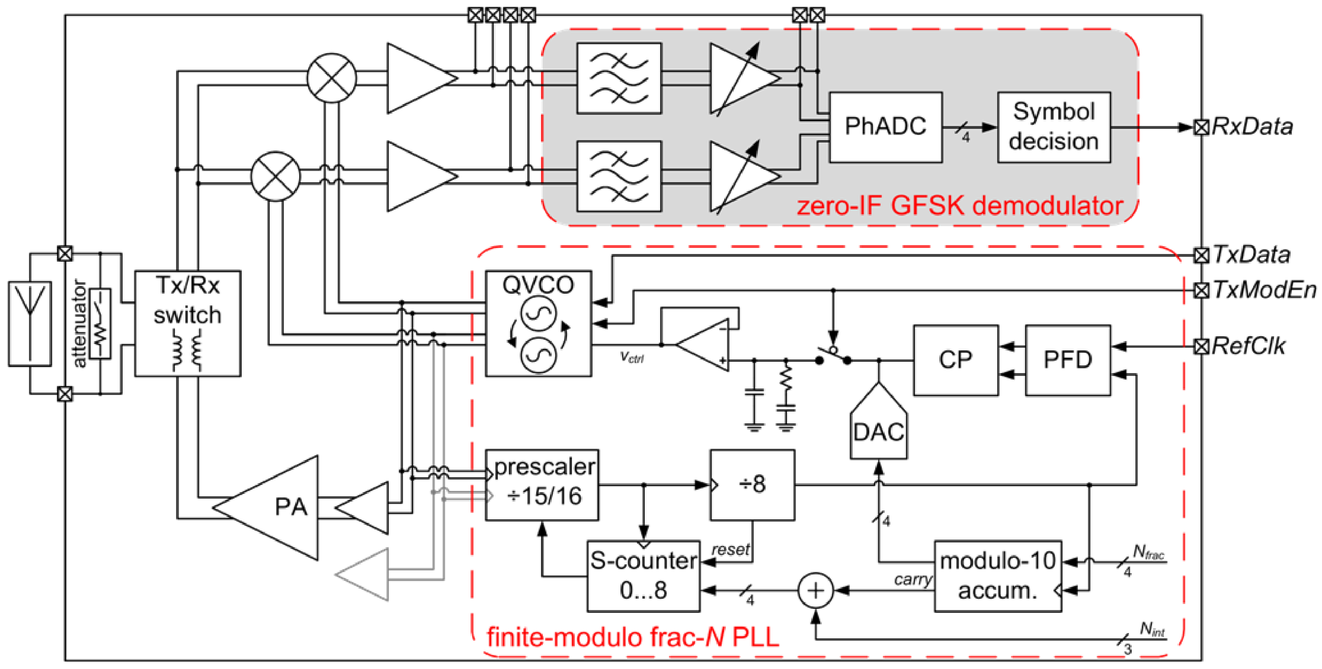
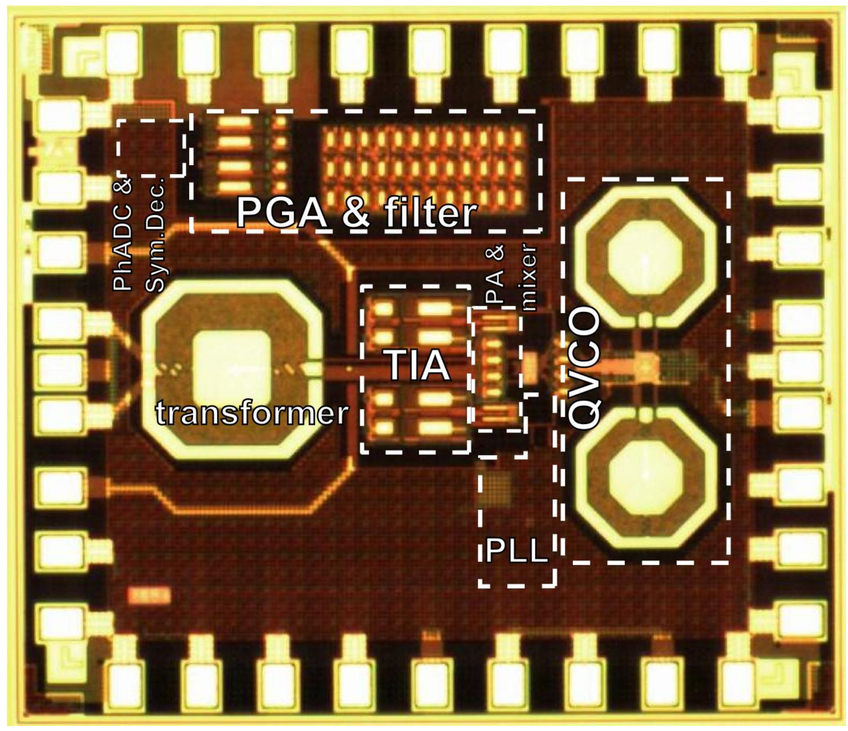
A 1.1mW-Rx, 5.9mW-Tx Bluetooth low energy transceiver with -81.4 dBm sensitivity

