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Optical Phase-Locking and Wavelength Synthesis

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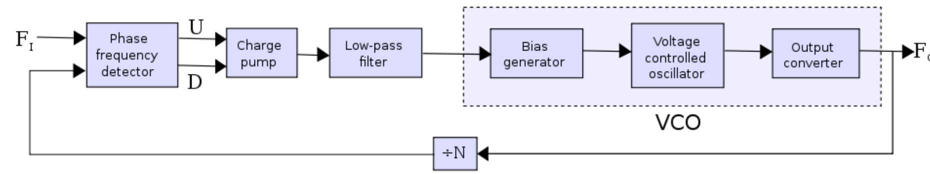
Teledyne Scientific

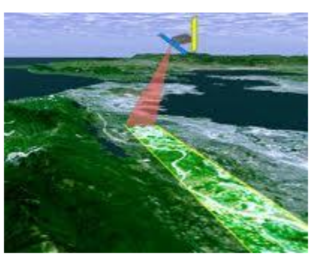
Wavelength synthesis: precise optical spectral control

1977 40-channel Citizen's band radio.

...had to purchase <u>40</u> quartz crystals

By 1980, frequency synthesis reduced this to <u>one</u>





<u>Frequency synthesis enabled modern RF systems :</u>

Precision phase/frequency control

→ efficient & controlled use of the spectrum

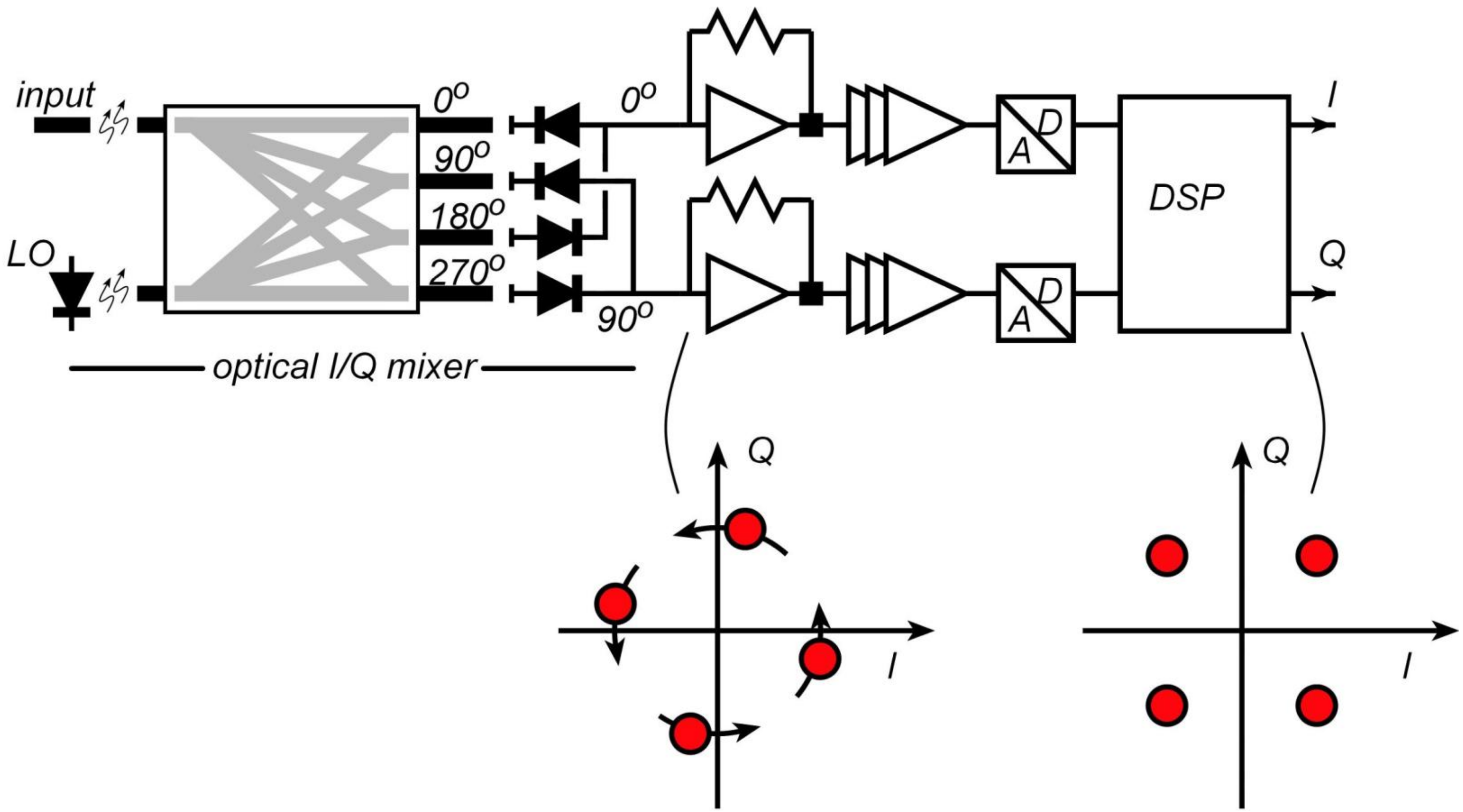
Today's optical systems look like a 1977 CB radio

Phase-locked coherent optical systems:

control optical channel spacings
over 100's of GHz,
with sub-Hz precision

→ sensitive, compact, <u>spectrally efficient</u>,
optical communications

Coherent Receivers Today: Free-Running LO



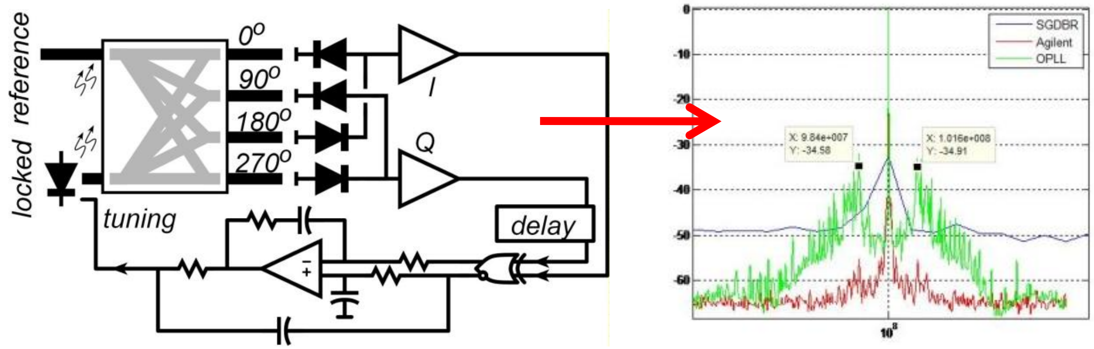
Optical LO is free-running

DSP corrects optical dispersion

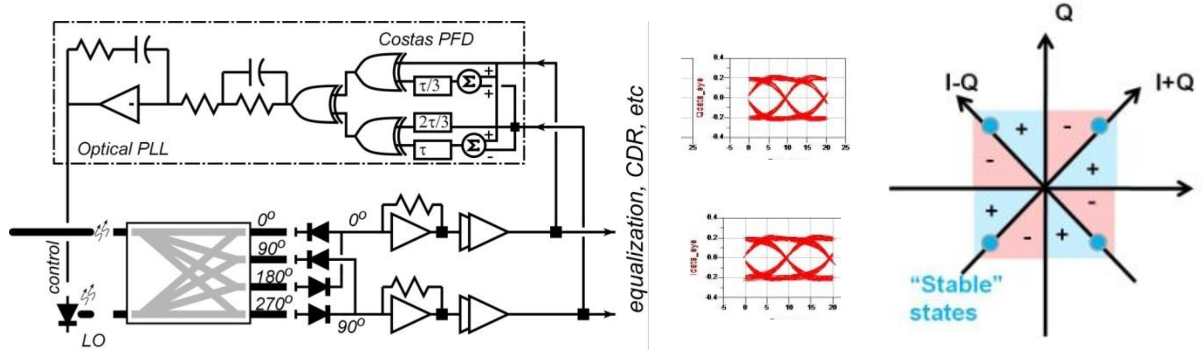
DSP corrects LO phase/frequency error

Optical Phase-Locked-Loops: Applications

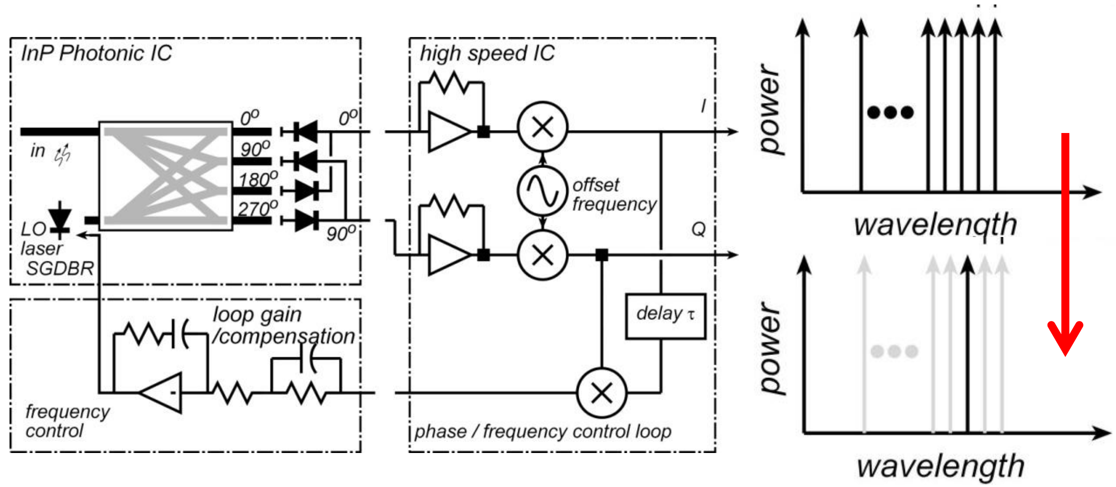
Wideband laser locking & noise suppression.
improved spectral purity without external cavities.



BPSK/QPSK Coherent Receivers
Short- to mid-range links,
no DSP,
inexpensive wide-linewidth lasers

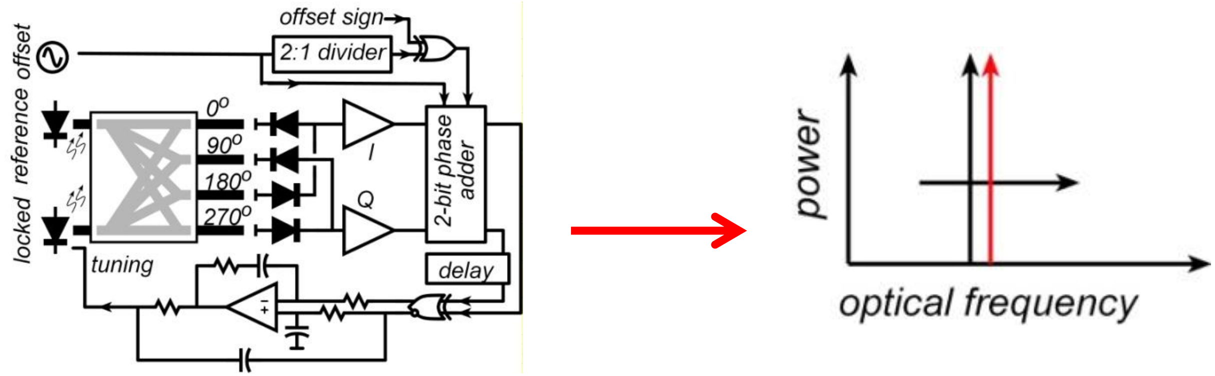


Tunable Wavelength-Selection in Receivers
WDM: electronic channel selection.

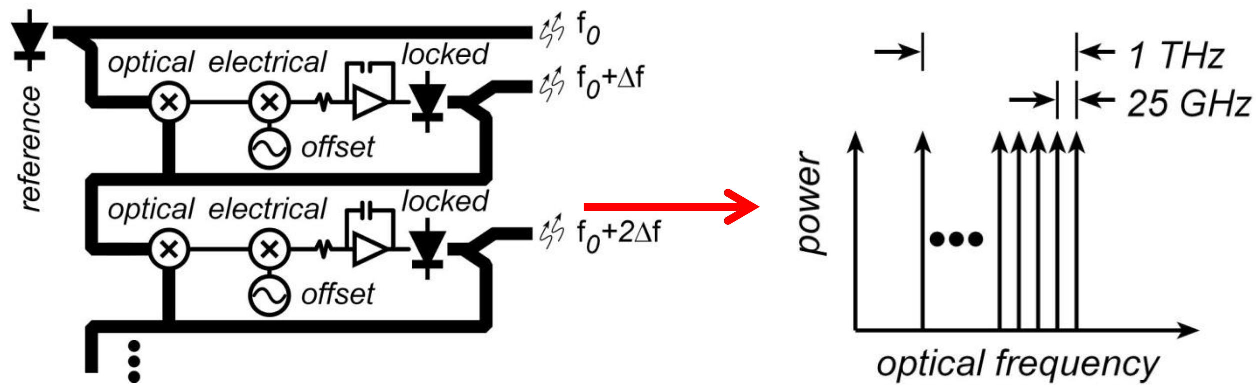


Optical Phase-Locked-Loops: Applications

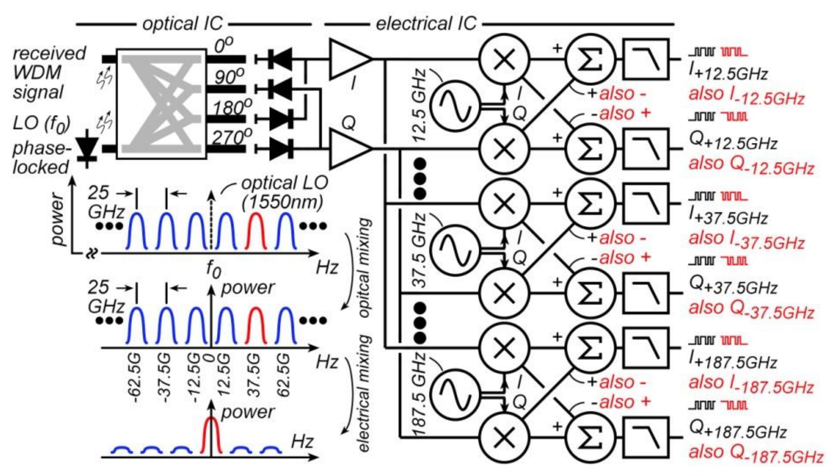
Wavelength synthesis,
& sweeping
→ digital control
of wavelength spacings.



