Reconfigurable and Spectrum Aware Receiver Architecture for Cognitive Radio

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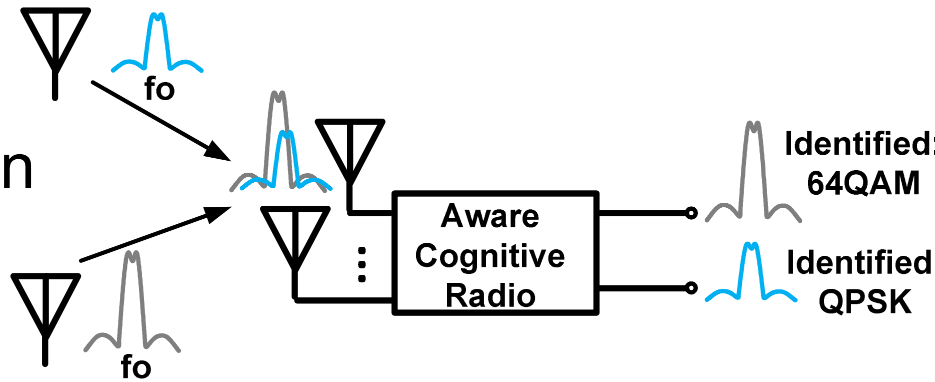
Outline

- Motivation: Spectrum aware Cognitive Radio
- Overview of system architecture
- Challenges of broadband receivers
- Front-end filtering: N-path filter approach
- Improving the N-path filter
  - T-line N-path filter
  - PN sequence N-path filter
- Conclusions

Motivation: Spectrum Aware Cognitive Radio

- Application of universal broadband signal classification
  - Spectrum aware cognitive radio
  - Spectrum surveillance



- Requirements of signal classification receiver
  - Robust broadband receiver for multiband coverage
  - Signal separation for classification
  - Wide bandwidth (up to 50 MHz) for multi-standard coverage
  - Low power for mobile applications

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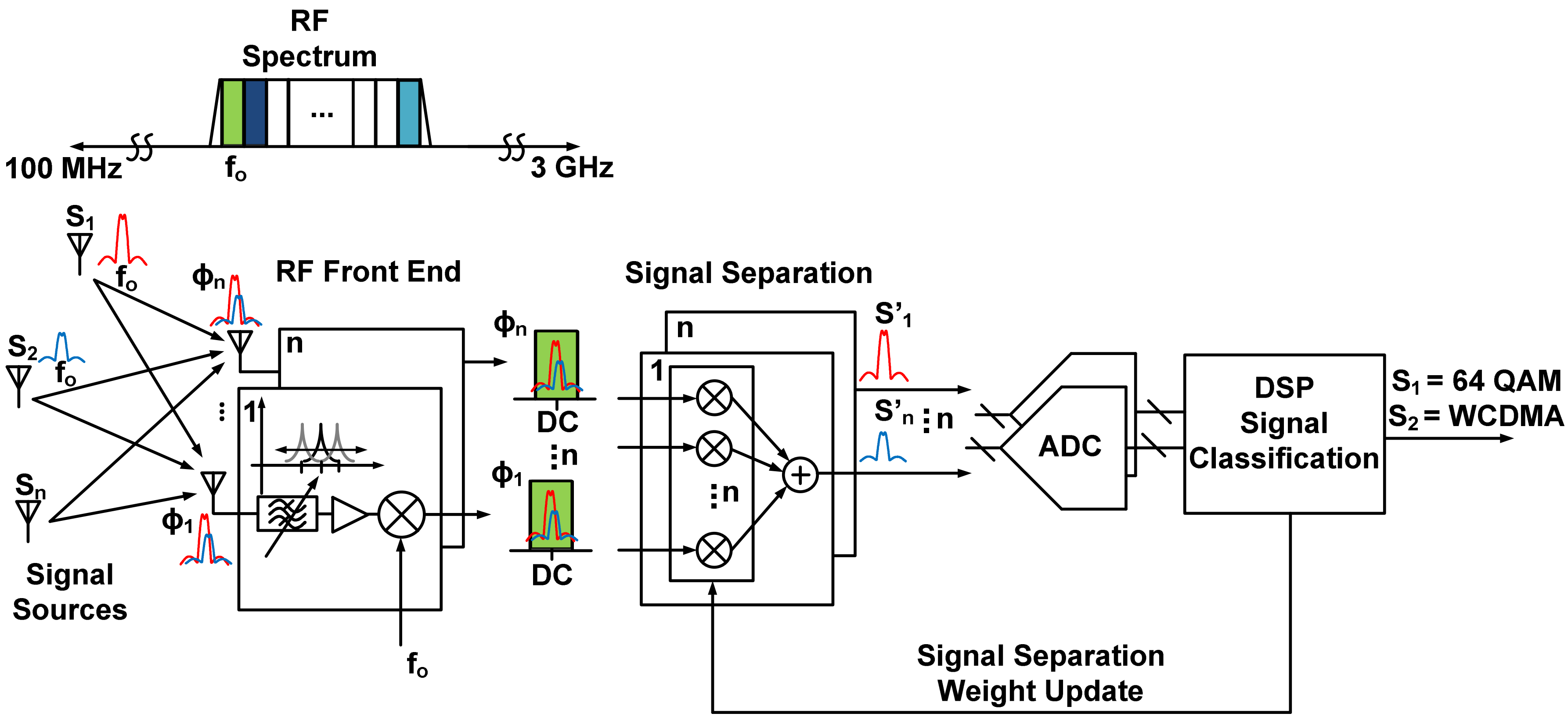
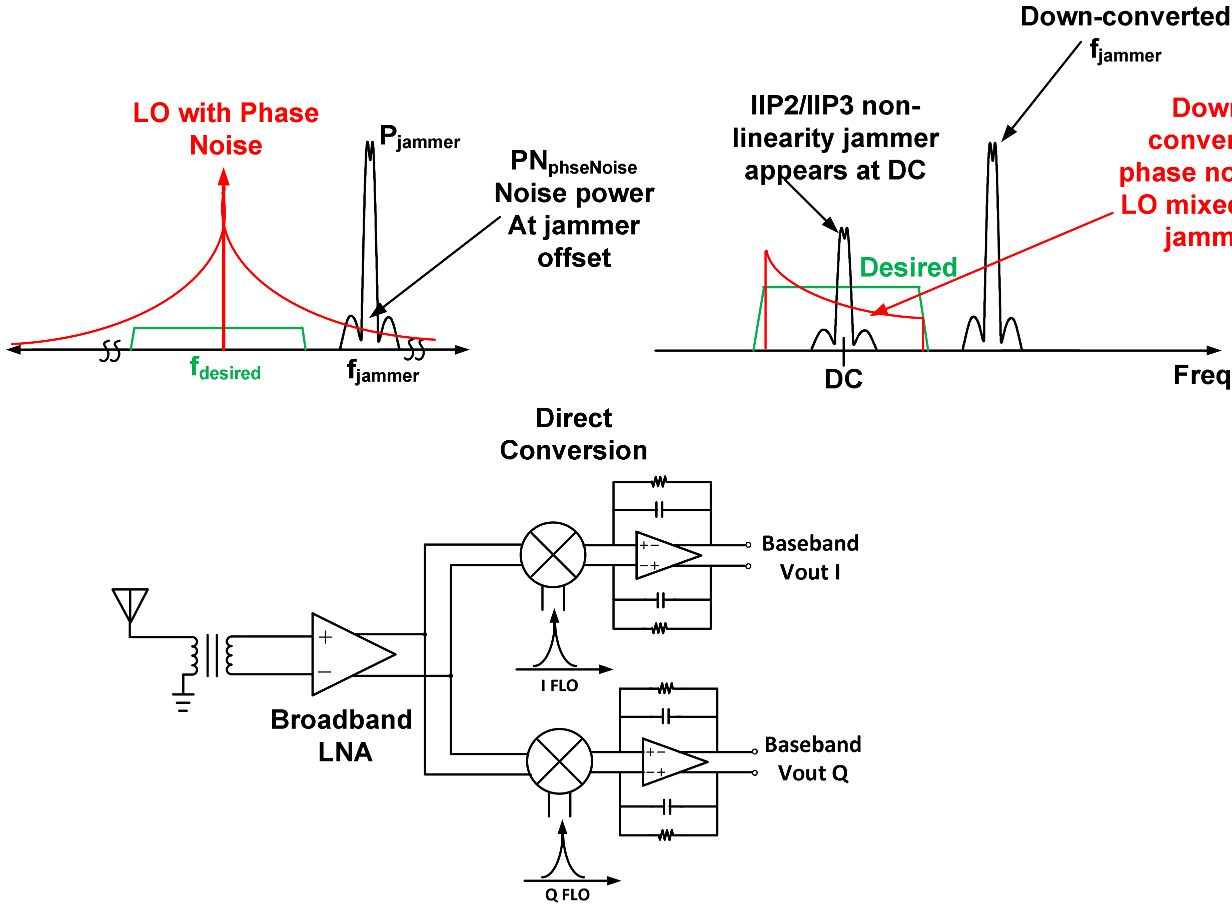
System Architecture of Classification Receiver