Architecture

- Zero-IF 2.4GHz transceiver for Bluetooth low energy (BLE) standard
- Passive Rx-frontend without LNA
- Transformer boosts antenna impedance to an internal level of ≈1kΩ
- QVCO based local oscillator with direct FSK modulation
- Demodulator with 4-Bit phase-domain ADC (PhADC)

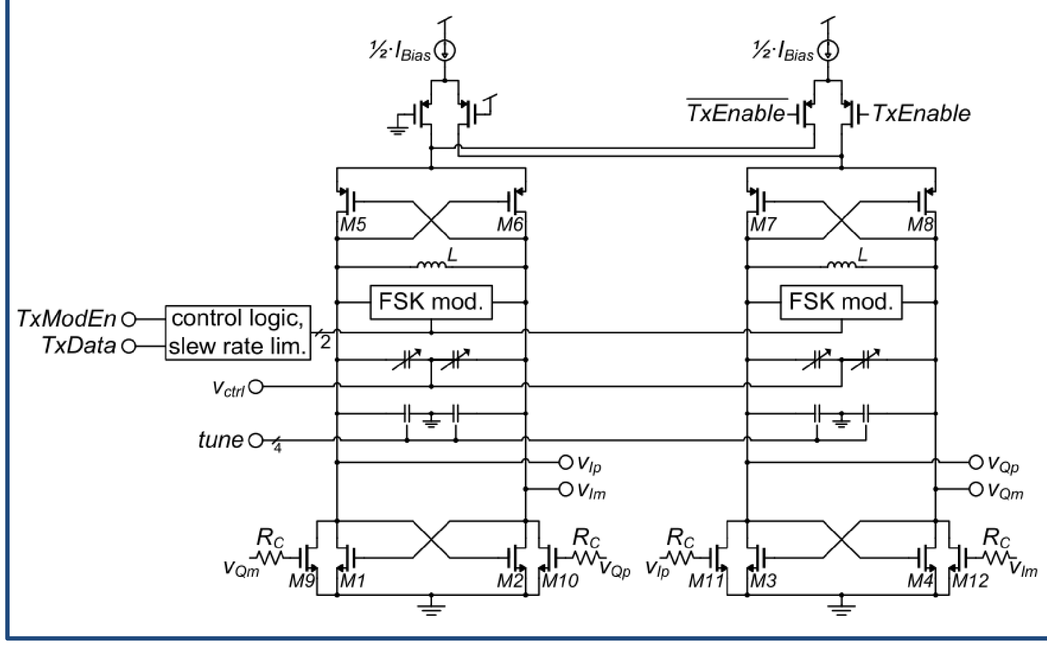




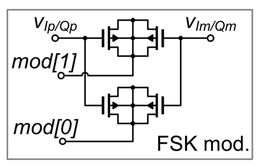
- 130nm CMOS technology (Triple-well, MIM)
- Chip area: 2.1 mm² (1.3mm x 1.6mm)

