# A reconfigurable 4-GHz VCO for 3G multimode transceivers

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# Motivation

- Application : multimode 3G transceivers
- Frame : IST project MuMoR
- Objective : design a VCO with reconfigurability features
- Targeted modes :
  - UMTS W-CDMA FDD and  TDD, RX & TX
- VCO design features :
  - fully on-chip integrated.
  - includes all the auxilliary blocks => get real-world data.
  - immunity to substrate and supply noise : architecture choice.
  - wide frequency tuning range : switched capacitors.
  - low power : automatic amplitude control (AAC) loop.

# Specifications

- VCO runs at twice the frequency.
- RX can be optimized for low power.
- TX must be optimized for low phase noise.
- Overall frequency range : 3800-4340 MHz

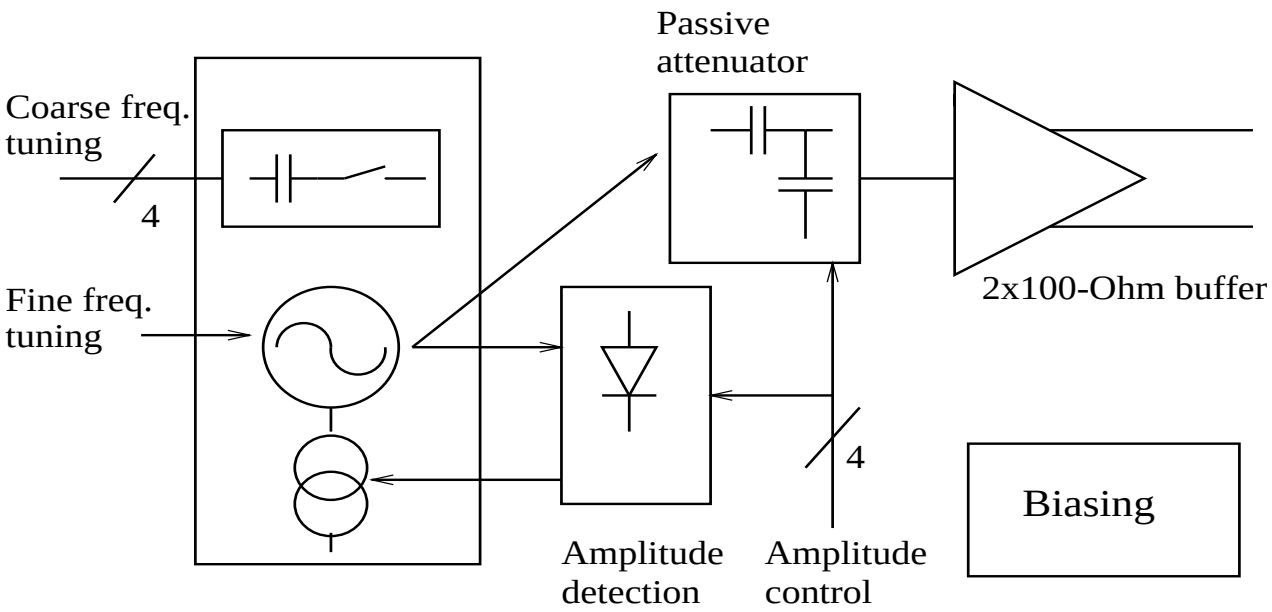
| RX MODES | | | | |
|---|---|---|---|---|
| Parameter | Mode | Value | | Unit |
| | | Min. | Max. | |
| Freq. | TDD band1 | 3800 | 3840 | MHz |
| | TDD band2 | 4040 | 4050 | MHz |
| | FDD | 4220 | 4340 | MHz |
| Noise @ 5 MHz | All | | -97 | dBc/Hz |
| Noise @ 10 MHz | All | | -107 | dBc/Hz |
| Noise @ 15 MHz | All | | -119 | dBc/Hz |
| Pushing | All | | 5 | MHz/V |
| Supply voltage | All | 2.7 | 2.9 | V |
| Temperature | All | -20 | +85 | $^{O}$C |

| TX MODES | | | | |
|---|---|---|---|---|
| Parameter | Mode | Value | | Unit |
| | | Min. | Max. | |
| Freq. | TDD band1 | 3800 | 3840 | MHz |
| | TDD band2 | 4040 | 4050 | MHz |
| | FDD | 3840 | 3960 | MHz |
| Noise @ 3 MHz | All | | -120 | dBc/Hz |
| Noise @ 12.5 MHz | All | | -123 | dBc/Hz |
| Noise @ 20 MHz | All | | -145 | dBc/Hz |
| Noise @ 85 MHz | All | | -148 | dBc/Hz |
| Pushing | All | | 5 | MHz/V |
| Supply voltage | All | 2.7 | 2.9 | V |
| Temperature | All | -20 | +85 | $^{O}$C |

# Overall architecture

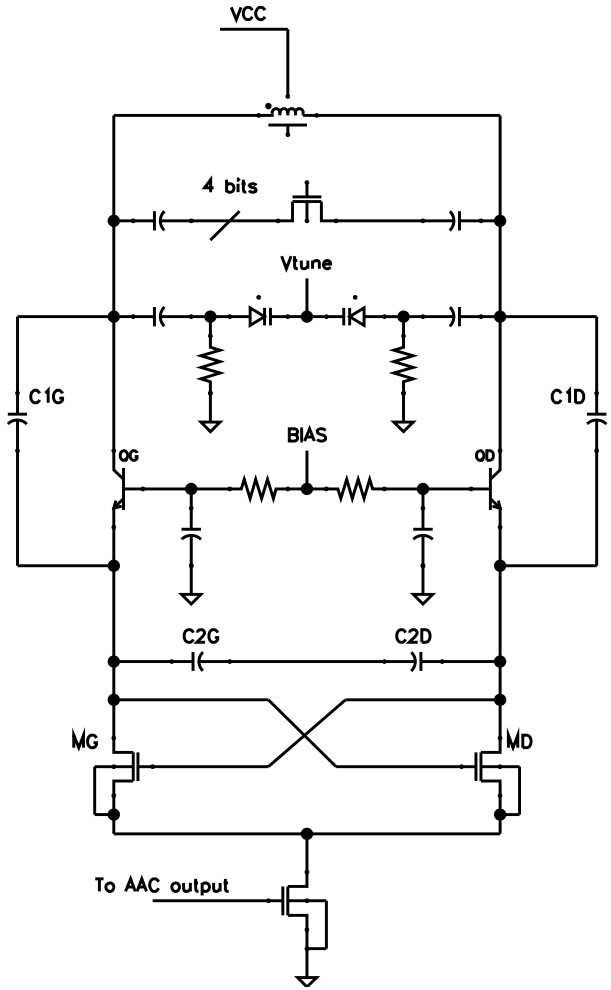
Three reconfigurable features :

- coarse freq. tuning to switch between modes.
- amplitude control to keep power as low as possible.
- output level maintained constant to ease integration in system-on-chip.