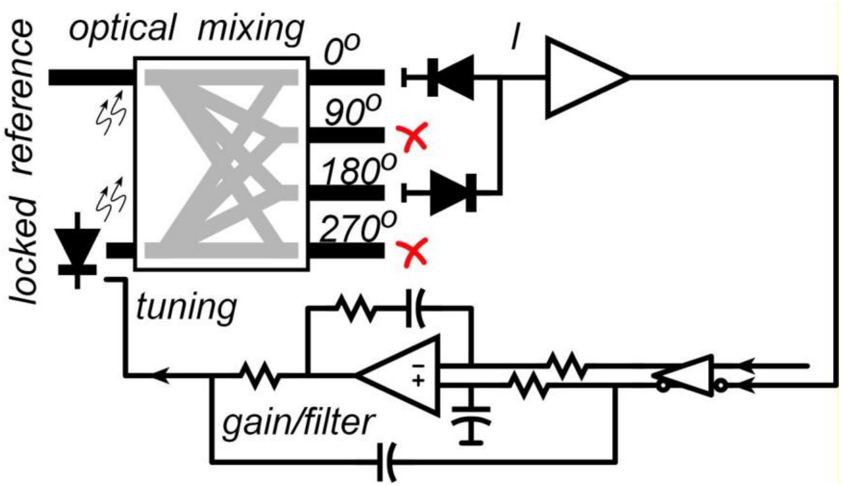
Synthesis, Sweeping
of Wavelength Combs
WDM: precise channel spacing,
no guard bands.



Single-Chip
Multi-Wavelength
Coherent Receivers
WDM



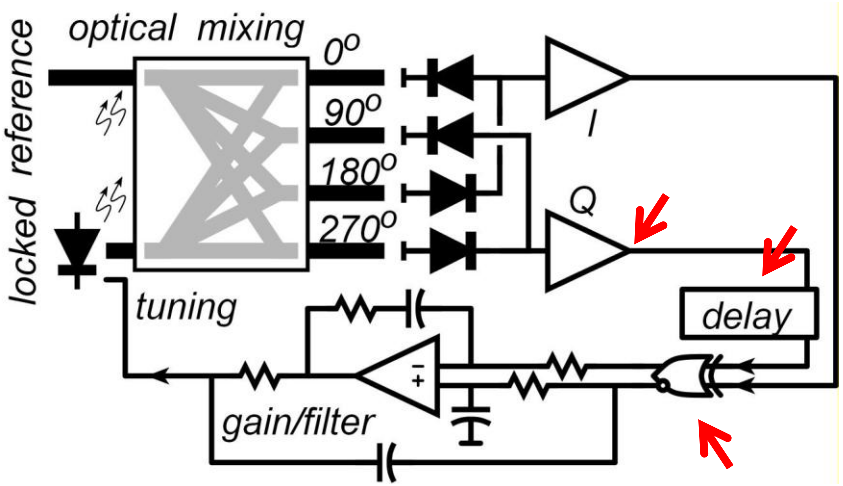
Optical PLLs: Basics



Phase-lock tunable laser to optical reference
Lock to one line + improve linewidth / SNR

Inexpensive laser with no external cavity ?
- ***→ large laser linewidth***
- ***→ 1GHz loop bandwidth for noise suppression***
- ***→ tight optical/electrical integration***

Optical PLLs: Frequency-Difference-Detector



~ 1 GHz loop bandwidth

~20 GHz initial frequency error

→ loop will not acquire lock

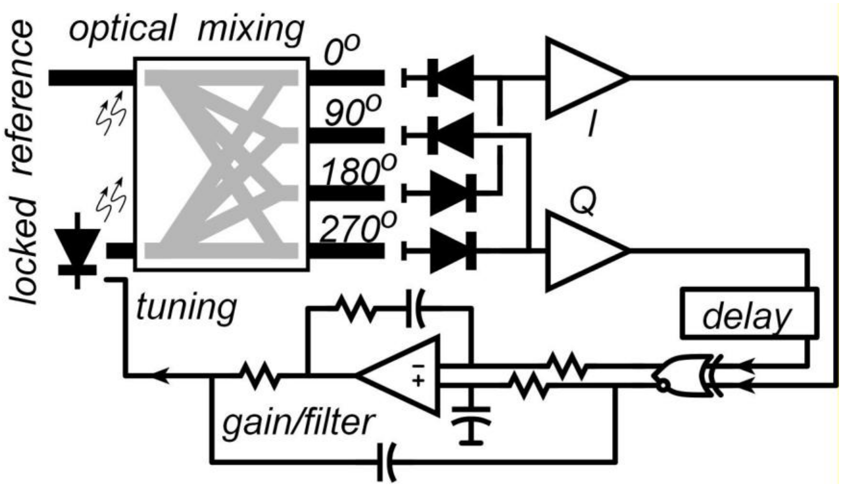
→Add frequency-difference detector

Requires I/Q (0°,90°) optical mixing

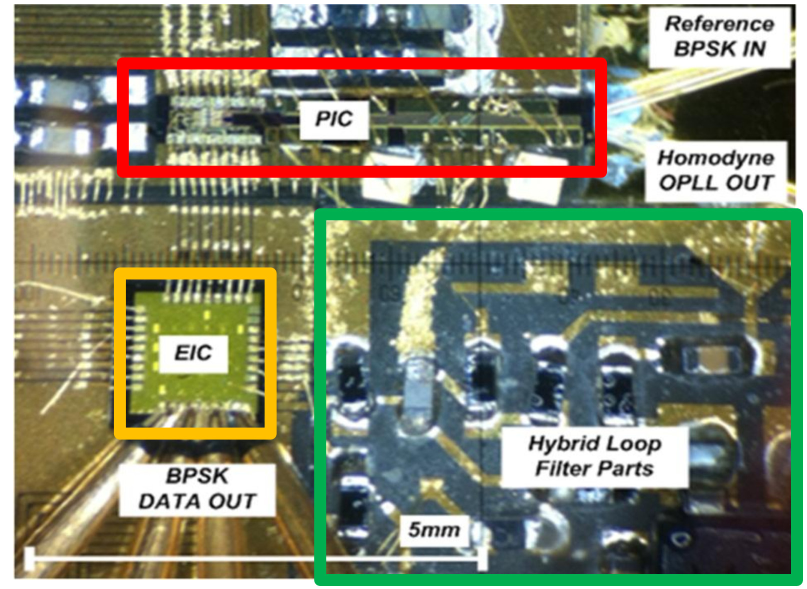
Full information of optical field is maintained

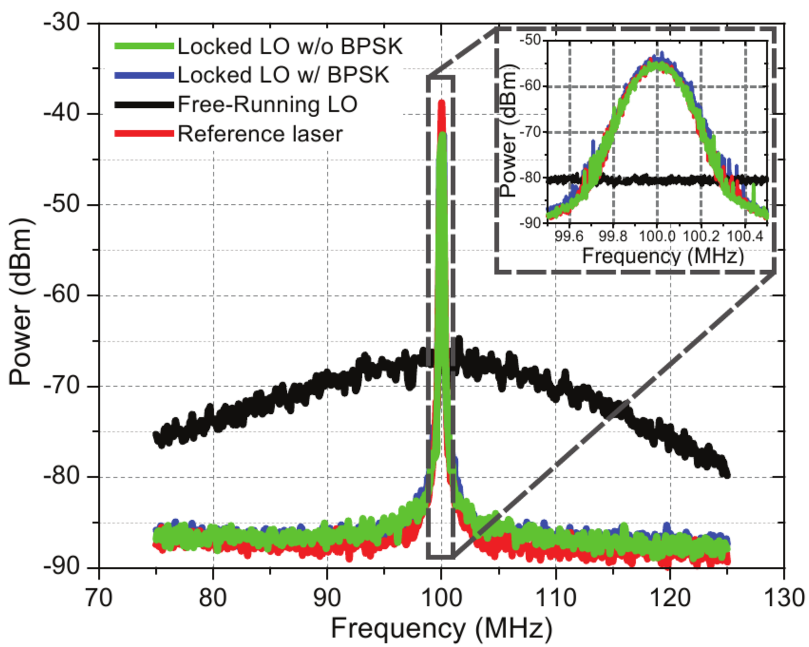
→ use later for other purposes

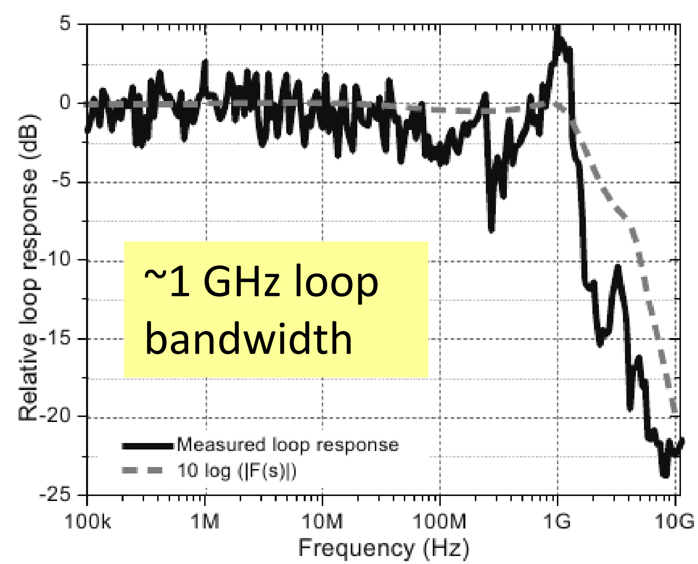
Optical PLLs: Demonstrated



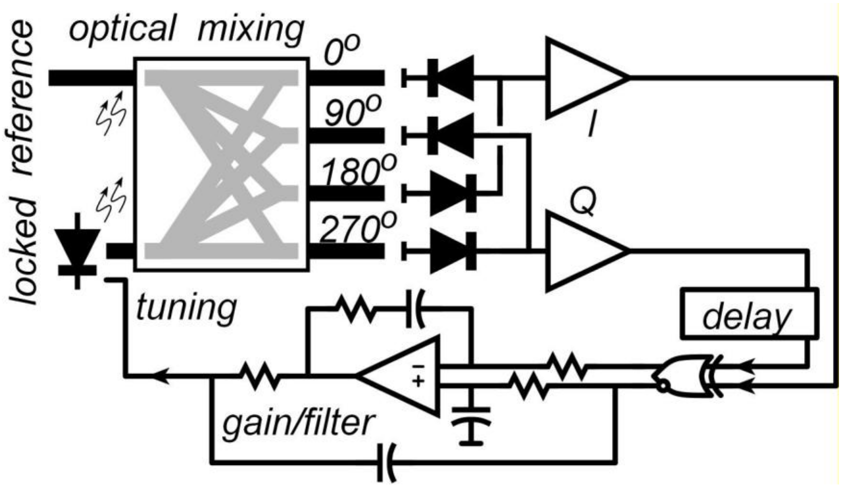
H. Park, M. Lu, et al, ECOC'12, Th3A.2 (2012)

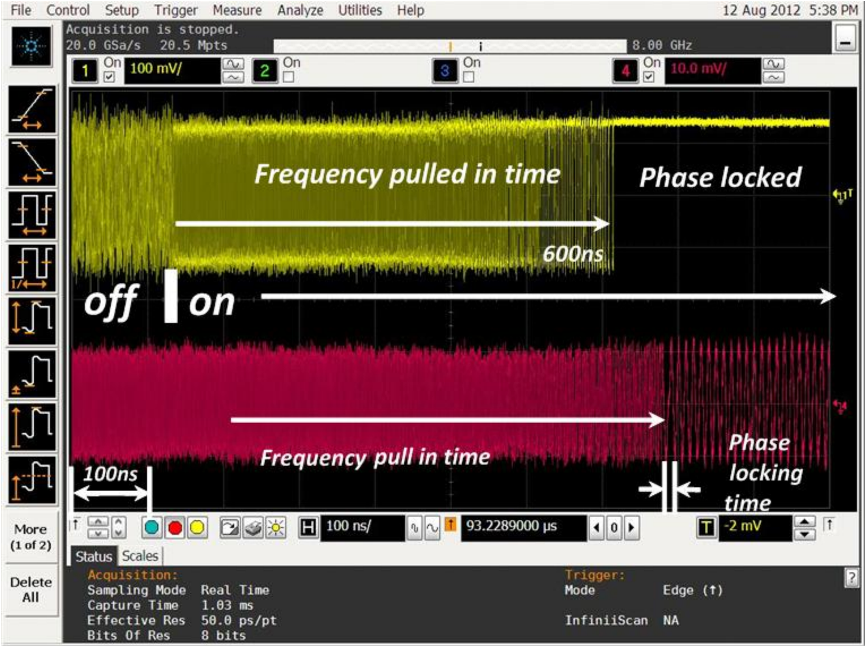






Optical PLLs: Frequency Acquisition





H. Park, M. Lu, et al, ECOC'12, Th3A.2 (2012)

High carrier frequency (200 THz) but limited OPLL bandwidth (1.1 GHz)