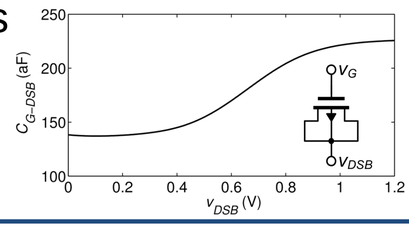
Frequency synthesizer with direct QVCO modulation

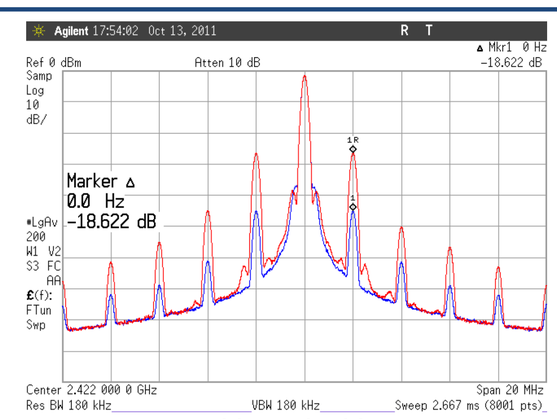
- Employs a QVCO with 2 large inductances (L=10nH) and complementary current-reuse transconductance stage → I_{bias}=400µA



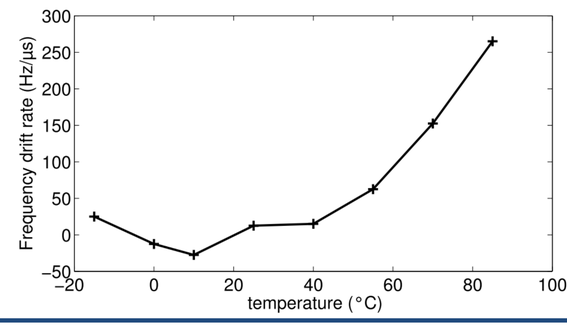
- Fractional-N PLL with 1MHz loop bandwidth
- DAC-based spur compensation
- BLE spec allows for direct QVCO modulation
  - Mod. Index h=0.5±10%
  - Short data packages (max. 376µs)
- Tank capacitance modulated with PMOS transistors





