Low Power Low Cost RFIC Design for Pulse Based UWB

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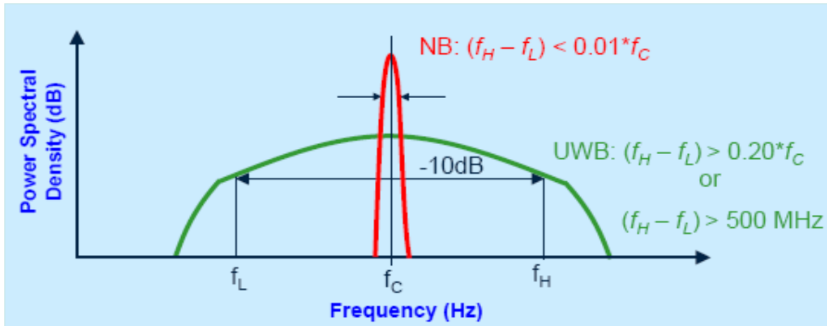
1. Introduction: UWB Signal



- Fractional bandwidth is greater than **0.2** or absolute bandwidth is greater than **500 MHz**
- Unlicensed spectrum 3.1 – 10.6 GHz
- Low power emission (< -41.3dBm/MHz) by FCC in 2002.

UWB Features

✓ **Advantages**

- Capability to deliver high data rate, proportional to bandwidth
- Low interference to existing applications due to low emission power
- Short range data communication (<10m)
- Robust to multipath, and fading (short pulse)
- Precise positioning (proportional to bandwidth)

✓ **Challenges**

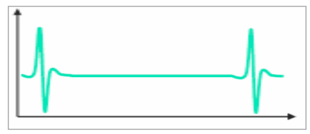
- Wideband circuit techniques
- Power constraint design
- Interference from NB transmitters: How to alleviate interference while maximizing efficient use of the spectrum (notch filtering, spread spectrum, adaptive filtering, etc.)?
- Antenna design

Impulse radio UWB (IR-UWB)

Uses extremely short pulses with duration on the order of nanoseconds to transmit information

✓ **Advantages:**

- Low duty cycle of pulses, the transmitter power can be small
- Carrier modulation is not required, no up and down conversion
- No need of RF power amplifier
- Simple architecture, low cost
- Robust to multi-path fading

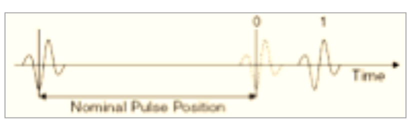


✓ **Disadvantages:**

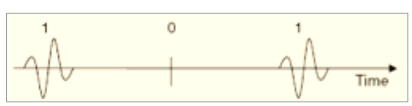
- Difficult to generate and send extremely short pulses
- Timing accuracy for short pulse reception, synchronization in the receiver.

IR-UWB: Modulation

PPM



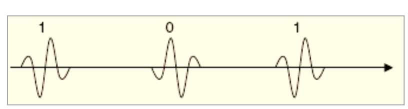
OOK



Suitable for low data rate radio

PAM

BPSK



UWB - Standard and Proposals

✓ **Time Hopped UWB (IEEE 802.15.4a Standard)**
- Old concept (radar)
- Impulse Radio (IR-UWB has been chosen for PHY)
- *Low/moderate data rate*

✓ **DS-CDMA UWB (IEEE 802.15.3a)**
- *High data rate*
- UWB Forum supporting DS-UWB

✓ **Multi-Band OFDM UWB (IEEE802.15.3a)**
- *High data rate*
- MBOA (MBO Alliance)

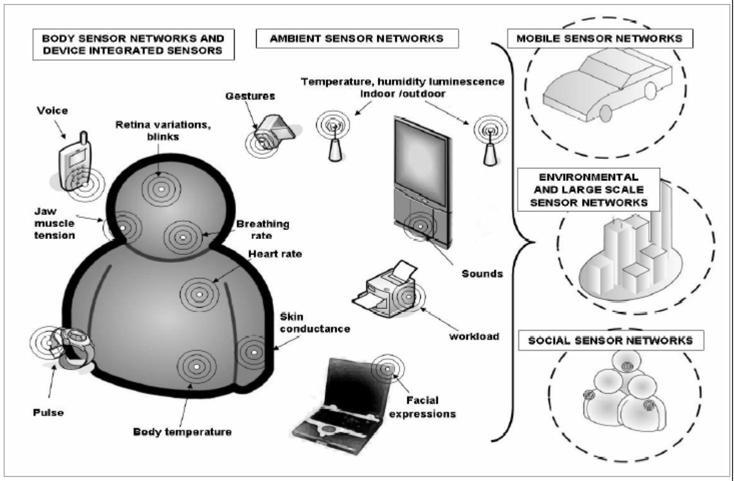
Applications of IR-UWB in WPAN

- Short range wireless communication, home network

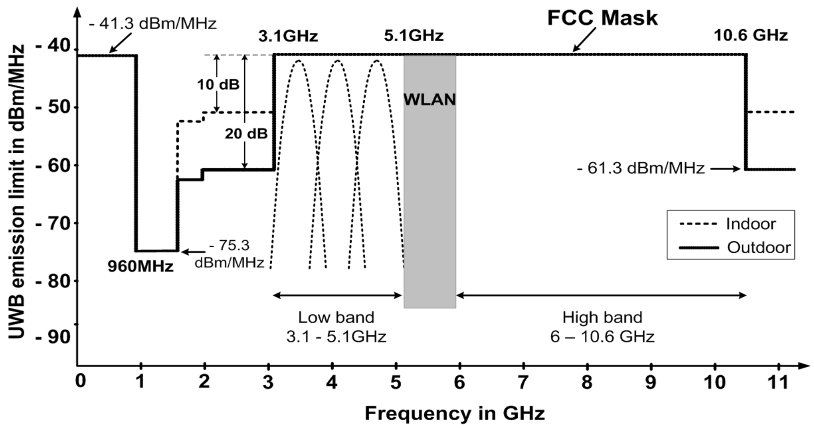
- Sensor networks (USN)