Slow frequency capture outside OPLL bandwidth

Need Optical Frequency Phase Lock Loop

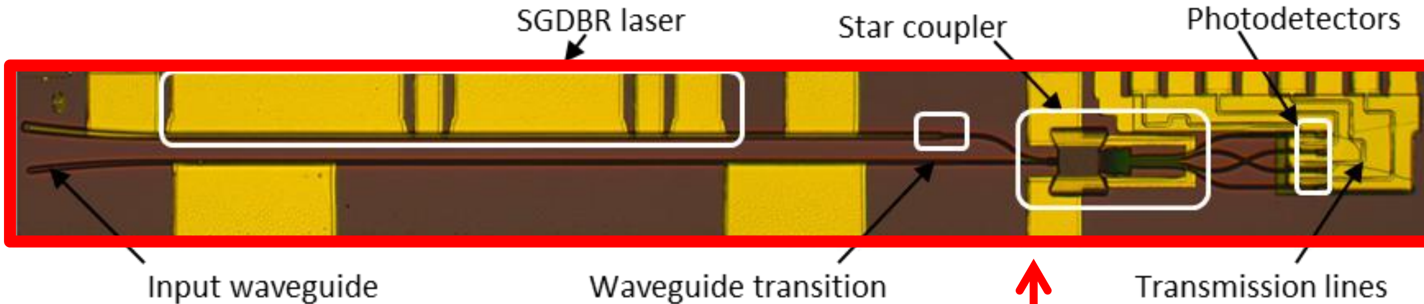
Phase-Frequency Locking Demonstrated→ 50 GHz pull-in range

600ns frequency pull-in time

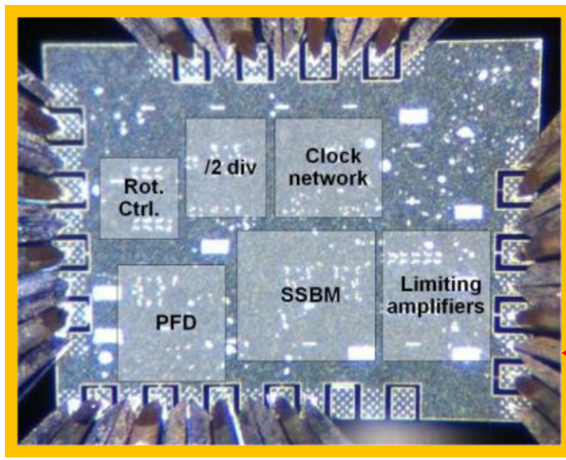
<10 ns optical phase lock time

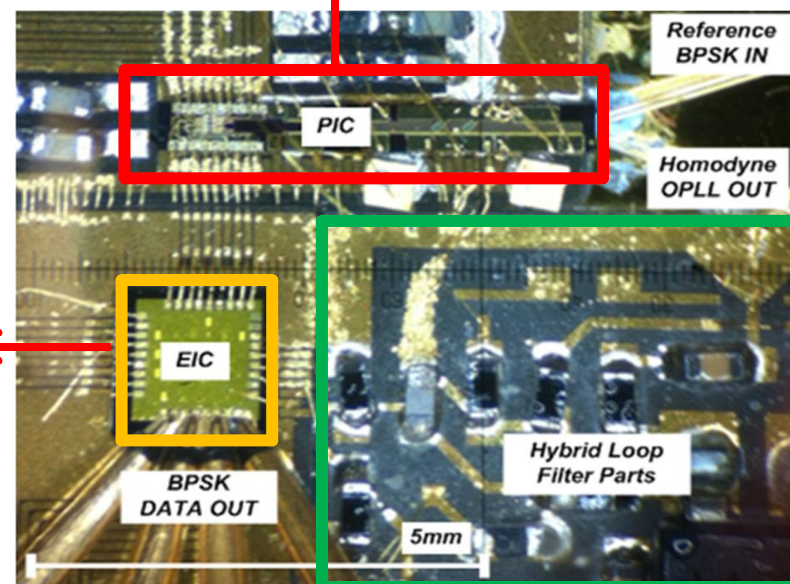
OPLL Components

Photonic IC
Coldren group
InP integration

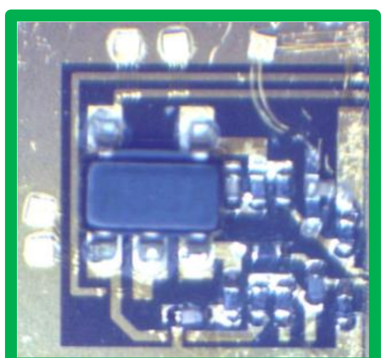


Fast electrical IC
Design: Rodwell group
Fab: Teledyne InP HBT
details to follow

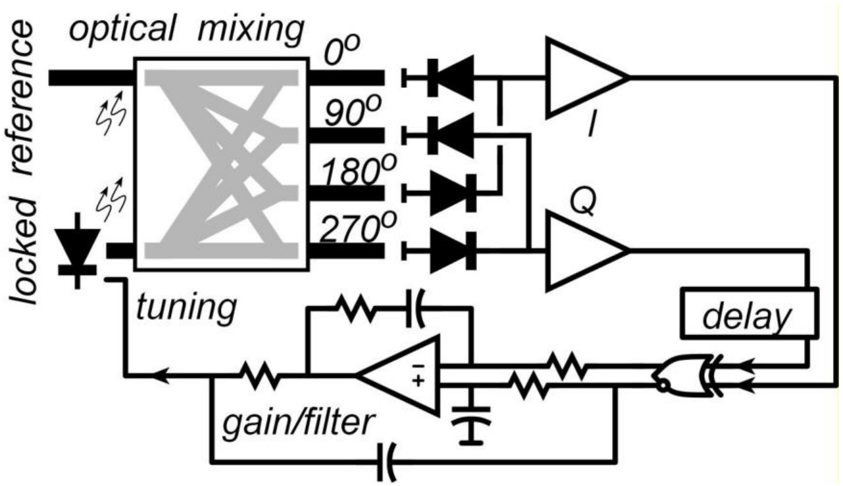




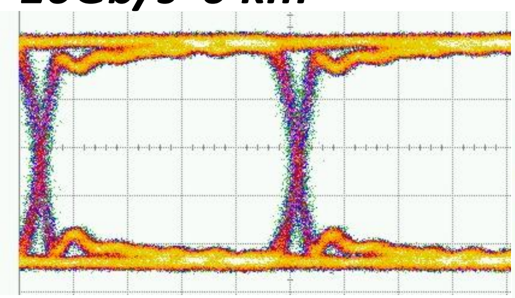
Hybrid loop filter
slow/fast design
slow: op-amp integrator
fast: passive feedforward



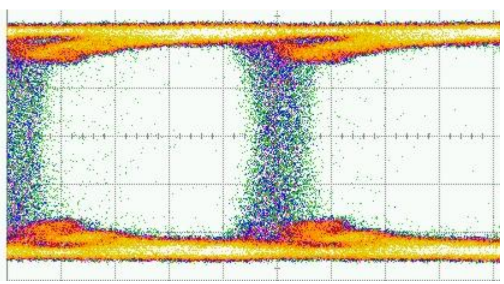
Optical PLLs: Phase-Locked **B**PSK Receiver



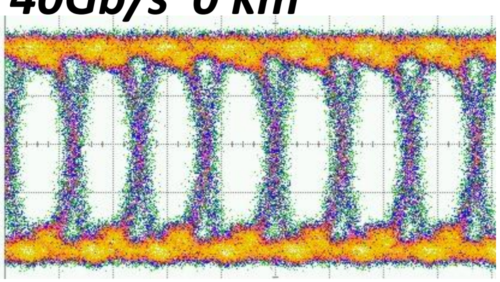
10Gb/s 0 km



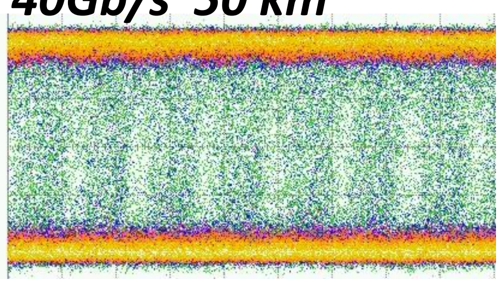
10Gb/s 75 km

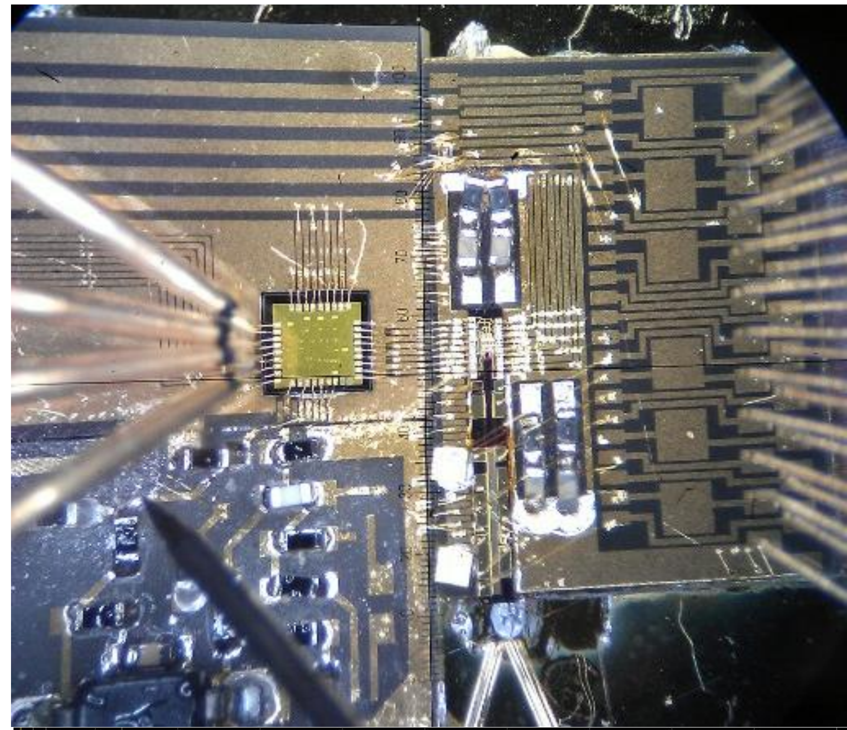


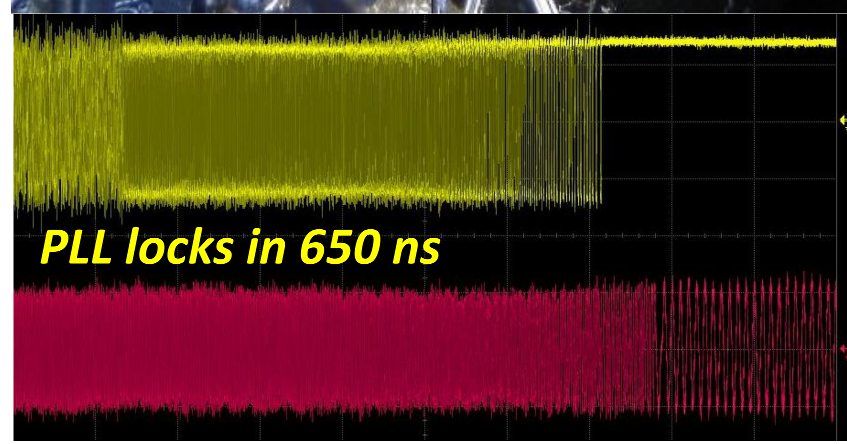
40Gb/s 0 km



40Gb/s 50 km

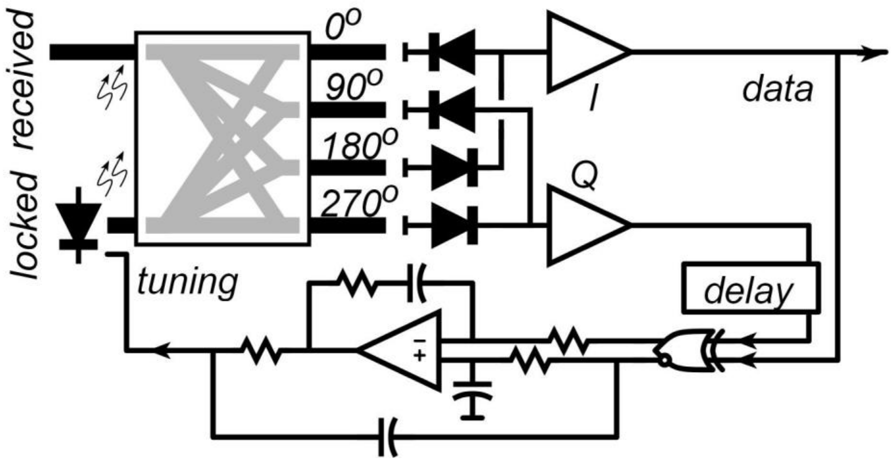


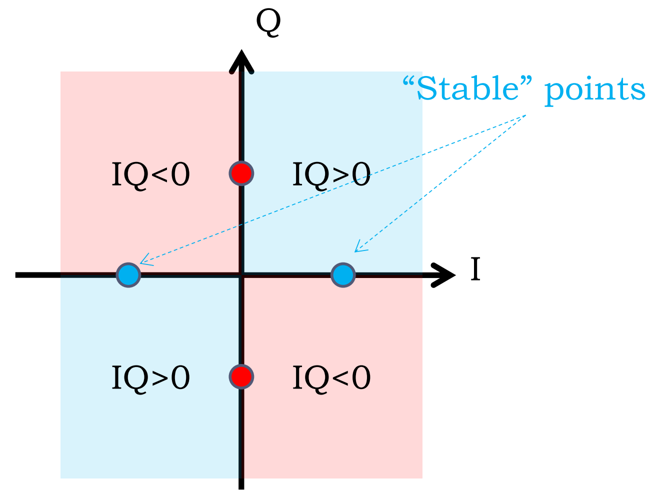




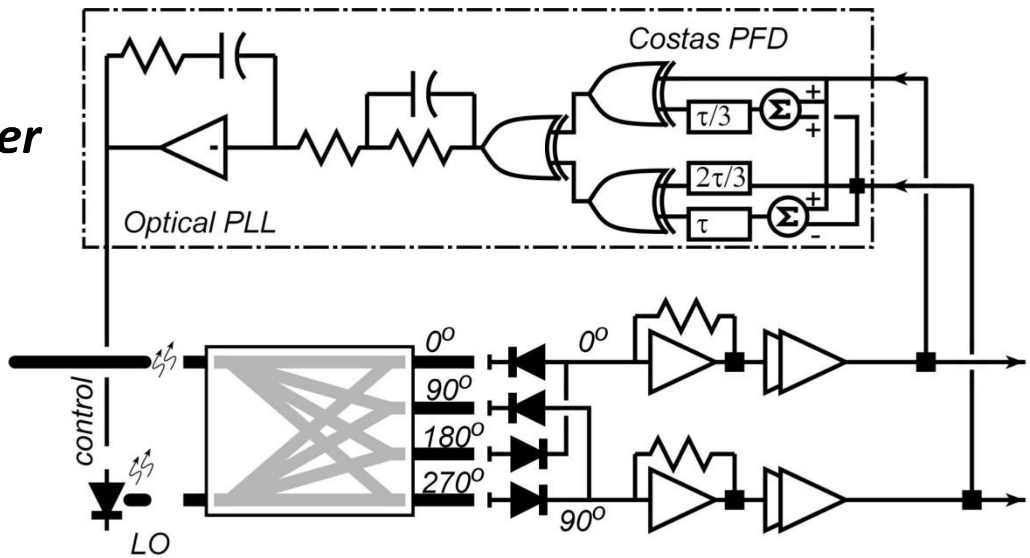
Optical PLLs: Phase-Locked QPSK Receiver