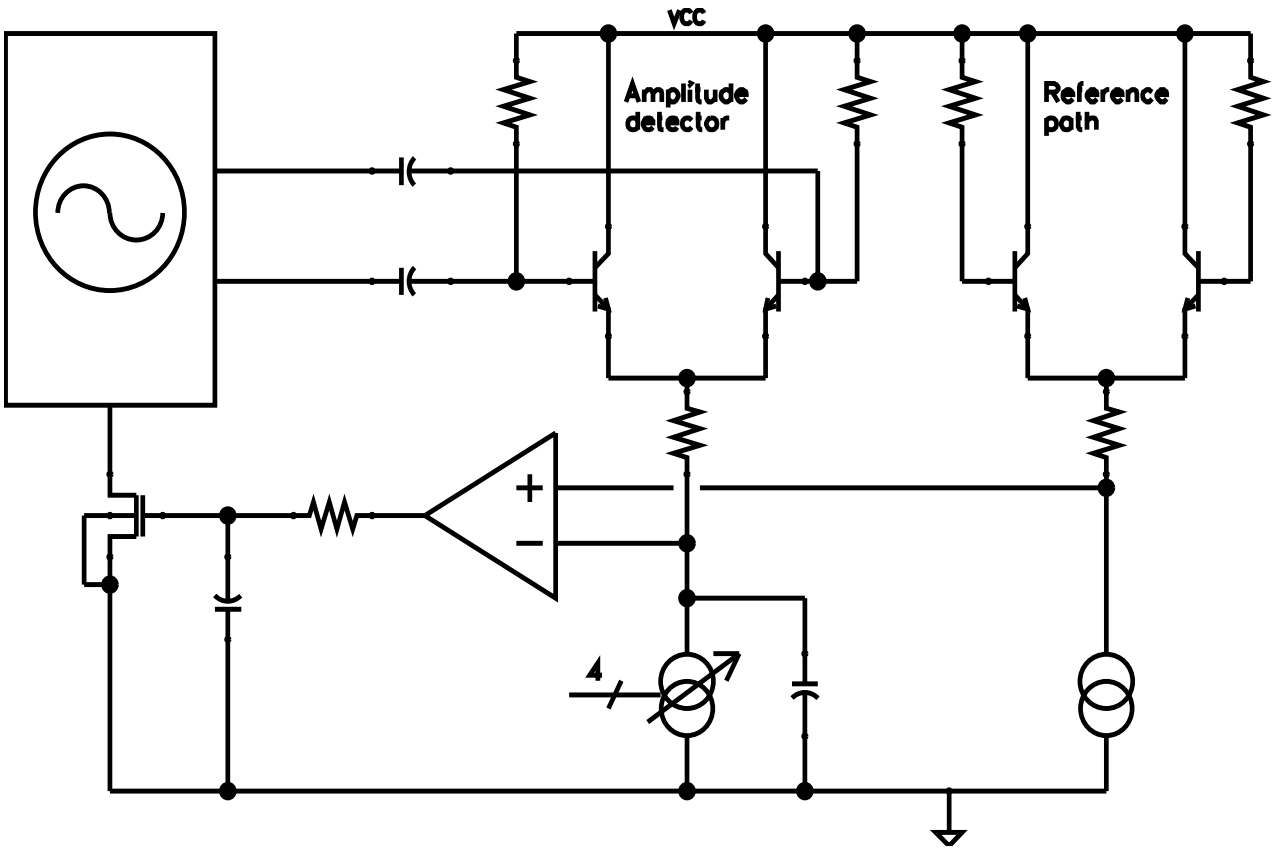
# Core oscillator

- recently published architecture [1] which combines low phase noise and low power :
  - each of the bipolars is connected in Colpitts configuration for best phase noise.
  - cross-coupled MOSFETs switch current from the source twice by period to reduce current consumption.
- Differential structure rejects common mode noise coming from substrate.
- Tail source provides isolation from supply.




[1] R. Aparicio, A. Hajimiri, “A CMOS differential noise-shifting Colpitts VCO”, ISSCC 2002.