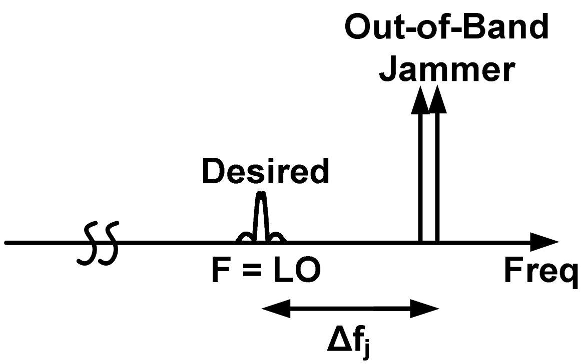
- Multiple Antennas for spatial diversity
- Broadband tunable front-end with reconfigurable filter
- MIMO spectral overlap signal separation
  - Multiplication of received matrix with learned weights that approximates inverse of the transmission channel
- ADC and DSP feedback learning

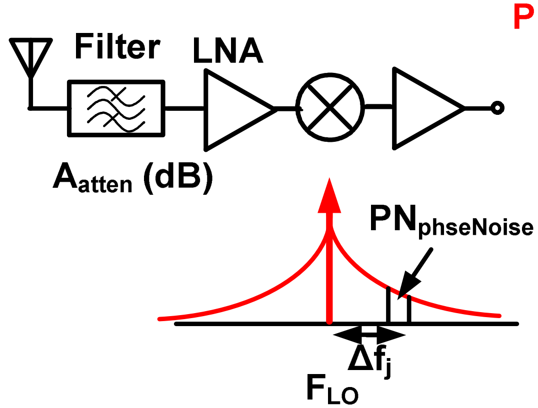
Broadband Receiver with Jammer Challenge

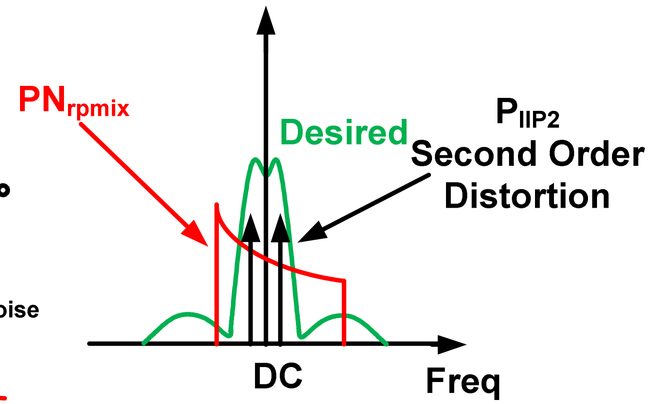


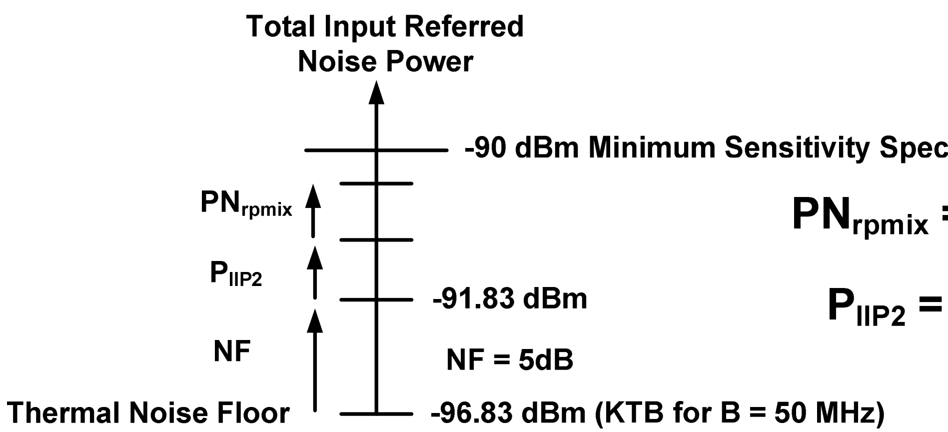
- Jammer coupled with receiver non-idealities (LO phase noise, finite linearity IIP2 and IIP3) raises noise floor.
- A highly tunable frequency band selective filter for out-of-band jammer rejection is desirable.

Direct Conversion Receiver Filter System Level Calculation









$$PN_{rpmix} = (P_{jammer} - A_{atten}) + PN_{phseNoise} + 10\log(BW\ Hz)$$

$$P_{IIP2} = 2(P_{jammer} - A_{atten}) - IIP2$$

- With P_{jammer} = +0 dBm, NF = 5 dB, IIP2 = +50 dBm, oscillator phase noise of -162 dBc/Hz at jammer offset, and Filtering of 30 dB gives the sensitivity as: -91.75 dBm.
- **Need approximately A_{atten} = 30 dB of filtering for 0 dBm jammer.**

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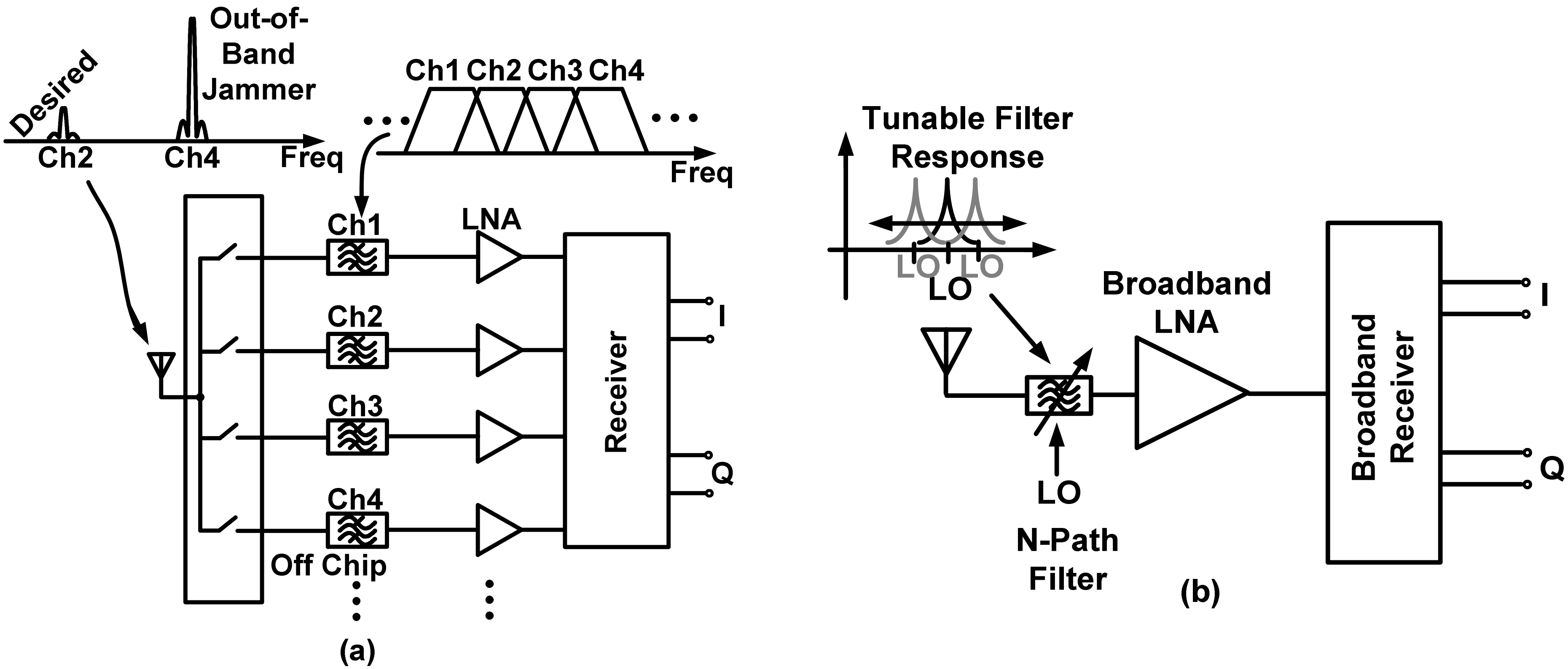
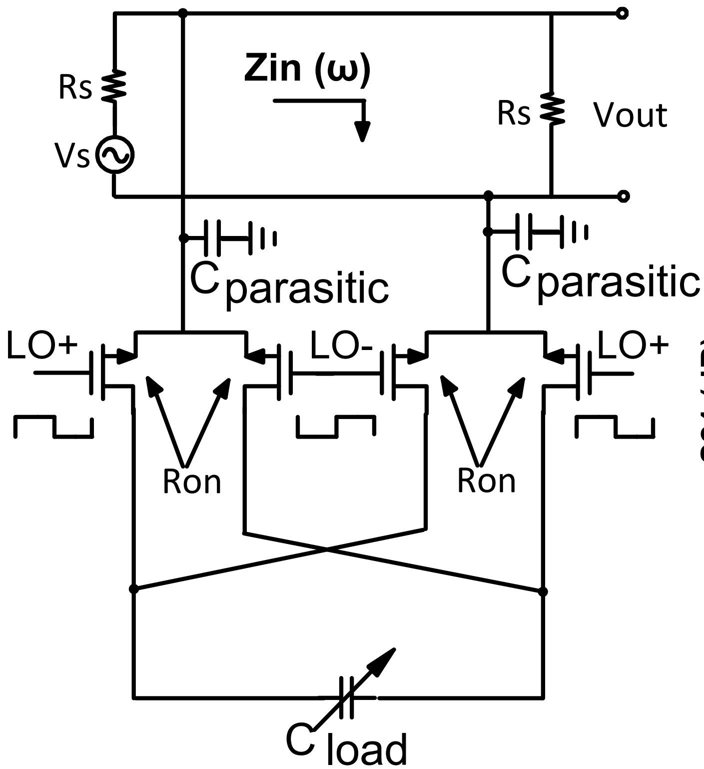
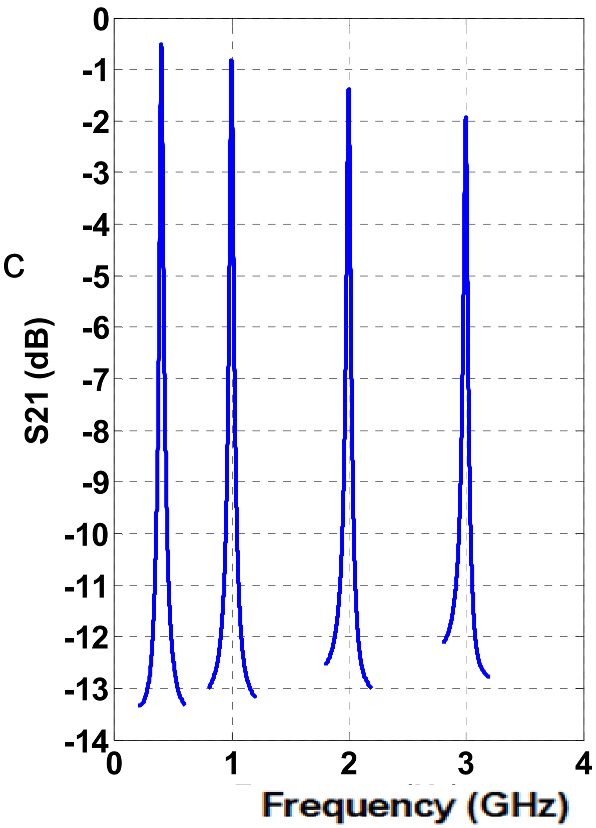
Broadband Tunable Receiver with N-path Filter Approach