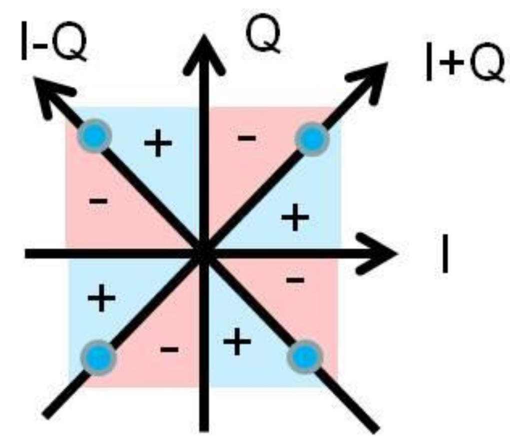
BPSK receiver





QPSK receiver

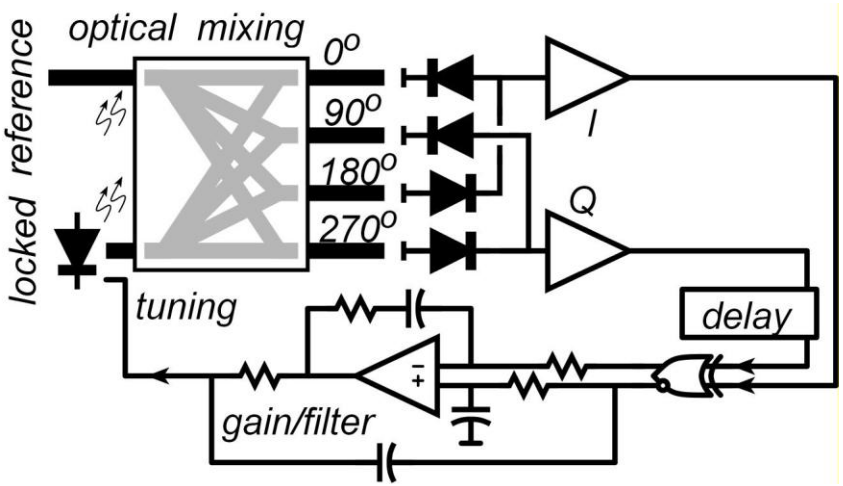


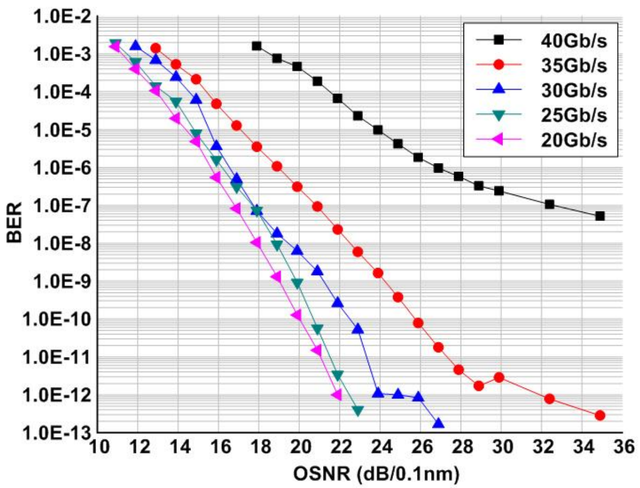


Designs attempted, ICs did not work properly

simply a design failure, should work just fine...

Phase-Locked B/QPSK Receivers: Good and Bad





Present coherent receivers: DSP coherent detection

- ***DSP compensates dispersion***
- ***DSP compensates LO phase & frequency errors.***
- ***sophisticated, high DC power, expensive***

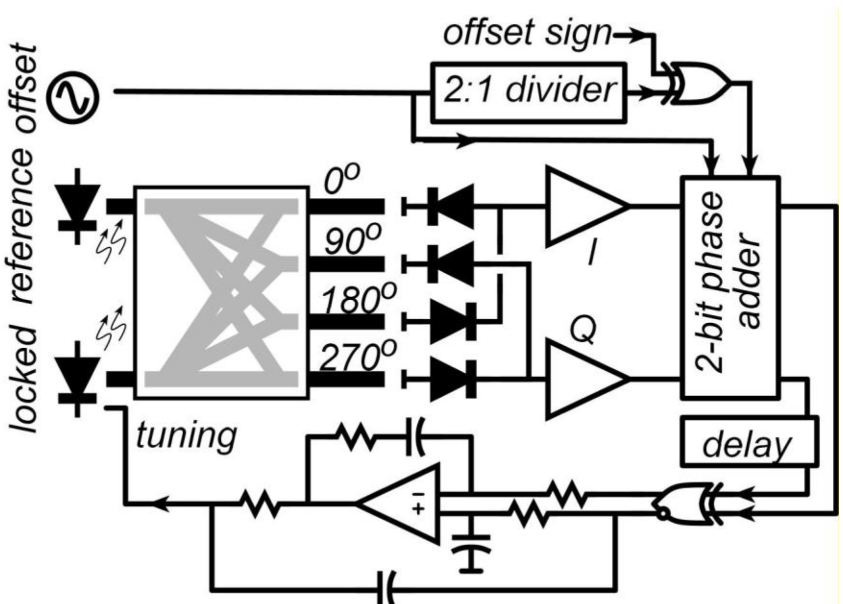
Phase-locked receivers in short-range links

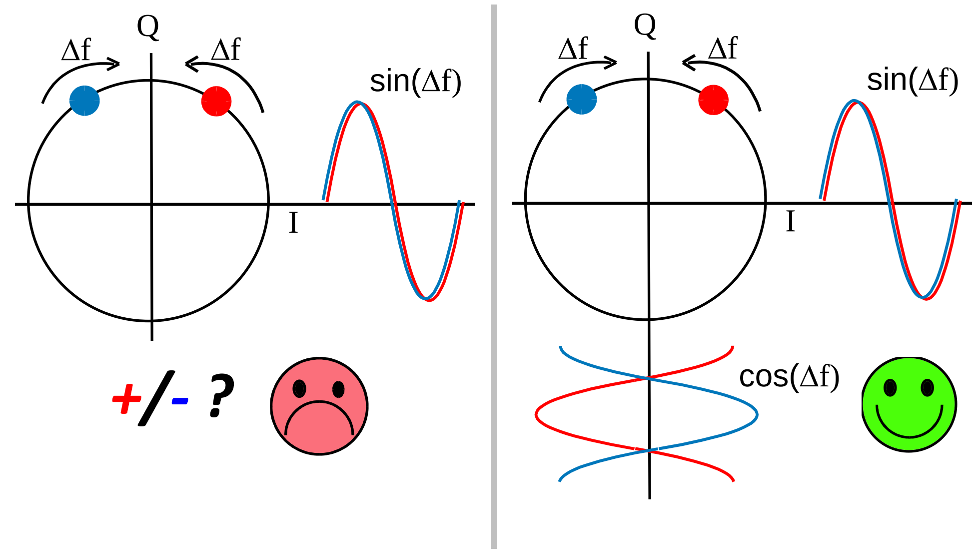
- ***No DSP required ! → reduced cost, reduced DC power***

Phase-locked receivers in long-range links

- ***fiber dispersion will close eye→ optical PLL will not lock***

Offset Locking → Wavelength Synthesis





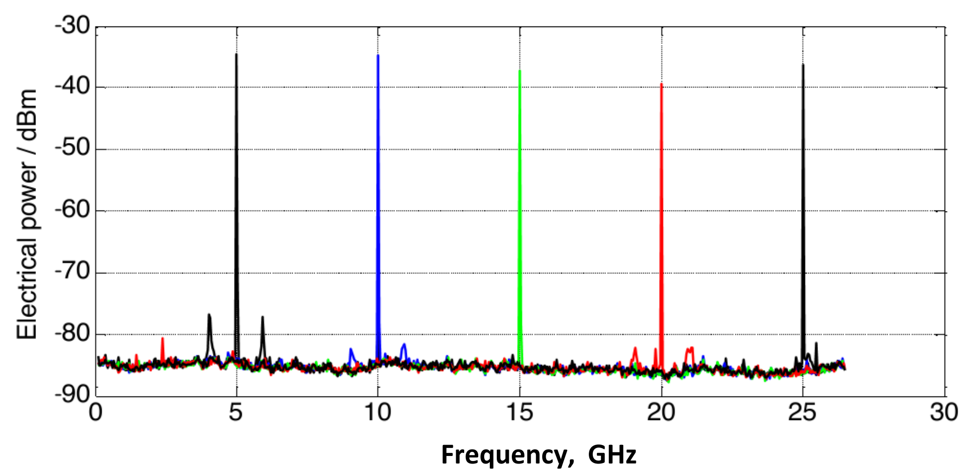
Offset locking to generate any optical frequency

Simple OPLL cannot distinguish +/- frequency offsets

(0°/90°) optical mixing:
no lost optical information
IC digital single-sideband mixing

300+ GHz offsets possible
fast UTC photodiodes, fast electronics

Mingzhi Lu, et. al, – Tu2H.4, OFC2014



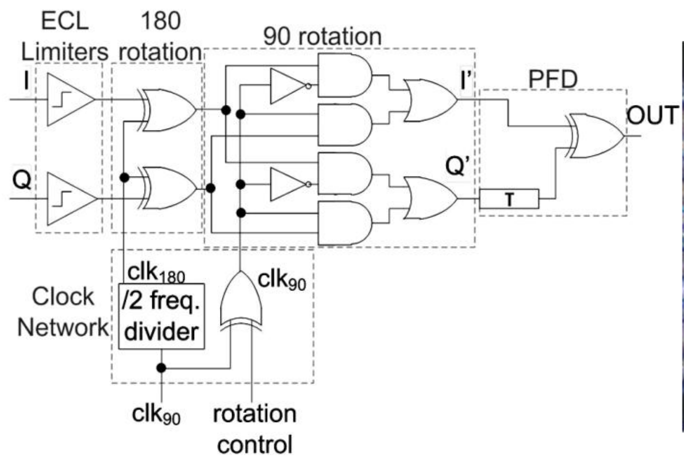
IC Design Details

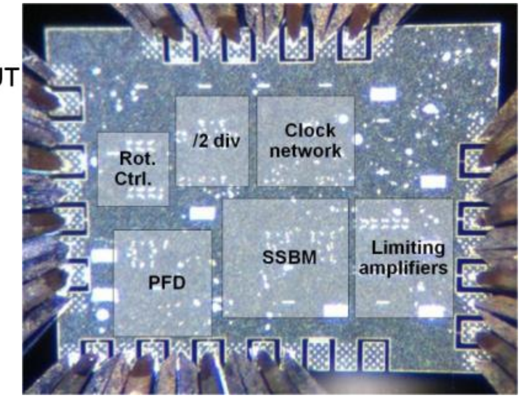
Features

- ***Phase detector***
- ***Frequency difference detector***
  - ***forces loop to lock***
- ***2-bit digital phase adder***
  - ***introduces frequency shift***
  - ***controlled sign of shift !***

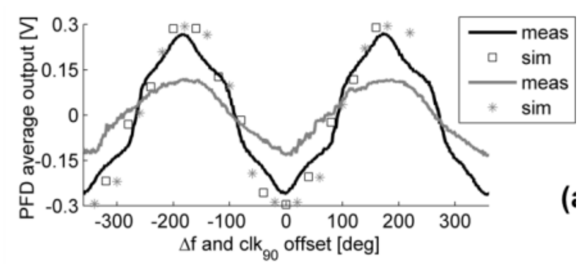
Implementation

- ***Teledyne 350 GHz, 500 nm InP HBT***
- ***Robust all-digital implementation***

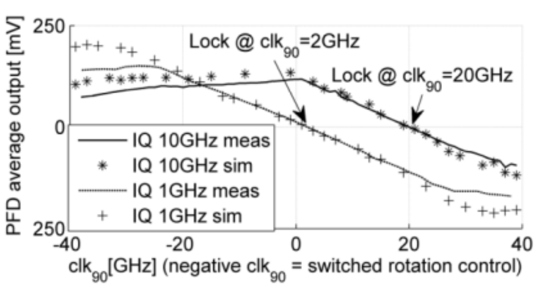




Phase detector test: works over +/- 30 GHz



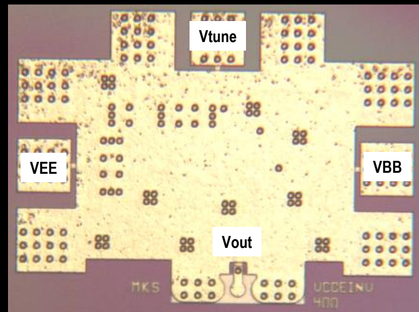
Frequency detector test: works over +/- 40 GHz



