11.30 to 12.10

"Photonic ICs for Coherent Communications and Sensors"

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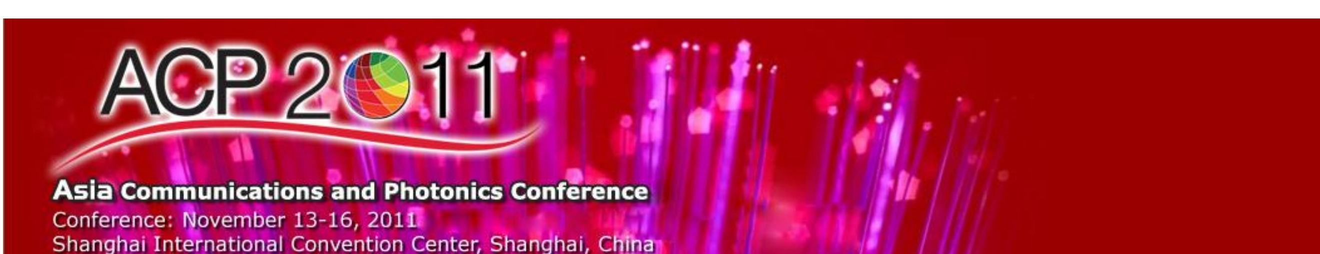
Abstract: Photonic ICs for Coherent Communications and Sensors-- The integration of many photonic components on a single chip has been shown to improve the efficiency of both transmitter and receiver systems as well as their size, weight and overall power consumption. As the technology has improved the performance is now also exceeding that of discrete solutions in many cases. Many years ago a key driver for photonic integration was the enhanced receiver sensitivity achievable in coherent communication systems. Somewhat ironically, as the need for more spectral efficiency, spectral selectivity, overall system efficiency, and cost have become critical issues today, coherent communication and sensor systems now again look to integrated coherent solutions. In this presentation we explore recent developments.

Biography: **Larry A. Coldren** is the Fred Kavli Professor of Optoelectronics and Sensors and Acting Richard A. Auhll Dean of Engineering at the University of California, Santa Barbara, CA. After receiving his Ph.D. Electrical Engineering from Stanford University and spending 13 years in research at Bell Laboratories, he joined UC-Santa Barbara in 1984 where he now holds appointments in Materials and Electrical & Computer Engineering. In 1990 he co-founded Optical Concepts, later acquired as Gore Photonics, to develop novel VCSEL technology; and in 1998 he co-founded Agility Communications, later acquired by JDSU, to develop widely-tunable integrated transmitters.

At Bell Labs Coldren worked on surface-acoustic-wave filters and later on tunable coupled-cavity lasers using novel reactive-ion etching (RIE) technology. At UCSB he continued work on multiple-section tunable lasers, in 1988 inventing the widely-tunable multi-element mirror concept, which is now used in numerous commercial products. Near this same time, he also made seminal contributions to efficient vertical-cavity surface-emitting laser (VCSEL) designs that continue to be implemented in practical devices. More recently, Prof. Coldren's group has developed high-performance InP-based photonic integrated circuits (PICs) as well as high-speed VCSELs, and they continue to advance the underlying materials growth and fabrication technologies.

Professor Coldren has authored or co-authored over a thousand journal and conference papers, a number of book chapters, a textbook, and has been issued 64 patents. He has presented dozens of invited and plenary talks at major conferences, he is a Fellow of the IEEE, OSA, and IEE, a recipient of the 2004 John Tyndall and 2009 Aron Kressel Awards, and a member of the National Academy of Engineering.



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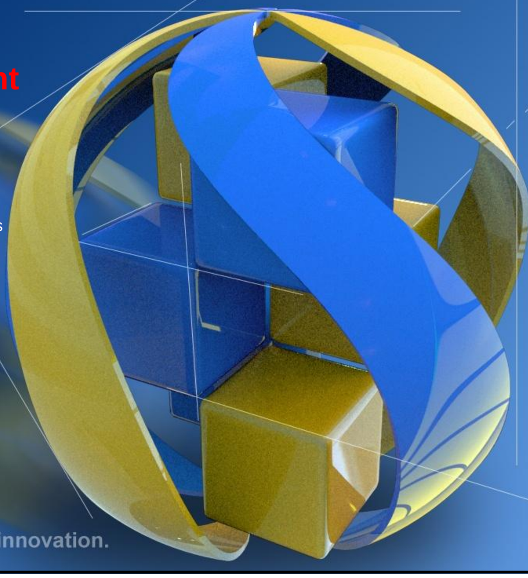
November 14, 2011

Photonic ICs for Coherent Communication and Sensing



Larry A. Coldren
Fred Kavli Professor of Optoelectronics and Sensors

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College of Engineering
UCSB

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The convergence of research and innovation.