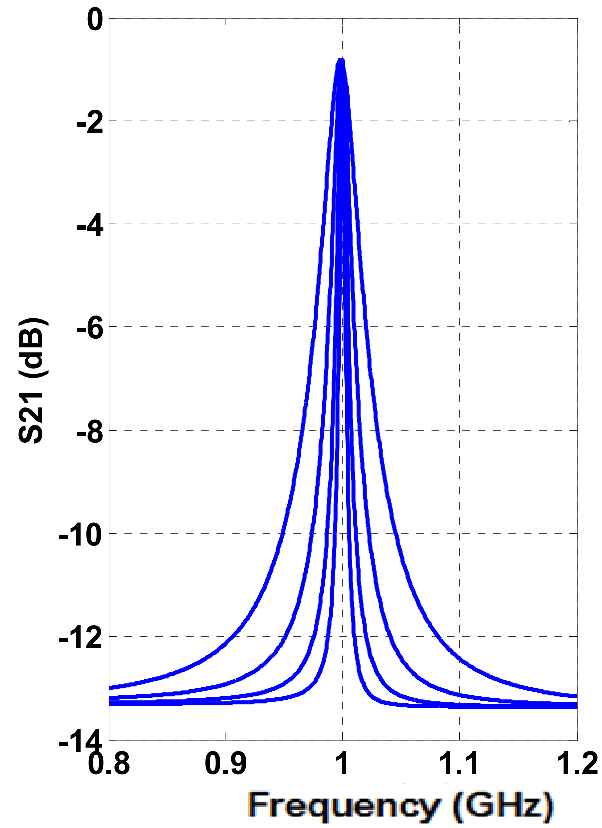


- (a) Multiple off-chip SAW filter approach
- (b) Tunable fully integrated filter approach [1]

N-path Filter







$$Zin(\omega) \approx Z_{C_{parasitic}}(\omega) \,\|\, \left(Z_{Load}(\omega_{LO} - \omega) + 2Ron\right)$$

65 nm RFCMOS / 50 ohm system

- Baseband capacitive impedance translated to ω_{LO}
- Out-of-band rejection limited by the resistance and parasitic capacitance of the CMOS switch

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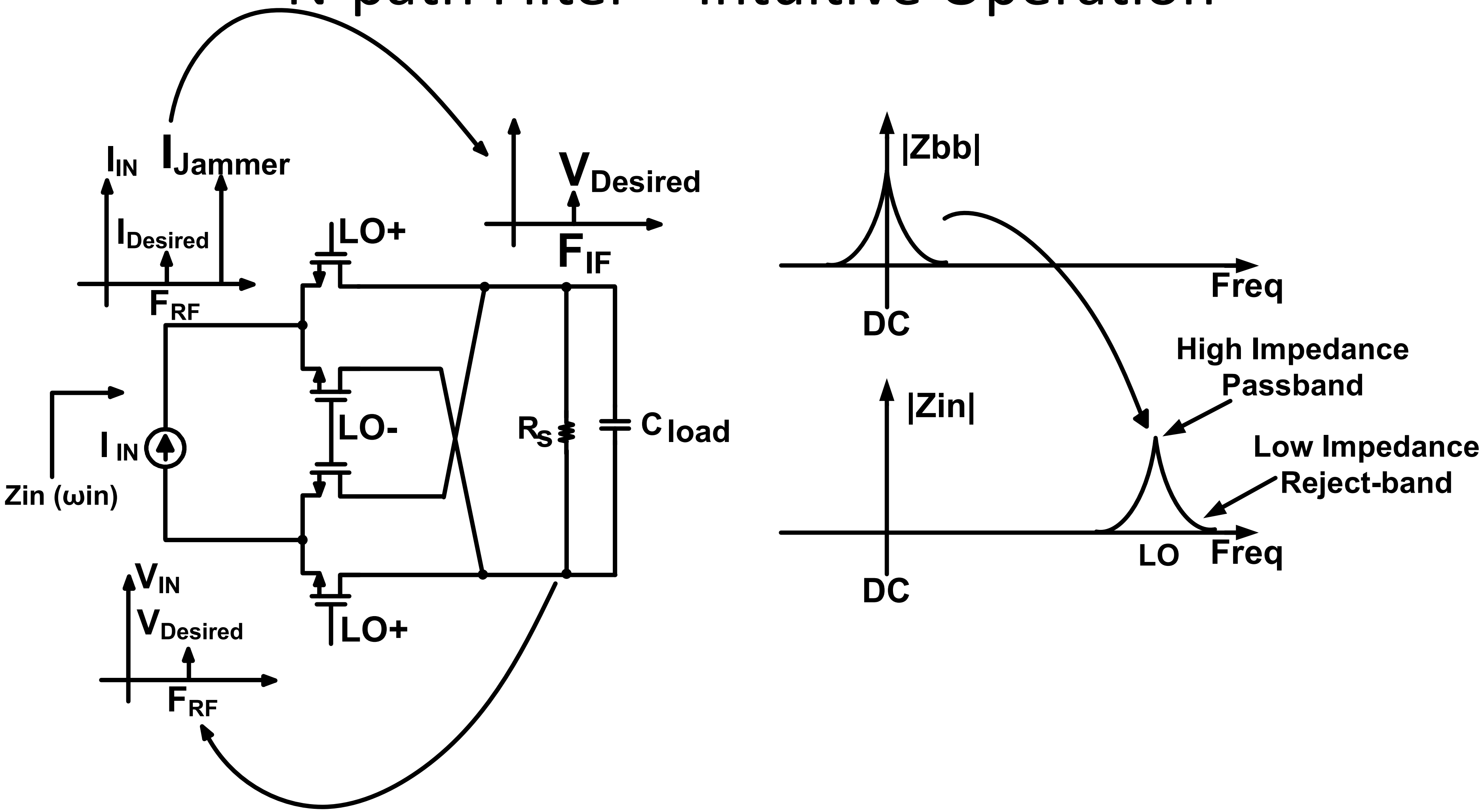
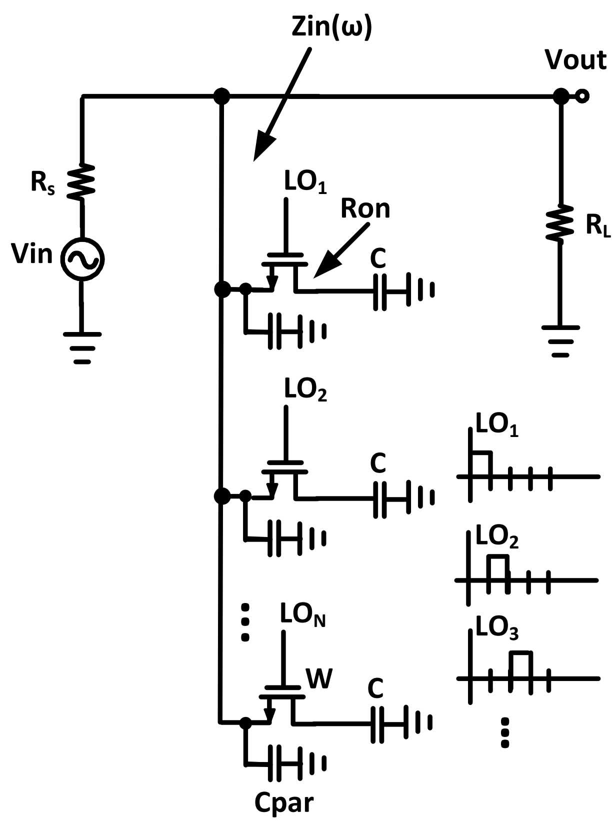
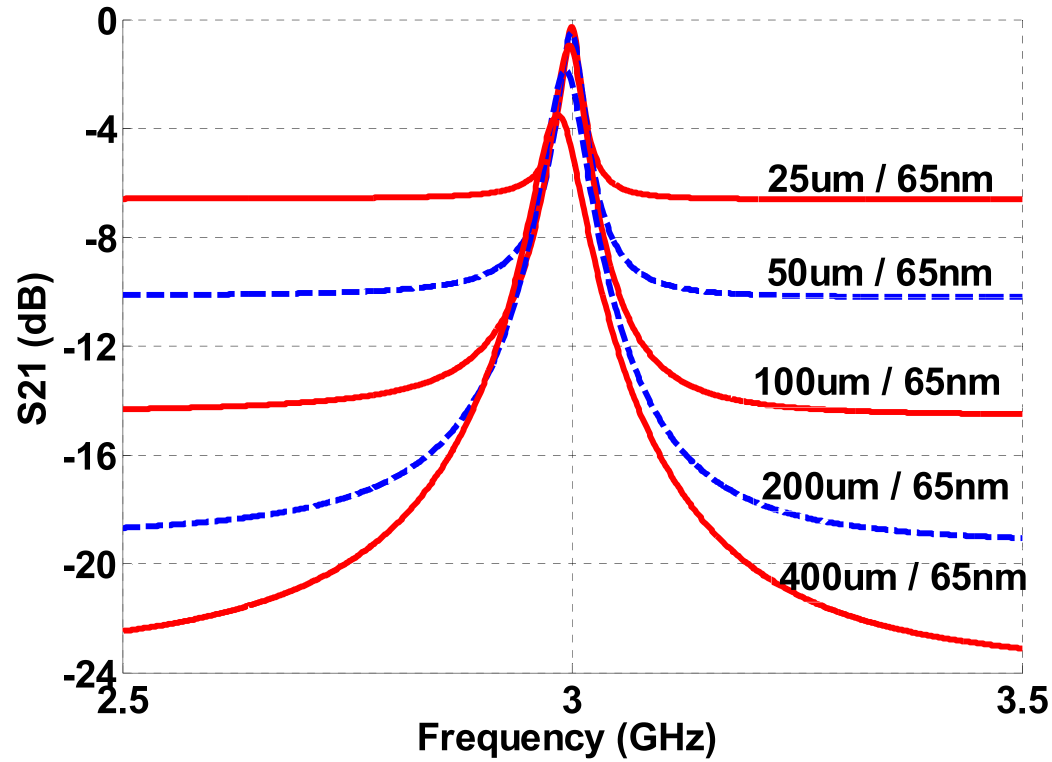
N-path Filter – Intuitive Operation