ICs Today: 670 GHz is done, 200 GHz is easy

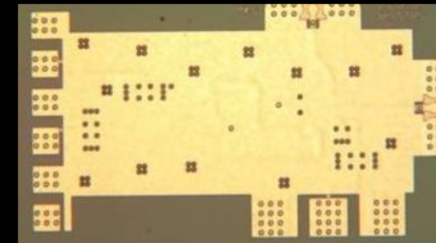
614 GHz fundamental VCO

M. Seo, TSC / UCSB



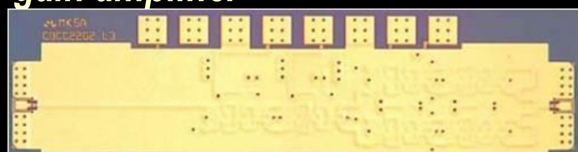
340 GHz dynamic frequency divider

M. Seo, UCSB/TSC
IMS 2010



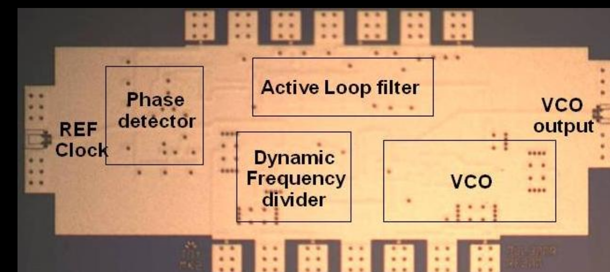
620 GHz, 20 dB gain amplifier

M Seo, TSC
IMS 2013



300 GHz fundamental PLL

M. Seo, TSC
IMS 2011

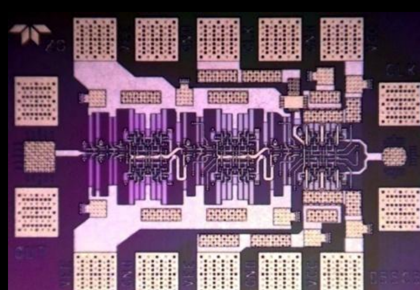


Not shown: 670 GHz HBT amplifier

J. Hacker, TSC, IMS 2013

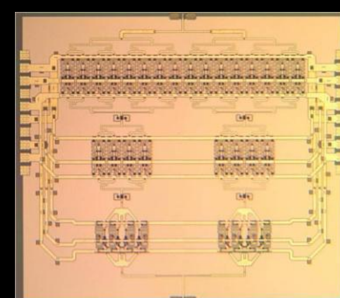
204 GHz static frequency divider (ECL master-slave latch)

Z. Griffith, TSC
CSIC 2010



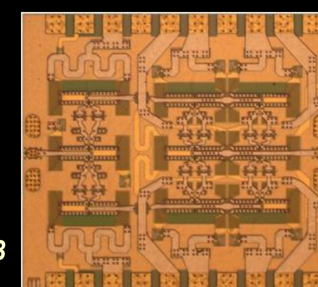
220 GHz 180 mW power amplifier

T. Reed, UCSB
CSICS 2013



81 GHz 470 mW power amplifier

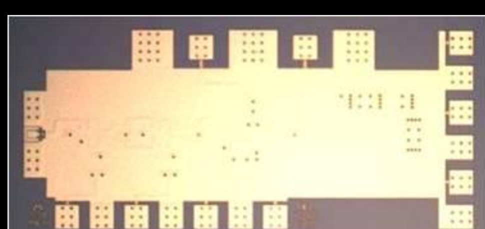
H-C Park UCSB
IMS 2014



Integrated 300/350GHz Receivers:

LNA/Mixer/VCO

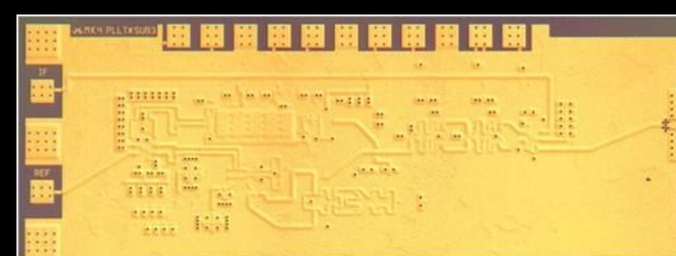
M. Seo TSC



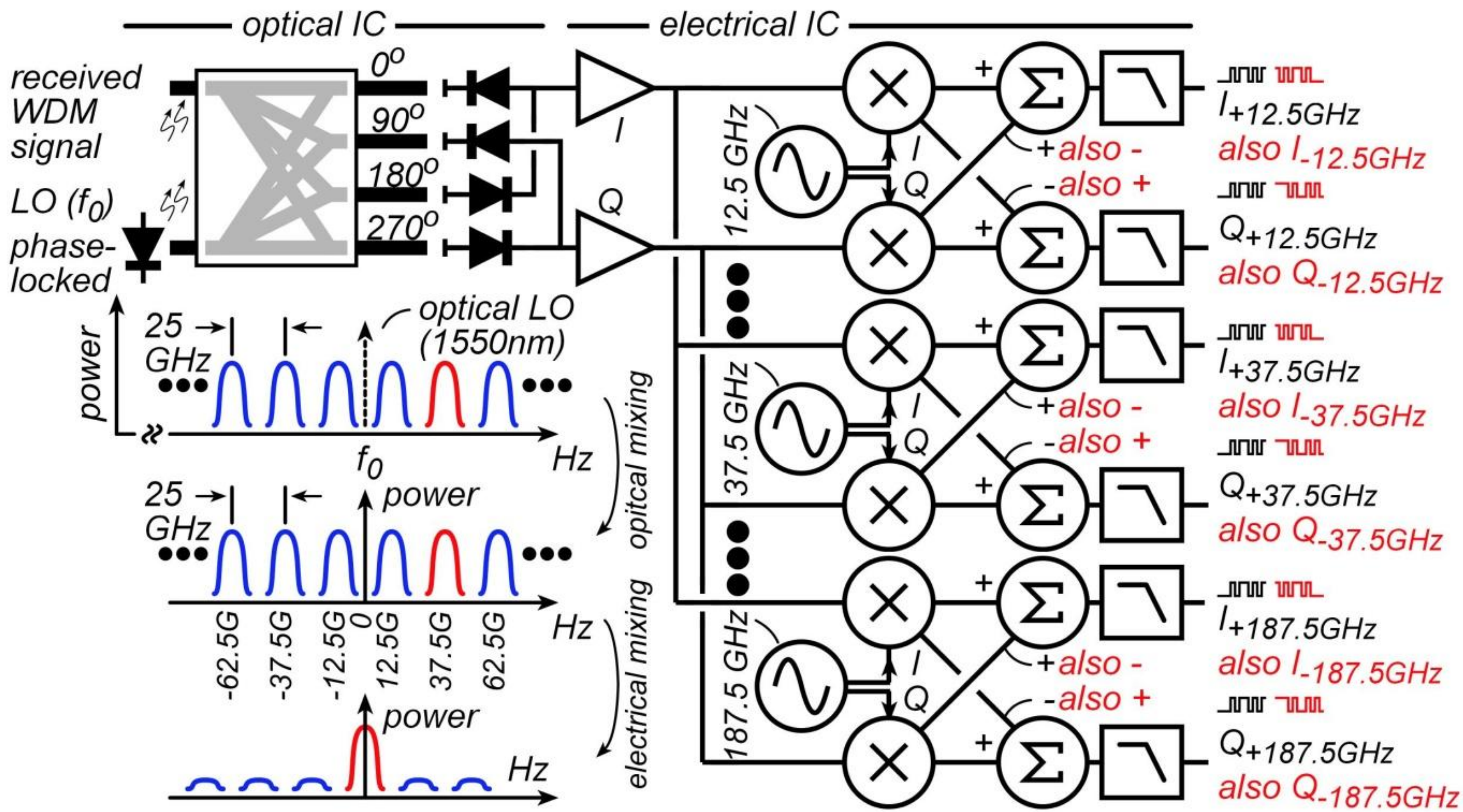
600 GHz Integrated Transmitter

PLL + Mixer

M. Seo TSC



Electrical Recovery of **WDM** for compact Tb/s Links



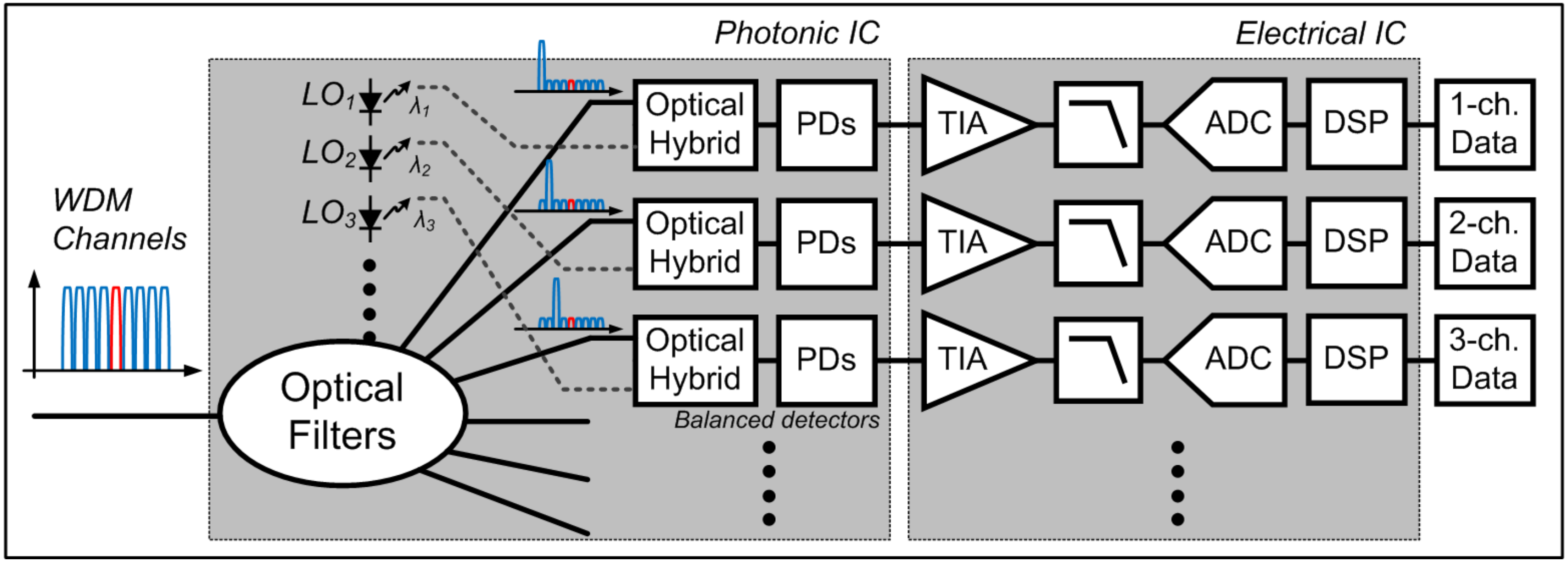
Assume: *25GHz channel spacing, DC-200 GHz ICs , DC-200 GHz photodiodes*

*→ **800 Gb/s receiver**= 50 Gb/s QPSK x 16 WDM channels*

*...**one** LO laser, **one** I/Q optical detector, **one** electrical receiver IC*

OPLL can lock to optical pilot → works even with highly dispersive channels

Optical-Domain WDM Receiver



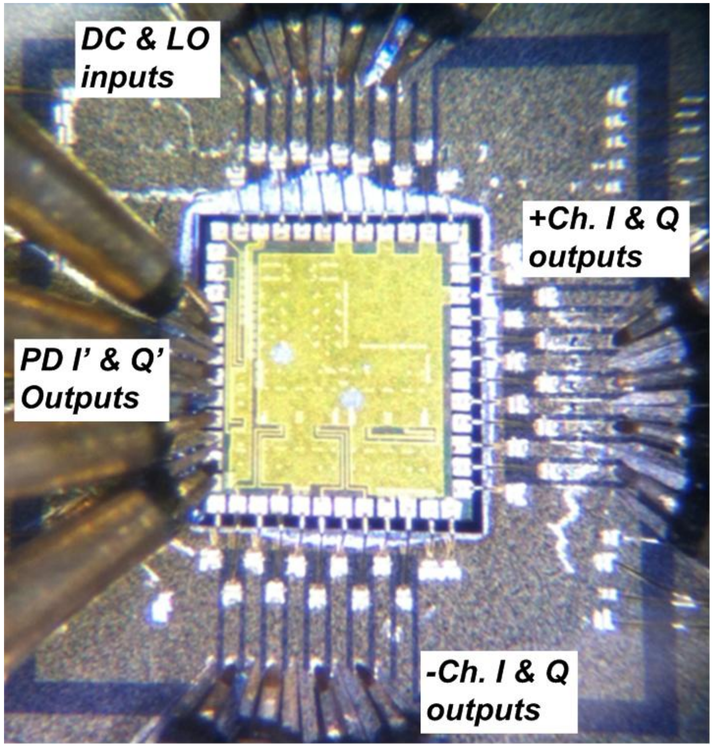
Complex photonic IC.

One electrical receiver IC for each wavelength→ many in total.