-Radar and Sensing: for Transportation, Police, Medical imaging.. Surveillance

- Tracking, localization like RF ID, TAG



FCC Spectrum Mask



- FCC Spectrum Mask and the frequency band of interest
- Three subbands with 520 MHz of bandwidth expected in this band

Choices of Architectures

➢ **Motivation: Low Complexity, Low cost, Low power dissipation for low data rate communication**

▪ **Conventional: Heterodyne or Direct conversion**

- High complexity
- High power dissipation
- Challenges in designing wideband building blocks

▪ **IR-UWB design approaches**

- Technology: CMOS
- Transmitter: no need of power amplifier
- No need of up/down conversion step
- Receiver: Analog approach for low power, low complexity and high level of integration

Receiver Architecture Consideration for IR-UWB

- **Coherent**

  - Input signal distorted after antenna → template signal not matched with incoming signal
  - Synchronization issue → complex circuit

- **RAKE**

  - Require number of fingers (bank of correlators) to gather signal power

- **Non-Coherent**

  + Energy Detection

  Pros: - OOK modulation, low complexity
  - Robust with clock jitter,
  - Relax distortion and phase non-linear requirement

  Cons: - Decision problem regarding determine optimal threshold
  - Simplicity vs Noise

  + Transmitted Reference (Autocorrelation)

  Pros: - 3dB better than ED

  Cons: - Required long and precise delay time (for integration time)

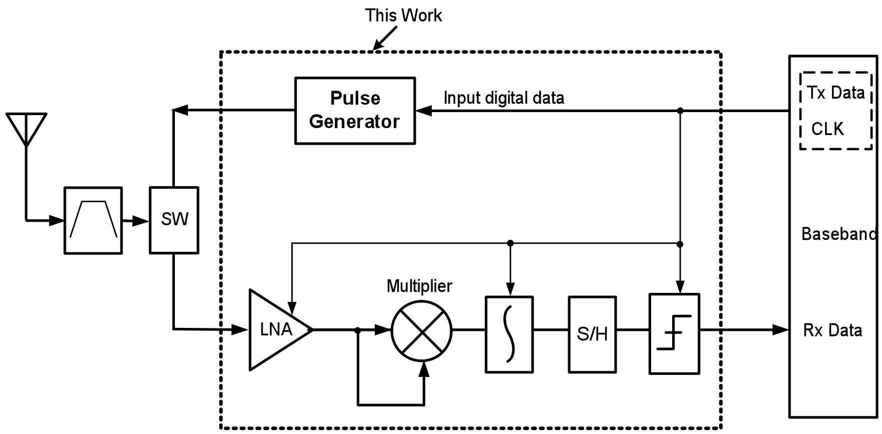
2. CMOS Transceiver Design

Impulse Radio UWB Transceiver

- **Proposed Pulse Generator**
- **Transmitter Design**
- **Energy Detection Receiver Design**

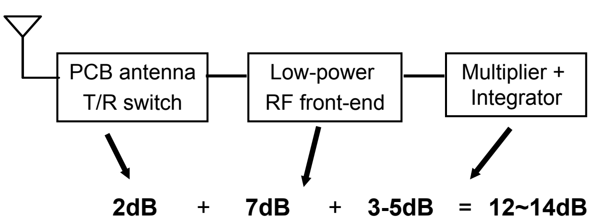
A. IR-UWB System Approach

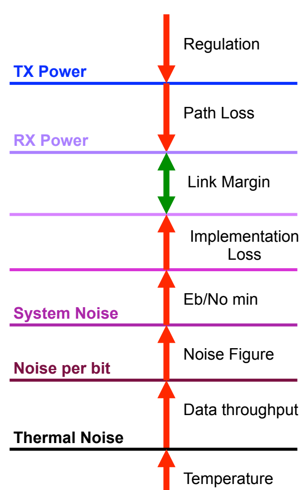
✓ **Proposed non-coherent architecture for LDR IR-UWB**



Link Budget: Loss

- **Implementation loss budget**





→ NF = 12 ~14 dB

LM = Pr-Pn-S(Eb/No)-I + PG

P_{min} = Pr- LM

- ***Duty gain: BW/PRF → reduce average NF***
- ***Processing gain: PG=10log(Np) → Improve SNR per symbol***

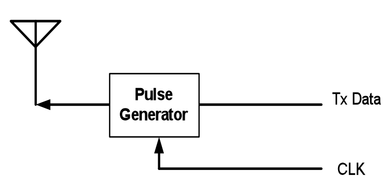
Design Specifications

	Specifications	Unit	Target	Condition
System	Frequency	GHz	3.1 ~ 5	Low UWB band
	Bandwidth	MHz	528	@ -10dB BW
	PRF	MHz	16	Variable
	Power Supply	V	1.5	TSMC 0.18um
Tx	Output Power	dBm	1.1	Peak Power
	Amplitude	mV	150-200mV	
	Pulse Width	ns	3~4	Real duration
Rx	NF	dB	12~14	
	Gain	dB	36 ~ 60	-30dBm @ Squarer Input

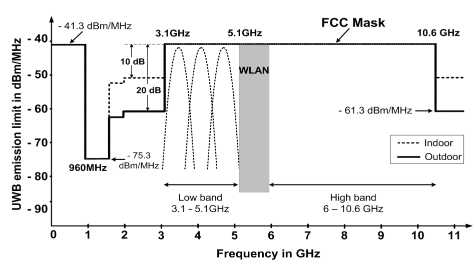
- Primary goal is low power, low complexity, low cost

B. Tx Design: Issues

✓ **Transmitter architecture**



- Simplify architecture, only pulse generator without PA
- Support OOK modulation