- Passive mixer translates baseband impedance to switching frequency [2].

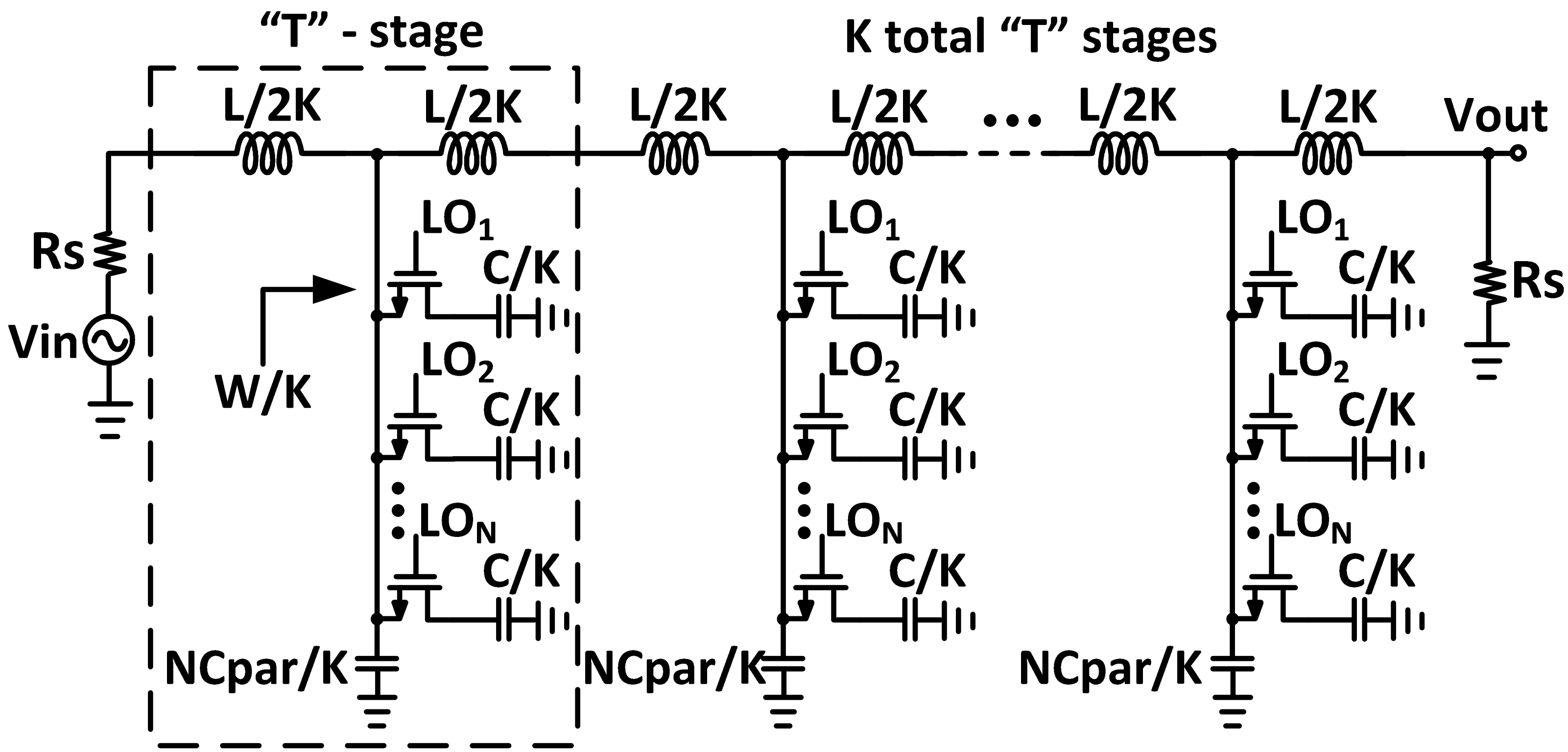
N-Path Filter Fundamental Limitation





- Pass-band loss is approximately $S_{21} \approx 1/\left(1+sR_sNC_{par}\right)$
- Out-of-band rejection is limited by switch R_{on}.
- Parasitic capacitance shifts peak S_{21} to lower frequency.

Proposed Transmission Line N-path Filter



- Parasitic capacitance absorbed into transmission line.
- Out-of-band rejection improved by further low-pass filter created by L and R_{on}.
- Improves tradeoff between pass-band loss and out-of-band rejection.

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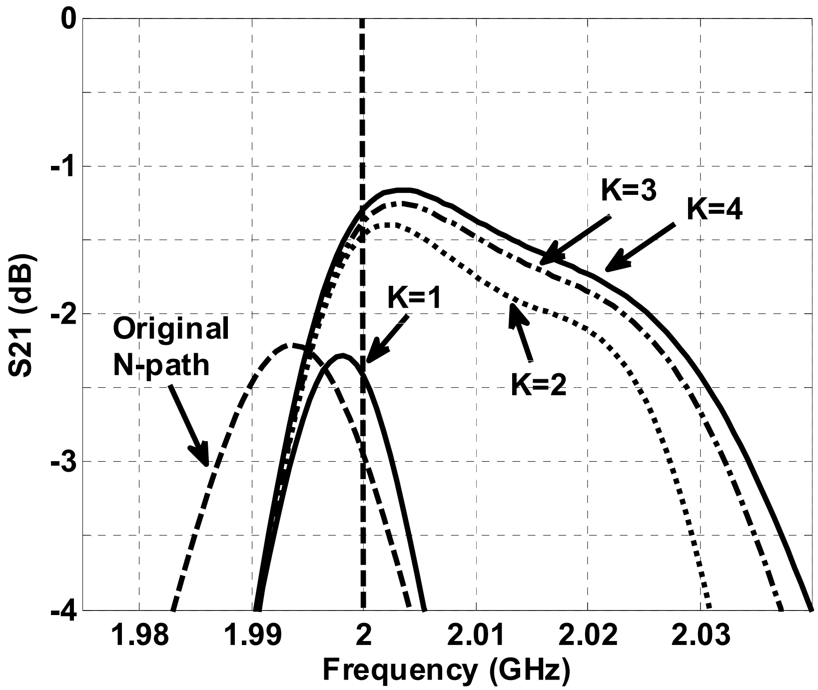
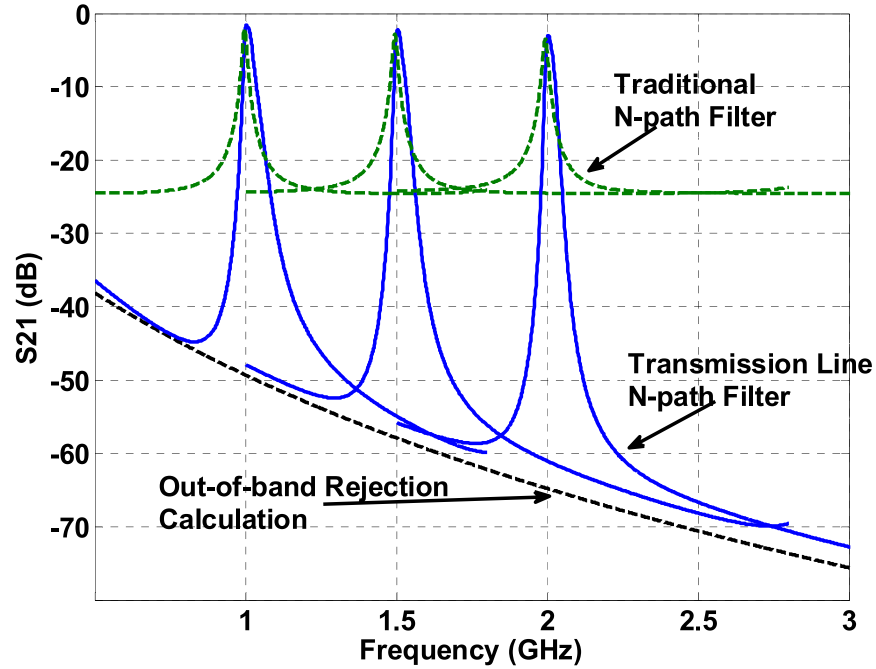
T-Line N-path Filter Simulation Results





$$S_{21}\left(S\right) \approx 8R_s R_{on}^K / \left(S^{K+1} L^{K+1}\right)$$

Out-of-band rejection approximation with T-line

- Parasitic capacitance absorbed into transmission line improving in-band insertion loss.
- Out-of-band rejection improved by further low-pass filter created by L and R_{on}.

