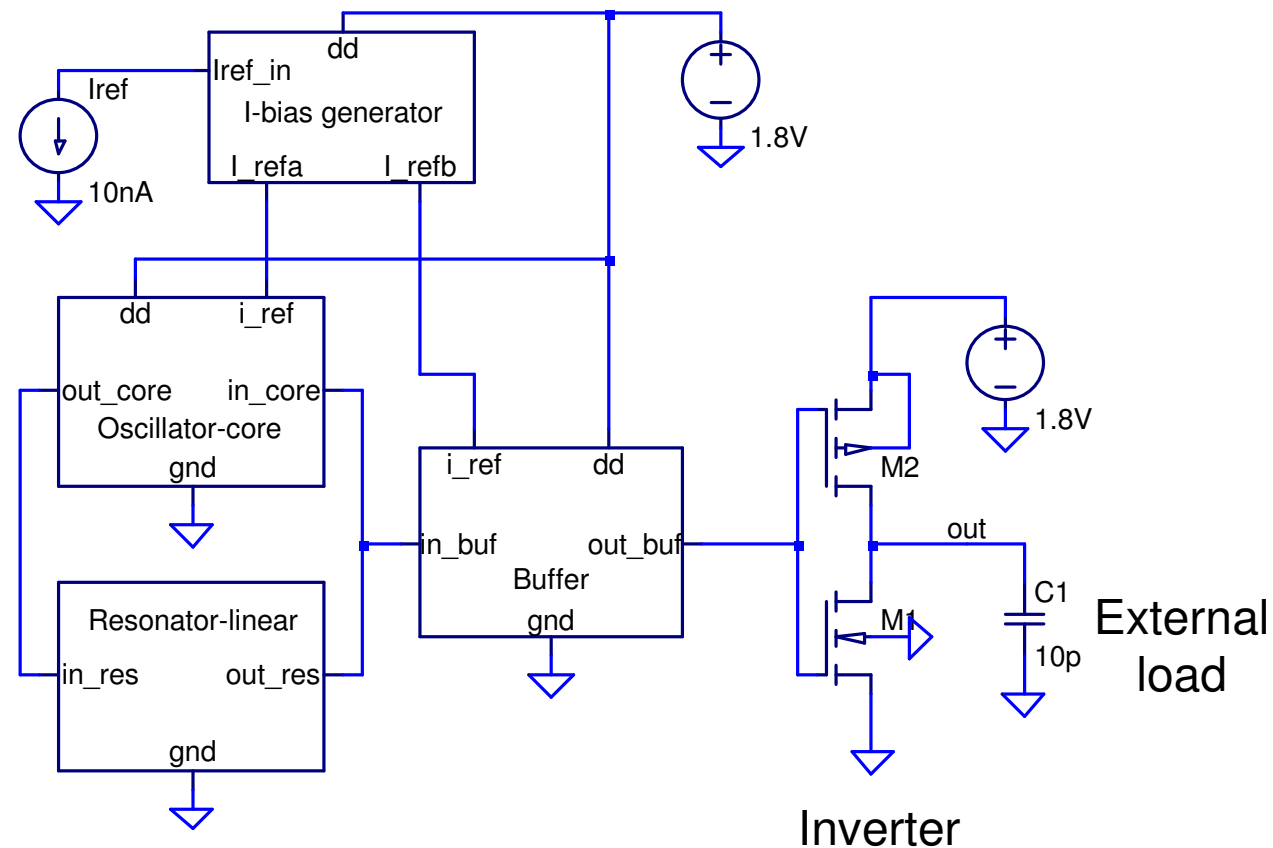
	Quartz crystal (32.678 kHz)	MEM resonator*	Ratio MEM/Quartz
R_m (Ω):	$50 \cdot 10^3$	$769 \cdot 10^3$	15.4
L_m (H):	$1.21 \cdot 10^4$	$9.37 \cdot 10^3$	0.77
C_m (F):	$1.95 \cdot 10^{-15}$	$4.0 \cdot 10^{-15}$	2.1
Q:	$50 \cdot 10^3$	$2 \cdot 10^3$	1/25
C_s (F):	$1.35 \cdot 10^{-12}$	$1.6 \cdot 10^{-12}$	1.2
FOM**:	72	5	1/15

* 26.13 kHz capacitive switch, (mis-)used as a resonator, $U_{DC}=0.5V$.