The FCC spectral mask to restrict the pulse power transmission

✓ **Requirement**

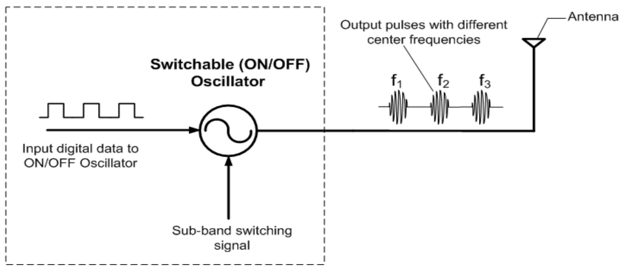
- Frequency range from 3.1 to 5.1GHz
- Three bands, 520MHz wide each

✓ **Challenges**

- Satisfy FCC spectral mask
- Low power, low complexity
- Band switching capability

Pulse Generation Principle

✓ **The key block in Tx**



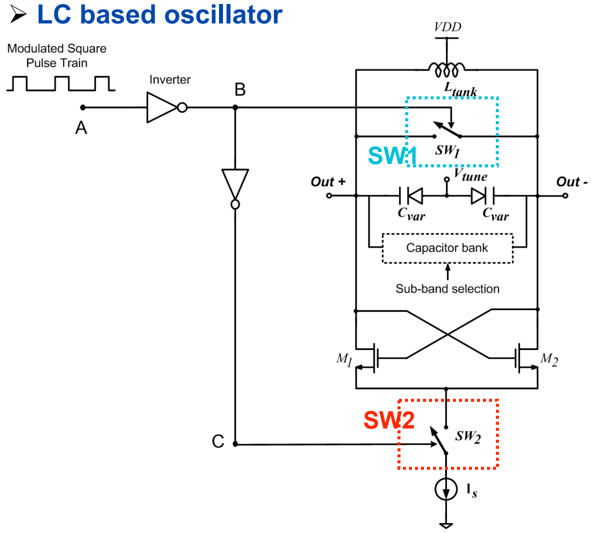
Proposed pulse generator concept

- Output pulse is generated by turning the oscillator ON/OFF
- Input square pulse train is used to control the oscillator operation
- Pulse BW is determined by input square pulse's duration

" The proposed Pulse Generator is Patent pending"

Proposed Pulse Generator

➢ **LC based oscillator**



- Two complementary switches **SW1**, **SW2**
- **SW2** helps remove baseline current dissip ation → save power
- **SW1** helps to obtain desired pulse envelope → good pulse PSD
- Input square pulse trai n is used to ON/OFF the oscillator operation

Pulse Envelope Analysis

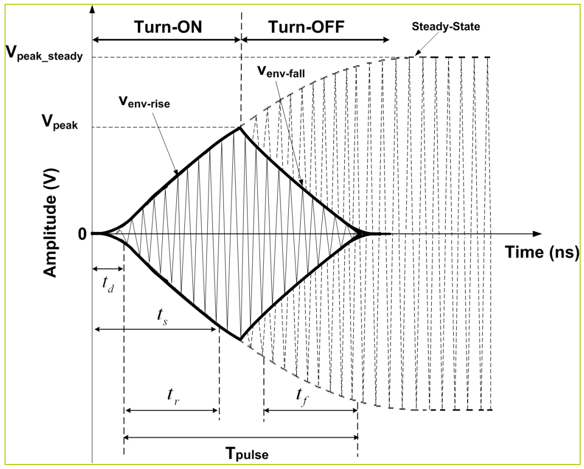
$$v_{env-rise} = 2V_{peak-steady}\, e^{(t-t_0)(A_{OL}-1)\omega_0/2Q}$$

$$t_r = t_s - t_d \approx 4.39\frac{Q}{(A_{OL}-1)\omega_0}$$

$$= 4.39\frac{1}{(A_{OL}-1)} \times CR_T$$

$$v_{env\text{-}fall} = V_{peak}\, e^{-t/\tau}$$

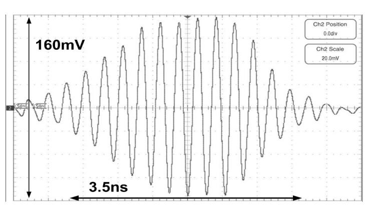
$$t_f \approx \tau \ln 9 = 4.39 CR_D$$



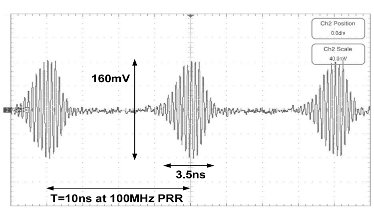
Pulse envelope determines its PSD shape

Measurement Results

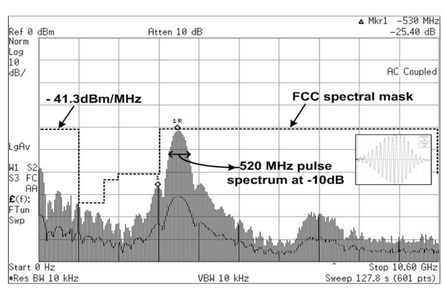
Measured Single Pulse



Measured Output Pulse Train



Pulse PSD in compliance with FCC Mask

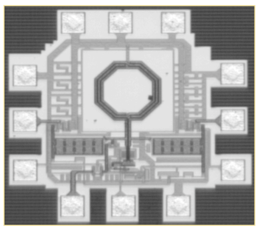


> 25dB of sidelobe suppression

Performance Summary

✓ Feature
- Ultra low power
- No static DC current consumption
- Low complexity, low cost
- FCC compliant pulse
- Large amount of sidelobe suppression
- Suitable for multiband operation

