A 4.5nW Wake-Up Radio with -69dBm Sensitivity

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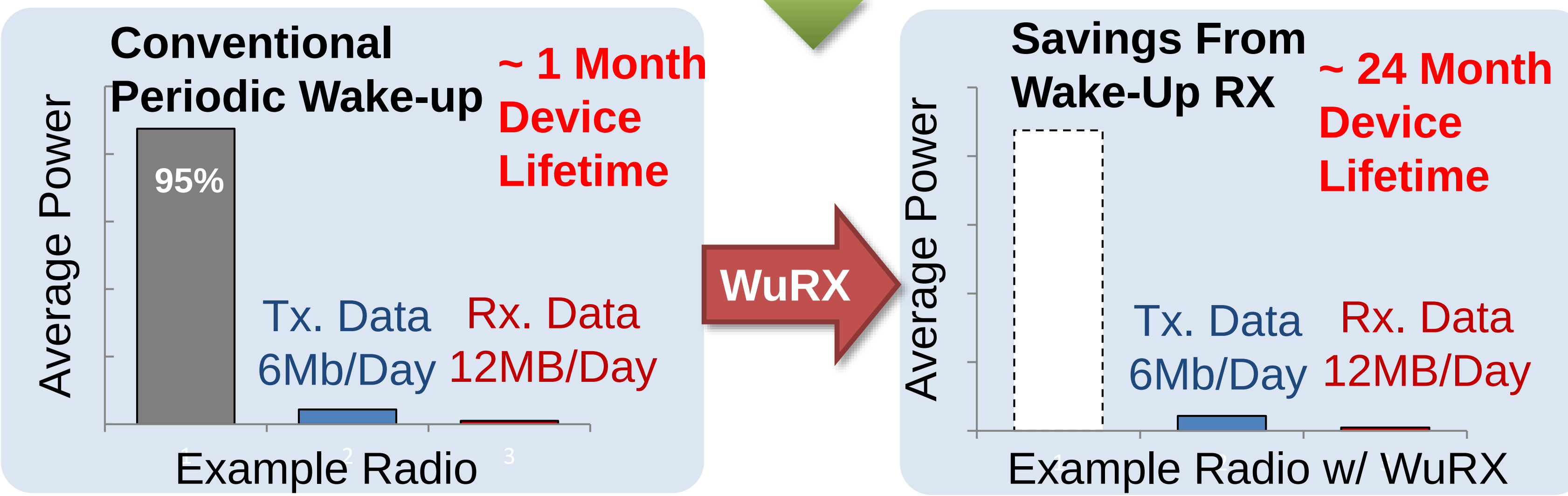
Motivation: IoT Devices

IoT devices: OFF (zero power) but ALERT!

Courtesy of Dr. Troy Olsson (DARPA)

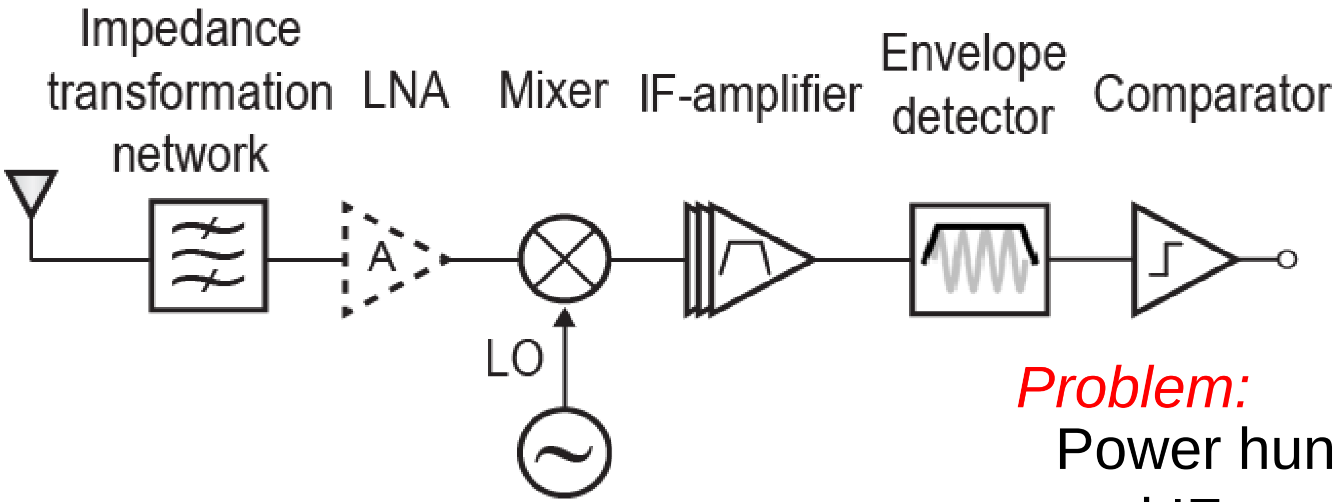


- Always-on → near-zero power
- Large network coverage → high sensitivity
- Infrequent event-driven manner → data rate less critical

Near-zero power WuRX greatly extends IoT system lifetime

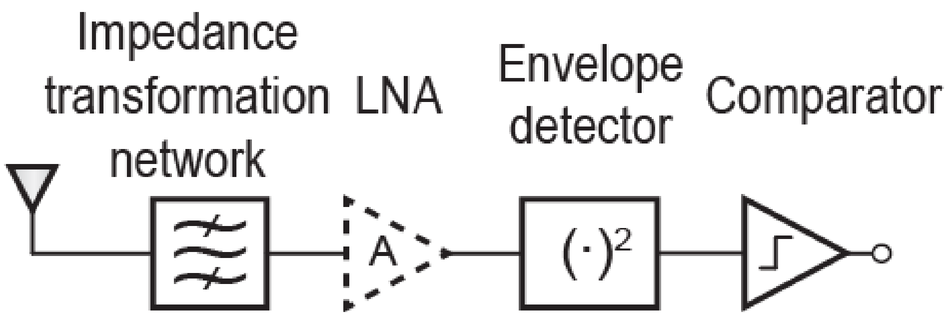
Conventional WuRX Architectures

IF/uncertain-IF:



Problem:
Power hungry LO generation and IF amplification

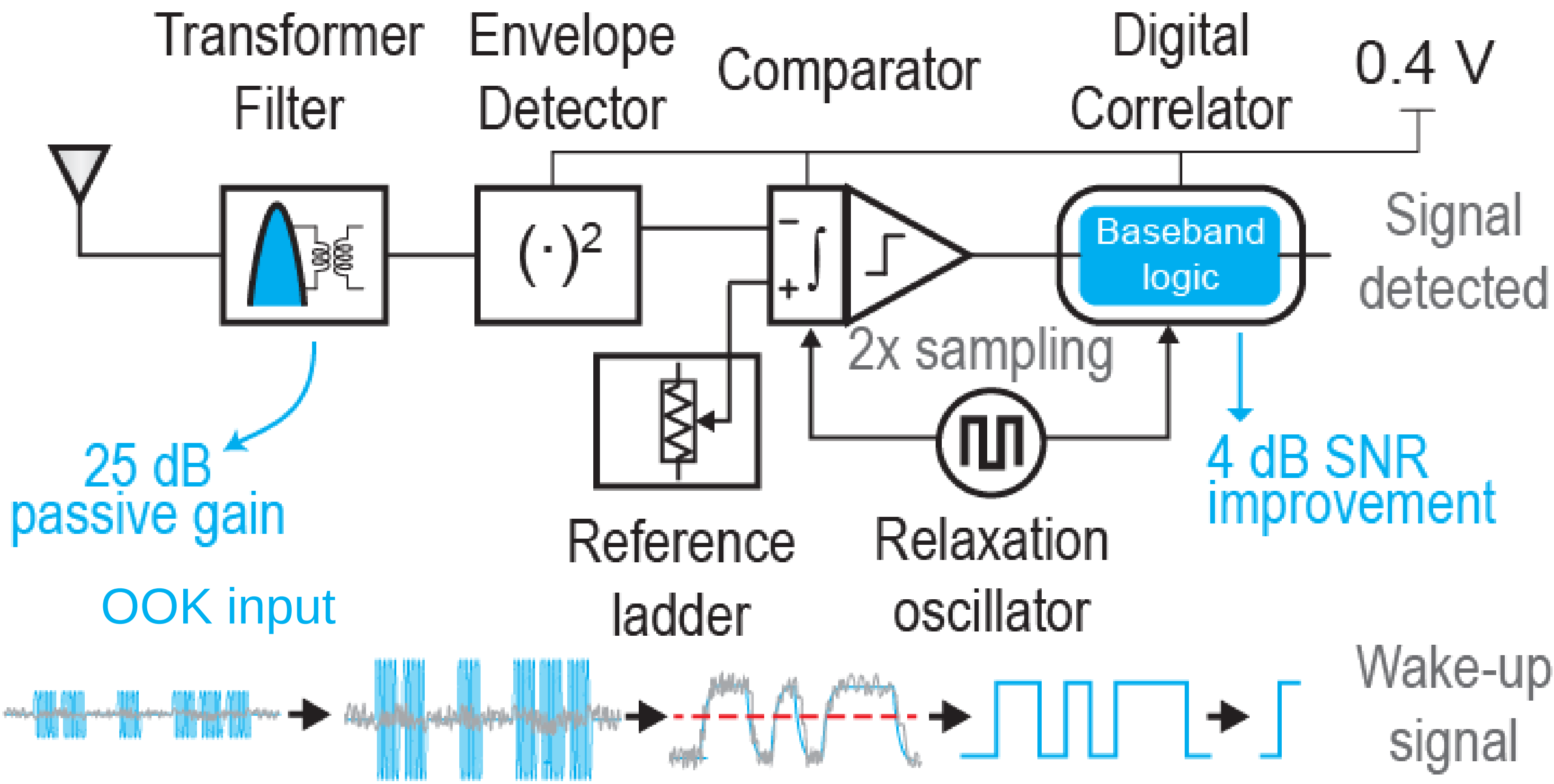
Direct envelope detection:



Problem:
Moderate RF/conversion gain
→ poor sensitivity
Low-*Q* front-end
→ poor interferer tolerance

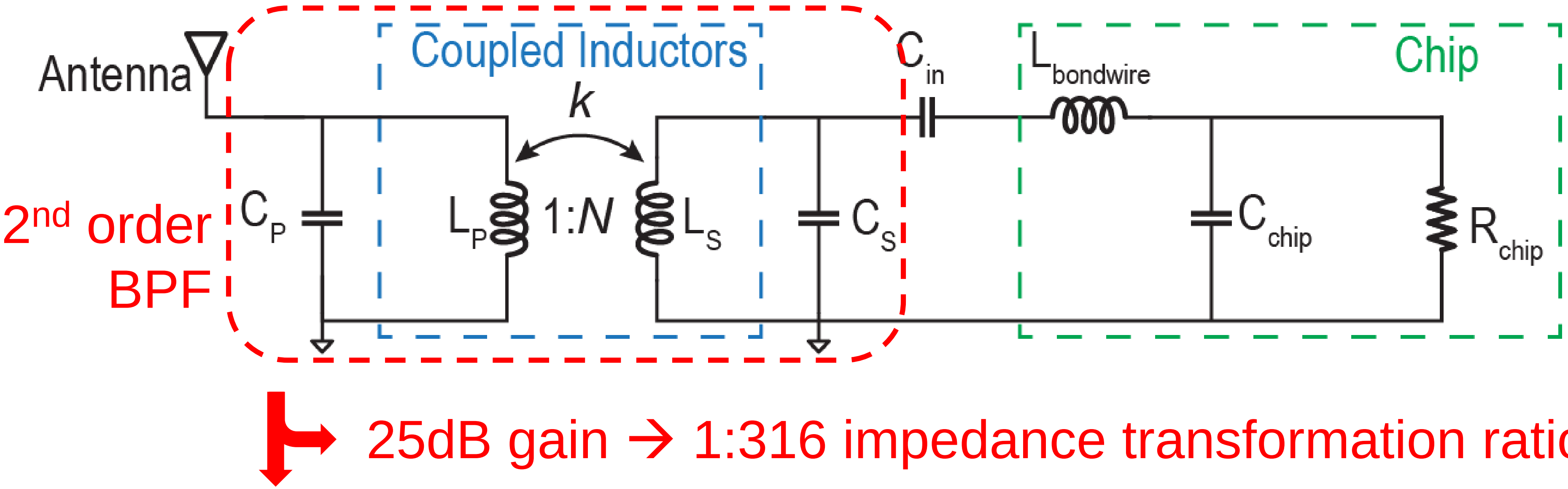
Challenge: achieving both high gain and low power

System Overview



High R_{in} ED supports high passive gain front-end w/ high-Q filtering at low power

Transformer Filter



25dB gain → 1:316 impedance transformation ratio

Requirements:

1. High ED R_{in} (>15.8kΩ)
2. Large L_s/L_p ratio (=316)
3. Small, well-controlled k (≲0.04)

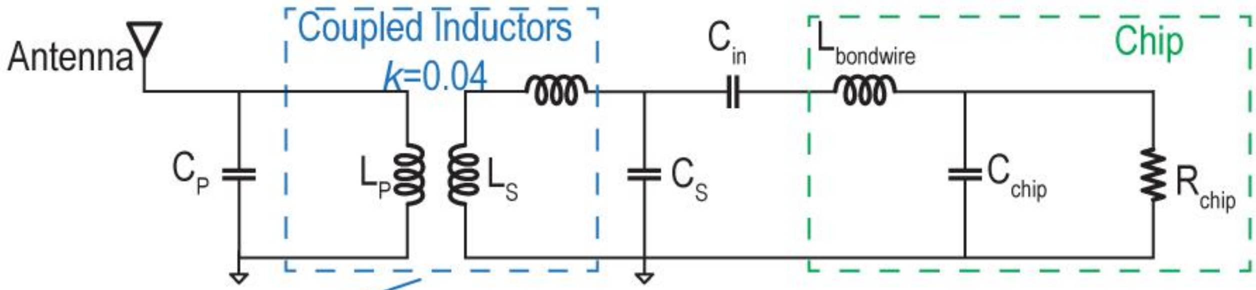
Implementation options:

1. Lumped L_p/L_s
   → Large L, but poor-defined k
2. Distributed L_p/L_s
   → Well-controlled k, but small L

Challenge: implement large L_p/L_s ratio with low and well-controlled k

Transformer Filter

Schematic of Transformer Filter



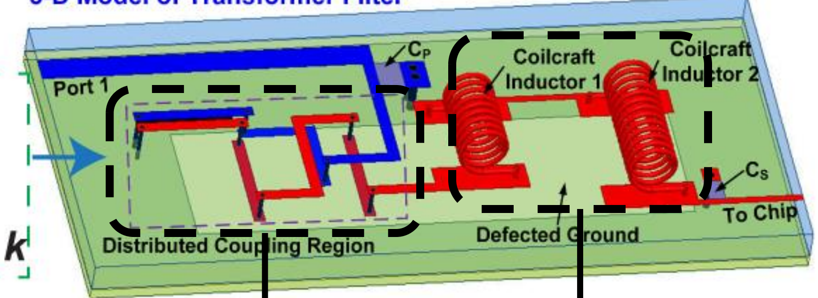
L_P: Distributed

+

L_S: Lumped+Distributed

Realize large L with well-controlled k

3-D Model of Transformer Filter

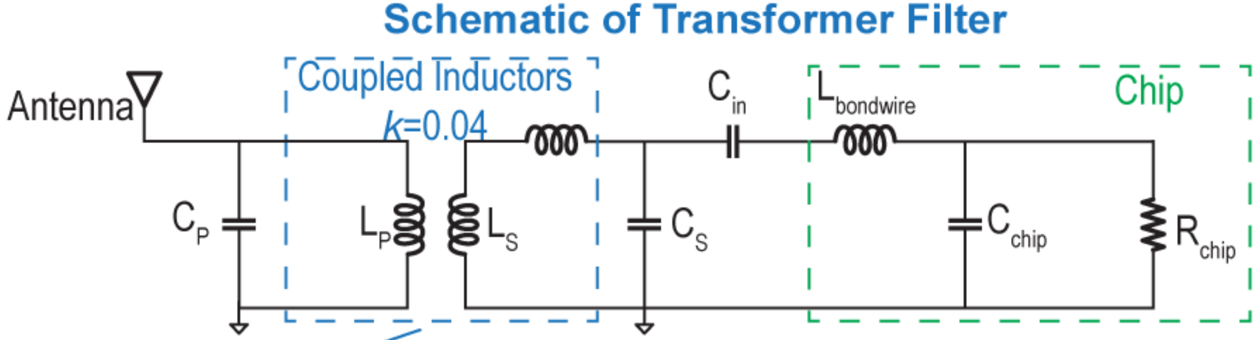


Distributed

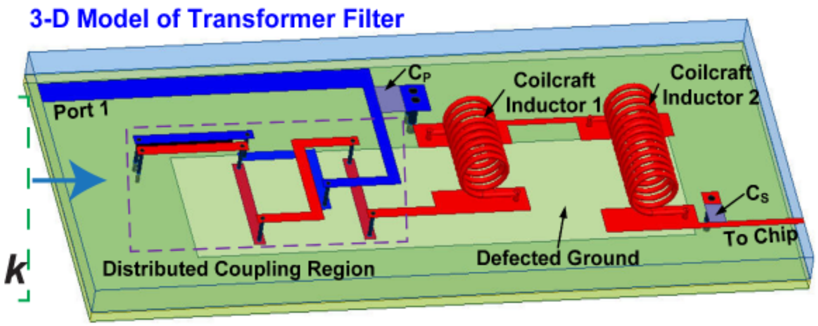
Lumped

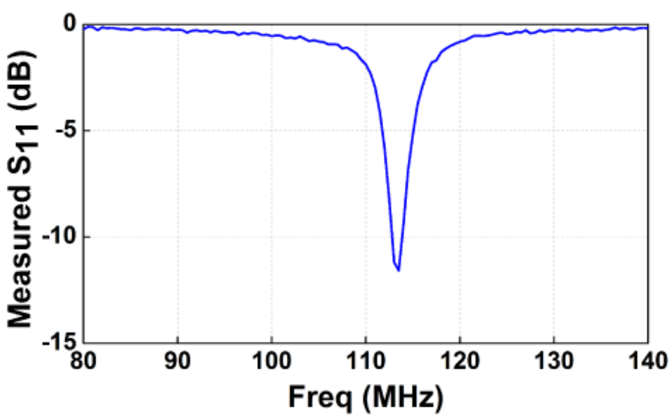
Discrete inductors + stripline inductor control *k* precisely