** FOM = Figure Of Merit (higher is better).

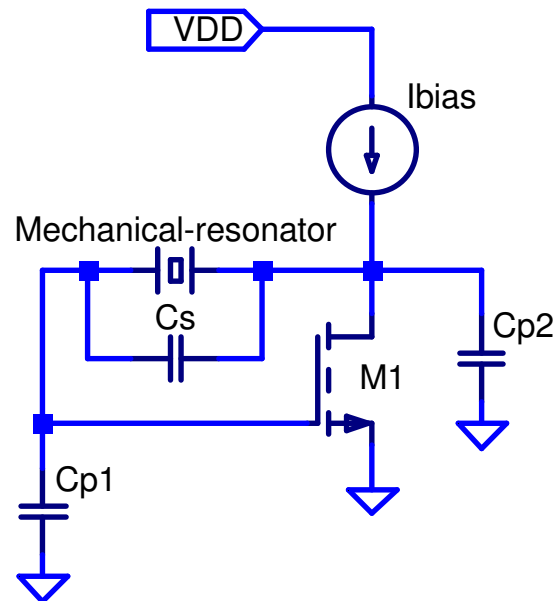


Top level diagram test circuit



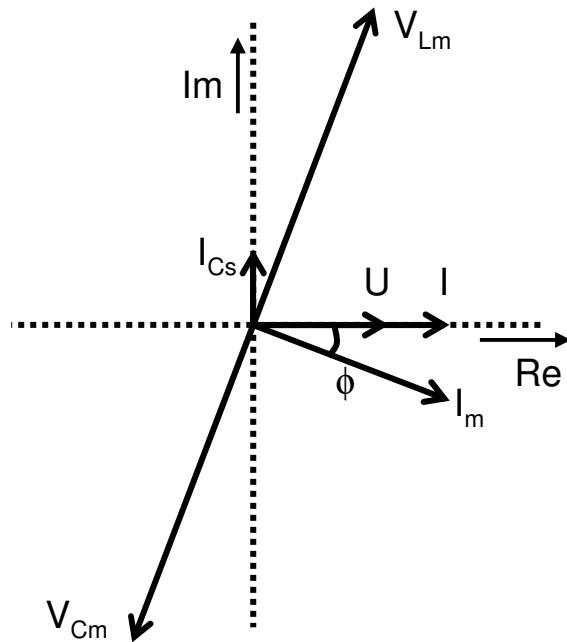
3 Points oscillator

- Amplifier: common source MOS device → “Pierce oscillator”:



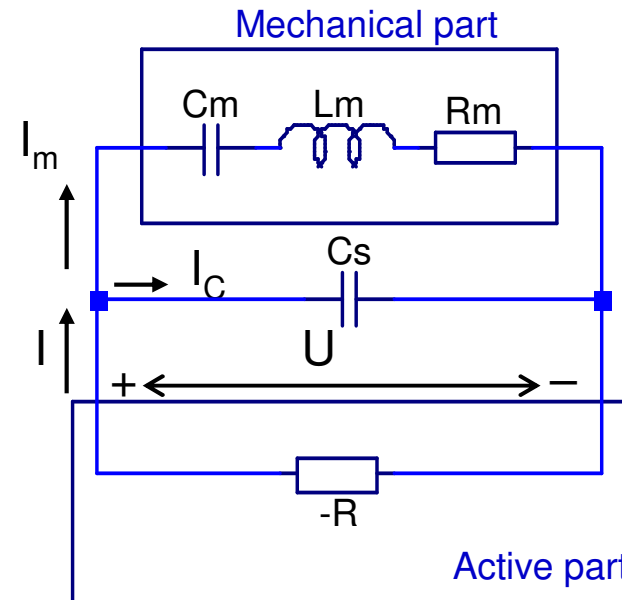
Behavior can best be described by the impedance Z_c , as observed into the active part: [Vittoz]

Requirement for oscillation



$$I_m + I_{Cs} = I$$

$$\text{Im}\{I_m\} = -\text{Im}\{I_{Cs}\}$$



$$\text{Im}\{I_m\} = \frac{U}{R_m} \cdot \frac{-v_m Q}{1 + (v_m Q)^2} \leq \frac{U}{R_m} \cdot \frac{-1}{2}$$

$$\text{Im}\{I_{Cs}\} = U \omega_{osc} C_s$$

$$v_m Q = \left(\frac{\omega}{\omega_m} - \frac{\omega_m}{\omega} \right) Q$$

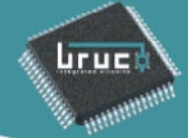


Figure Of Merit (FOM)

- When the undamping-impedance is resistive (current and voltage are in-phase), then oscillation is only possible when:

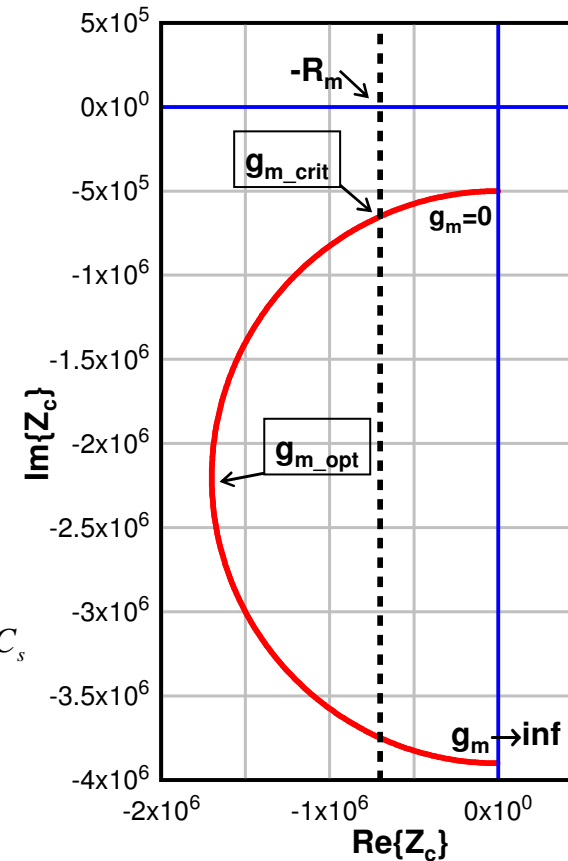
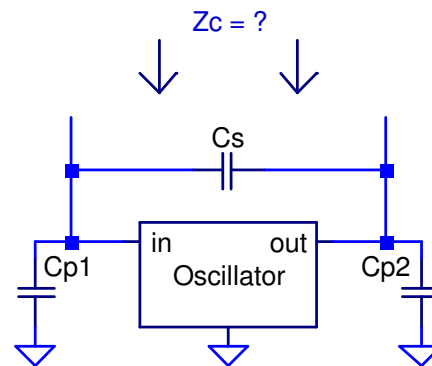
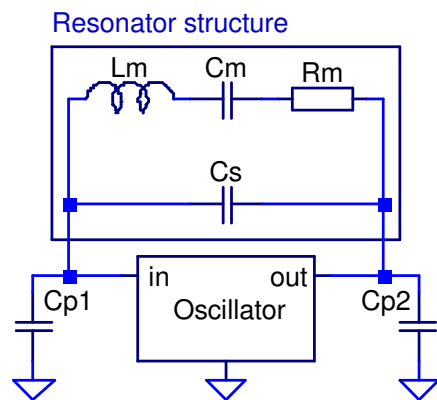
$$\text{FOM: } \boxed{\frac{1}{\omega_{osc} R_m C_s} > 2}$$

Example of $2\omega_{osc} R_m C_s$ values (≈ 32 kHz):

- Quartz: 72
- MEMS: 5 (resonant switch)

Impedance circle

For $\omega = \omega_{osc}$, observe: $Z_c = R_c(g_m) + jX_c(g_m)$

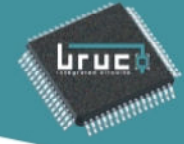


$$g_{m_{opt}} = \omega_{osc} \frac{C_{p1} C_{p2}}{C_s^2} C_{eq} \cong \frac{I_{bias}}{nV_T}$$

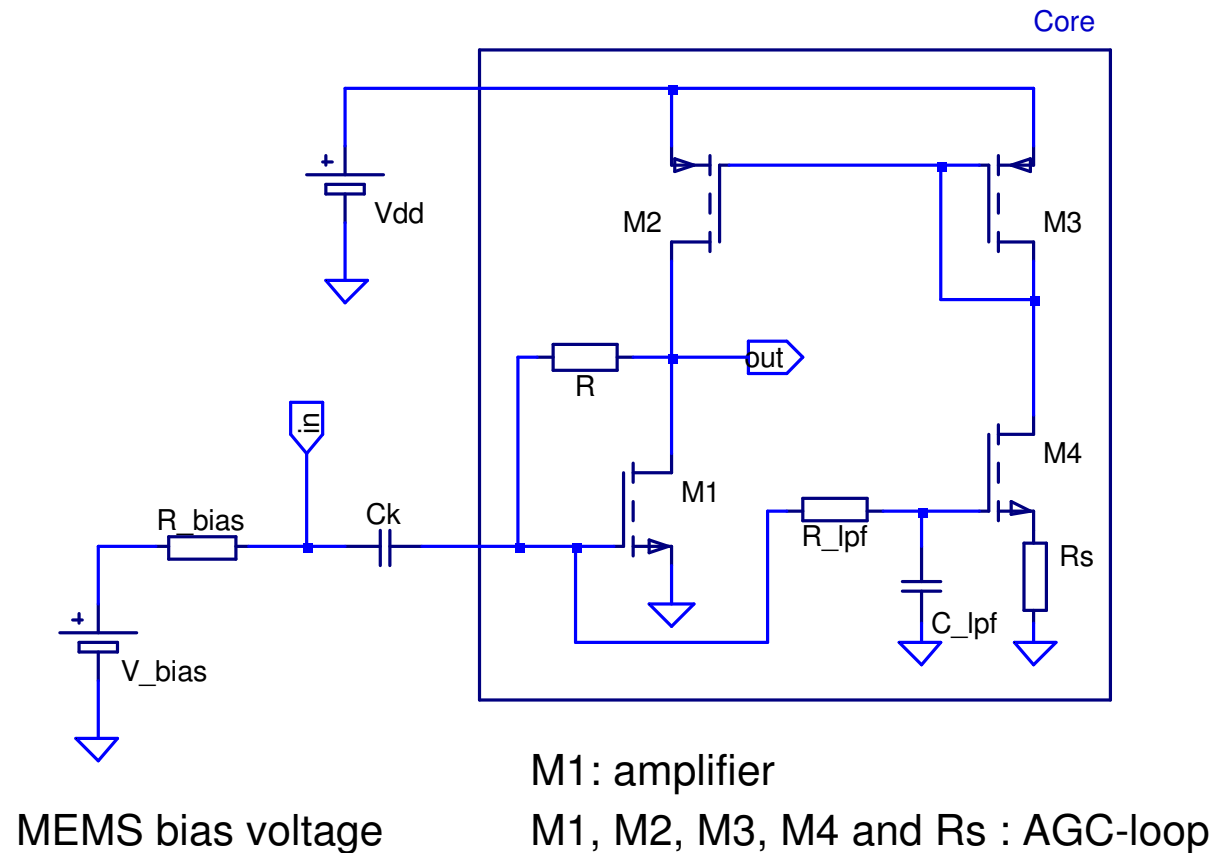
$$C_{eq} = C_s \cdot \left(1 + \frac{C_s}{C_{p1} // C_{p2}} \right) \cong C_s$$