Parameters	Measured Results
Center frequency	3.8 GHz
Bandwidth	520 MHz
Peak power spectral density (PSD)	– 41.3 dBm/MHz
Sidelobe suppression	> 25 dB
V_{pp}	160 mV
Pulse duration	3.5 ns
V_{DD} / I_{DD}	1.5 V / 0 mA
Dynamic current at PRF of 100, 40, and 0.1 MHz	1120, 450, and 1.13 μA, respectively
Energy consumption per pulse	~ 16.8 pJ
Chip size	560 x 550 μm^2
Technology	CMOS 0.18 μm



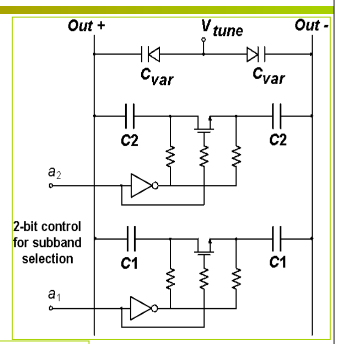
Die size 560 μm x 550 μm

***Tuan-Anh Phan**, JeongSeon Lee, Vladimir Krizhanovskii, Le Quan, Seok-Kyun Han, and Sang-Gug Lee, "Energy-Efficient Low-Complexity CMOS Pulse Generator for Multiband UWB Impulse Radio," IEEE TCAS-I,2008*

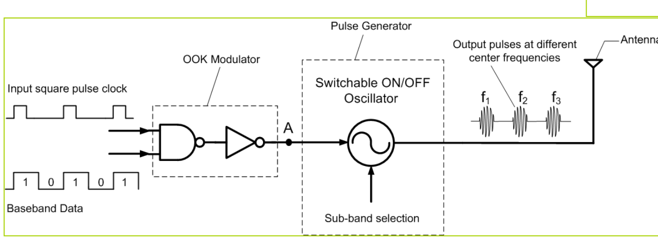
Tx IR-UWB Design

✓ **Added feature**
- OOK modulation
- Band switching capability

Capacitor bank

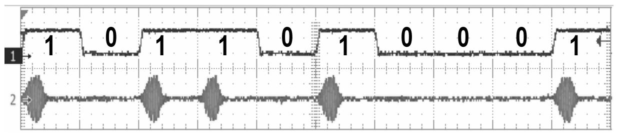


Proposed transmitter with OOK modulation



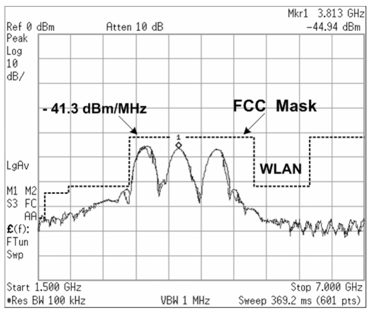
Tx IR-UWB Measurement Results

OOK data stream and modulated pulse train

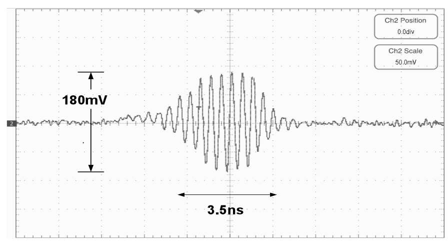


Maximum pulse rate ~200 MHz

3 sub-bands with 500MHz BW

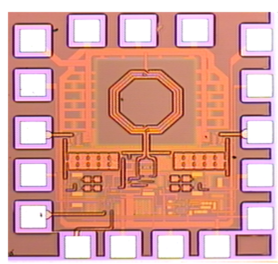


A single impulse



Tx Performance Summary

Parameters	Measured Results
Sub-band center frequencies	3.2, 3.8, and 4.4 GHz
Bandwidth	520 MHz
Peak power spectral density (PSD)	– 41.3 dBm/MHz
Maximum sidelobe suppression	> 20 dB
V_{pp}	180 mV
Pulse duration	3.5 ns
Dynamic current at PRF of 0.1, 40 , and 100 MHz	1.2, 486, and 1215 μ A, respectively.
Energy consumption per pulse	~ 18 pJ
V_{DD}	1.5 V
Chip size	580 x 680 μm²
Technology	CMOS 0.18-μm



Core die size 580 x 680 μm²

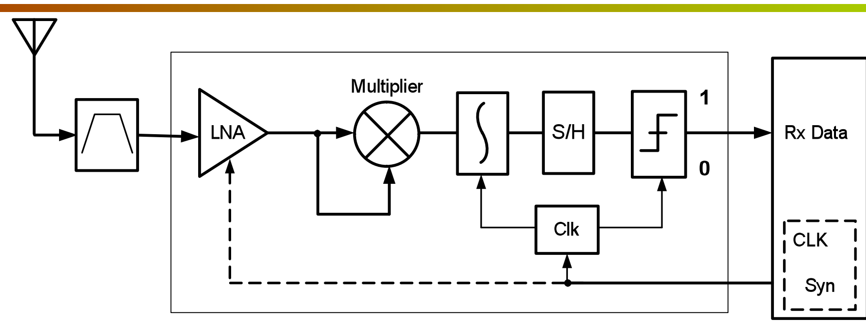
Transmitter Summary

✓ **Main Advantages:**

- Output pulse PSD compliant with FCC mask.
- No static current dissipation, only dynamic current which is proportional to PRF.
- Pulse center frequency can be changed, switchable for multi-band.
- Support OOK modulation.
- Simple circuit, very compact in size leading to low complexity low cost.