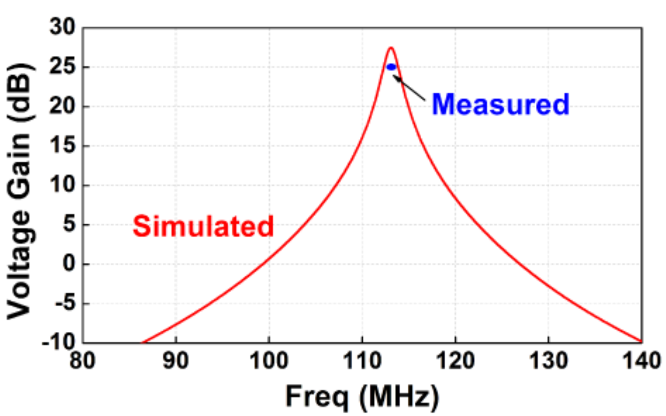
Transformer Filter



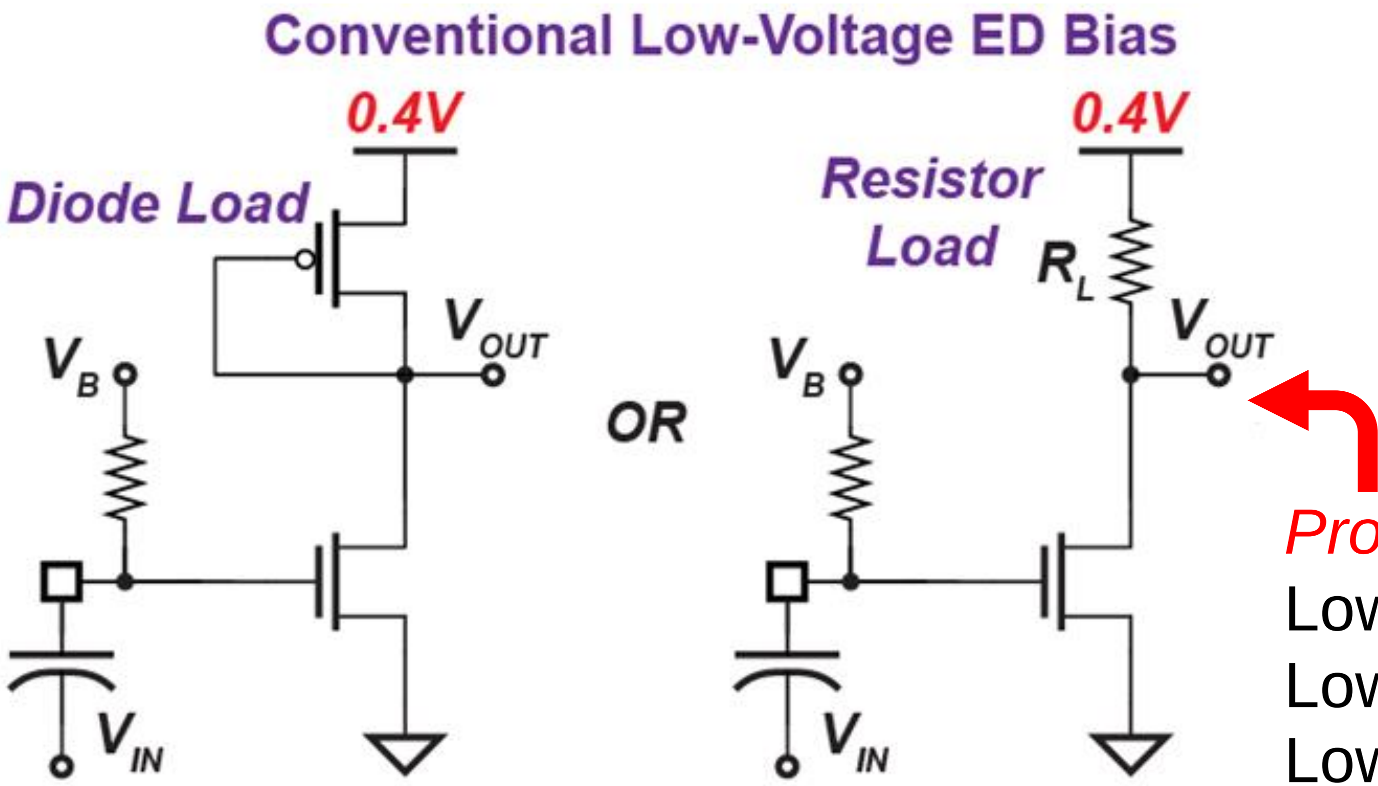
L_P: Distributed
+
L_S: Lumped+Distributed
Realize large *L* with well-controlled *k*







Envelope Detector (ED)



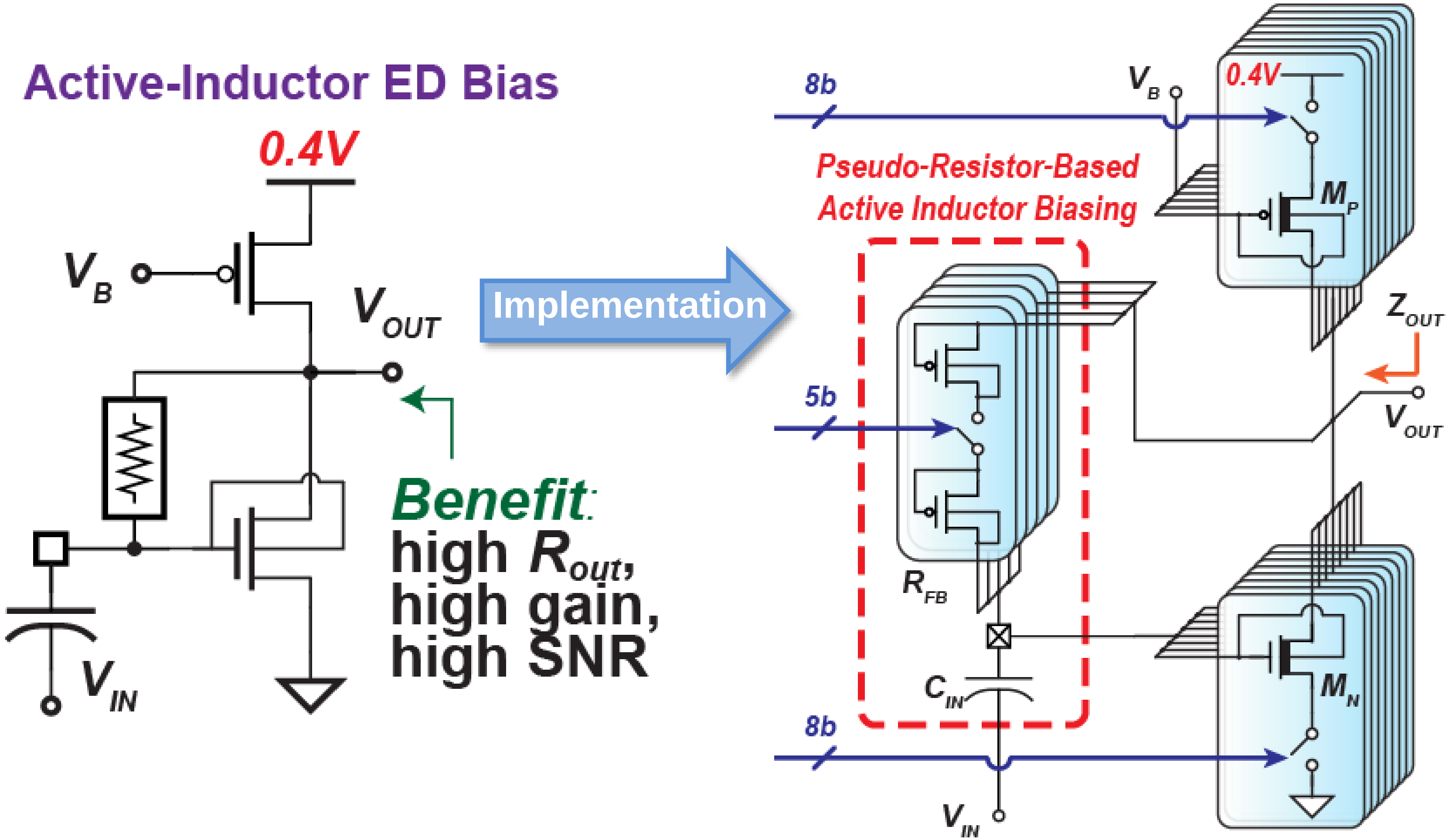
Problem:
Low R_{out}
Low gain
Low SNR

Benefit:

Active ED has high input impedance to support high RF gain

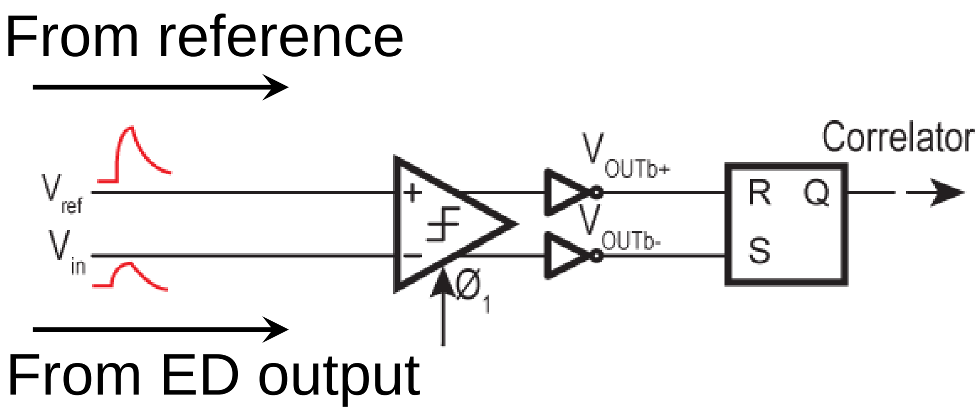
2nd order g_m non-linearity realizes the ED squaring-function