Electrical WDM: 2-Channel Demonstration

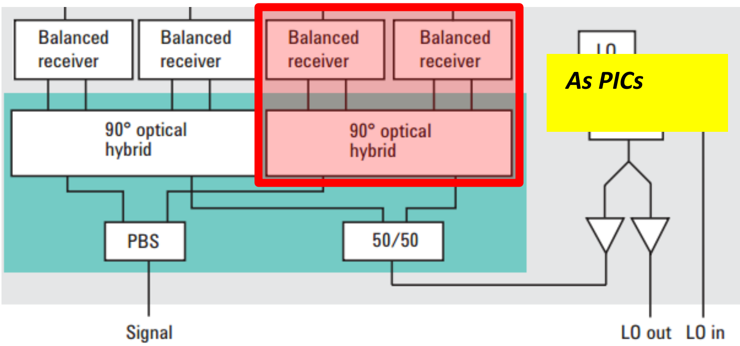
Real-time oscilloscope

OMA as PICs*
Free space optics
90° optical hybrid
& Balanced PDs

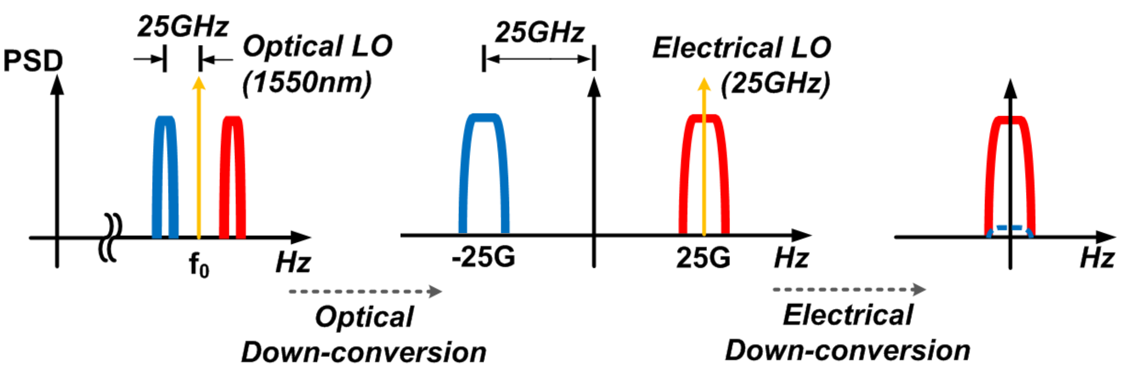


2-channel electrical IC

OMA blocks*



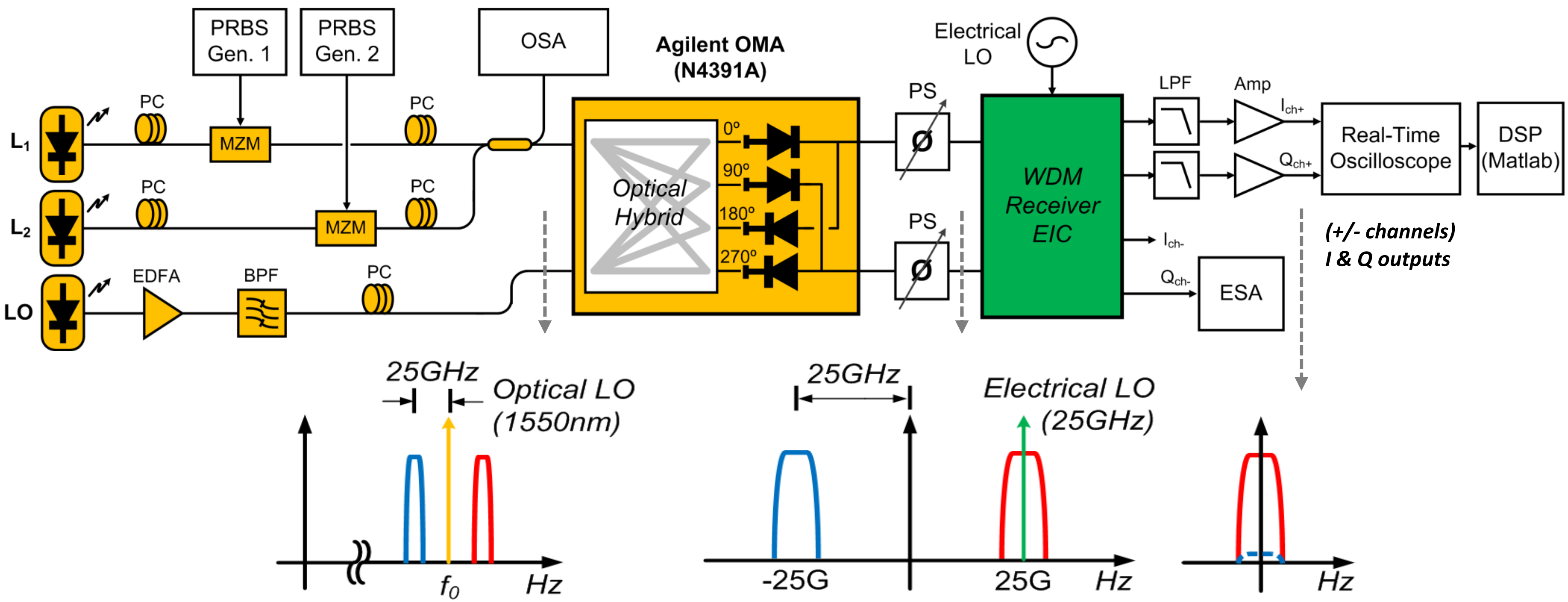
ure 30. Block diagram of the optical modulation analyzer.



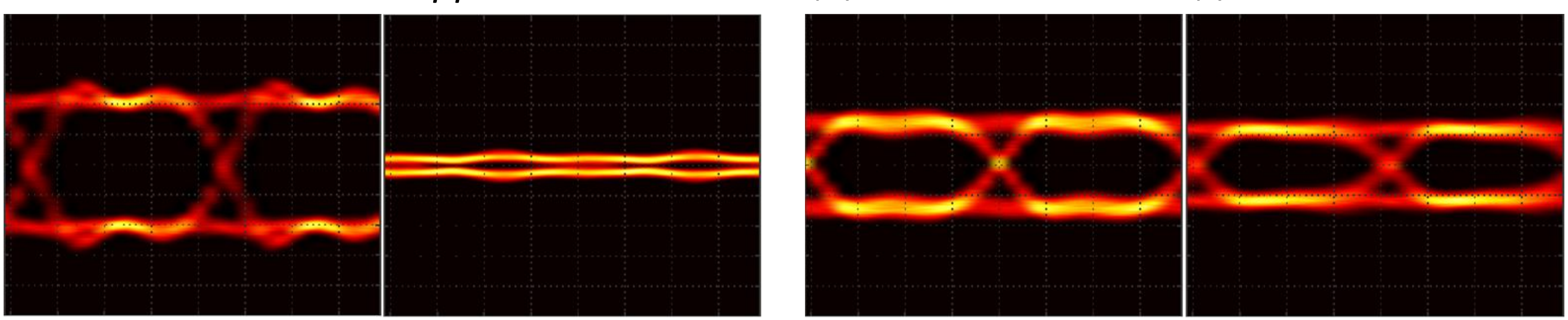
**OMA – optical modulation analyzer*

Agilent N4391A

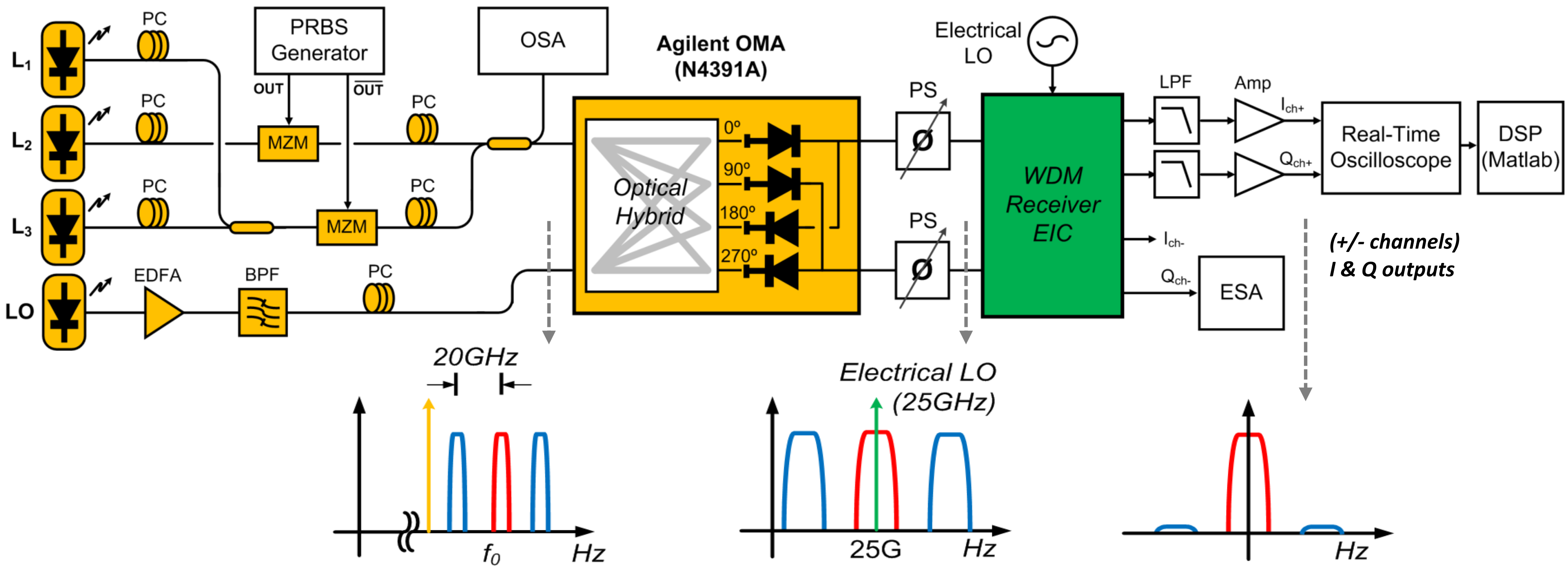
2-channel Tests: Opposite-sideband Suppression



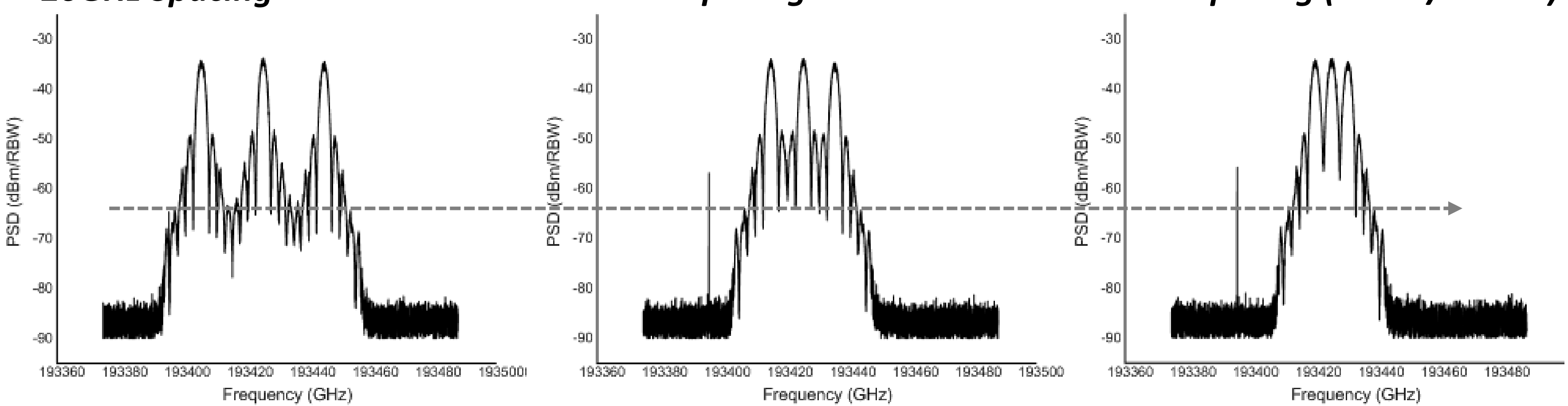
Activated channel *Suppressed channel* *(+) channel* *(-) channel*