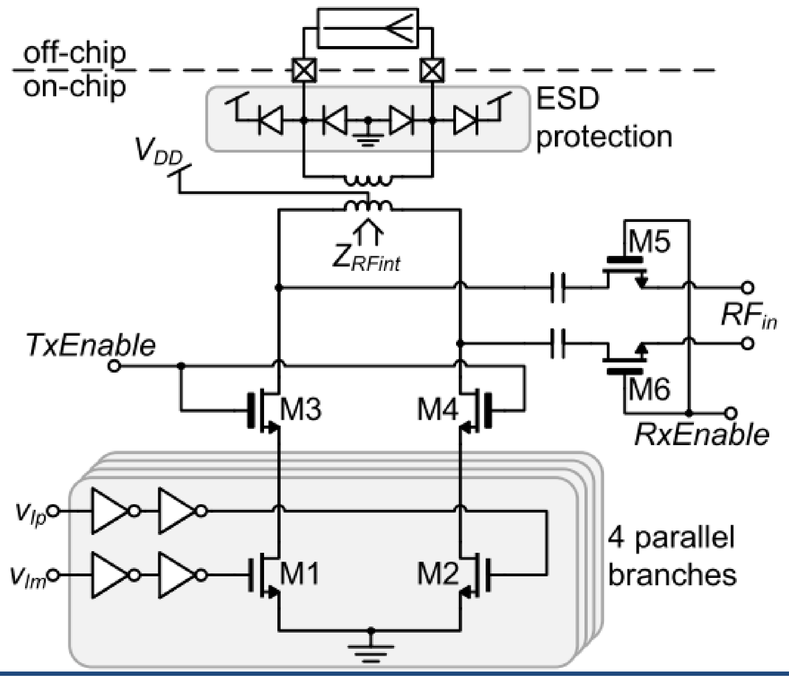


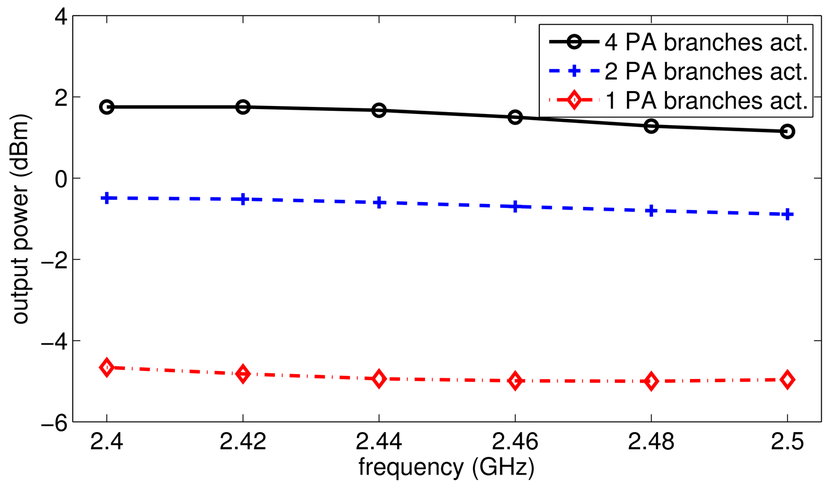
LO spectrum with and without spur comp.

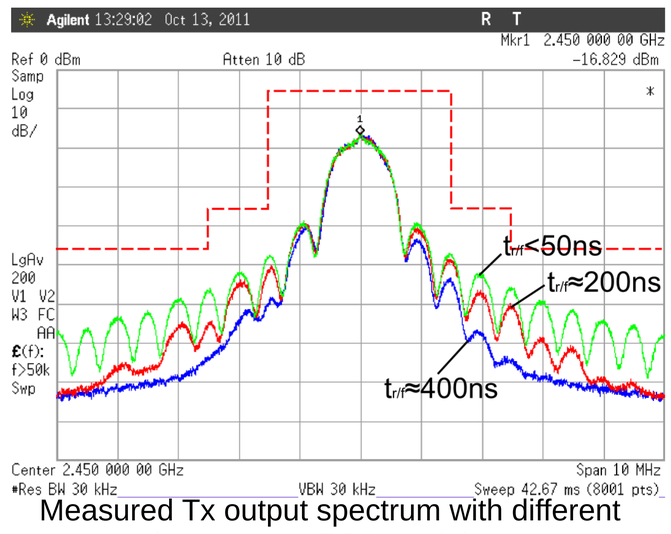


Tx with Class-E power amplifier

- 2:6 step-up transformer raises internal RF impedance to Z_{RFint}≈1kΩ
- Allows for 2*V_{DD}-swing at class-E PA without exceeding rails at antenna pads