Tuan-Anh Phan, *JeongSeon Lee, Vladimir Krizhanovskii, and Sang-Gug Lee, "A 18 pJ/pulse OOK CMOS Transmitter for Multiband UWB Impulse Radio," IEEE Microwave and Wireless Components Letter (MWCL), Sept. 2007.*

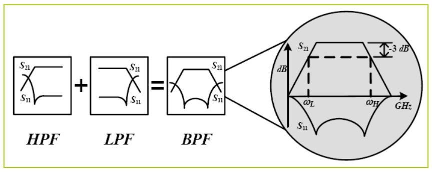
C. Energy Detection IR-UWB Receiver



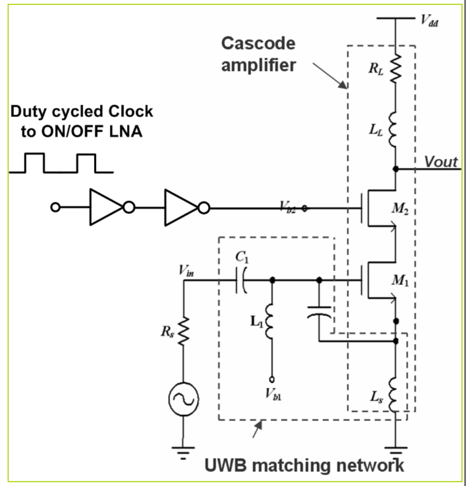
- Simplicity, low cost and low-power
- Multiplier acts as Squarer for energy collection, no need of synchronization, avoid performance degradation due to timing jitter
- Gating ON/OFF the whole Rx to reduced the baseline power dissipation
- Able to recover the input data, acquisition based on Threshold estimation
- Narrow band interference can be blocked using BPF
- 1.5V supply in 0.18um CMOS, fully integrated with analog solution

IR-UWB LNA

➢ **Wideband LNA is the most power hungry block in Rx**

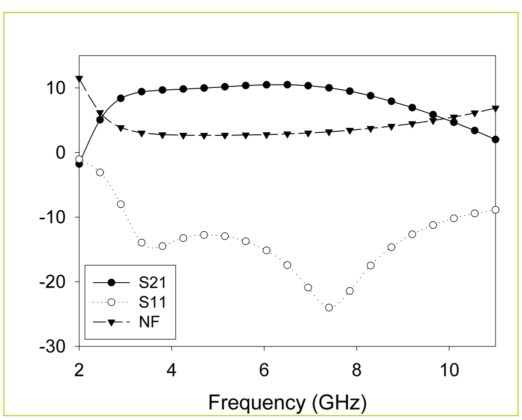


- LC filter combined with cascode topology
  → lowest NF among wideband LNA design techniques
- 1.5 Supply
- Gating ON/OFF to reduce the baseline power consumption



UWB LNA Schematic

IR-UWB LNA: Simulation

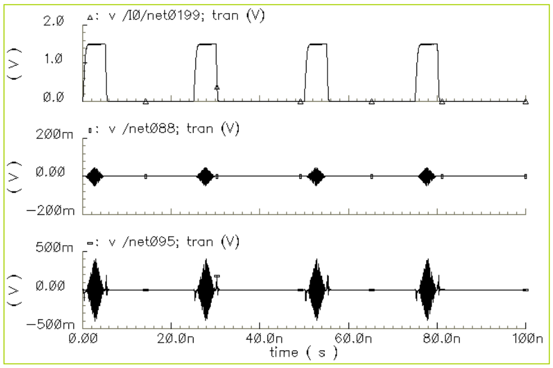


Continuous LNA S-parameter, NF performance

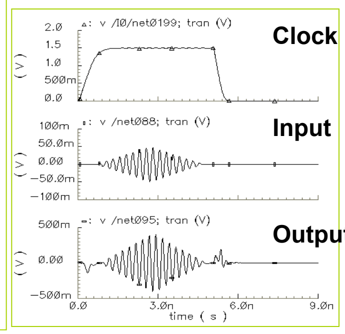
Band Width [GHz]	**3 ~ 8**
Max Gain [dB]	**10.5**
NF [dB]	**Min: 3.2 @ 4.9 GHz**
	Max: 3.9 @ 8 GHz
IIP3 [dBm]	**0**
Input matching (dB)	**<-12**
Static current / Supply [mA / V]	**3.5 / 1.5**

ON/OFF Transient

- Clock is applied at the CG Transistor [W] reduce settling time (5ns)
- ON/OFF UWB LNA reserves wideband characteristic
- Voltage gain is around 12 dB



Input and output transient of the ON/OFF UWB at PRF of 40MHz

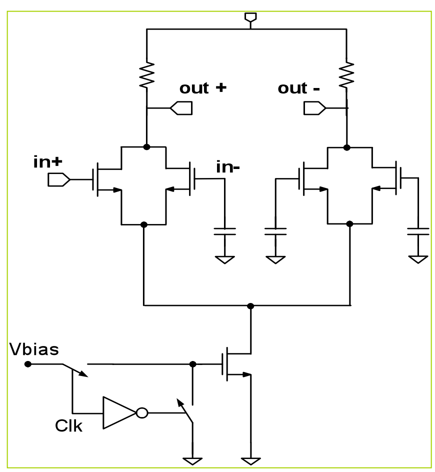


Transient of one period

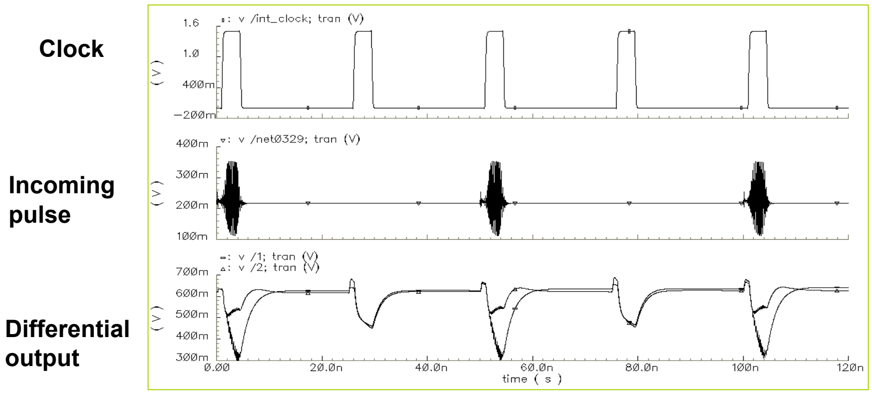
Gated Active Squarer

- Gilbert Cell based multiplier
- Higher Gain
- Gated current source [W] No static power dissipation
- Using square law