Introduction and Overview

- Photonic ICs and coherent approaches are not new ideas, and in fact, synergistic
- Coherent for fiber optics delayed by WDM → due to EDFA
- PIC technology continued to develop (for WDM) → power (energy efficiency) a key attribute
- Coherent makes a comeback—mostly due to spectral efficiency, not sensitivity (spectral selectivity still important)
- Heterodyne vs. Intradyne—optical phase locked loops (OPLLs) for energy efficiency in sensors and communication
- Concepts & results for OPLL-based transmitters and receivers

Early Coherent Communication efforts motivated by sensitivity, but these goals also motivated Photonic Integration activities

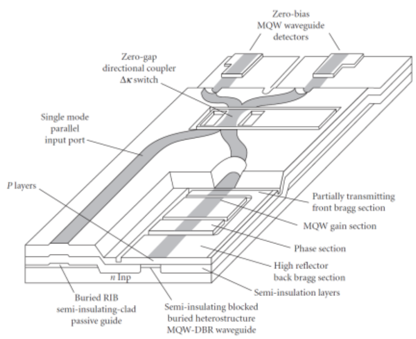
- In the 1980's coherent communication was widely investigated to increase receiver sensitivity and repeater spacing. It was also seen as a means of expanding WDM approaches because optical filters would not be so critical.

Y. Yamamoto and T. Kimura, "Coherent optical fiber transmission systems," *IEEE J. Quantum Electron*, vol. 17, no. 6, pp. 919-925, Jun. 1981.

- This early coherent work drove early photonic integration efforts—Stability; enabled phase-locking

T. L. Koch, U. Koren, R. P. Gnall, F. S. Choa, F. Hernandez-Gil, C. A. Burrus, M. G. Yung, M. Oron, and B. I. Miller, "GaInAs/GaInAsP multiple-quantum-well integrated heterodyne receiver," *Electron. Lett.*, vol. 25, no. 24, pp. 1621-1623, Nov. 1989

Integrated Coherent Receiver



- The EDFA enabled simple WDM repeaters (just amplifiers) and coherent was put on the shelf

Sensors still desire enhanced sensitivity

LUNA TECHNOLOGIES
A Division of Luna Innovations Incorporated

OPTICAL BACKSCATTER REFLECTOMETER™
(Model OBR 4600)

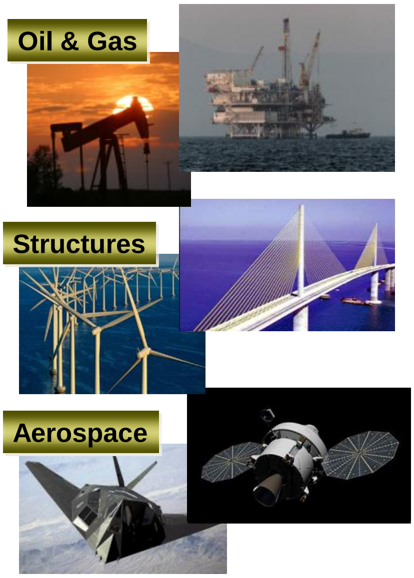
KEY FEATURES AND PRODUCT HIGHLIGHTS
- Easily locate, identify and troubleshoot macro-bends, splices, connectors and breaks
- Locate Insertion Loss points at every point in the network or assembly – eliminate cut-back
- Look inside components to evaluate each interface for RL and IL
- Measure 30 m with 10 μm resolution in less than 7 seconds
- Continuously measure a 1 m segment at up to 3 Hz
- Test and troubleshoot short-run networks (<2 km)
- Automate pass/fail verification of fiber assemblies
- Monitor distributed temperature and strain profiles along network or inside a component or module

The **OBR 4600** is the latest model of Luna Technologies' award winning Optical Backscatter Reflectometer™ product line. Designed for component and short-run network testing and troubleshooting, the OBR 4600 enables ultra-high resolution reflectometry with backscatter-level sensitivity. With spatial resolution as fine as 10 microns, zero dead-zone, options for integrated temperature and strain sensing and extended device length mode, the OBR 4600 offers the ultimate in fiber diagnostics.