Measured Tx output spectrum with different slew-rates at FSK modulator

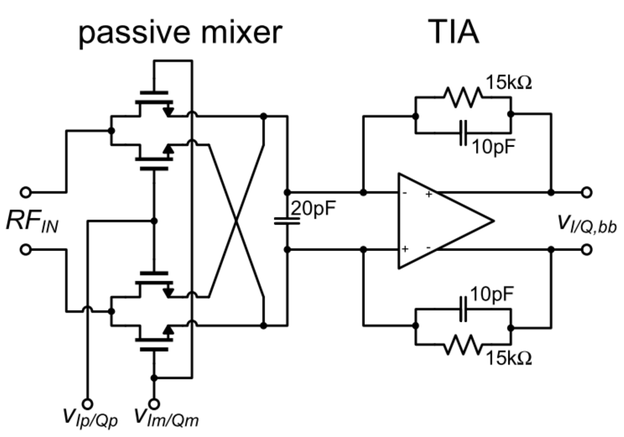
- 4 parallel PA branches, class-E operation only when all active
- At max. output power of 1.6 dBm the PA achieves an efficiency of 28% (includes PA driver)
- Output spectrum complies with BLE spectrum mask
- Limited slew-rate at FSK modulator improves spectral efficiency

Jens Masuch (Advisor: Dr. Manuel Delgado-Restituto)

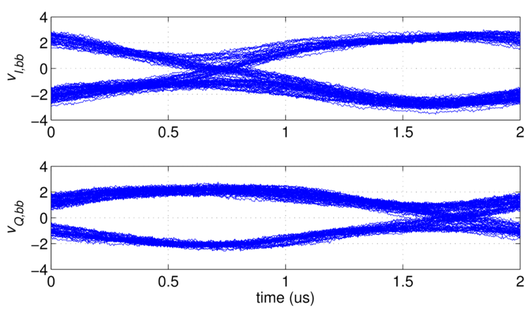
Institute of Microelectronics of Seville (IMSE-CNM-CSIC)

This work has been supported by the Spanish Ministry of Science and Innovation under grant TEC2009-08447 and the 2007-2013 FEDER Program

Passive Rx-frontend

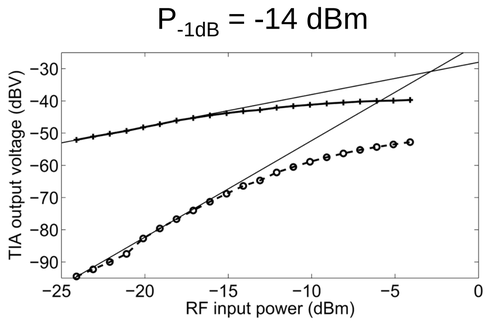


- Current-steering passive mixer
- Directly driven by QVCO
  - Capacitive load of mixer tuned out by QVCO inductors
- Transimpedance amplifier (TIA) is the first stage of amplification
  - NF given by preceding passive losses (package, transformer, mixer)
  - Measured NF is 15.5 dB



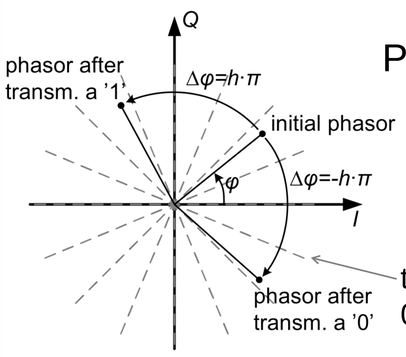
Measured eye-diagram with an RF input power of -70dBm:
=> SNR > 25 dB