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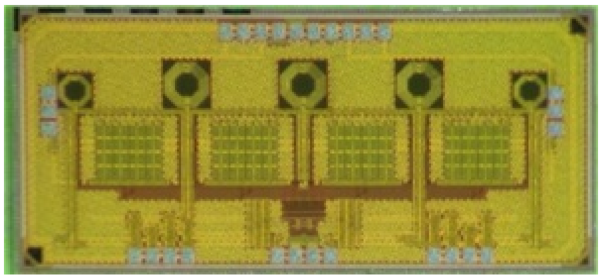
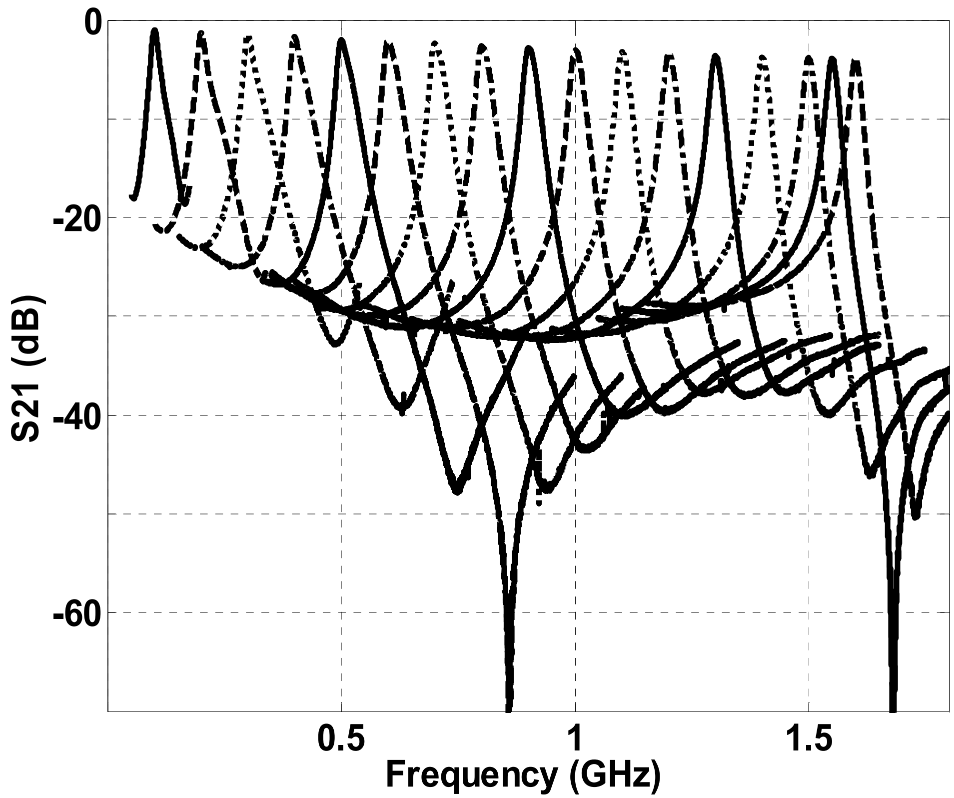
T-Line N-path Filter Measurement Results



Chip micrograph (3mm x 1.4mm).

K = 4, L/K = 3.8 nH, Q_{ind} = 16 at 2 GHz, Selfres = 7.5 GHz

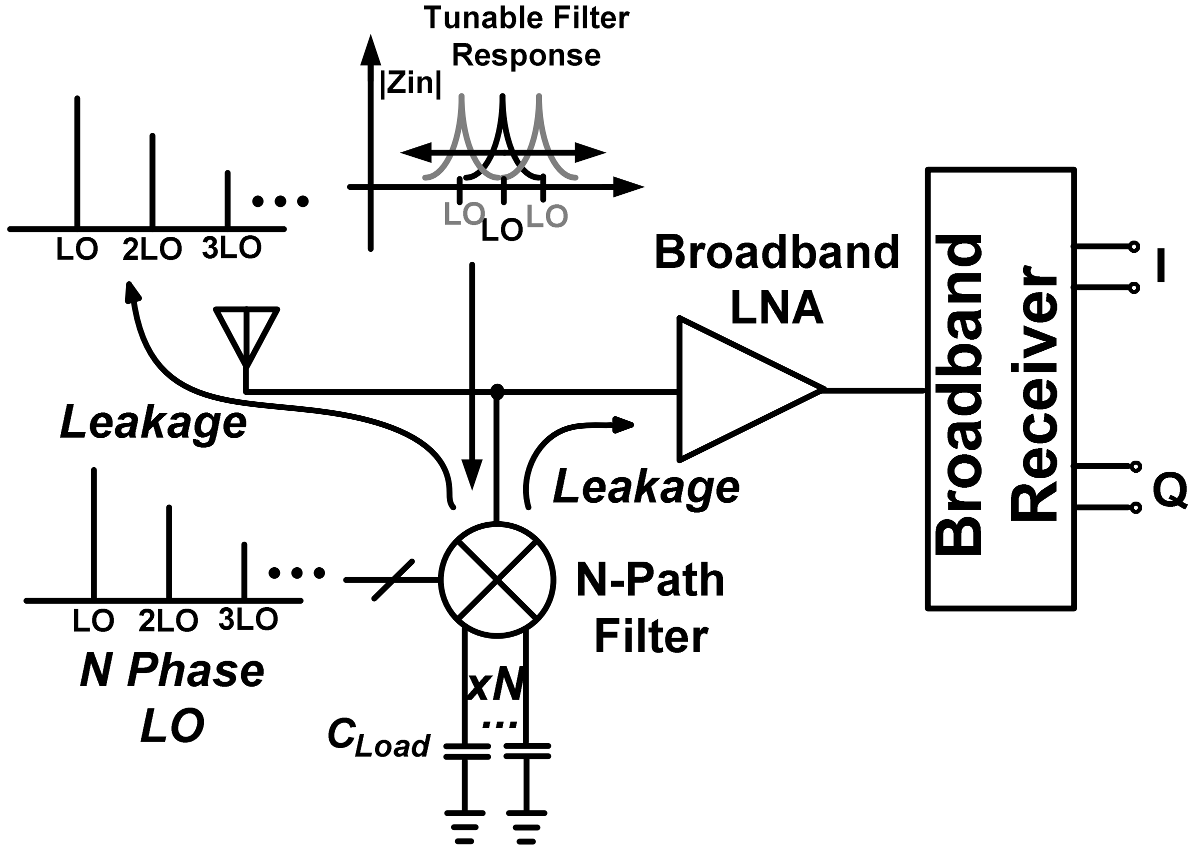


- Parasitic capacitance absorbed into transmission line improving in-band insertion loss.
- Out-of-band rejection improved by further low-pass filter created by L and $R_{on.}$

T-Line N-path Filter Measurement Summary

	This Work	Ghaffari Nauta 2011	Darvishi Nauta 2013	Darvishi Nauta 2013	Thomas Larson 2014
Technology	65 nm	65 nm	65 nm	65 nm	65 nm
Frequency Range	0.1–1.6 GHz	0.1–1 GHz	0.4–1.2 GHz	0.1–1.2 GHz	0.5-1.5 GHz
Out-of-band Rejection	30-50 dB	15 dB	55 dB	59 dB	31-53 dB
In-band IIP3	+29 dBm	+14 dBm	+9 dBm	-12 dBm	+4.9 dBm
Jammer P1dB Compression	+ 11 dBm	> +2 dBm	< +2 dBm	+ 7 dBm	+7 dBm
NF	1.5–5.4 dB	3–5 dB	9.7-10.5 dB	2.8 dB	5-10 dB
Power	30-200 mW	2–16 mW	21.4 mW	15-48 mA	50-200 mW

N-path Filter LO Leakage Problem



- Uncalibrated leakage can range from -50 to -70 dBm [3].
- FCC limits spurious out-of-band emissions to -70 dBm (often violated) [3].
- Desensitize receiver or create DC offset [3].