MEASUREMENT PERFORMANCE HIGHLIGHTS
- -130 dB sensitivity
- 70 dB dynamic range
- 2 kilometer length range with no dead-zone
- Micrometer resolution up to 70 meters
- < 0.05 dB insertion loss resolution

The OBR 4600 offers unbeatable testing and troubleshooting capabilities now at unprecedented measurement speeds.

New Applications include structural & industrial sensors



Bragg gratings:
- Temperature
- Pressure
- Displacement / Strain
- Damage/Delamination

Coherent Fiber Sensing
- Distributed Acoustics
- Vibration
- Flow
- Intrusion
- Perimeter Monitoring

New lasers, such as all-semiconductor very high-speed swept lasers (>kHz rates), are enabling new methodologies

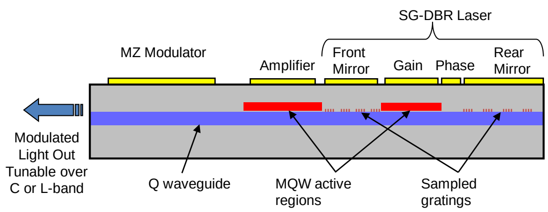
(photo courtesy of Insight Photonic Solutions)

Continued integration efforts have provided improved technology platforms

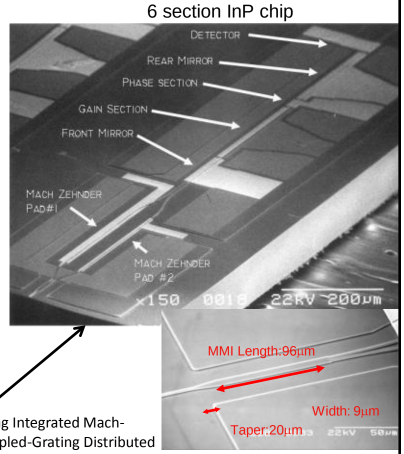
SGDBR+X widely-tunable transmitter:
- Foundation of PIC work at UCSB

"Multi-Section Tunable Laser with Differing Multi-Element Mirrors," US Patent # 4,896,325 (January 1990)

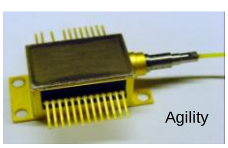
(UCSB'90-- → Agility'99-'05 → JDSU'05→)



6 section InP chip



- Vernier tuning over 40+nm near 1550nm
- SOA external to cavity provides power control
- Currently used in many new DWDM systems (variations)
- Integration technology for much more complex PICs

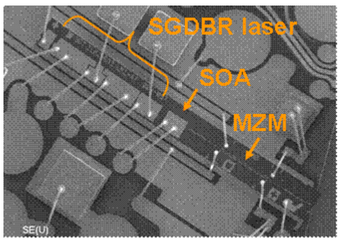


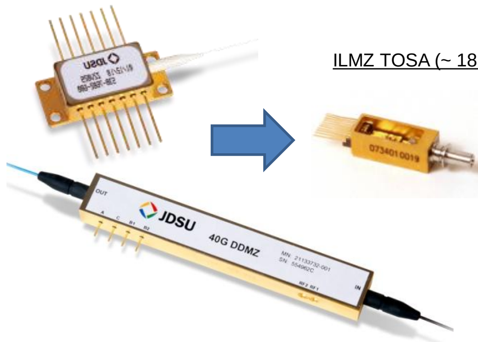
J. S. Barton, et al, "Tailorable Chirp using Integrated Mach-Zehnder Modulators with Tunable Sampled-Grating Distributed Bragg Reflector Lasers," *ISLC,* TuB3, Garmish, (Sept, 2002)

JDSU Roadmap Enabled by InP Monolithic Integration

- Volume deployment typically needs form factors optimized for port count, size, power dissipation and cost
  - Transceiver module form factors are MSA driven and ecosystem is more mature
  - Photonic integration is essential to achieve cost, power and size roadmap
  - ILMZ is a good example of photonic integration

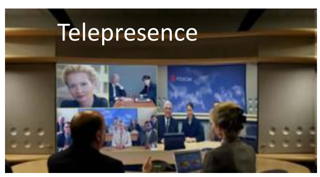
ILMZ chip (~ 4mm)