$$V_{out} = kV_{in}^2 + DC - DC$$
$$= kV_{in}^2$$



Gated Active Squarer

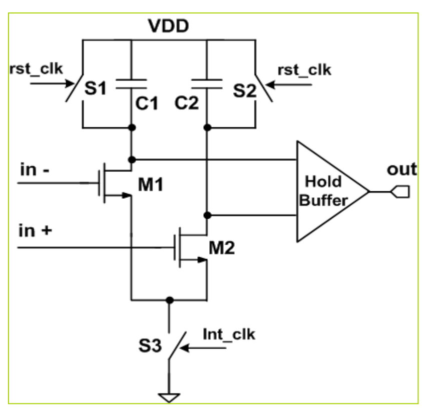


- Average energy consumption per pulse (at 40MHz PRF) is 4.9pJ

Analog Integrator

- Integration is proportional to the amount of discharge on $C_{1,2}$
- $C_{1,2}$ are fully charged at first
- Base band Input signal after squarer turns on $M_{1,2}$ to create the path for discharging
- Higher input, larger discharging current
- $S_{1,2}$ for reset for each integration
- S_3 to remove the static DC dissipation
- Hold buffer is just amplifier

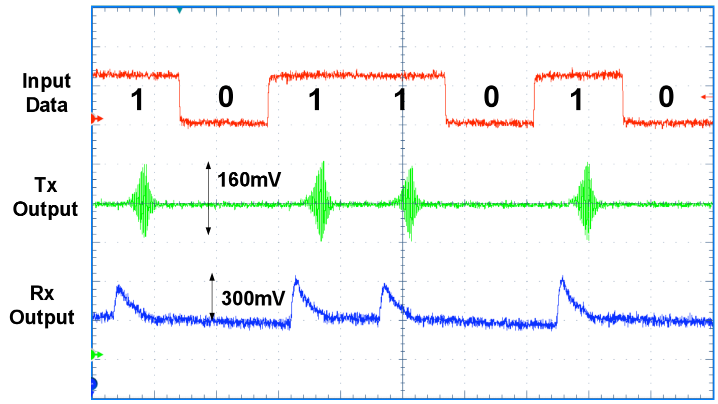
[From K. Vladimir]



Analog integrator (*)

(*) Vladimir Krizhanovskii, Tuan-Anh Phan and Sang-Gug Lee, "Analog pulse correlator for 3.5-5 GHz impul se radio ultra-wideband receiver," submitted for publication.

Measurement Results

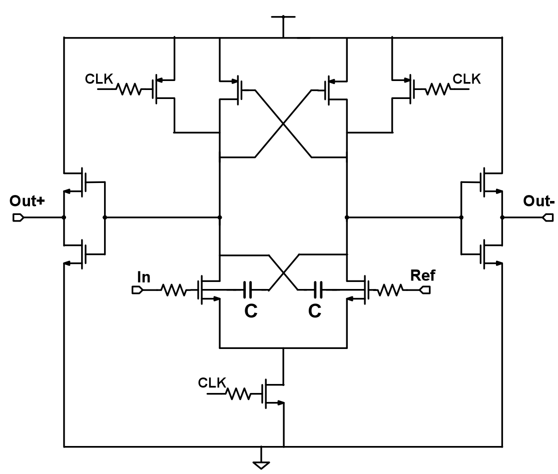


Measured output pulse trains of the Tx and Rx with the 100MHz OOK data pulse train at the input

__Tuan-Anh Phan__, Vladimir Krizhanovskii, and Sang-Gug Lee, "Low-Power CMOS Energy Detection Transceiver for UWB Impulse Radio System," IEEE Custom Integrated Circuits Conference (CICC' 07), San Jose, CA, USA, Sept 2007.

Comparator Block

- Dynamic latched comparator
- No static power dissipation
- Resolution: few 10mV
- Extra Cap to remove the overshoot of clock