3-channel Test: Adjacent Channel Rejection



20GHz Spacing ***10GHz Spacing*** ***5GHz Spacing (2.5Gb/s BPSK)***

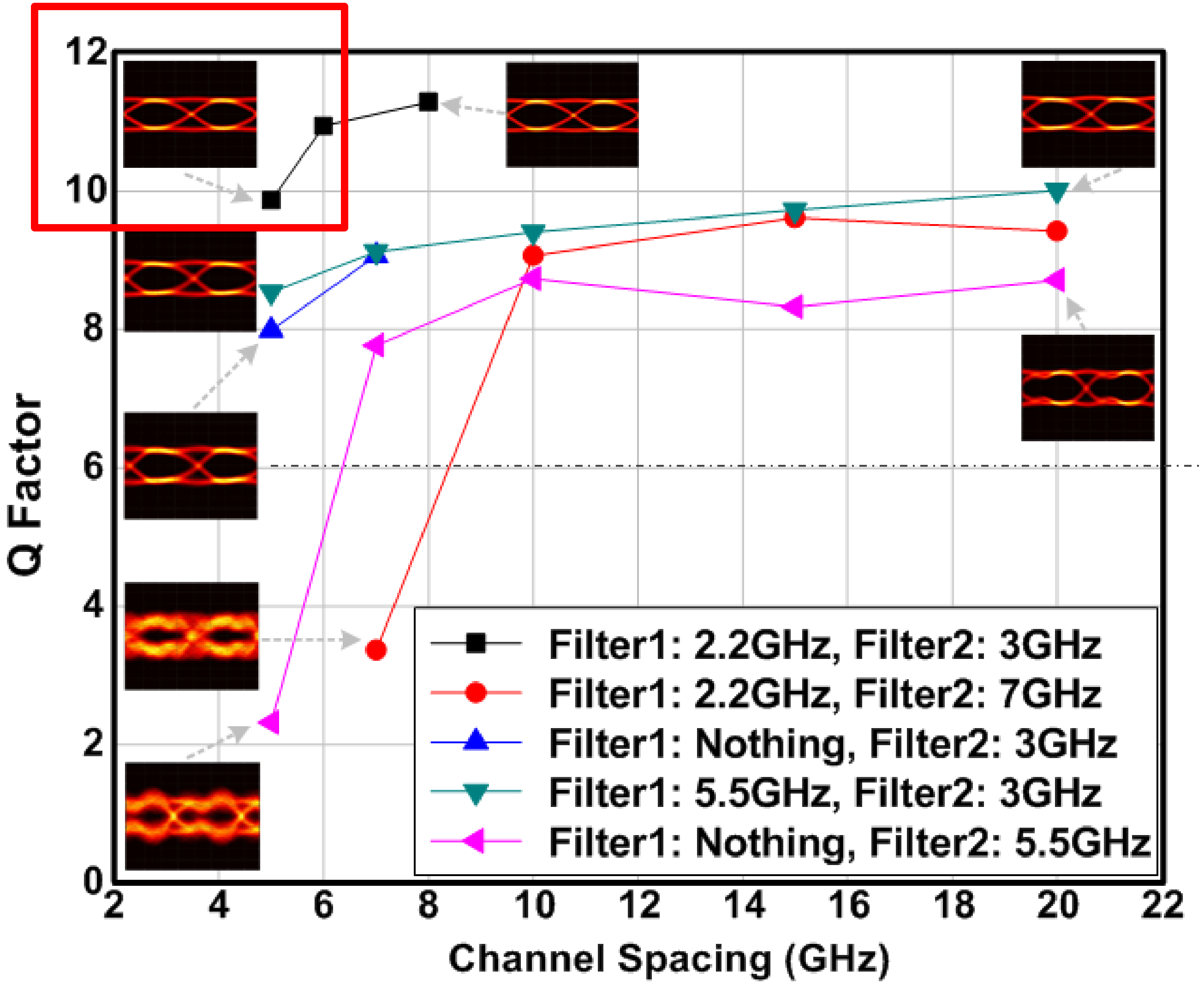


**spectra measured using optical spectrum analyzer*

Tested with various channel spacings

3-channel Test: Adjacent Channel Rejection

Eye Quality with Different Transmitter/receiver filter bandwidths



**Filter1: transmitter*
**Filter2: receiver*

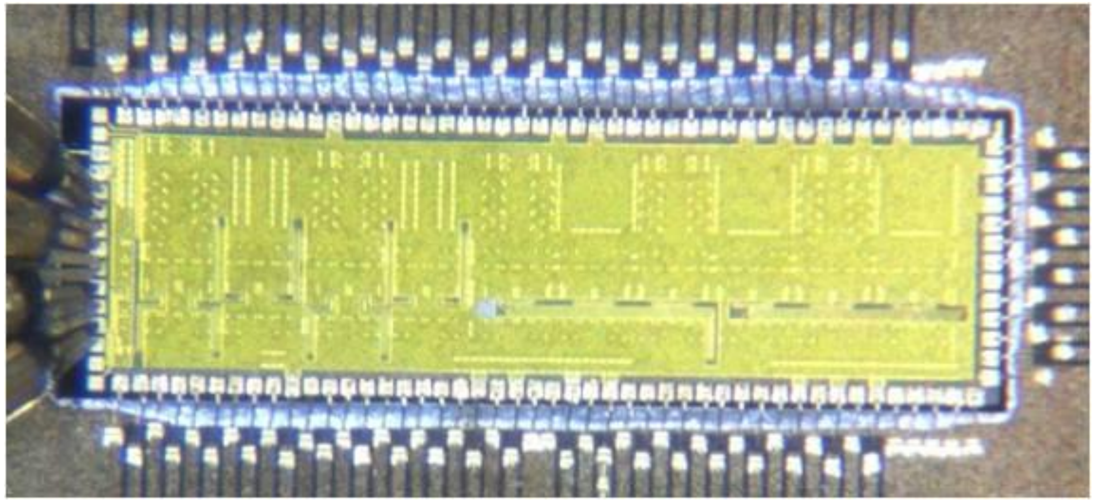
BER 1.0E-9

2.5 Gb/s BPSK per channel, 5 GHz channel spacing→ minimal interchannel interference

6-channel WDM Receiver Design

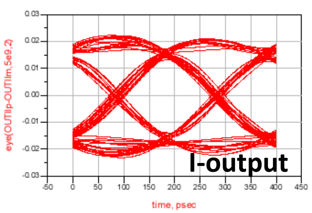
Teledyne 500nm InP HBT (350GHz f_τ, f_{max})

6 channels: +/- 12.5, 37.5, 62.5 GHz

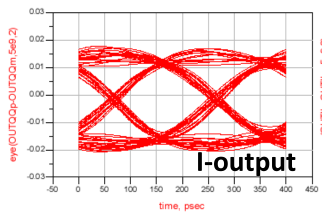


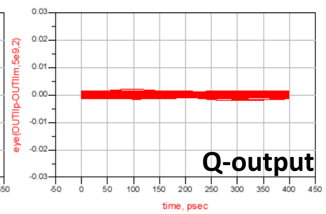
Simulations look fine...

±12.5GHz

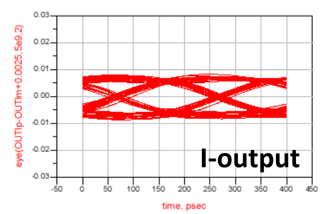


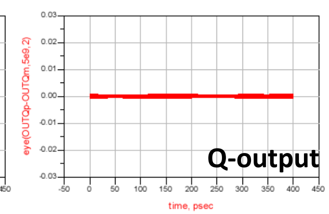
±37.5GHz





±62.5GHz





But problems:

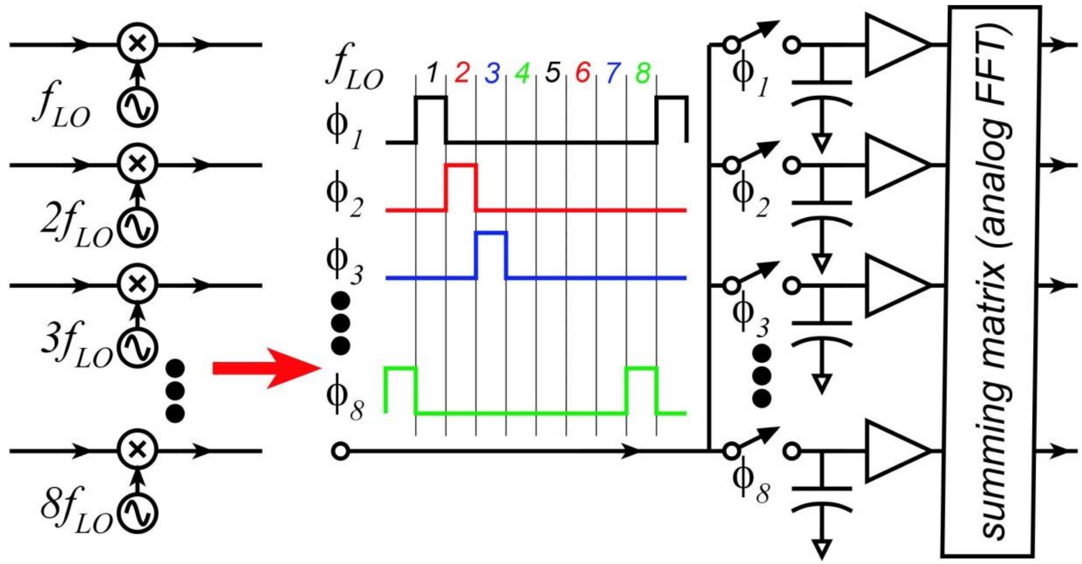
(1) very high DC power consumption (>10W)

(2) low IC yield...all ICs have at least one broken receive channel

Next steps ?

Electrical-Domain WDM Receiver: Reducing Power

Replace mixer array with analog FFT

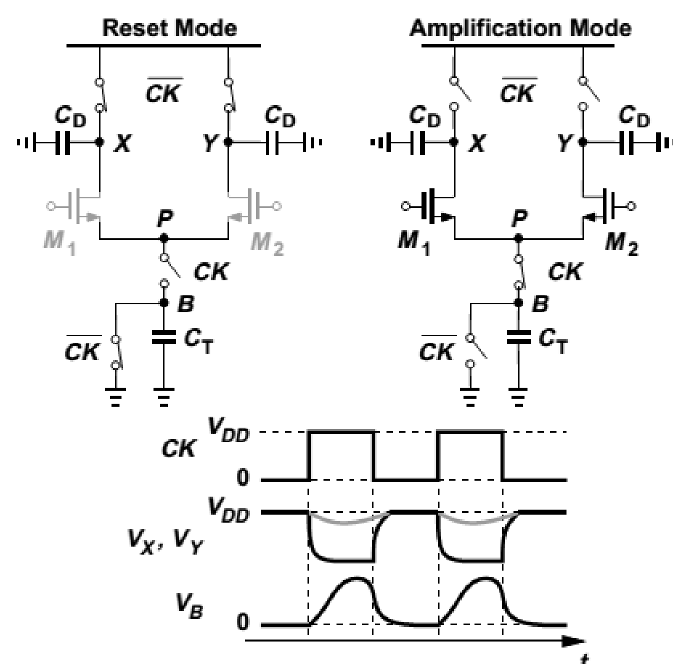


Use charge-domain CMOS logic

Razavi, IEEE Custom IC Conference, Sept. 2013.

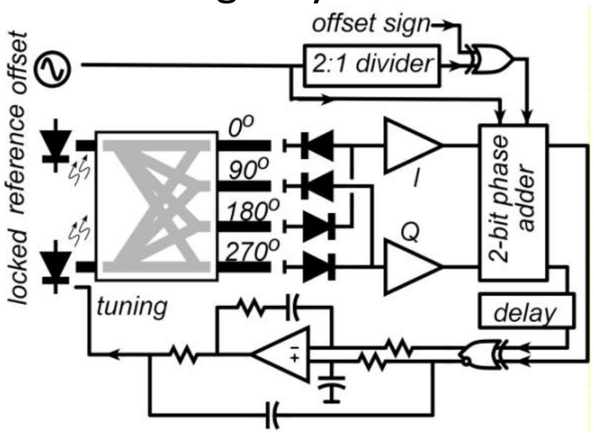
"Employing charge steering in 65-nm CMOS technology, a 25-Gb/s CDR/deserializer consumes 5 mW"