Envelope Detector (ED)



Active-L ED bias improves SNR by 3dB/25dB

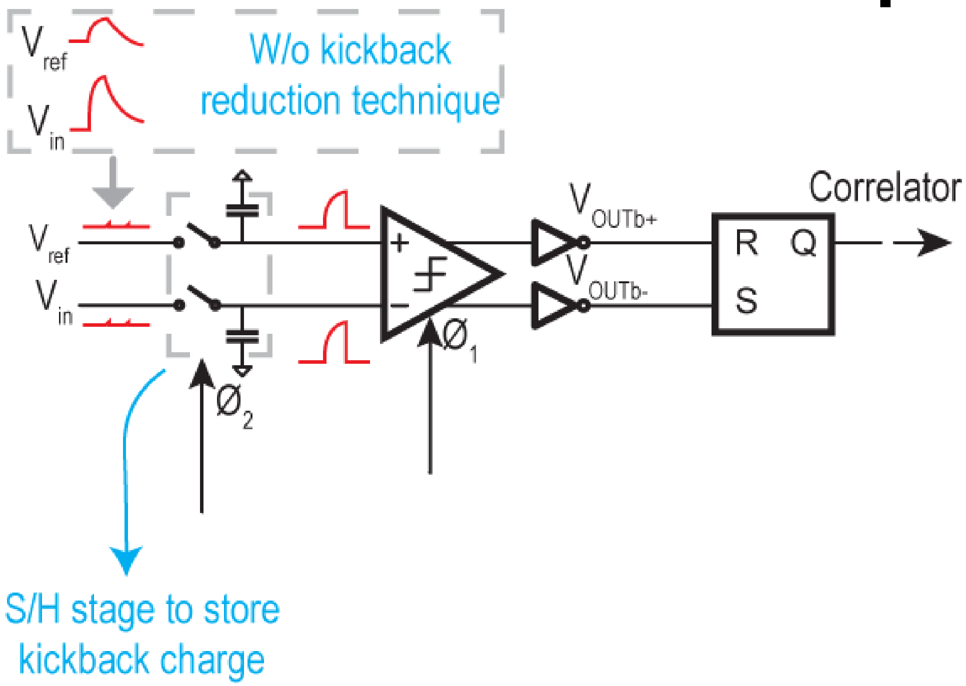
Comparator

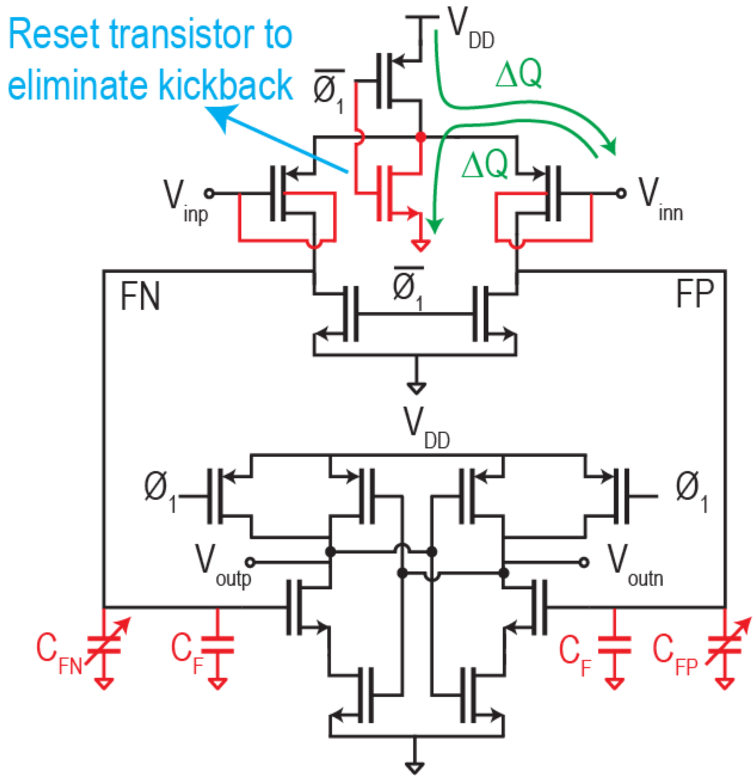


- Unbalanced impedances (ED vs. reference ladder) at comparator input

Challenge: Asymmetric kickback and unequal settling time

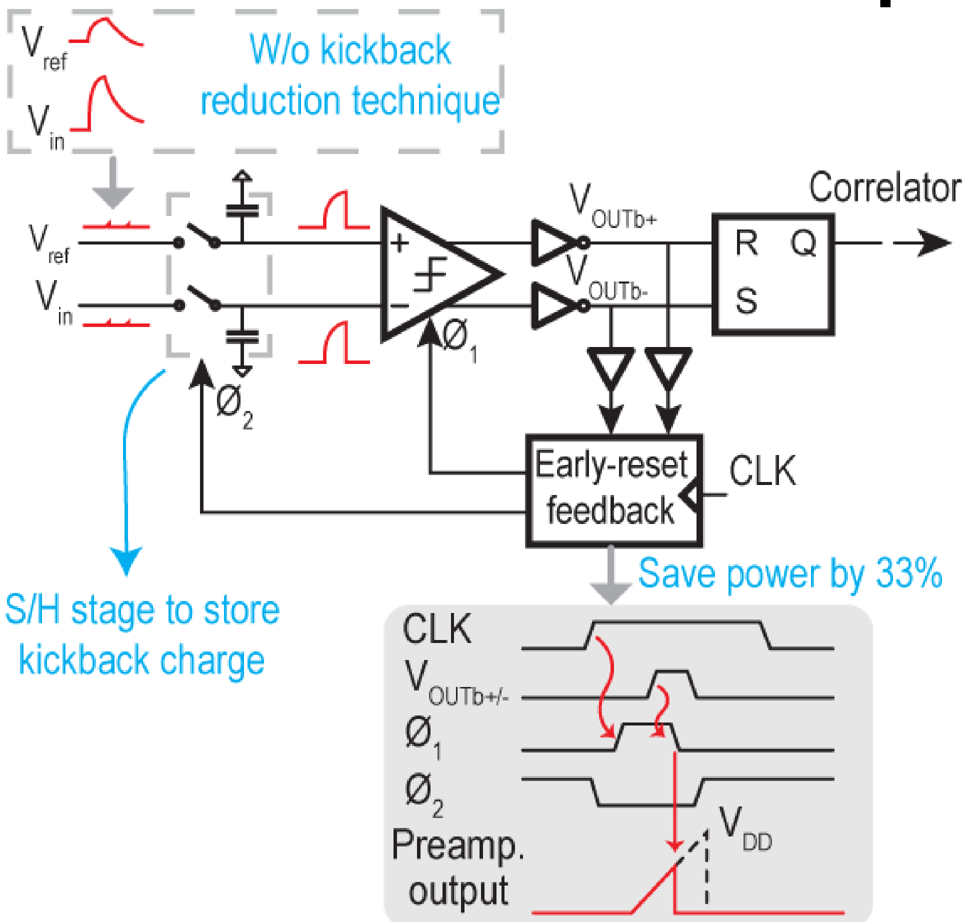
Comparator



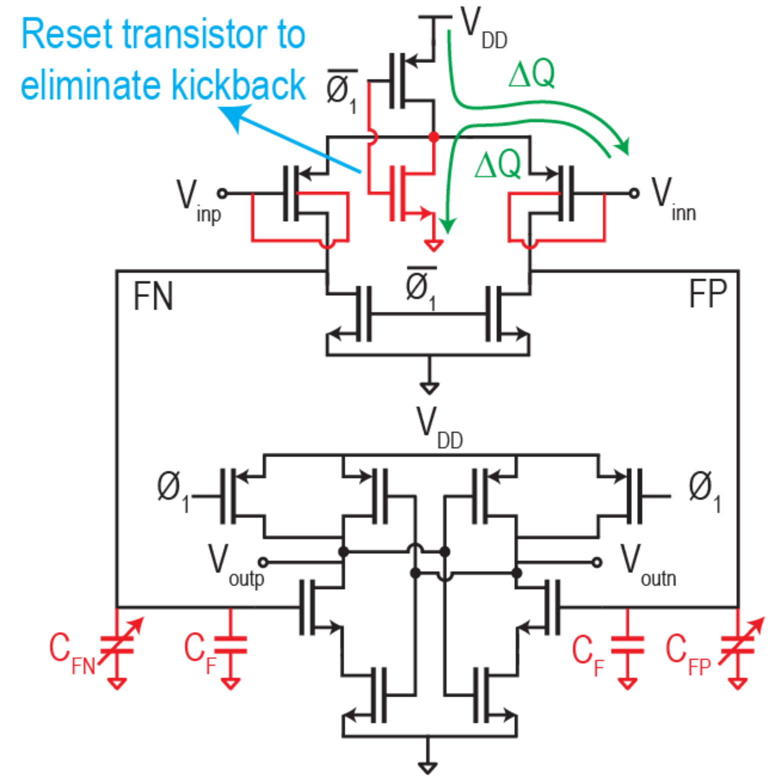


S&H: balanced impedances & stores kickback charge temporarily
Reset transistor: Purge kickback charge before next cycle