Measured linearity of receiver :
IP3 = -2.7 dBm
P_{-1dB} = -14 dBm



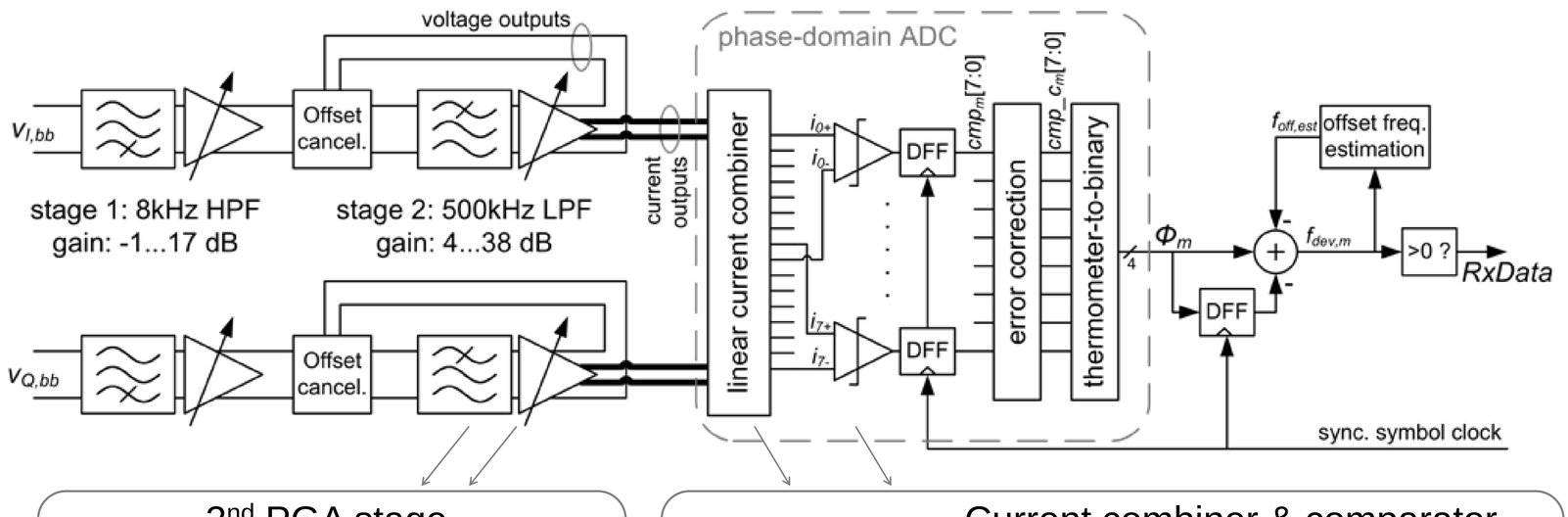
Zero-IF GFSK demodulator

- IQ-signals band-pass filtered and equalized by PGA (6dB steps)
- Rotational direction of IQ phasor detected by quantizing the phase
- 4-Bit PhADC sufficient for GFSK with h=0.5 (±90° per symbol)

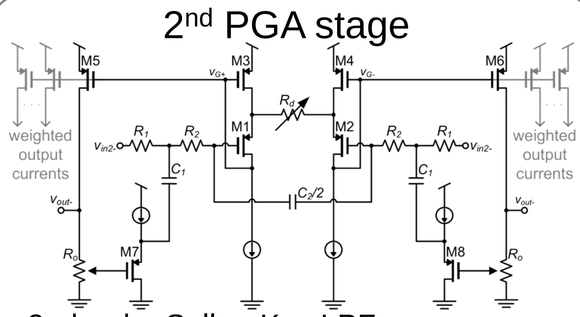


PhADC concept:
- Zero-comparing linear combinations of I and Q
- Map 8-Bit thermometer code to 4-Bit binary code

this threshold is characterized by:
$0 = -I \cdot \sin(-\pi/8) + Q \cdot \cos(-\pi/8)$

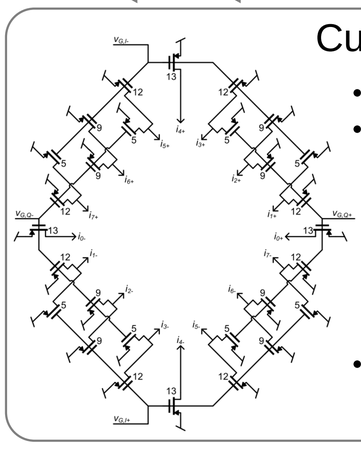


2nd PGA stage



- 2nd order Sallen-Key LPF
- Gain controlled by source degeneration
- Output currents easily available