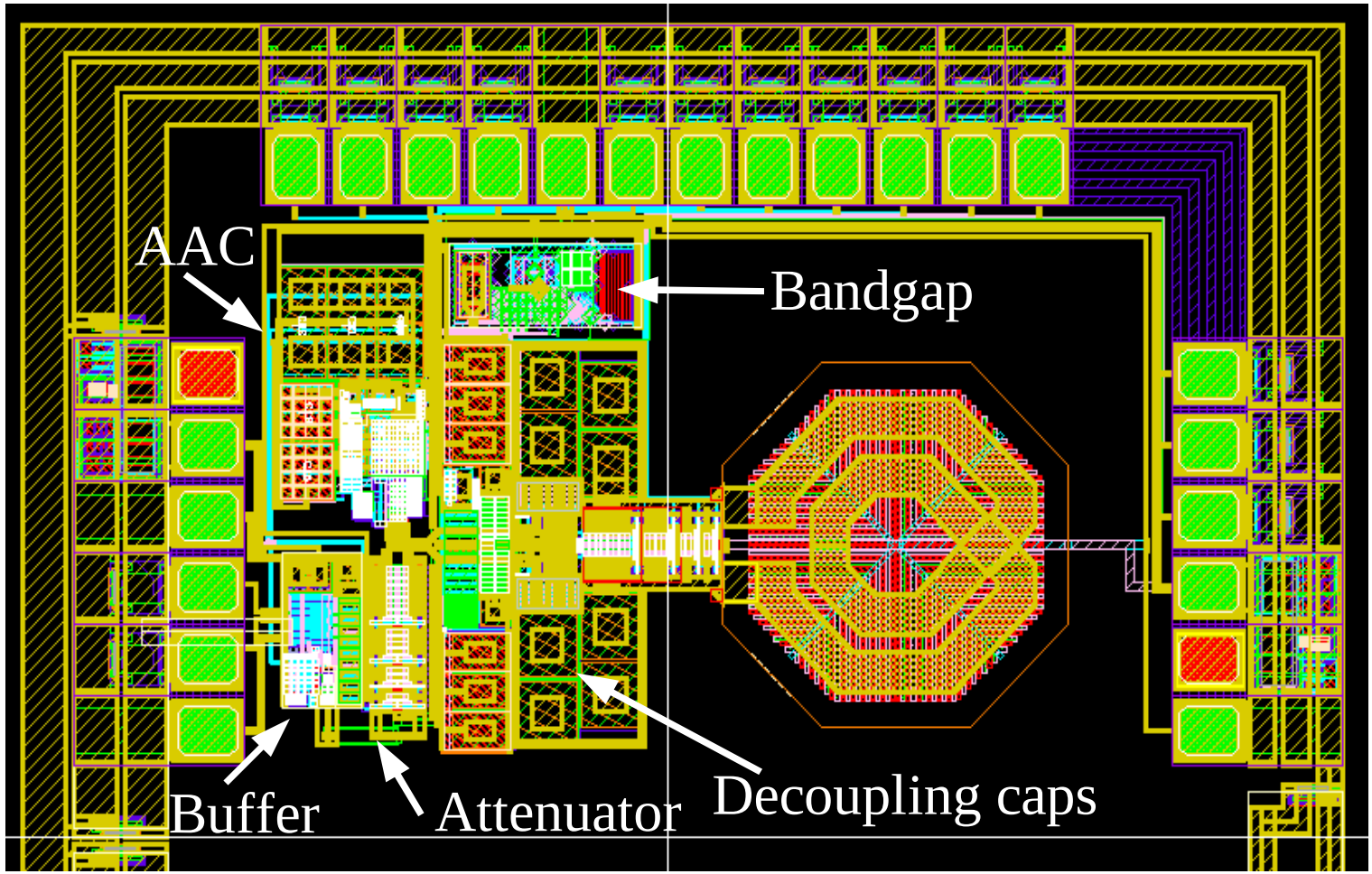
- VCO 4-GHz output is rectified and low-pass filtered.
- Resulting voltage is compared to reference.
- Good low-pass filtering is needed to get good low-offset phase noise (i.e. @ 1 MHz and less).
- settling time for a full-range step is 2-3 µs.



# Layout

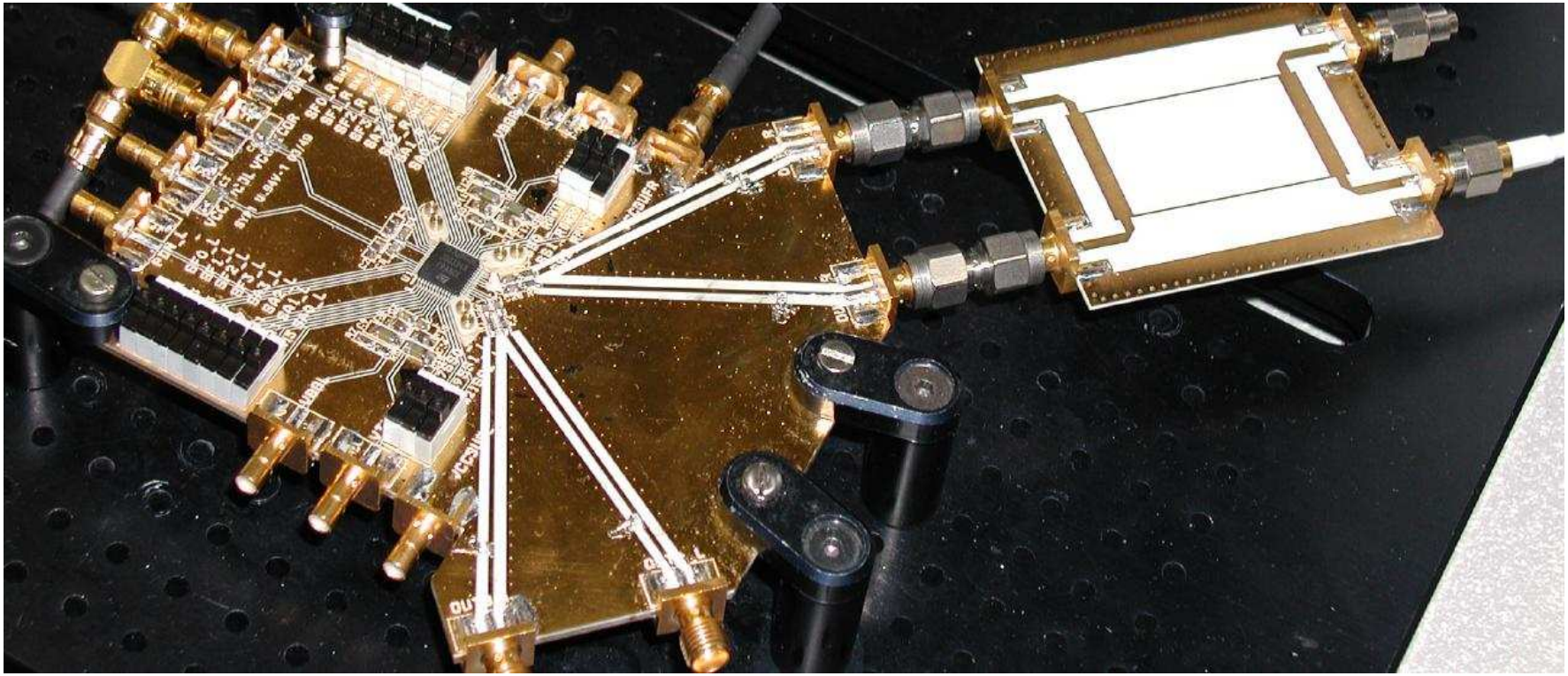
Size without bonding pads :
1000 x 600 µm.

Output buffer has its own supply.