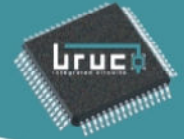
$$g_{m_{crit}} = \frac{C_{p1} C_{p2}}{C_s^2} \cdot \frac{1}{2R_m} \left(1 - \sqrt{1 - (2\omega_{osc} R_m C_{eq})^2} \right)$$

$$-R_m < \frac{1}{2\omega_{osc} C_{eq}}$$



Basic three points oscillator circuit + AGC-loop





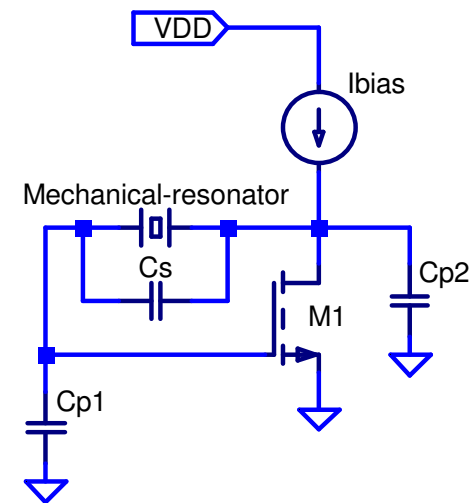
Power consumption oscillator

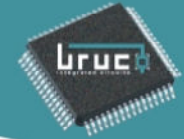
Example:

$C_{p1}=19 \text{ pF}$, $C_{p2}=38 \text{ pF}$, $C_s=1.6 \text{ pF}$, $R_m=768 \text{ k}\Omega$
 $f_{osc} = 26 \text{ kHz}$ and $n \approx 1.5$ (weak inversion):

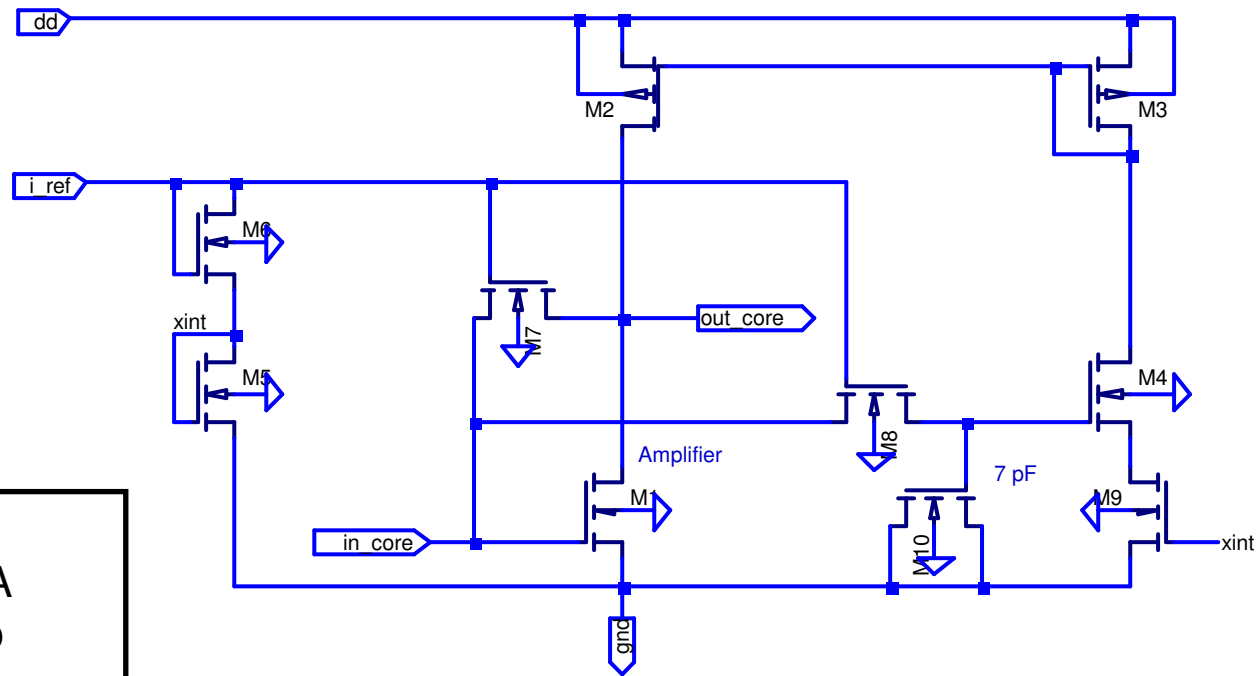
$g_{m_opt} = 84 \text{ }\mu\text{A/V} \rightarrow I_{bias_max} = \mathbf{3.28 \text{ }\mu\text{A}}$ (class A)