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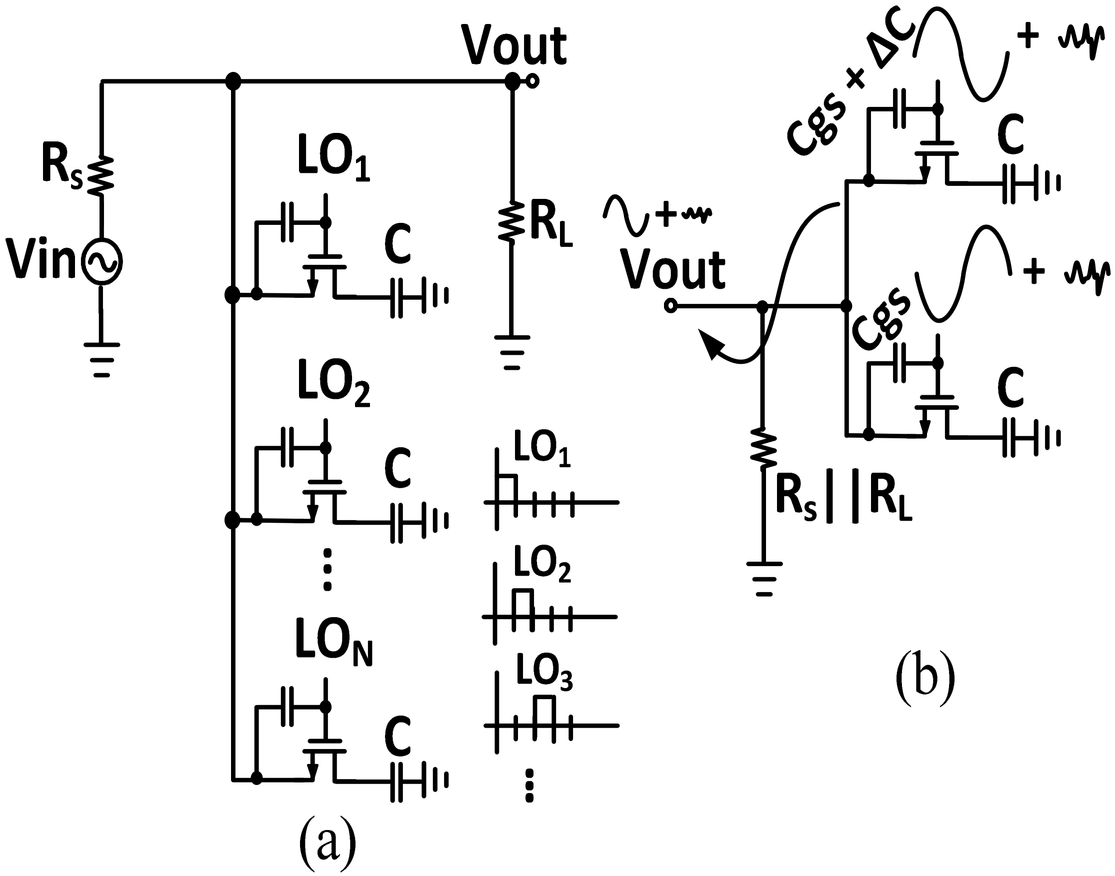
Mechanism of LO Leakage Radiation

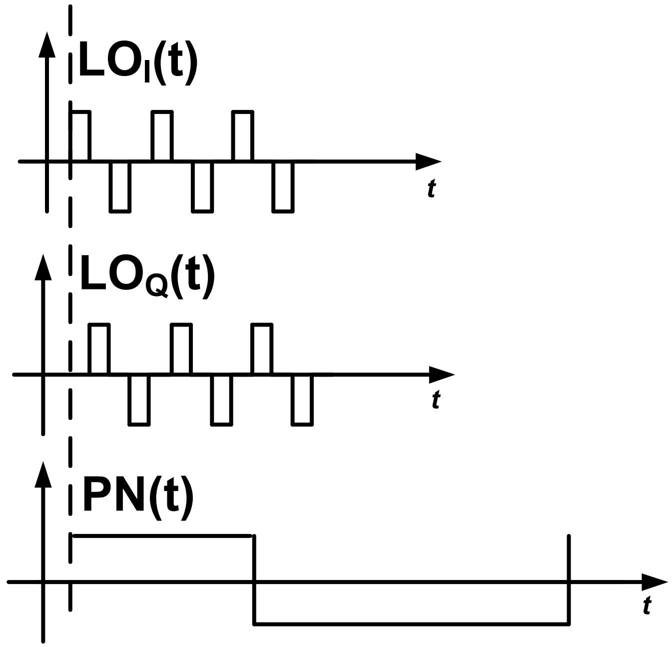


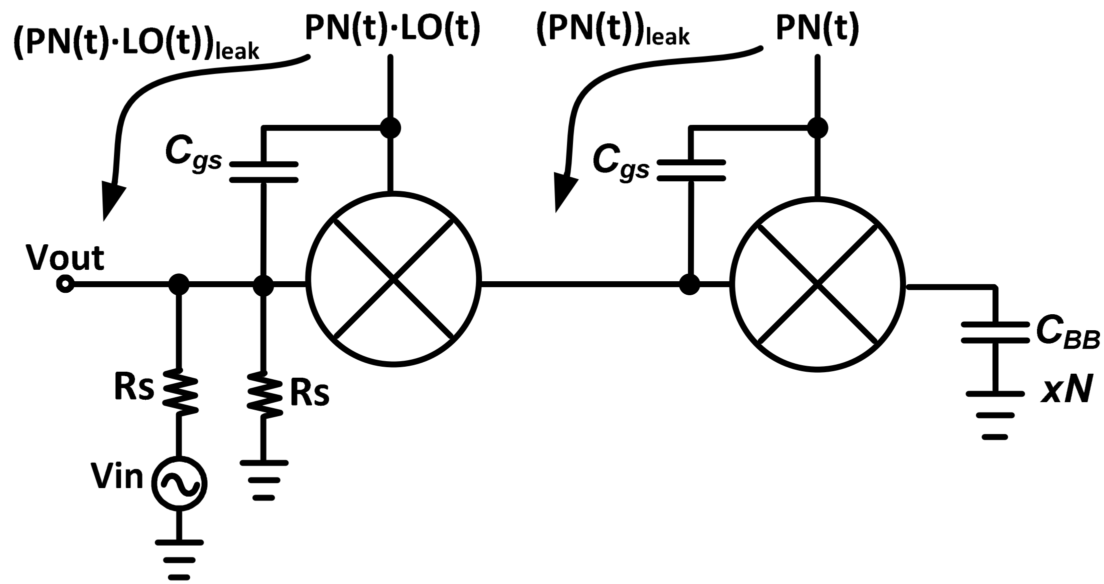
Differential LO feed-through proportional to:

$R_s \cdot \Delta C \cdot s$

- **Any** asymmetry leads to LO leakage.
- Differential LO feed-through directly proportional to parasitic capacitance mismatch and frequency.

Proposed N-path Filter with Pseudorandom Clocking



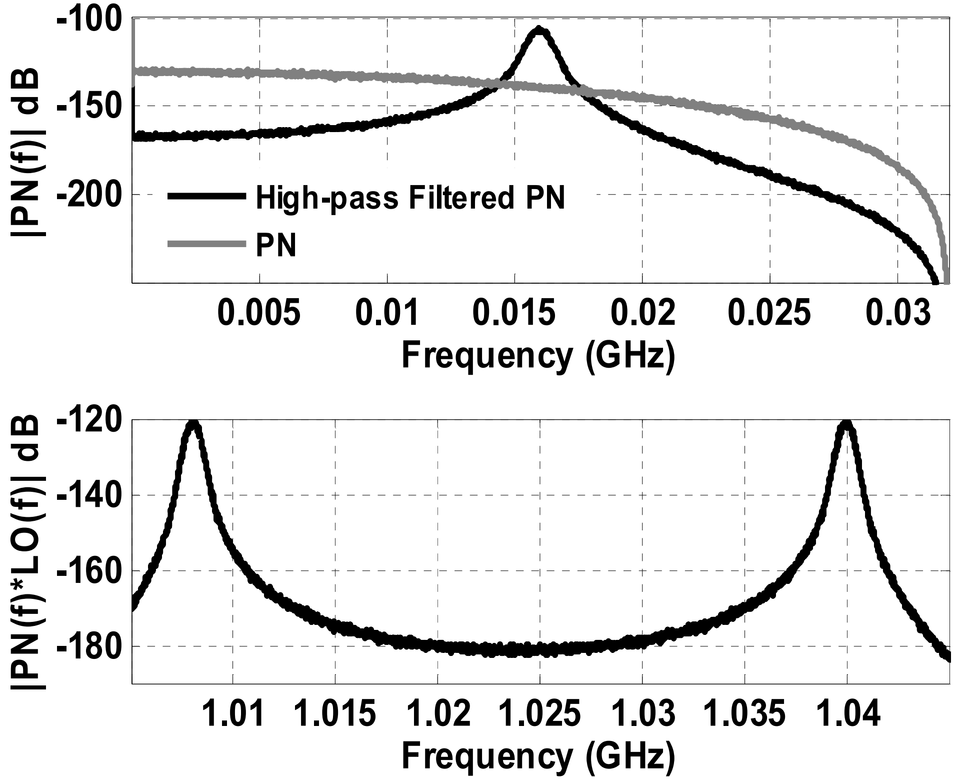


$$\mathbf{Leakage_{total} \approx (PN(t)\cdot LO(t))_{leak} + \{PN(t)\cdot LO(t)\}\cdot(PN(t))_{leak}}$$