Comparator

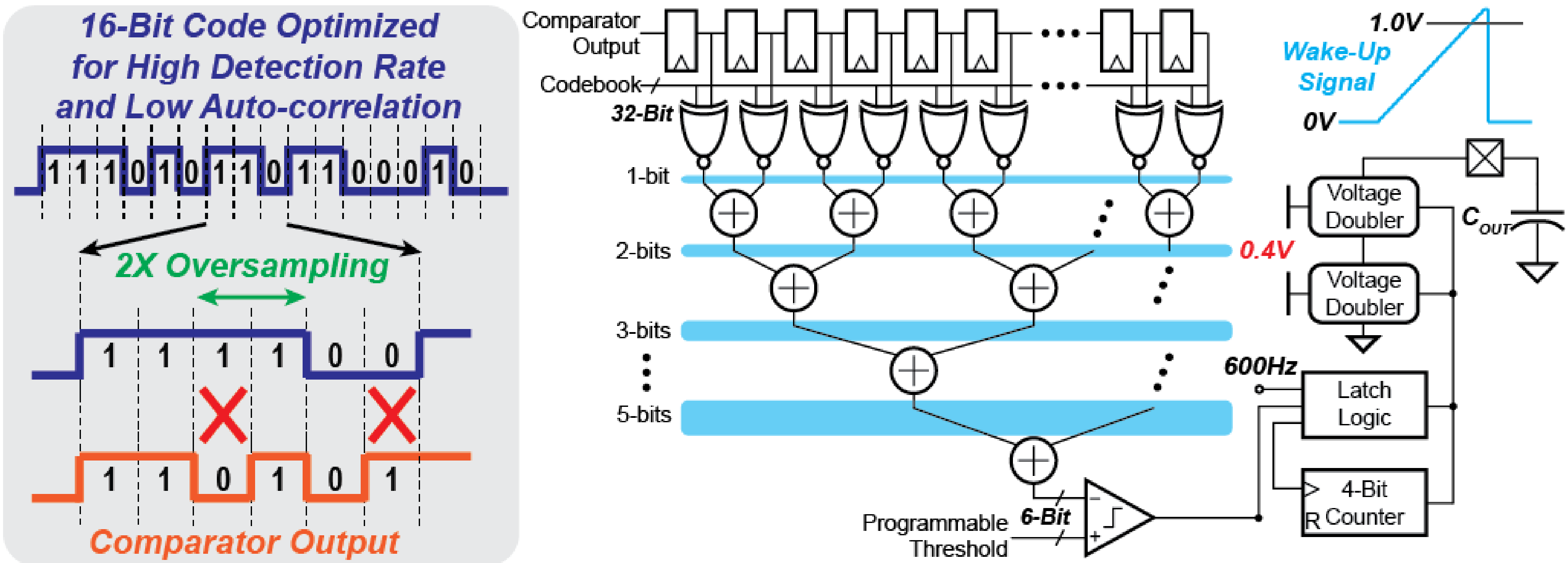


- DTMOS increases g_m+g_{mb} by 51% and reduce noise by 66%



Early-reset: save dynamic power & generate non-overlap clock

Coding and Digital Baseband



❑ 16b code scheme:
• 2× oversampling

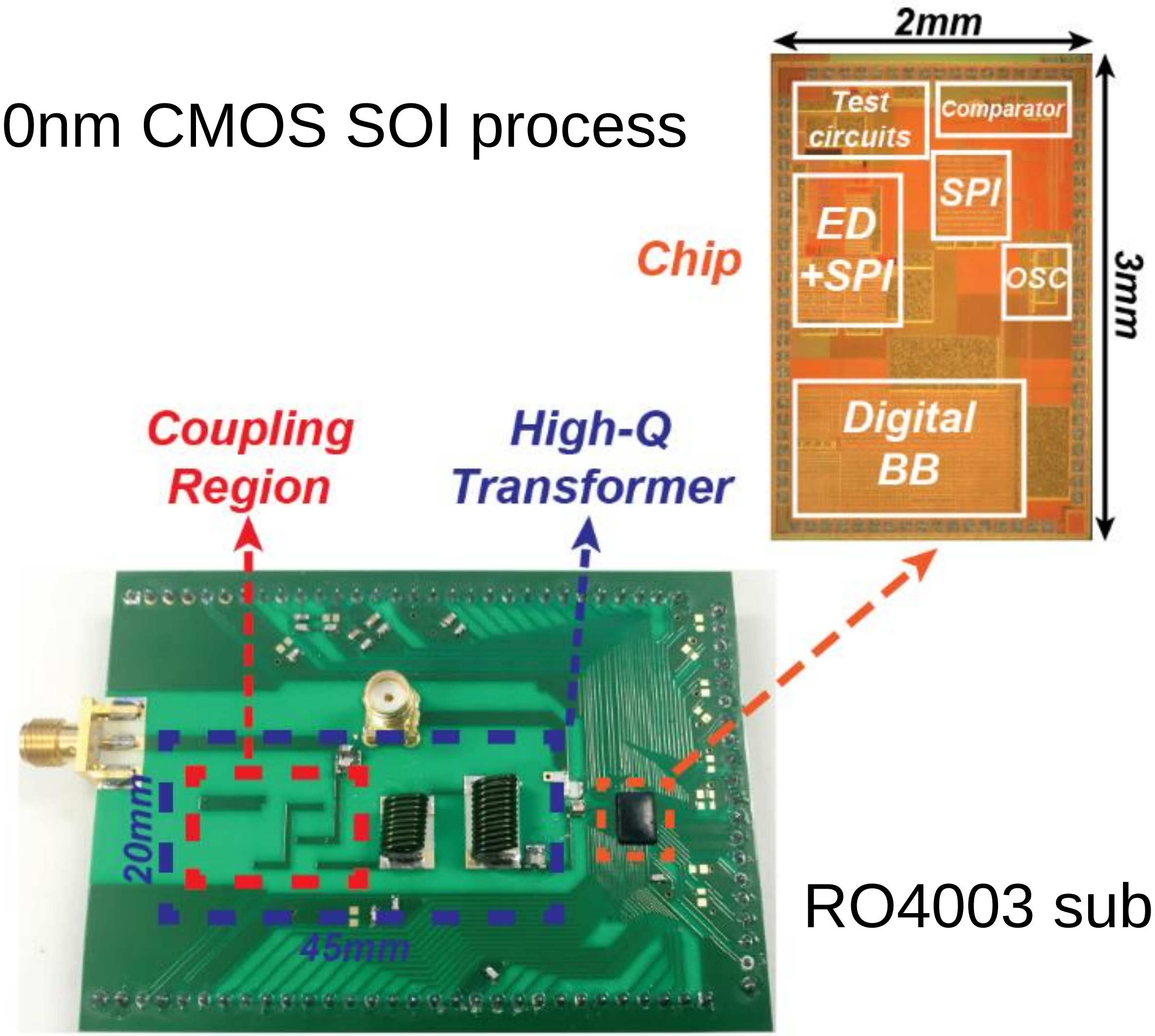
❑ 32b digital correlator

❑ Output driver

Optimal codeword improves 4dB SNR at low power cost

Die & Board Photo

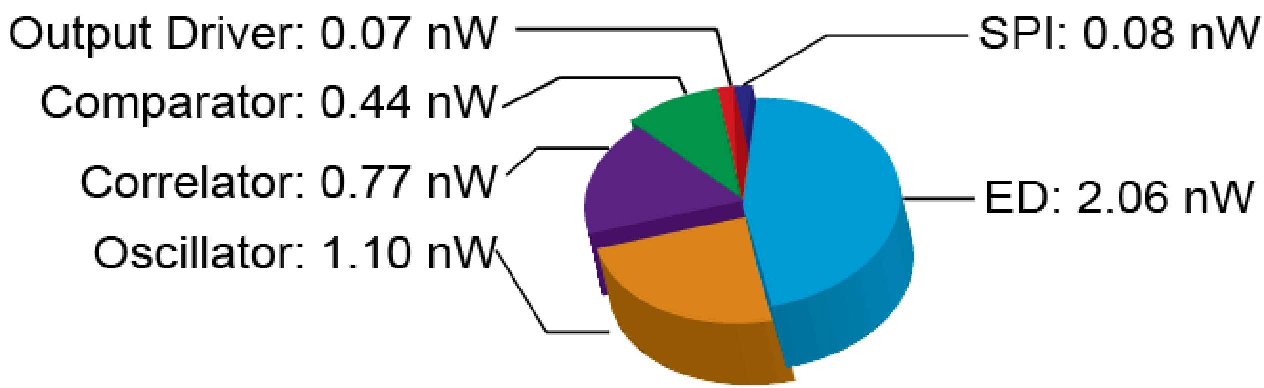
GF 180nm CMOS SOI process

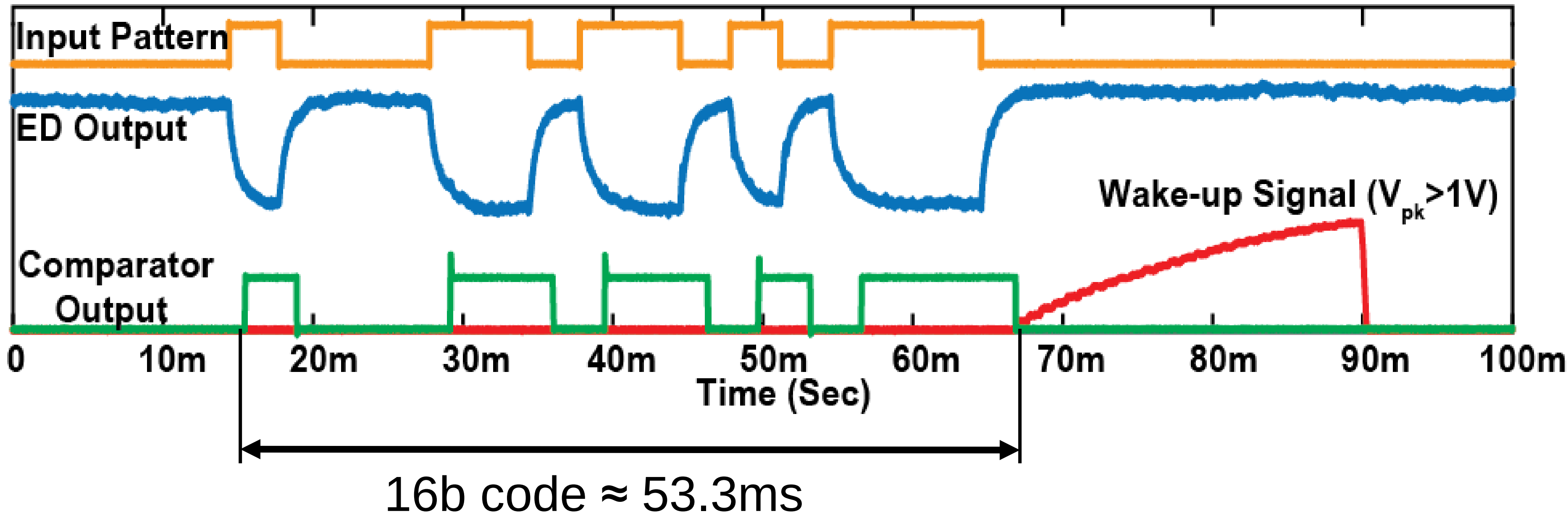


RO4003 substrate

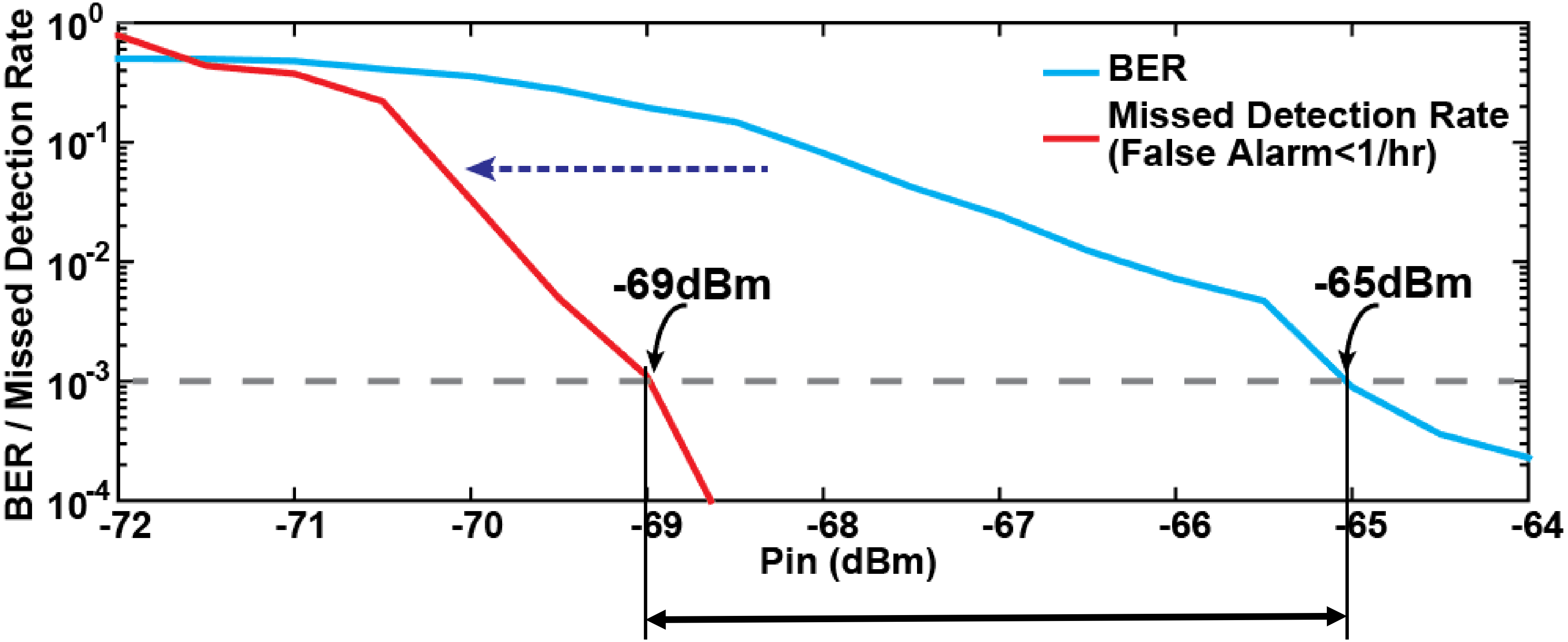
Measurement Results

Total power: 4.5 nW



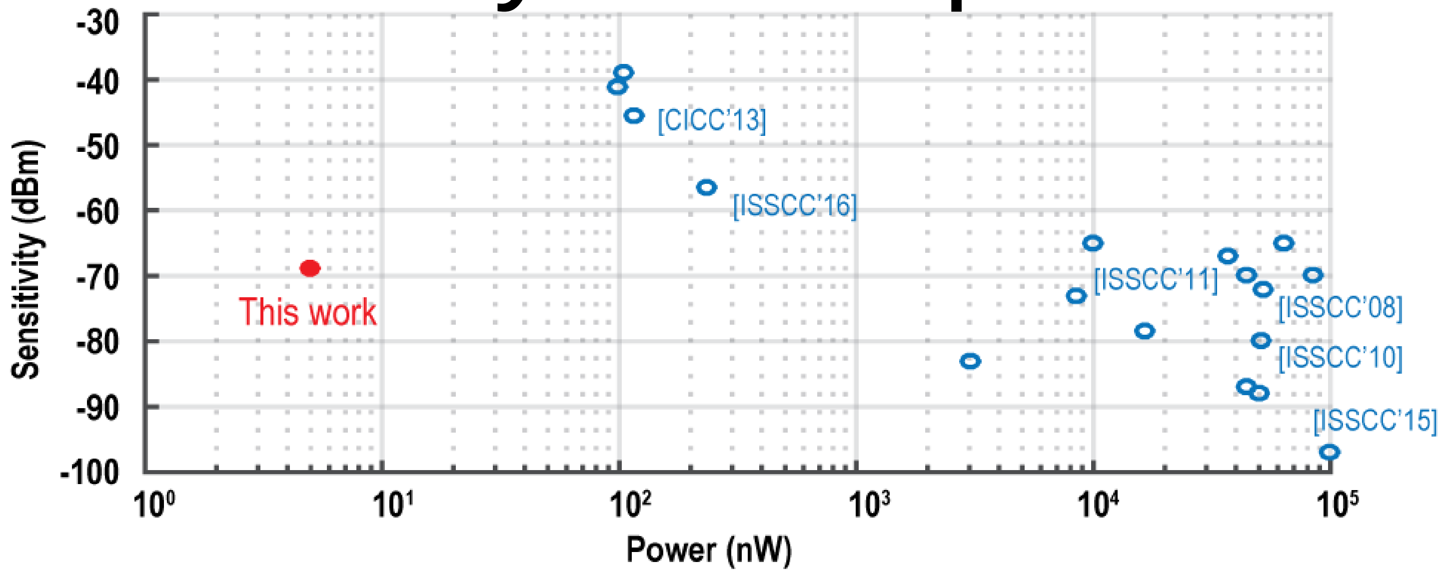