$g_{m_crit} = 20 \text{ }\mu\text{A/V} \rightarrow I_{bias_crit} = \mathbf{0.79 \text{ }\mu\text{A}}$ (class A)

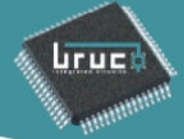




Implementation of oscillator core:

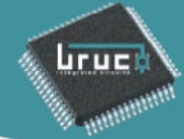


$V_{dd} = 1.8 \text{ V}$
 $I_{sup} = 1060 \text{ nA}$
@ startup
 $I_{sup} = 920 \text{ nA}$
@ steady state



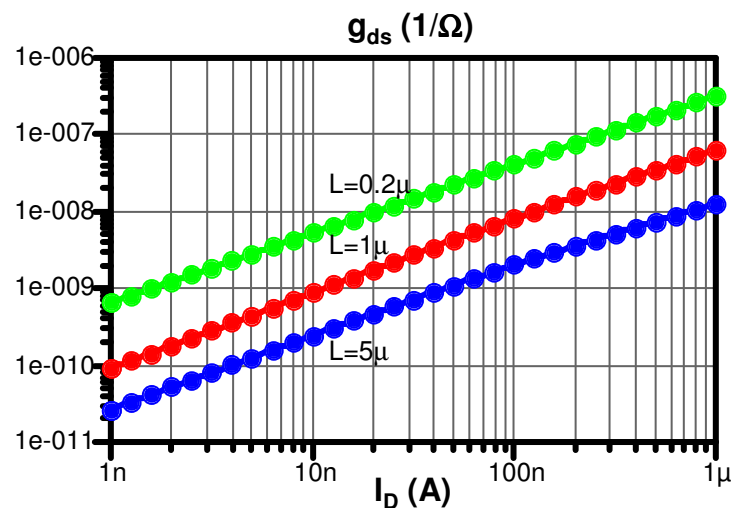
Buffer circuit

- Converts small oscillation signal to a rail to rail driving signal for an external load of 10 pF
- Copy the input-signal of the oscillator and exploit the intrinsic voltage gain of MOS devices in weak inversion:
 - Voltage gain at low frequencies is independent of bias current
 - g_{ds} is relatively independent of U_{DS}
 - Temperature dependence of g_{ds} is roughly $-0.2 \text{ %/}^\circ\text{K}$.
- Bias current is set by slew rate at input of (first) inverter



g_{ds} in weak inversion and saturation

- PMOS device:
TSMC 0.18 μm n-well CMOS process, $W = 5 \mu\text{m}$ $U_{DS} = 0.9 \text{ V}$



$$A_v(\omega) \cong \frac{\frac{V_{eq}(L)}{nV_T}}{1 + j\omega \frac{V_{eq}(L)}{I_D} C_{out}}$$

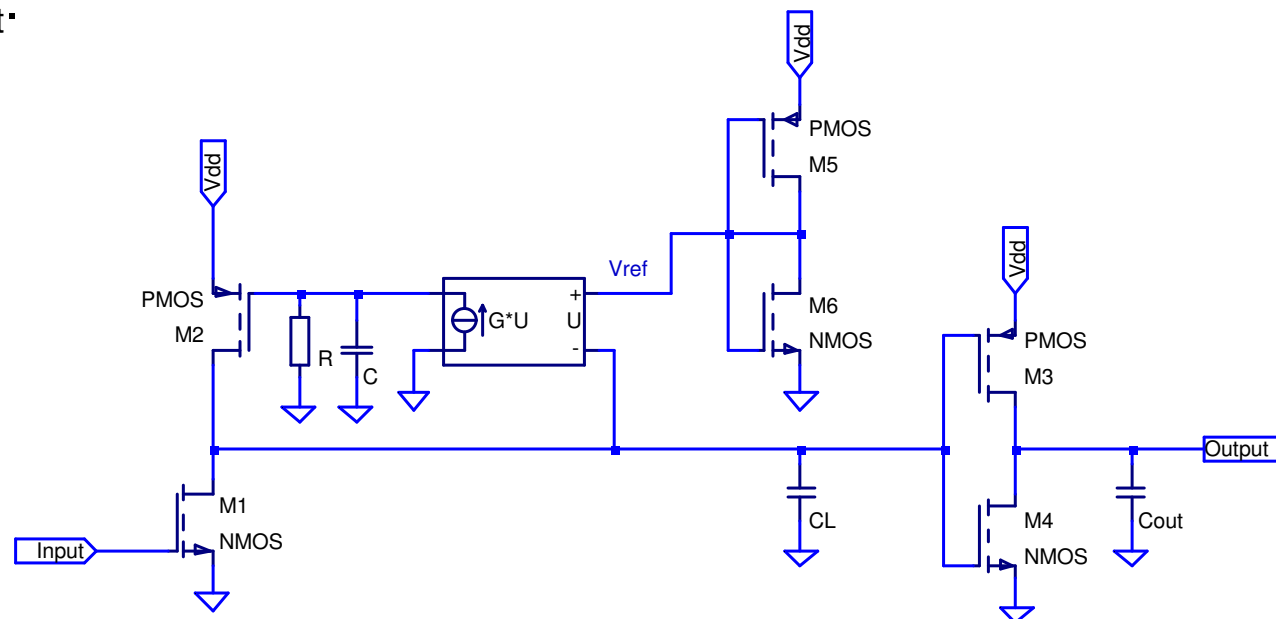
V_{eq} = constant, mainly depending on length of device
($L = 0.2 \mu\text{m}$: $V_{eq} \approx 2 \text{ V}$.)