# Test setup

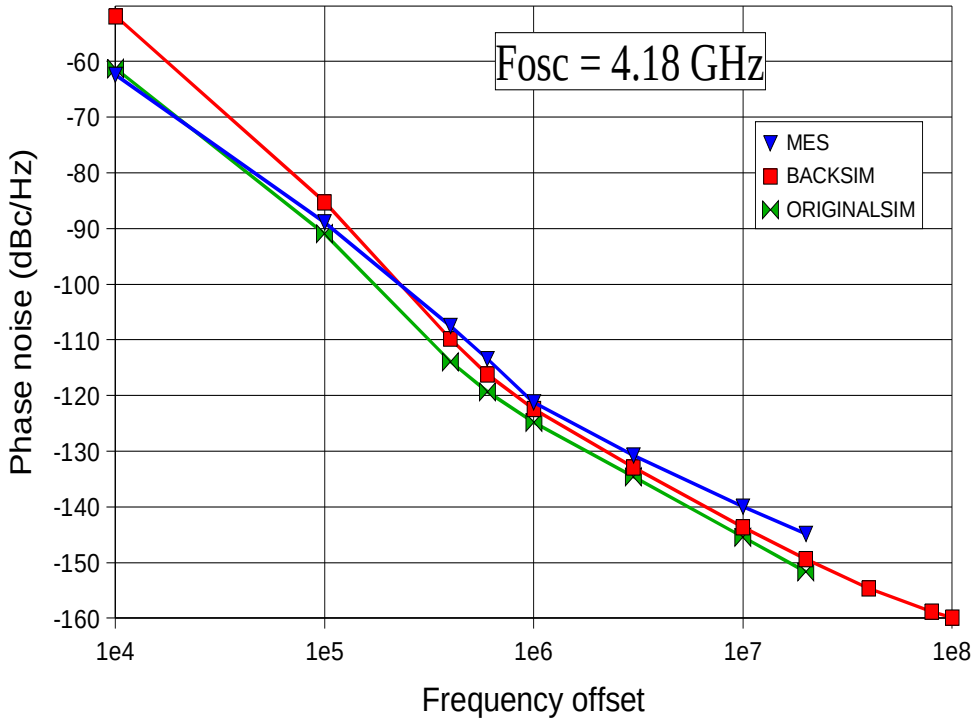
- Rogers 4350 board + hybrid coupler (diff -> single) on outputs.
- 2x100 Ω → 2x50 Ω matching made on PCB.

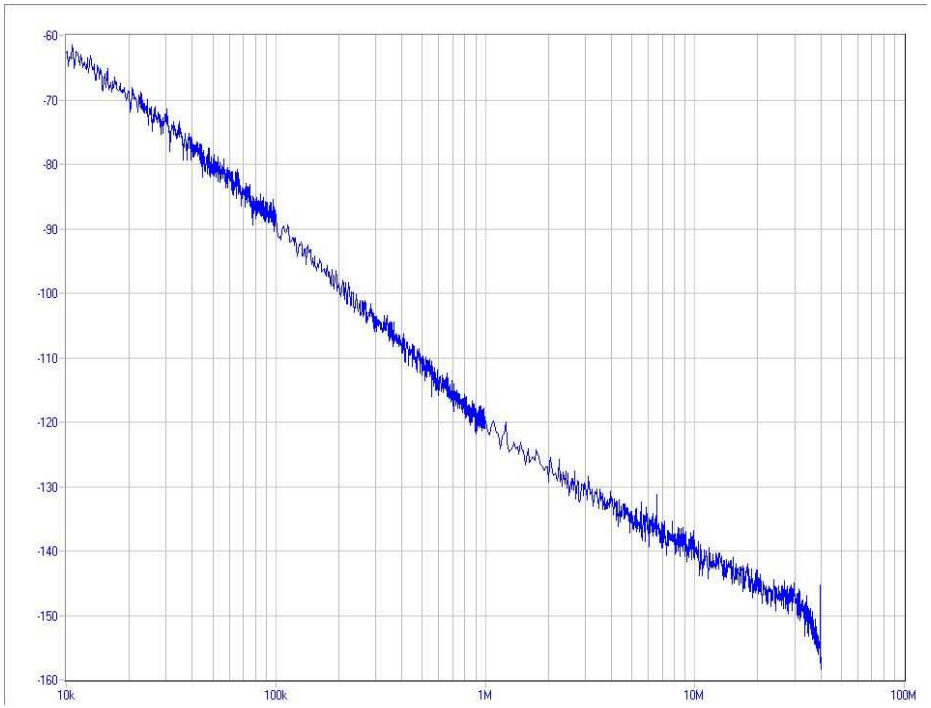


# Phase noise measurement

Phase noise measured on PN9000 testbench.

Frequency : 4.18 GHz
Core VCO current : 8 mA



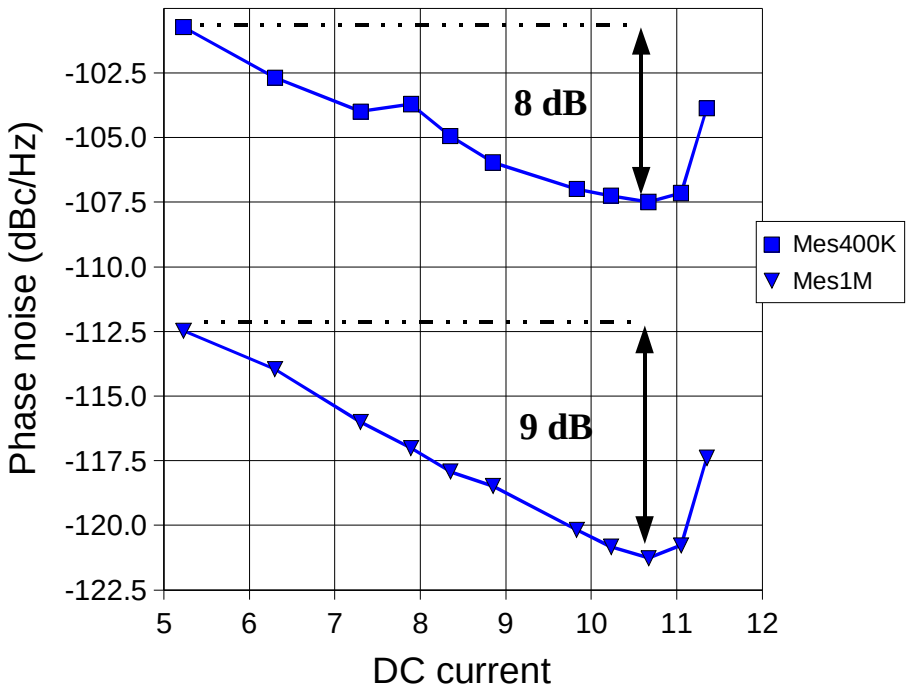
# Comparing simulated and measured phase noise