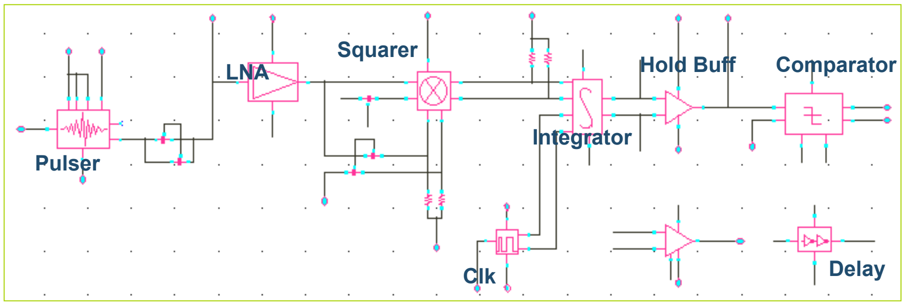


- Average power dissipation ~6.3pJ/pulse

Dynamic latched comparator

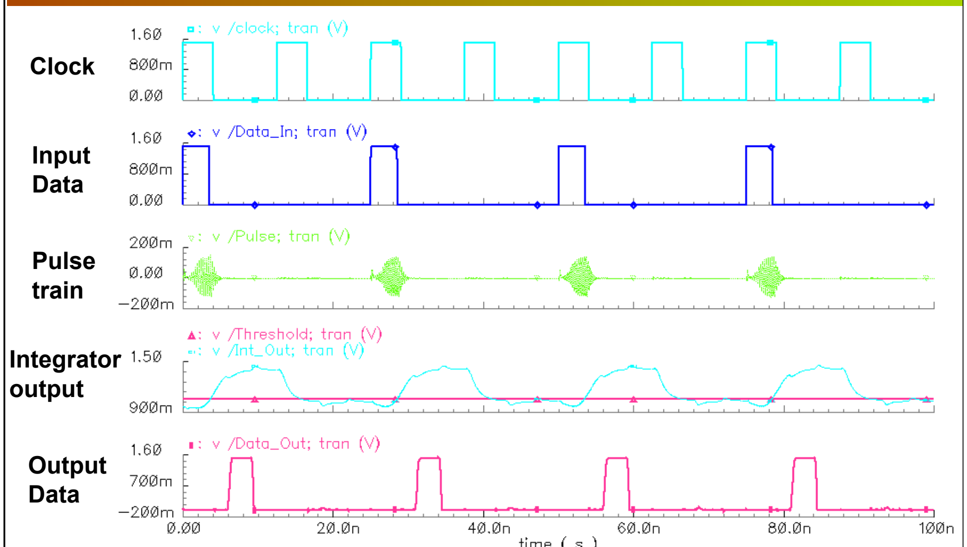
Complete Energy Detection Receiver

✓ **Rx simulation**

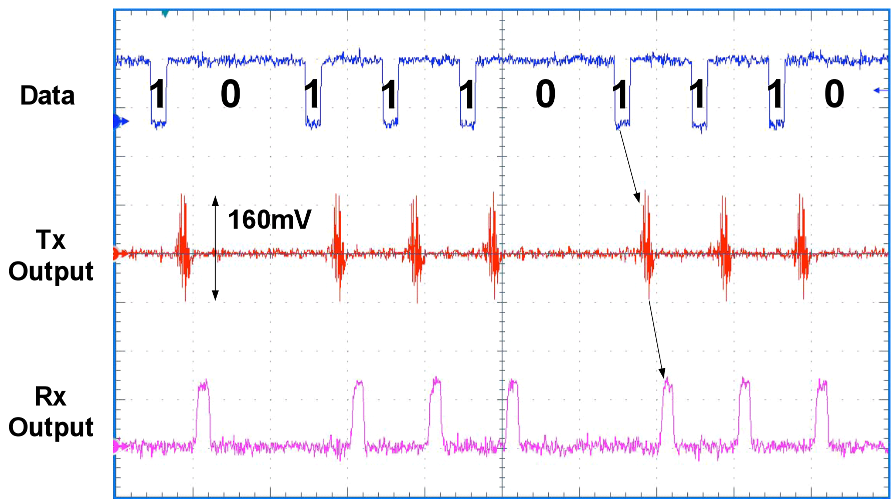


- Pulse train from Tx act as input signal of the receiver to test the Rx operation

Transient Timing Diagram



Measurement Results: Transient



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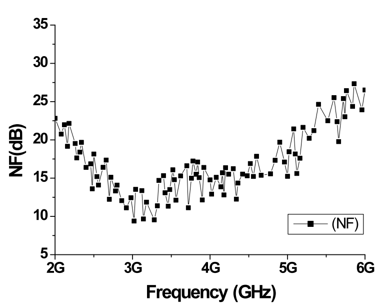
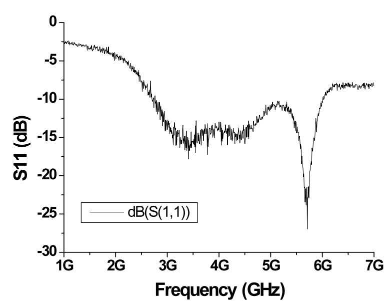
Measurement Results: NF and S11

- Measured receiver front-end NF



- Average NF is around 13.5dB over the 3-5GHz band

- Measured receiver input matching S11



- S11 <-10 dB in 3-5 GHz range

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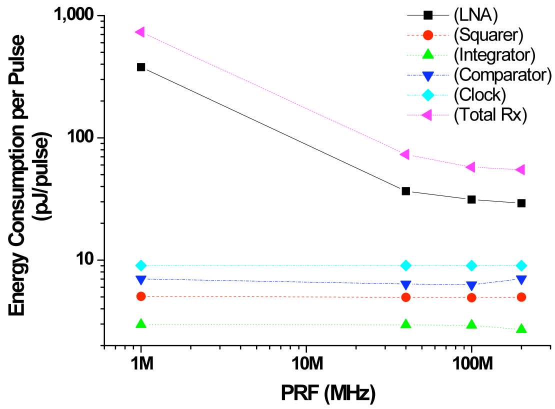
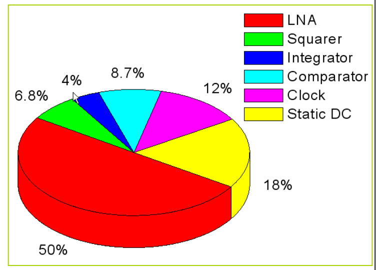
Power Dissipation

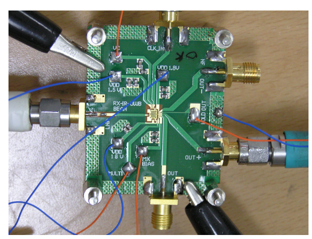


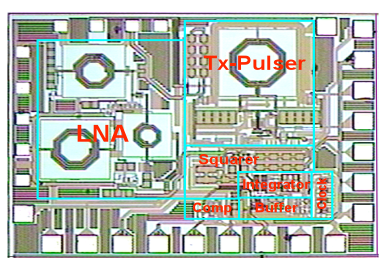


- Static DC current: 450uA
- Average power dissipation: ~ 73pJ/pulse
- At low PRF, leakage and static DC currents dominate energy efficiency