Broadband Leakage — Tonal Leakage

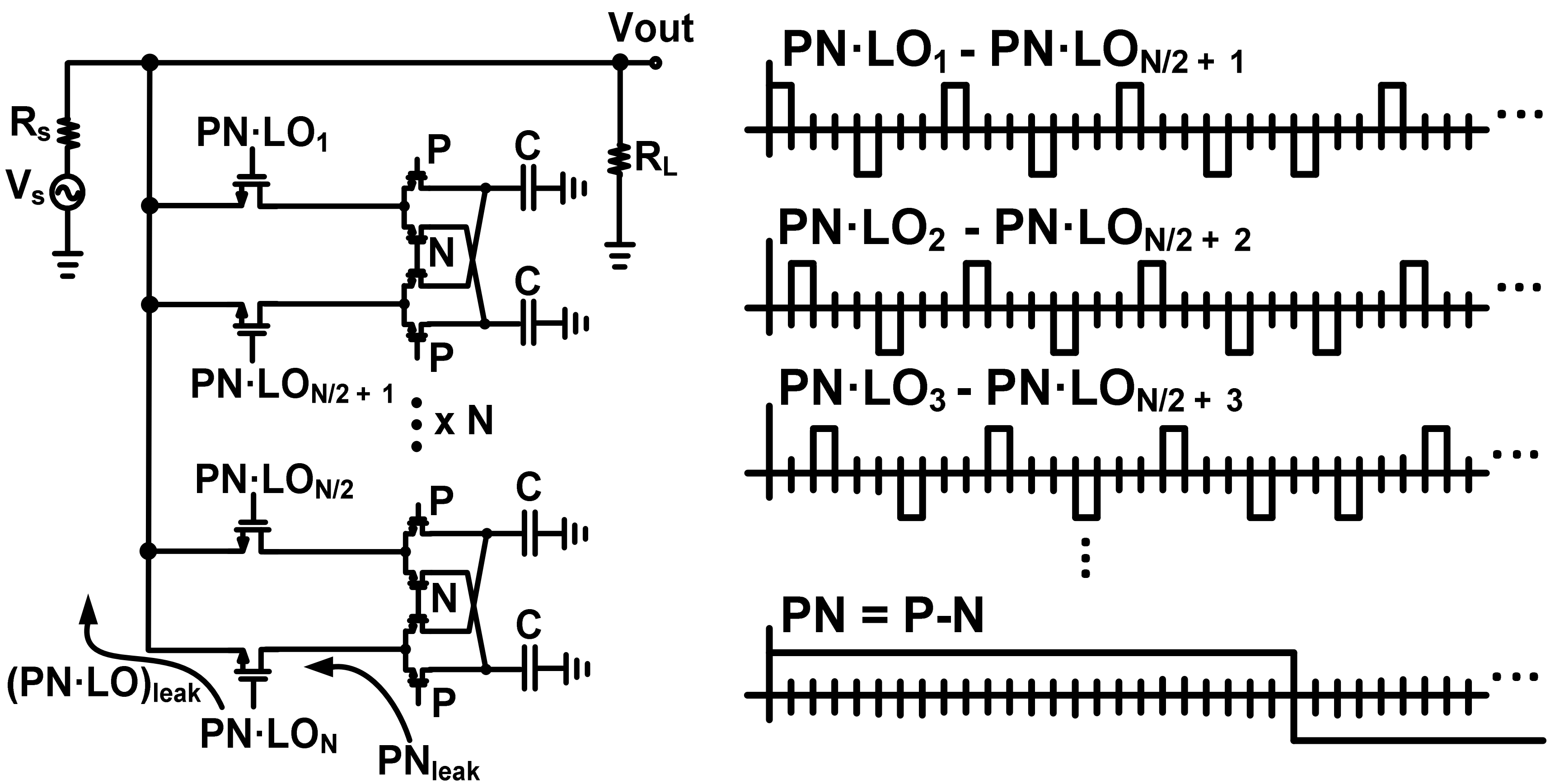
- Same transfer function utilizing: LO(t)·PN(t)·PN(t) = LO(t).
- PN(t) is a low frequency, broad-spectrum PN sequence.

Simulated PN Sequence Spectrum Shaping



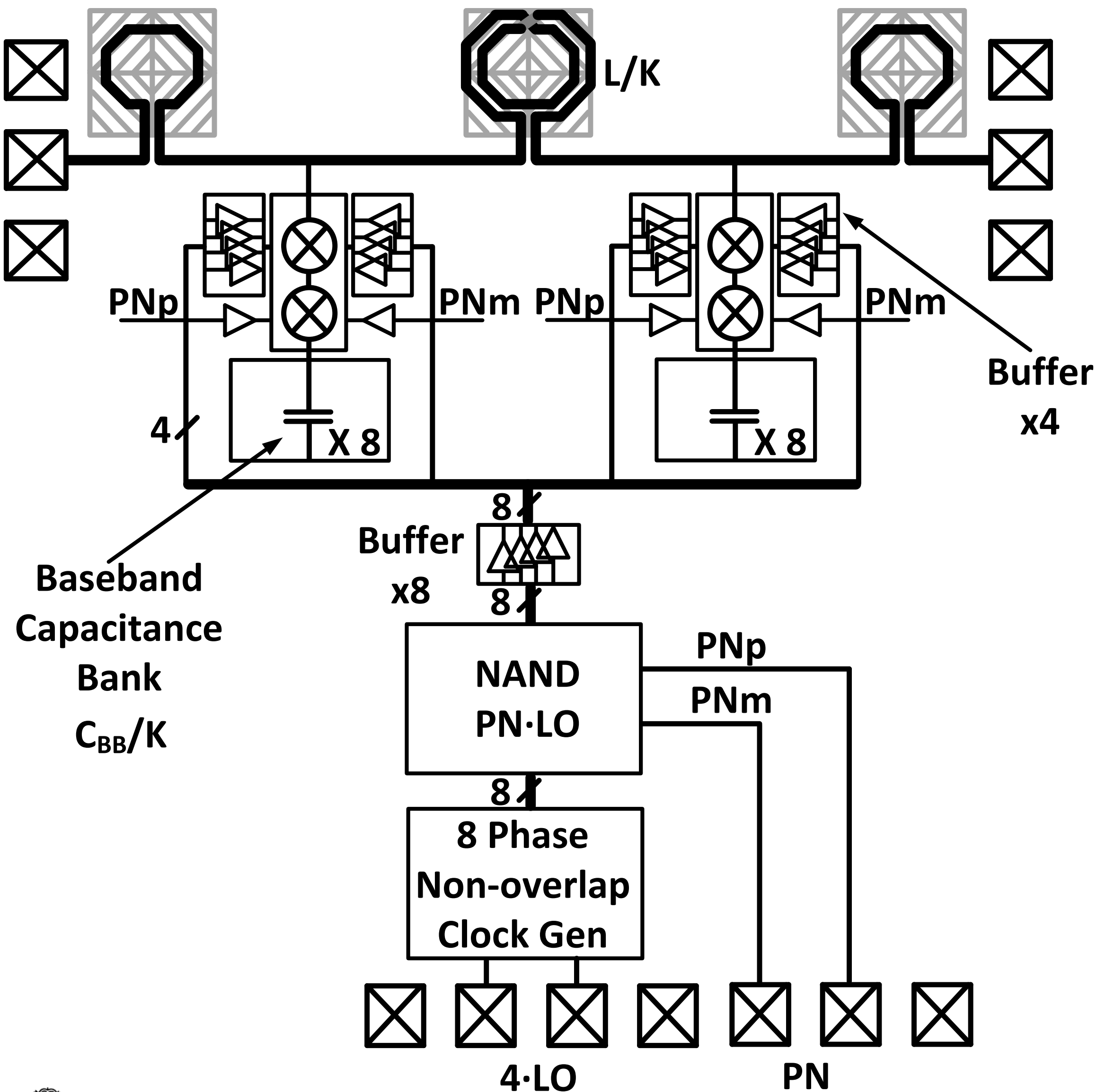
- Simulation of high-pass filtered PN (using iterative digital high pass: $1 - Z^{-1}$).
- Simulation of filtered PN(t)·LO(t) giving in-band null.

PN N-path Bandpass Implementation



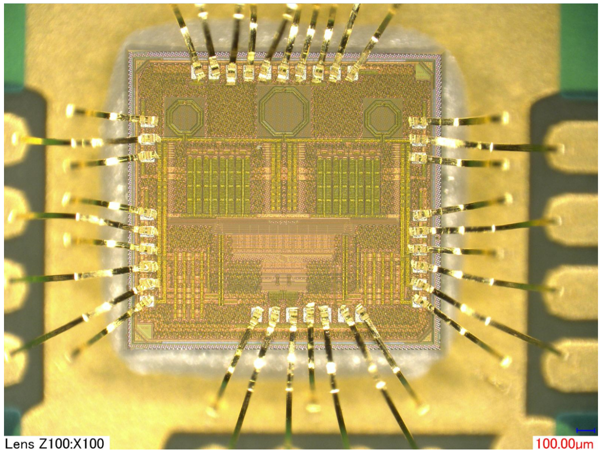
- Differential PN mixer to single-ended interface.