- Limitations :
  - AAC loop can not deliver currents high enough :
    - ✔ bandgap resistor was changed to allow more measurements.
    - ✔ but bandgap and biasing blocks are more noisy than they should.
  - bad substrate connections => some instability.
- Comparing back-simulations and measurements :
  - Phase noise difference is quite good (2-3 dB) at low offsets (< a few MHz).
  - Uncertainty on the substrate modelling which impact the simulation accuracy.
  - At higher offsets the bigger difference can be explained by the noise of the supply which improves significantly above 5 MHz and which is not modelled.
- Comparing original simulation and measurements :
  - phase noise behavior over all offset frequencies is well modelled.

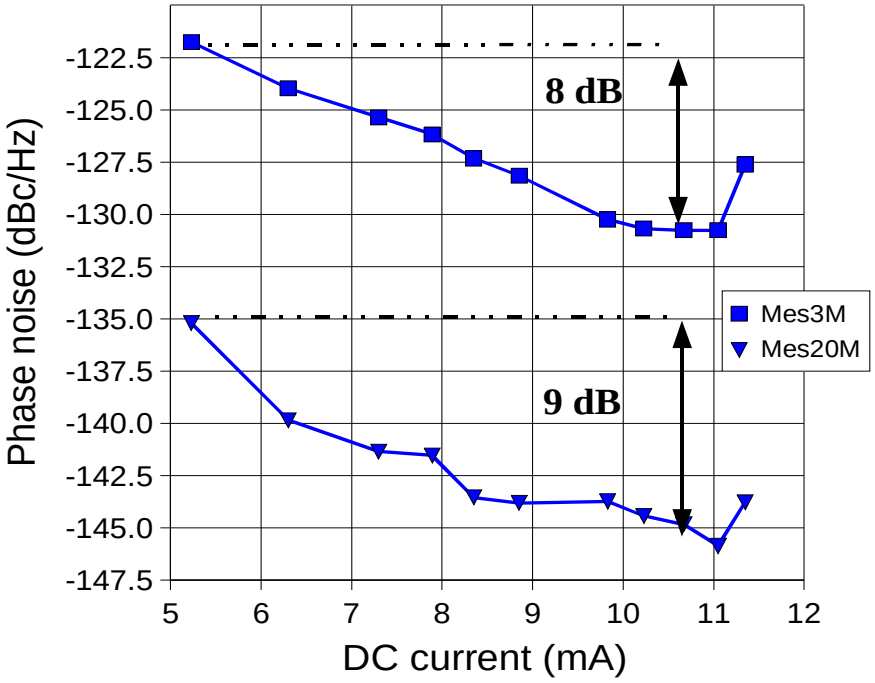
# Switching between low-power and low-noise configurations

- When current is halved high-offset phase noise is degraded by 8 to 9 dB.