→0.2 pJ/bit

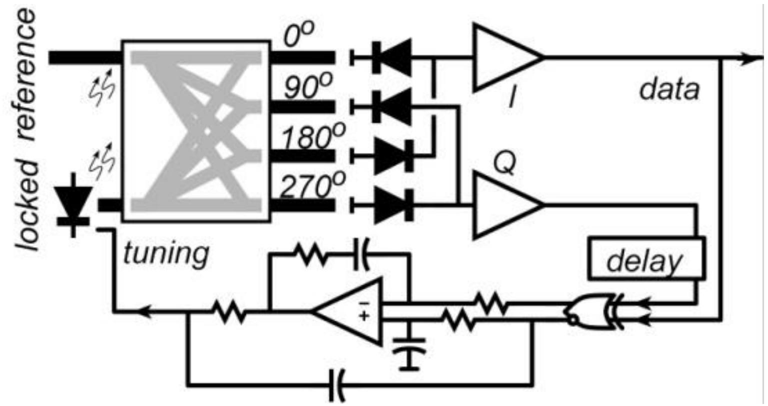


Optical Phase-Locked-Loops: Applications

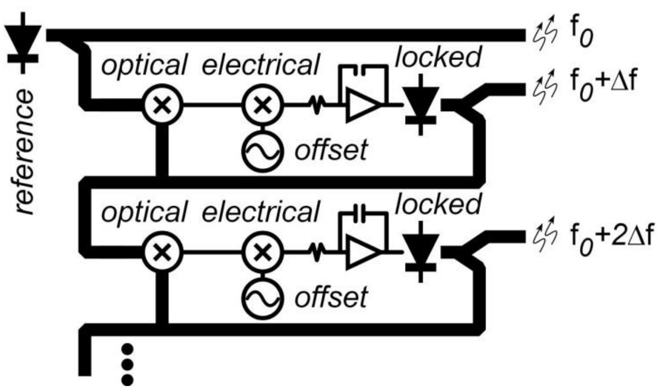
Wavelength synthesis



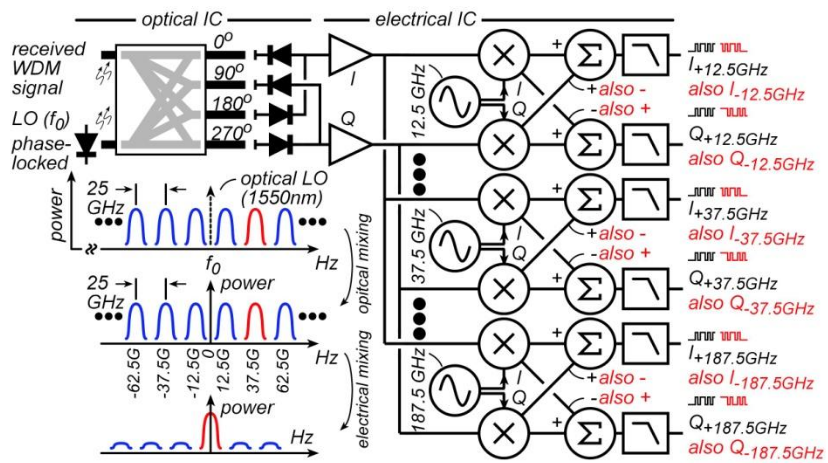
Phase-locked coherent receivers



Zero-guardband WDM generation



Single-chip Electrical WDM receivers



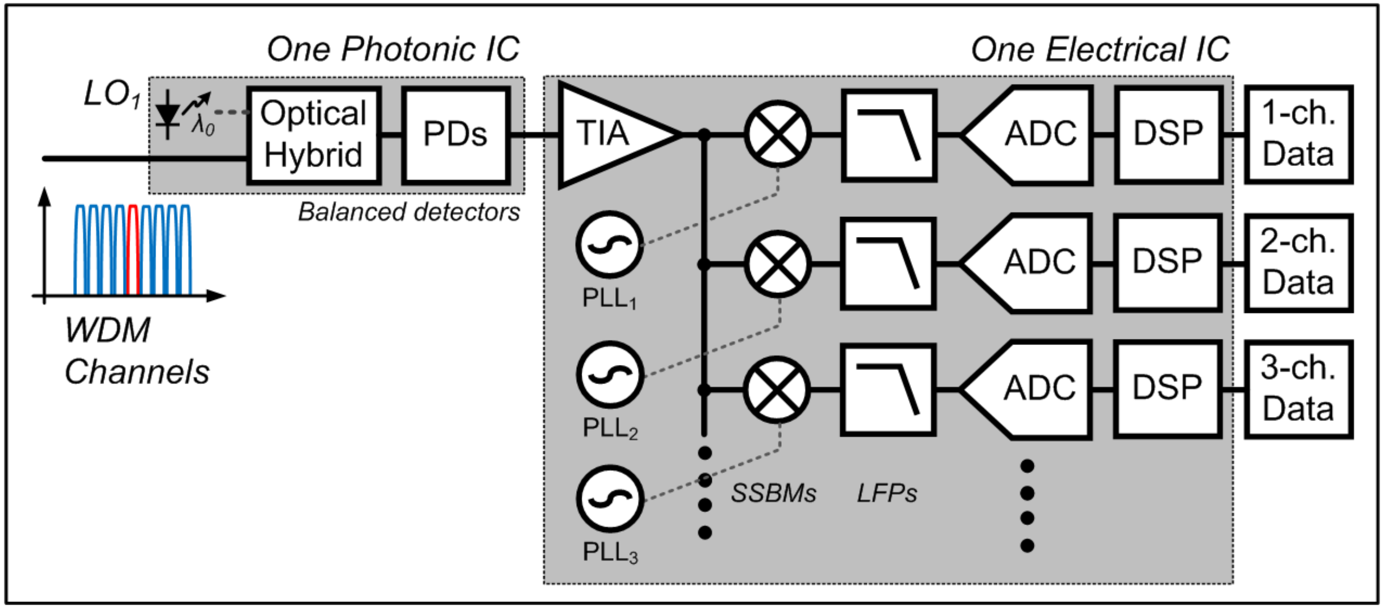
Electronic polarization DMUX ?

Analog polarization compensation ?

(end)

Backups

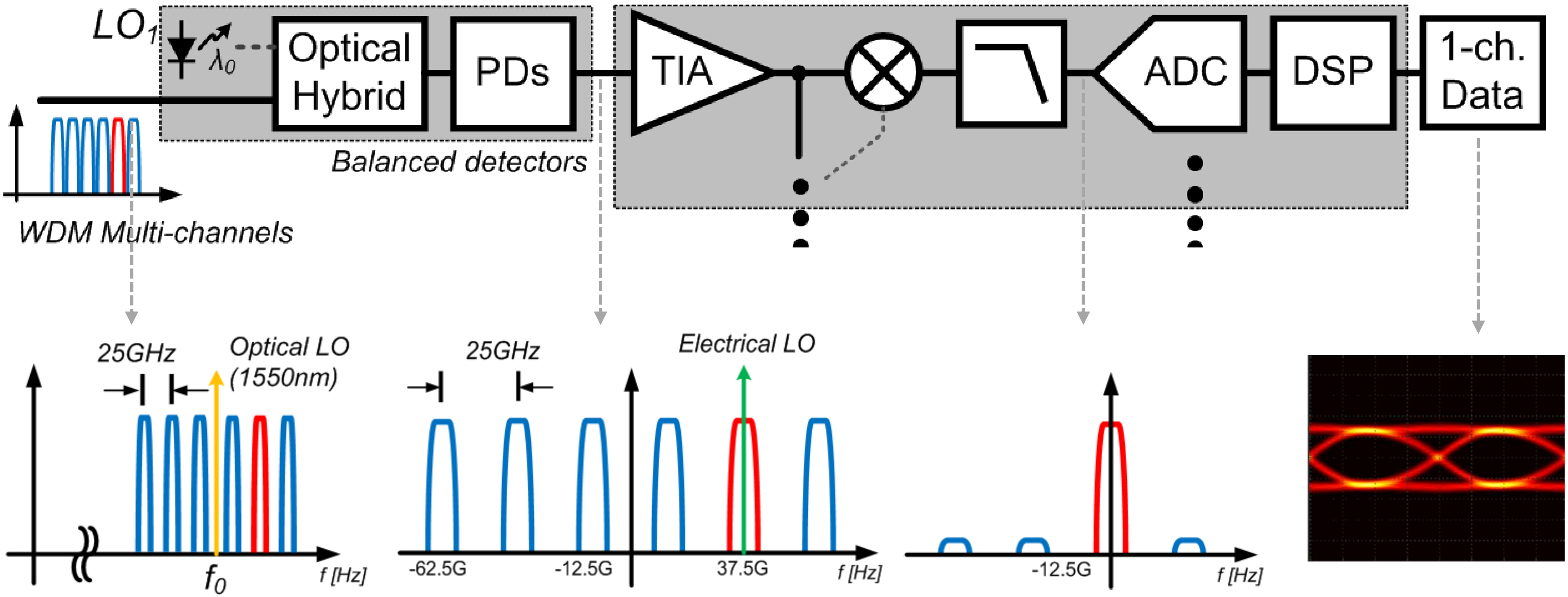
Electrical-Domain WDM Receiver



Small and simple photonic IC.

One electrical receiver IC covers all wavelengths.
IC might be complex;
can we design it for low power & low complexity ?

2-Stage Down-Conversion: Optical, Electrical



Phase-locked LO down-converts all WDM channels to RF @ 25 GHz spacing

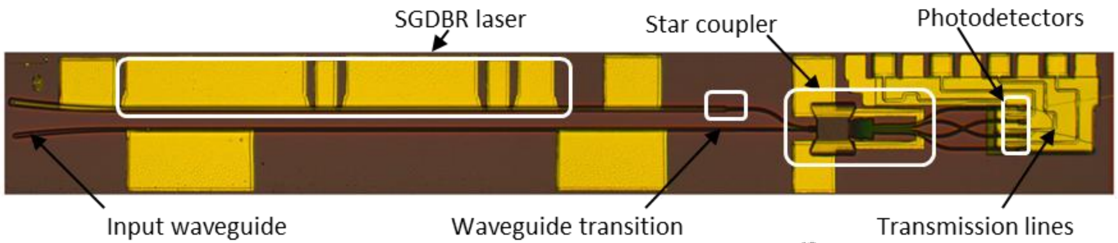
Electrical receiver down-converts each channel separately to baseband

Note: OPLL can lock to narrow-spaced optical pilot tone
→ phase-locked receiver even with highly dispersive channels

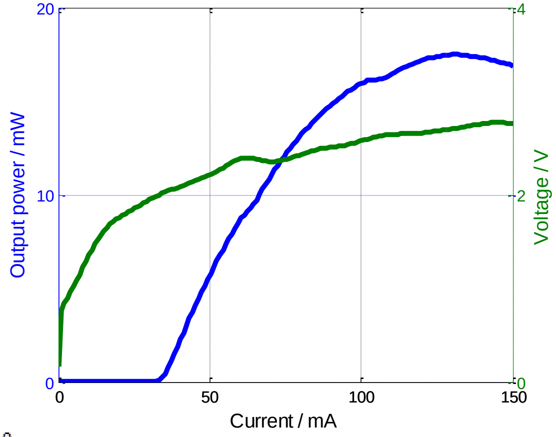
Technology Details

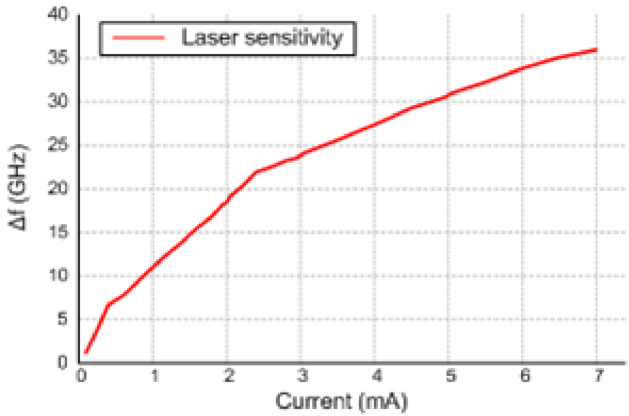
PICO

OPLL with PFD and SSBM *Photonic IC*



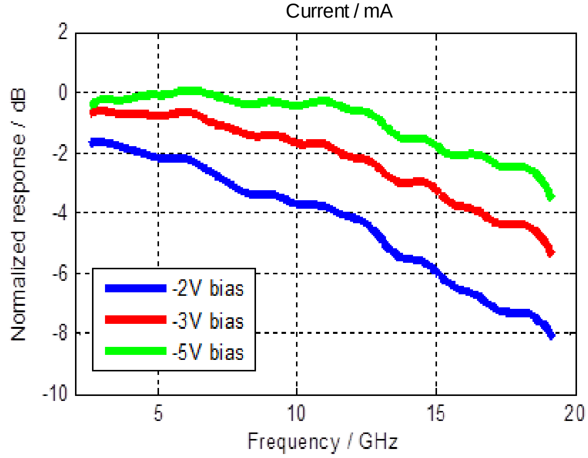
Laser LIV curve

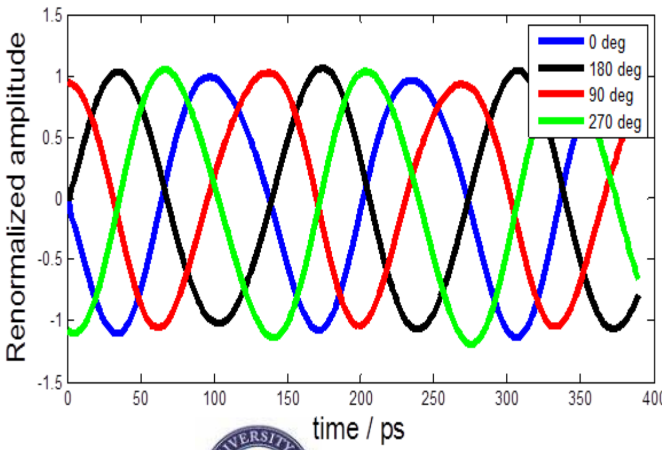




Laser phase pad tuning

PD bandwidth





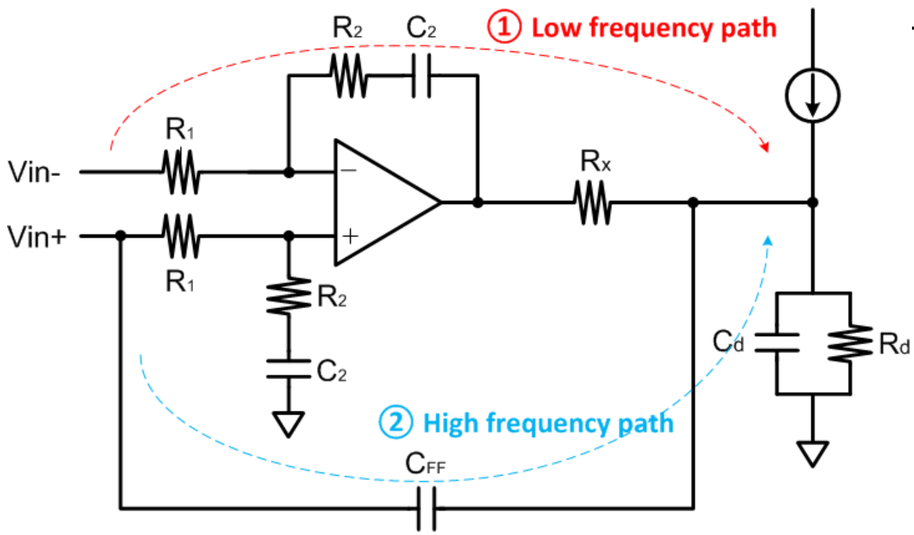
90° hybrid output

UCSB

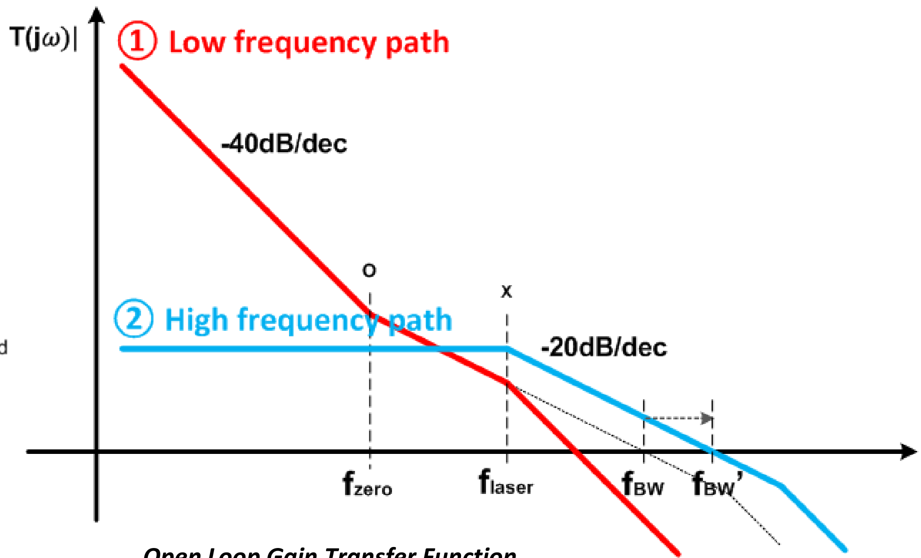
LEHIGH UNIVERSITY.

PICO

Feedforward Loop Filter
High Gain yet High Speed



Schematic



Open Loop Gain Transfer Function

Loop needs high gain at DC → op-amp needed.

Commercial op-amps too slow to support needed ~500 MHz loop bandwidth

Solution: feedforward loop filter

> ***low frequencies: op-amp for high gain***
>
> ***high frequencies: passive filter for low excess phase shift***