Current combiner & comparator

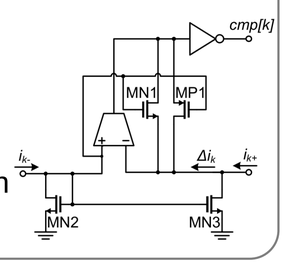


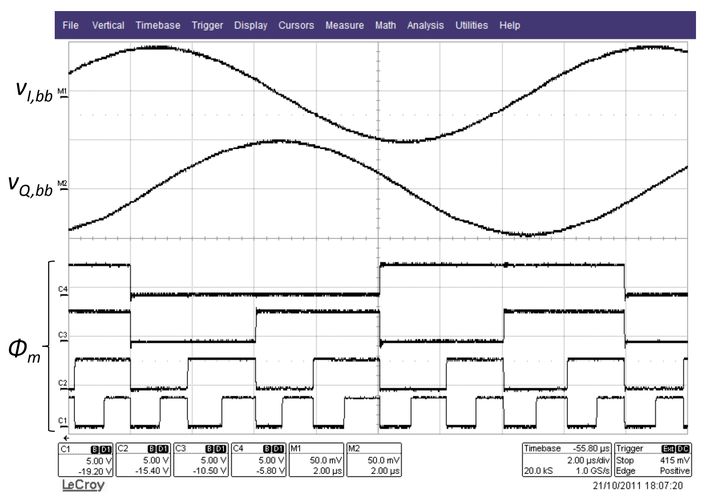
- Replaces conventional resistor array
- Weight factors (sin(-kπ/8), cos(-kπ/8), k=0…7) approximated using m-factors

$$\frac{12}{13} + j\frac{5}{13} = 1.000 + e^{j22.62°}$$

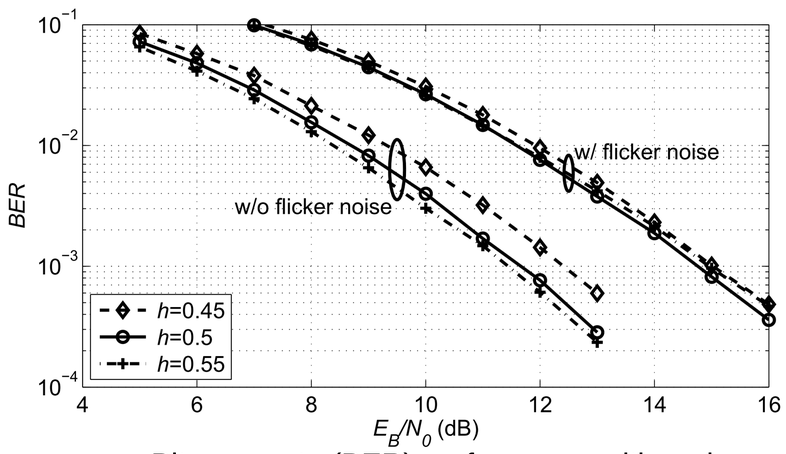
$$\frac{9}{13} + j\frac{9}{13} = 0.979 + e^{j45.00°}$$

- Diff. comparator with non-linear feedback

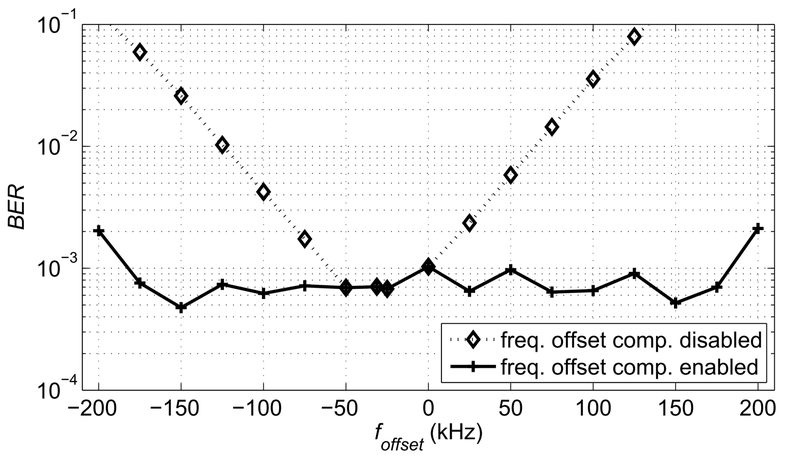




Measured PhADC output for a rotating phasor in counter-clockwise direction
(INL=0.23LSB, DNL=0.16LSB)