Low-offset phase noise

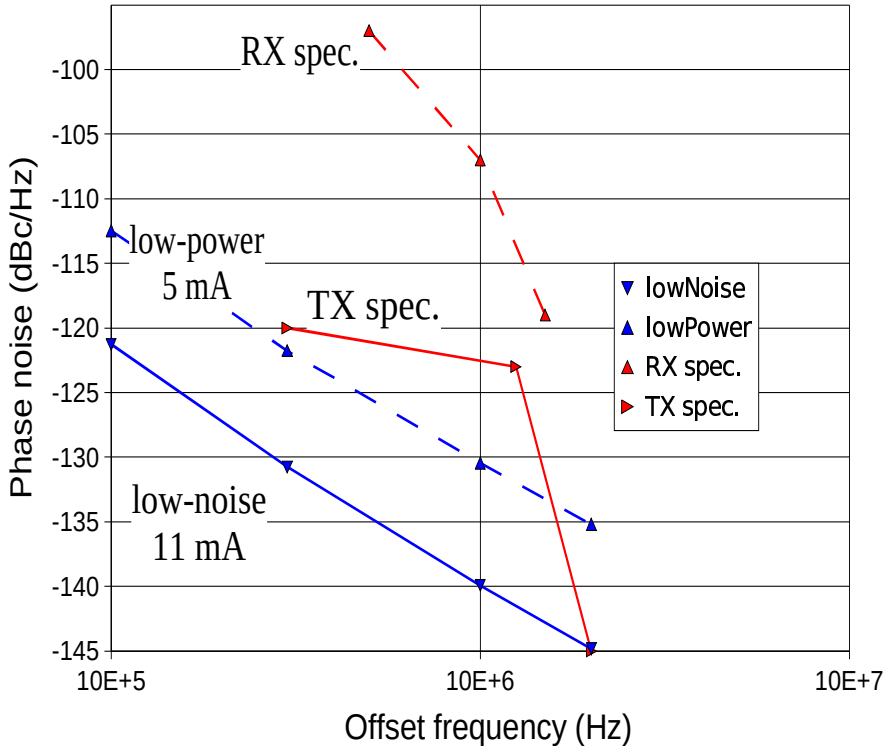


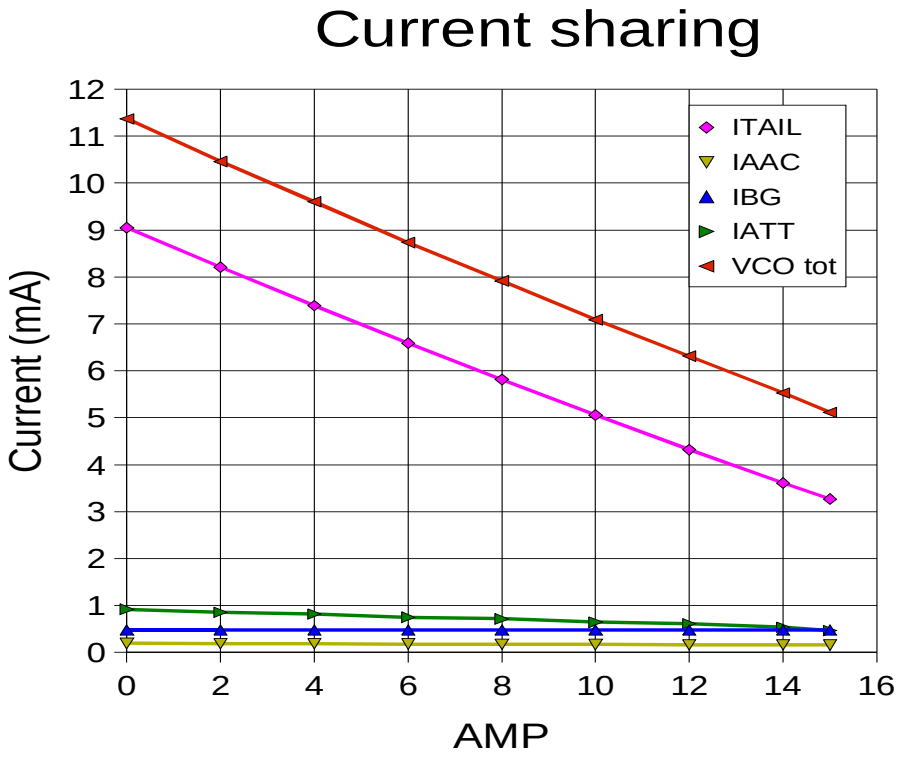

High-offset phase noise



# Low-noise and low-power configurations

- Current consumption can be halved from TX to RX.
- Auxiliary blocks consumption is moderate compared to the VCO.



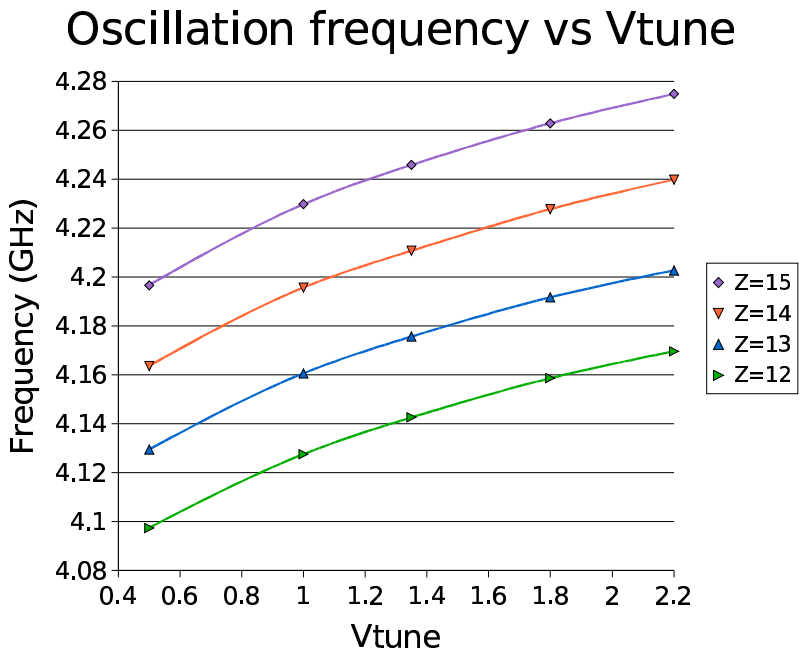



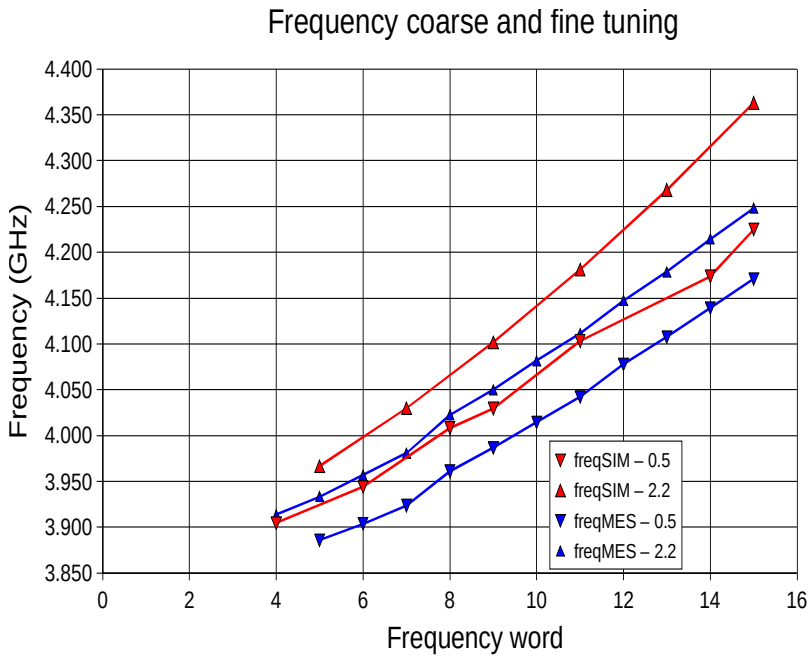
# Phase noise figures

| Freq. offset | VCO Meas. | VCO Back-simul. | VCO Original simul. | UMTS W-CDMA RX | UMTS W-CDMA TX |
|---|---|---|---|---|---|
| @ 10KHz | -62.4 | -51.9 | -61.3 | | |
| @ 100KHz | -88.9 | -85.3 | -90.9 | | |
| @ 400KHz | -107.5 | -109.8 | -113.9 | | |
| @ 600KHz | -113.4 | -116.2 | -119.3 | | |
| @ 1MHz | -121.3 | -122.4 | -124.8 | | |
| @ 3 MHz | -130.8 | -132.9 | -134.6 | | -120.0 |
| @ 5 MHz | -135.2 | -137.3 | -139.0 | -97.0 | |
| @ 10MHz | -139.9 | -143.6 | -145.4 | -107.0 | |
| @ 12.5MHz | -141.8 | -145.5 | -147.3 | | -123.0 |
| @ 15MHz | -143.4 | -147.1 | -148.9 | -119.0 | |
| @ 20MHz | -144.8 | -149.4 | -151.7 | | -145.0 |
| @ 85MHz | | -158.8 | | | -148 |
| @ 100MHz | | -159.8 | | | |