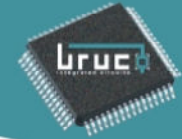
$V_T = kT/q$

C_{out} = total capacitance at drain-node

Buffer circuit, bias method

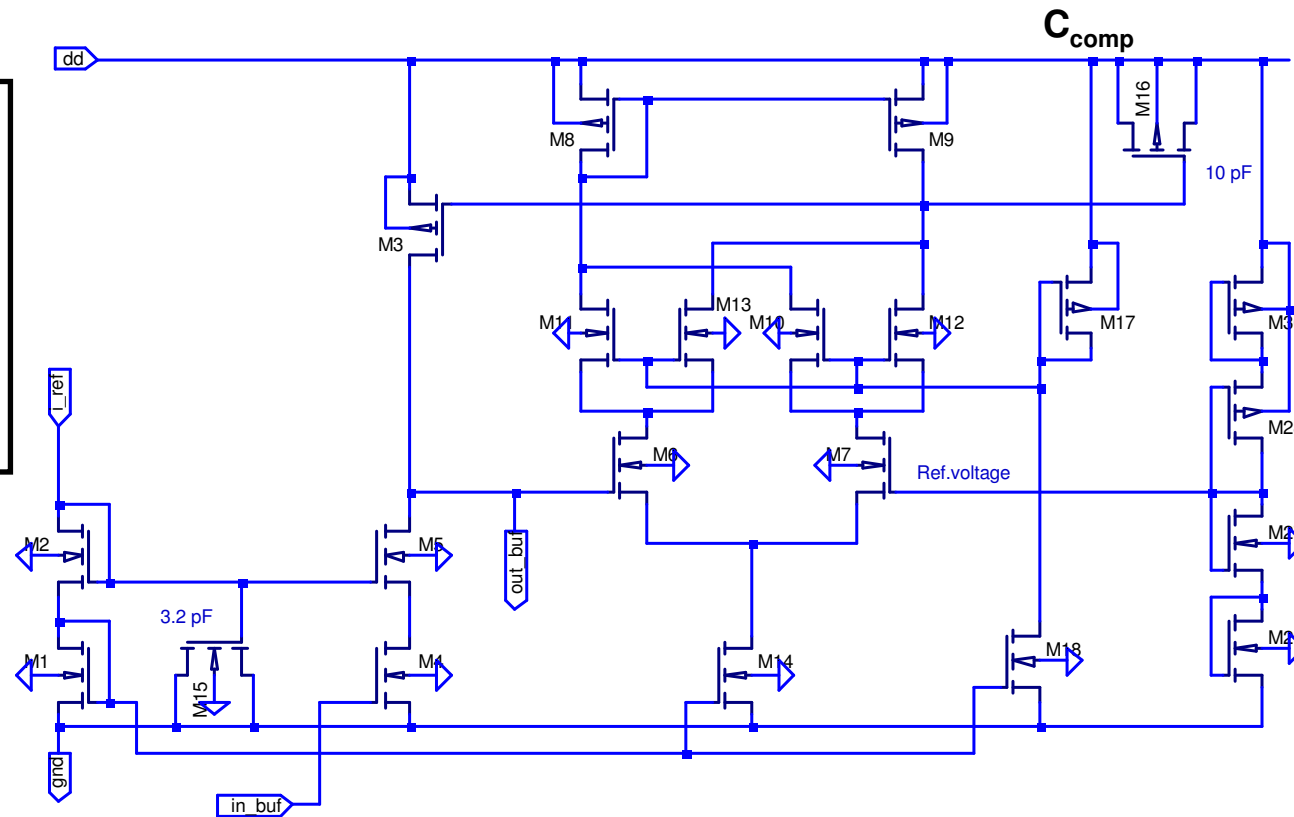
- Copy the input transition voltage level of an inverter to the output of the amplifier M1 and M2 by means of a voltage follower with a small closed-loop bandwidth
- Power consumption depends on value of load capacitors C_L and C_{out}