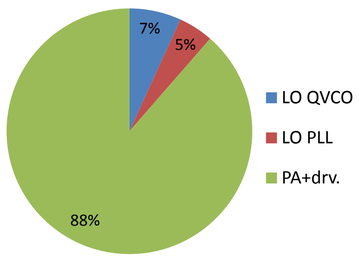
Bit-error-rate (BER) performance with and without flicker noise (corner 150kHz)



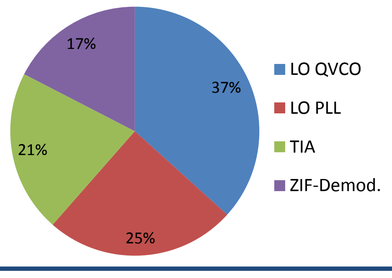
Performance considering carrier frequency offset

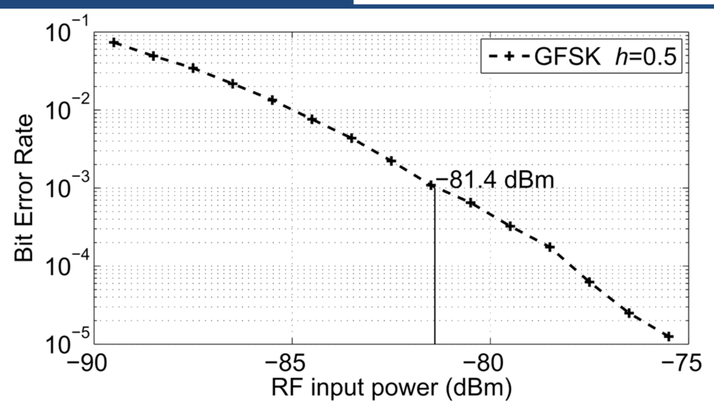
Performance summary

Tx power split (total 5.9 mW)



Rx power split (total 1.1 mW)





Additional Rx Parameters	
Interference blocking	
C/I co-channel	14.5 dB (<21dB*)
C/I @ 1MHz offset	1.1 dB (<15dB*)
C/I @ 2MHz offset	-17.5 dB (<-17dB*)
C/I @ 3MHz offset	-30.0 dB (<-27dB*)
Input-ref. IP3	-2.8 dBm
Carrier frequency offset tolerance	170 kHz (> 150 kHz*)

Comparison to recent low power 2.4GHz transceivers

	ISSCC'08 D. Weber et al.	ASSCC'10 M. K. Raja et al.	BIOCAS'10 M. Contaldo et al.	ISSCC'11 M. Vidojkovic et al.	This work
CMOS process	0.13µ	0.18µ	0.18µ + BAW	0.13µ	0.13µ
Standard	BT v2.1	Zigbee	BLE	-	BLE
Modulation	GFSK	OQPSK	GFSK	OOK	GFSK
Tx power cons.	56.5 mW	18 mW	47.3 mW	4.2 mW	5.9 mW
Tx output power	2 dBm	0 dBm	5.4 dBm	0 dBm	1.6 dBm
Tx efficiency	2.8 %	5.6 %	7.3 %	24 %	24.5 %
Rx power cons.	35.6 mW	22.3 mW	18.7 mW	0.5 mW	1.1 mW
Sensitivity	-88 dBm @ 1Mbps	-94 dBm @ 250kbps	-75 dBm @ 200kbps†	-75 dBm @ 5Mbps	-81.4 dBm @ 1Mbps

† Preliminary measurements