# Frequency tuning

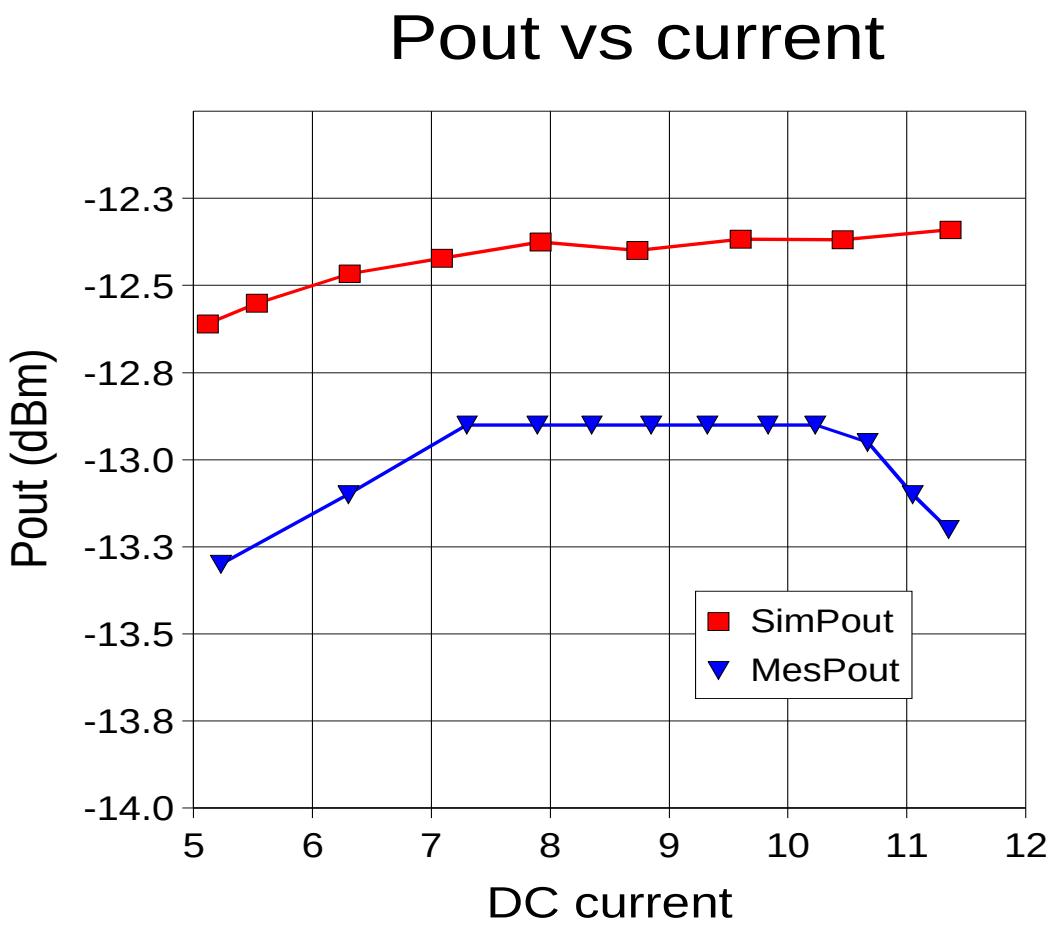
- Full frequency range not measured :
  - the VCO needs more current at low frequency… but the AAC loop cannot provide it.
  - back-simulations reproduce these phenomenons.
- Frequency range can be widened with additional switched capacitors.



# Output level vs. amplitude

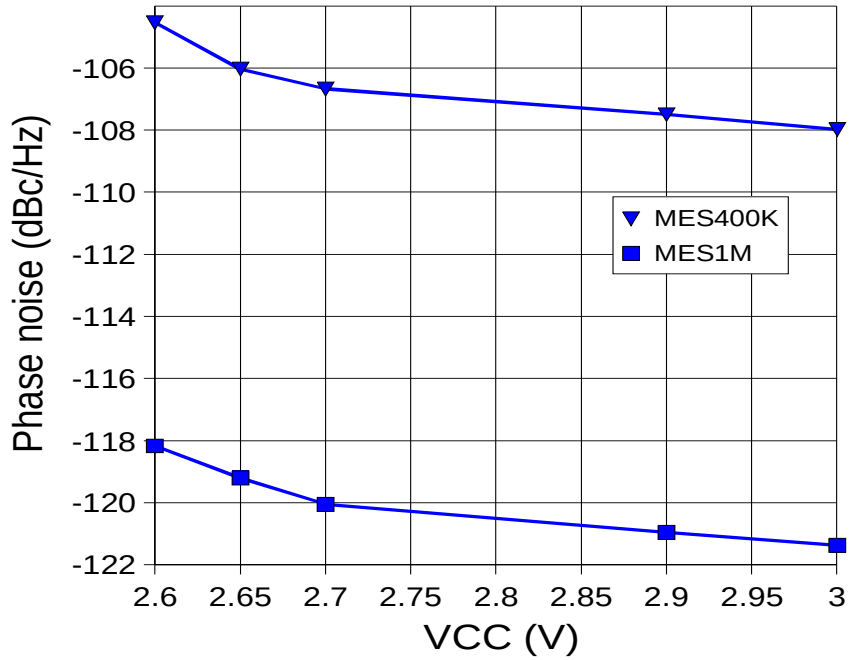
- Output level remains within 0.5 dB when switching between low-power and low-noise configurations.
- The combination of the amplitude control and the variable attenuator performs well.