Two Stage T-Line N-Path Filter

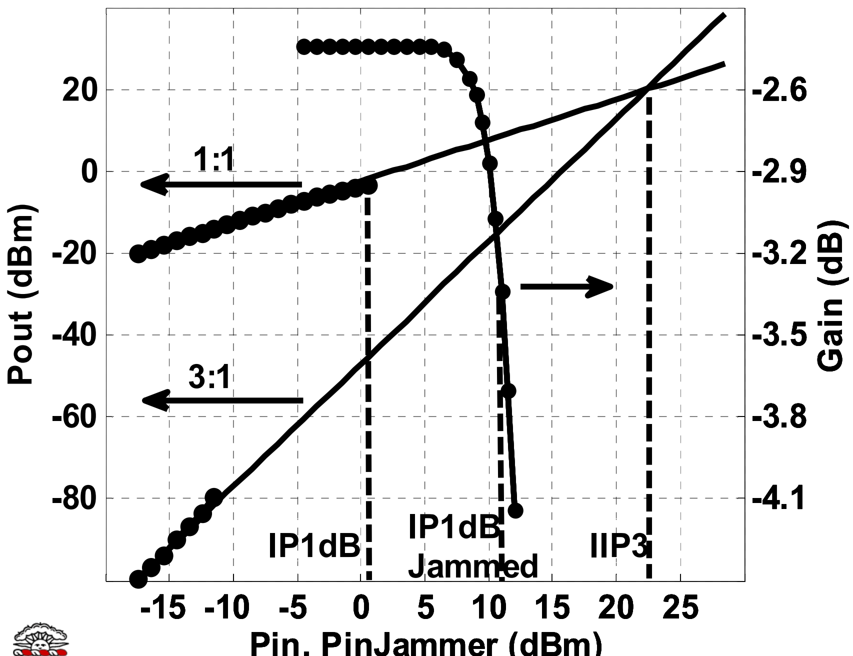


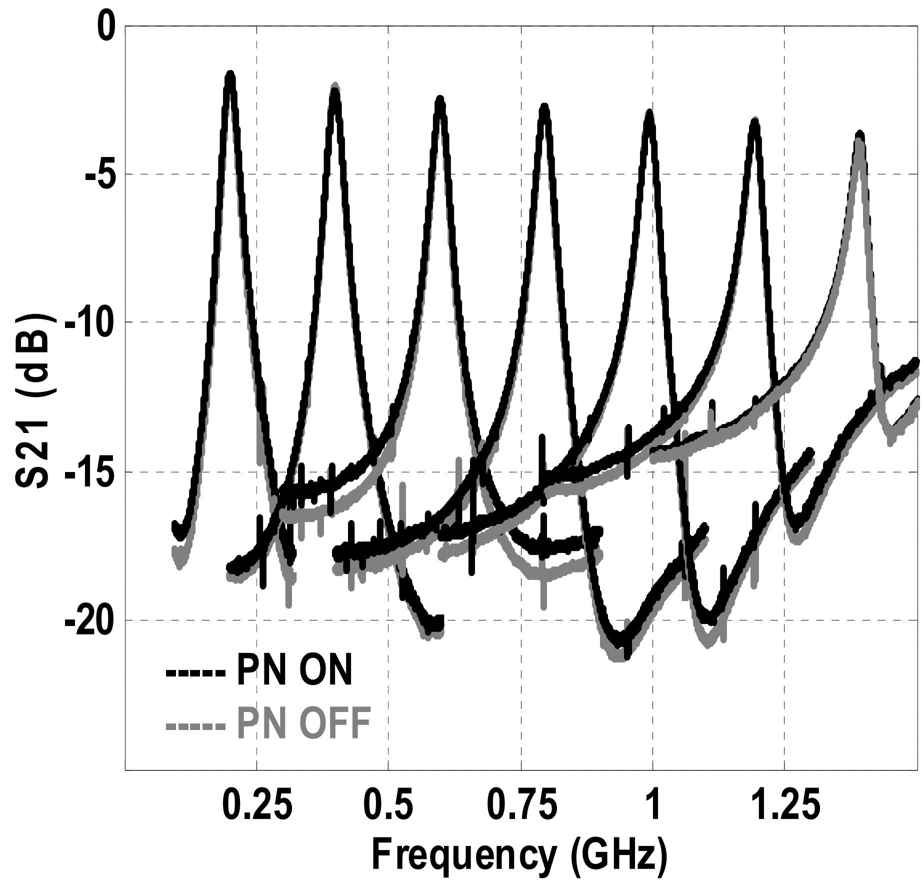
- T-Line N-path Filter Technique [5].
  - Ideally improve insertion loss
  - Ideally improve rejection
- Two Stage Design.

PN N-path Filter Measured Results



Chip micrograph (1.1mm x 1mm) in 65nm CMOS ribbon bonded to PCB.





- Minimal degradation with PN ON and OFF.
- Jammer IP1dB compression +11 dBm (600 MHz offset), In-band IIP3 +22 dBm.

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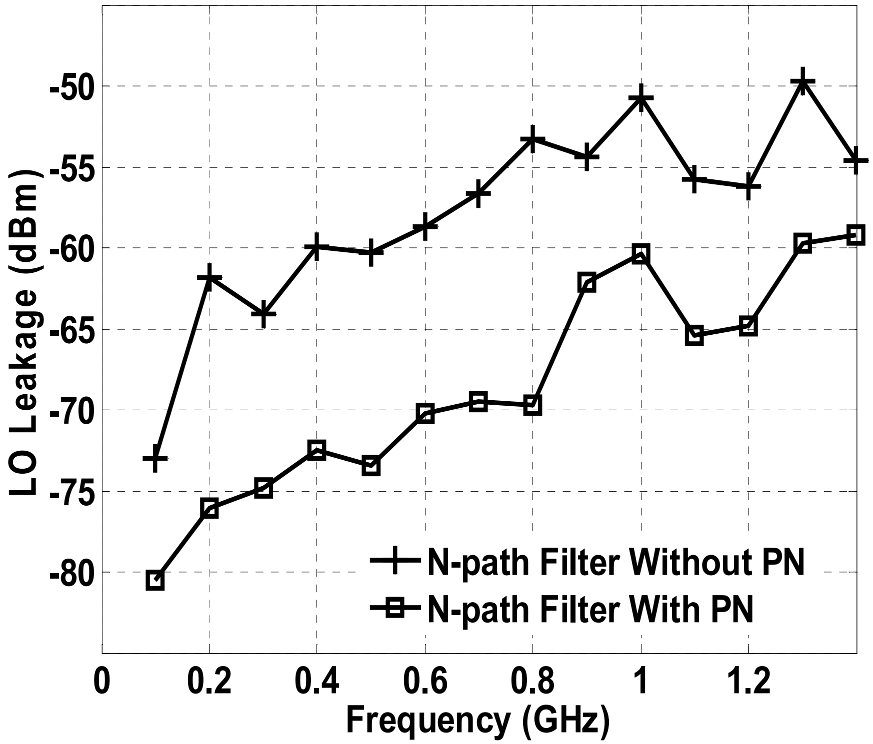
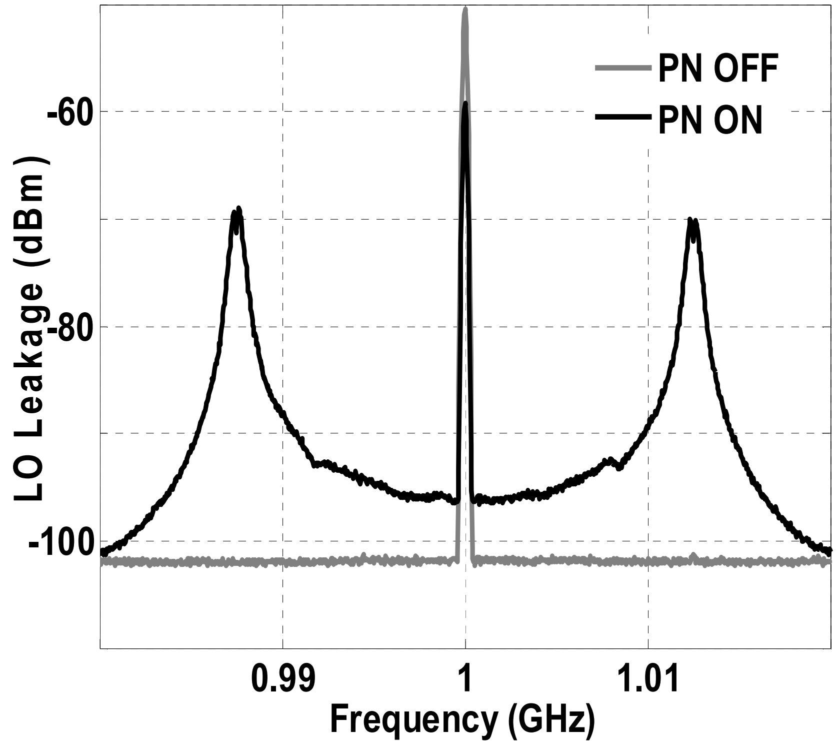
Measured LO Leakage Improvement





Measured in-band LO leakage at 1 GHz (RBW = 200 KHz, span = 40 MHz).

- LO Leakage improvement: 10 to 15 dB.
- High-pass filtered PN sequence spreads LO leakage replicating expected spreading shape.

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PN N-path Filter Measurement Summary

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Frequency Range	0.1–1.4 GHz	0.4–1.2 GHz	0.1–1.2 GHz	0.1-1.6 GHz
Out-of-band Rejection	15 dB	55 dB	59 dB	30-50 dB
In-band IIP3	+22 dBm	+9 dBm	-12 dBm	+23 dBm
Jammer IP1dB Compression	+11 dBm	< +2 dBm	+ 7 dBm	+10.1 dBm
LO Leakage	-60 to -80 dBm	< -60 dBm	-	-60 dBm
NF	2-5 dB	9.7-10.5 dB	2.8 dB	2.2-5.4 dB

Conclusions

- A broadband signal classification receiver faces many challenges, namely: front-end filtering
- Presented a broadband tunable T-line N-path filter that improves in-band insertion loss and out-of-band rejection of the traditional N-path filter
- Presented a PN sequence N-path filter that improves spurious leakage of the traditional N-path filter

References/Questions?/Thank You!

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