Measurement Results



Sensitivity increases by 4dB w/ coding

Summary & Comparison



	ISSCC'08	ISSCC'10	ISSCC'11	CICC'13	ISSCC'15	ISSCC'16	**This Work**
Tech.	90nm	90nm	130nm	130nm	65nm	65nm	**180nm**
Carr. Freq.	2GHz	915MHz	402MHz	402MHz	2.4GHz	2.4GHz	**113.5MHz**
Modulation	OOK	OOK	FSK	OOK	OOK	OOK	**OOK**
Supply	0.5V	1V	1V	1.2/0.5V	0.5V	1/0.5V	**0.4V**
Data Rate	100kbps	10kbps	200kbps	12.5kbps	10kbps	8.19kbps	**0.3kbps**
Energy/bit	520pJ	5100pJ	220pJ	9.3pJ	9900pJ	28.8pJ	**15.0pJ**
Sensitivity	-72dBm	-80dBm	-70dBm	-45dBm	-97dBm	-56.5dBm	**-69dBm**
Power	52µW	51µW	44µW	116nW	99µW	236nW	**4.5nW**

Conclusions

- Infrequent event-driven networks with low-average throughputs can benefit from low-data rate WuRXs
- Key challenges: power and sensitivity
- To address this we:
  - Designed a transformer filter with 25 dB passive gain and 1.9MHz bandwidth at 113.5MHz
  - Designed an active-*L* biased ED with high input impedance Designed a dynamic comparator with low noise/kickback
  - Proposed an optimal coding design which provides 4dB sensitivity gain at low power cost
- Result: **a 4.5nW 0.4V WuRX with -69 dB sensitivity**

Acknowledgements

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- Thank Mentor Graphics for the use of Analog FastSPICE tool (AFS)