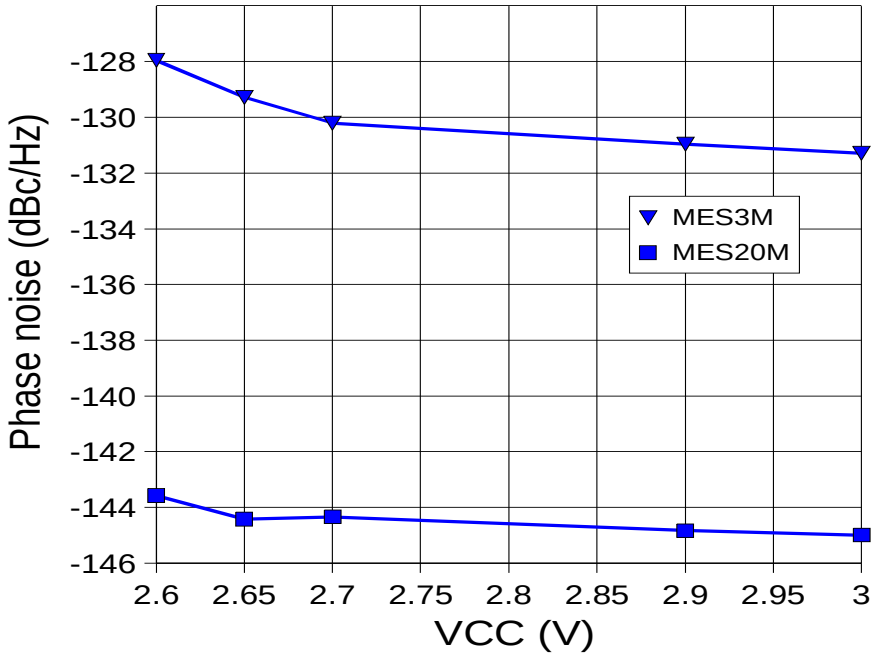
# Varying supply voltage

- Phase noise loosely depends on $V_{CC}$.

Low-offset phase noise vs. VCC

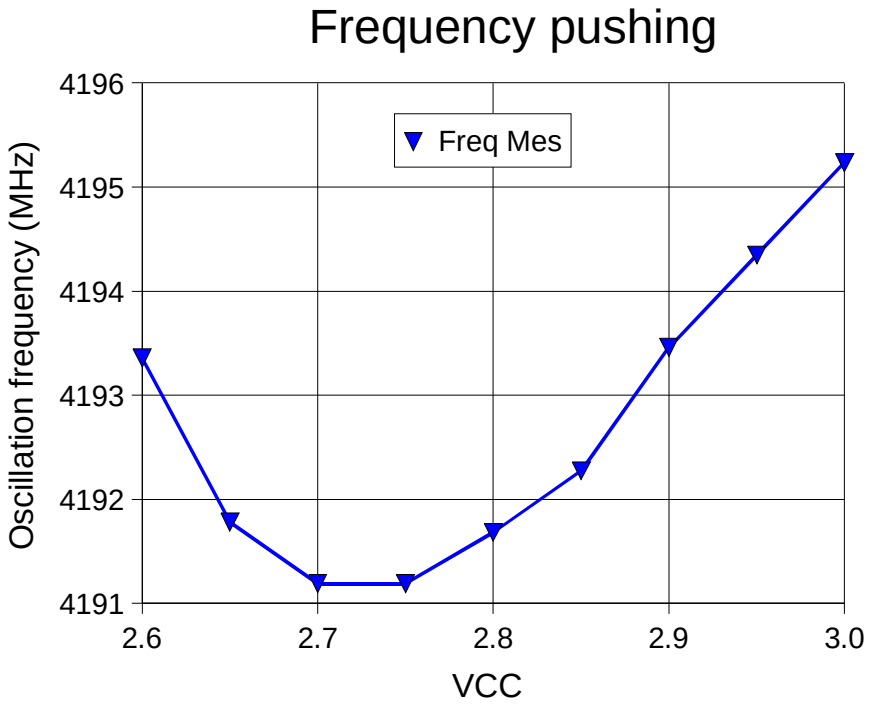


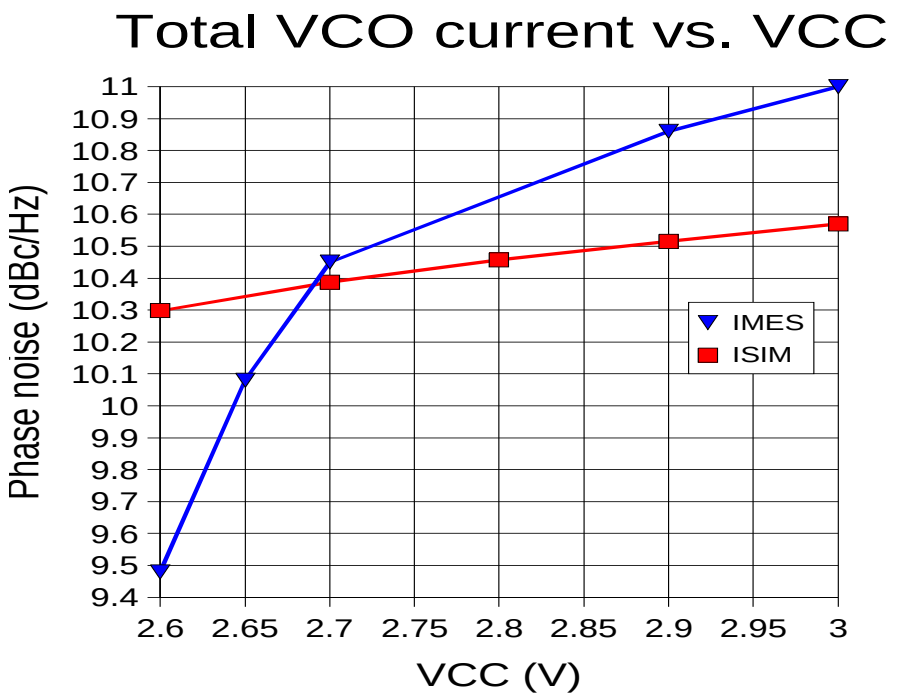

High-offset phase noise vs. VCC



# Varying supply voltage

- Low frequency pushing
- Current consumption loosely depends on $V_{CC}$.



# Conclusion

- UMTS W-CDMA TX & RX noise specifications from MuMoR fulfilled.

- benefits of reconfiguration demonstrated :
  - low-power or low-noise modes possible with the same VCO.

- differential Colpitts architecture demonstrates good performance :
  - phase noise and current are comparable to classical differential pair.
  - FOM = -180 dBc/Hz (measured) and -185 dBc/Hz (simulated).