Performance Summary

Parameters	Measurement Results
Operation frequency range	3-5 GHz
Subband bandwidth / Center Freq	528 MHz / 3.8 GHz
Min detectable input	– 60 dBm (Sim)
S11	< -10 dB in 3-5 GHz band
NF	~ 13.5 dB
Dynamic power dissipation	~73 pJ/pulse
Static DC current consumption	450 μA
V_{DD}	1.5 V
Core chip size	1.3 mm^2
Technology	CMOS 0.18-*μ*m





Chip photo of the Tx/Rx, 1.1 x 1.5 mm^2

Conclusions

✓ A new pulse generation technique is proposed
- Energy efficient, ultra low power, low complexity
- Fully satisfy FCC spectral mask
- Multiband operation

✓ Energy Detection Receiver Architecture is best suited for low data rate (LDR) IR-UWB system
- Low complexity, low power
- No need accurate timing for synchronization
- Relax accuracy requirement of pulse center frequency

✓ Building blocks
- Highly integrated using CMOS
- Energy efficient design by removing static current dissipation

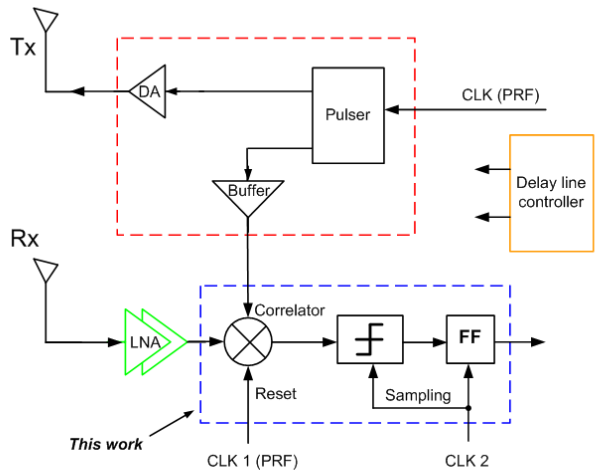
Feasible energy efficient, low cost IR-UWB transceiver

RF Design Consideration

✓ Design and simulation
- PVT and frequency shift are significant
- Bond and pad models should be included
- Separate analog and digital GND and VDD
- Design with wide frequency tuning range
- Confirmed with post-simulation is a must

✓ Layout and PCB
- Small devices and short signal path: reduce parasitic
- Guard ring for different blocks: RF and digital
- The less numbers of Pads, the higher chance of chip working

3. IR-UWB for Radar



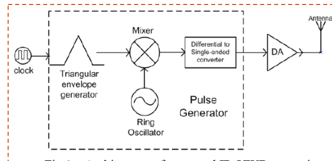


Fig 1. Architecture of proposed IR-UWB transmitter

Tx:
- **540mV**
- **20dBr sidelobe rejection**

Rx:
- **Coherent approach**
- **Reduce misdetection due to jamming environment**

Transceiver architecture of the UWB pulse radar.

Operation

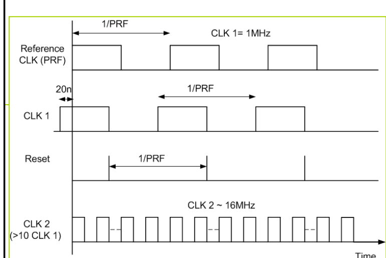


Fig. 1. System clock timing.

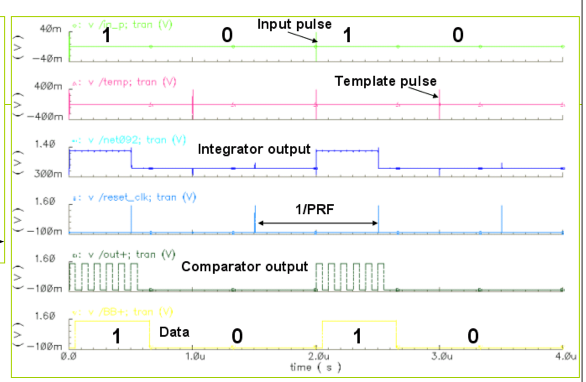


Fig. 2. System with input and output transient simulation.

Anh Tuan Phan, Ronan Farrell, Min-suk Kang, Seok-Kyun Han, and Sang-Gug Lee, "Low-Power Sliding Correlation CMOS UWB Pulsed Radar Receiver for Motion Detection," *IEEE International Symposium on Circuits and Systems (ISCAS' 09)*, Taipei, Taiwan, May 2009.

4. Future Plan

➢ Research direction on IR-UWB

- Improve the performance like the sensitivity: more gain stages
- Include the Antenna for design and test
- Other approach for Tx (digital synthesized pulser) and Rx (other than non-coherent ED)
- Design with other alternative approach, such as differential transmitted correlation receiver (DTR)

Differential Transmitted Reference (DTR)

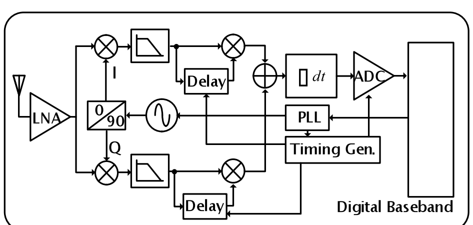


Fig. 1: DTR UWB Receiver with an envelop detection scheme

- Reduced freq, mismatch, relax ADC
- Provide good correlation template
- Avoid multipath signals

-> Improve SNR and BER
-> More accurate correlation, remove false alarm

→ At the Cost of more complex and high power dissipation

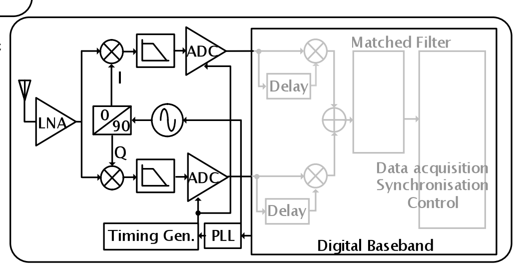


Fig. 2: Fully Digital DTR UWB Receiver with an envelop detection scheme

Thank you !