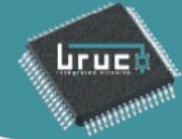




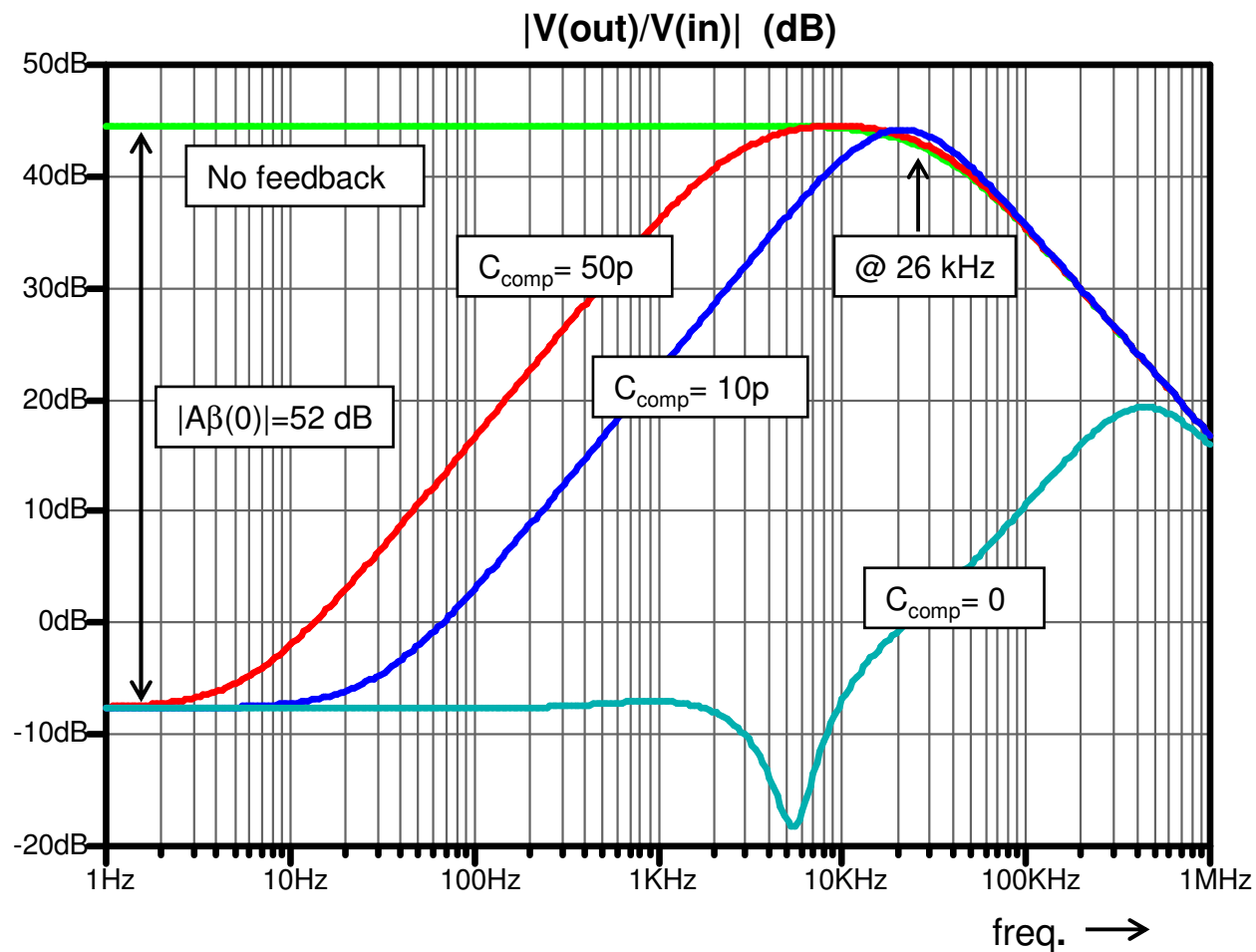
Implementation of buffer circuit:

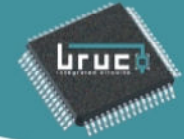
$V_{dd} = 1.8 \text{ V}$
 $I_{sup} = 158 \text{ nA}$
 $A_{vo} = 150x$
 $C_L = 20 \text{ fF}$
(no inv.)
 $= 75 \text{ fF}$
(with inv.)





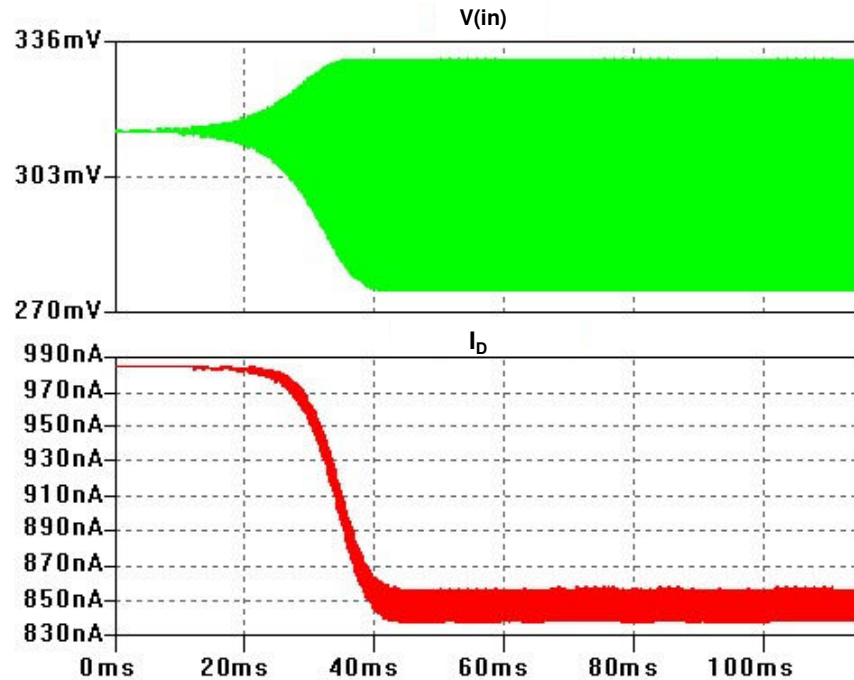
Characteristics of buffer:





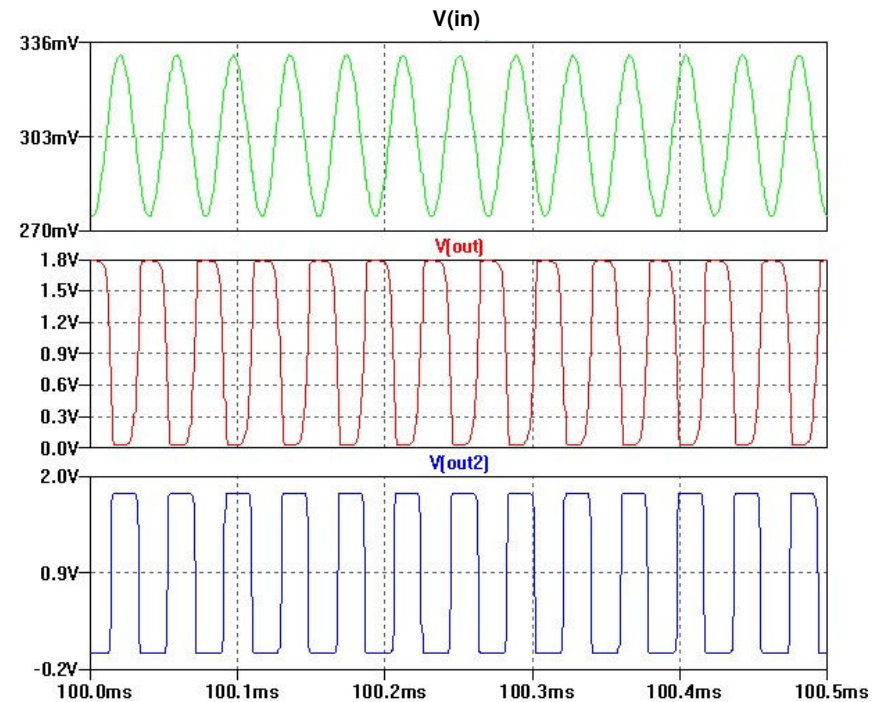
Waveforms

Oscillator core:

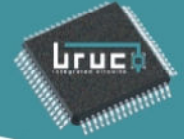


Oscillator signal at input of oscillator transistor and its associated drain current.

Buffer:



Signals at input and output of the buffer and the output signal of the inverter.

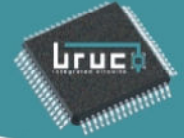


Simulation results:

- Power consumption numbers (nominal values):
 - Oscillator core: 1.66 μW (Theor. min.= 1.5 μW)
 - Buffer circuit: 0.21 μW
 - Bias circuit: 0.07 μW
 - **Total:** **1.94 μW**

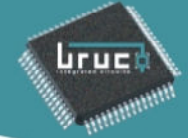
 - Inverter + C_{load} : 1.60 μW

- Signal power dissipated by resonator: 4.1 nW



Summary

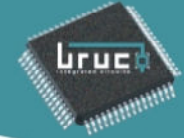
- Oscillators based on MEM resonators:
 - Equivalent element values of MEM resonator are quite different compared with their Quartz counterparts
 - Pre-bias voltage required, which usually requires a charge-pump circuit + voltage regulator + coupling capacitor(s)
 - Inherent non-linearities affect noise behavior
 - Temperature behavior worse than Quartz resonators (Si-MEMS: -30 ppm/°C)
 - FOM of MEM resonator is (much) lower than its Quartz counterpart
 - Power consumption of oscillator-core depends on capacitances C_{p1} , C_{p2} and C_s (for a given ω_{osc})
- On-going activities at Bruco:
 - Design of new oscillator circuit topologies for low-power applications ($P_{diss} \ll 1 \mu W$ for core + buffer).



Contributions by:

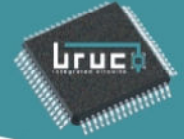
- Siti Amalina Enche Ab Rahim, ENSERG, Grenoble, France (internship project at Bruco)
- Jurjen Tangenberg, Bruco
- Frank van der Aa, Bruco
- Joël Geerlings, Bruco

- Joost van Beek, NXP research, Eindhoven, the Netherlands



References

- BRUCO website: www.bruco.nl
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