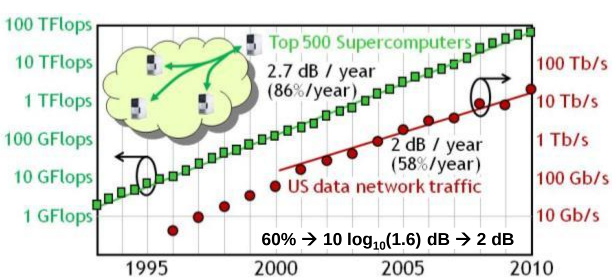




ILMZ TOSA (~ 18mm)

Network traffic is growing exponentially



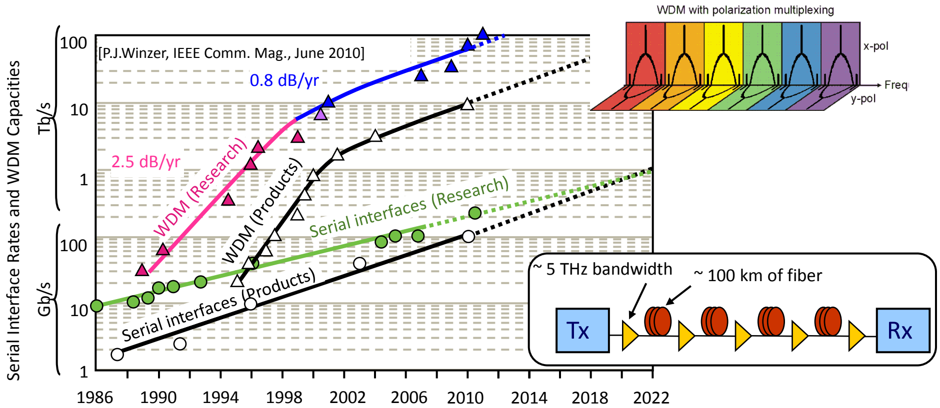


Exponential network traffic growth is driven by high-bandwidth digital applications

Video-on-demand, telepresence, wireless backhaul, cloud computing & services

Courtesy P. Winzer

Scaling spectral efficiency through WDM



~10 Terabit/s WDM systems are now commercially available

~100 Terabit/s WDM systems have been demonstrated in research

Growth of WDM system capacities has noticeably slowed down

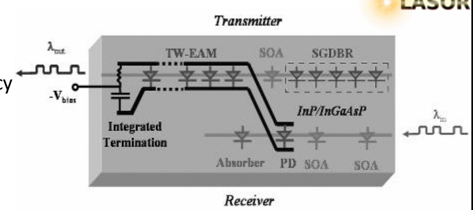
Courtesy P. Winzer

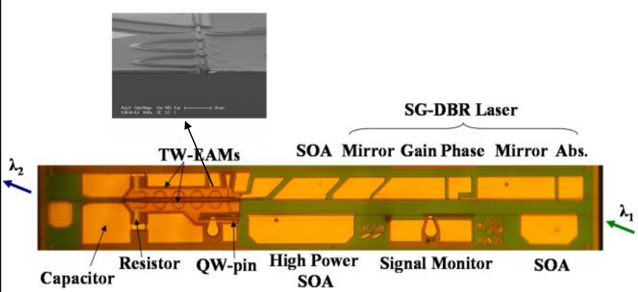
Evolution of InP Integration technology enables more functionality: (tranceiver/wavelength-converter)

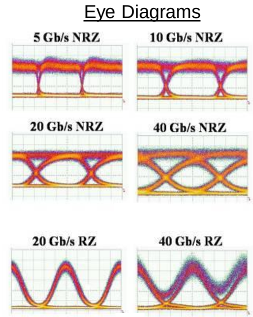
High-efficiency SOA-PIN Receiver & SGDBR-TW/EAM Transmitter

LASOR

- Data format and rate transparent 5-40Gb/s
- No filters required (same λ in and out possible)
- Two-stage SOA pre-amp for high sensitivity & efficiency
- 2R regeneration possible
- Traveling-wave EAM with on chip loads; ~ 0 dB out/in optical insertion loss
- Only DC biases applied to chip—photocurrent directly drives EAM → 1W/40 Gb/s → 25 pJ/bit
- 40 nm wavelength tuning range







M. Dummer et al. Invited Paper Th.2.C.1, *ECOC 2008.*

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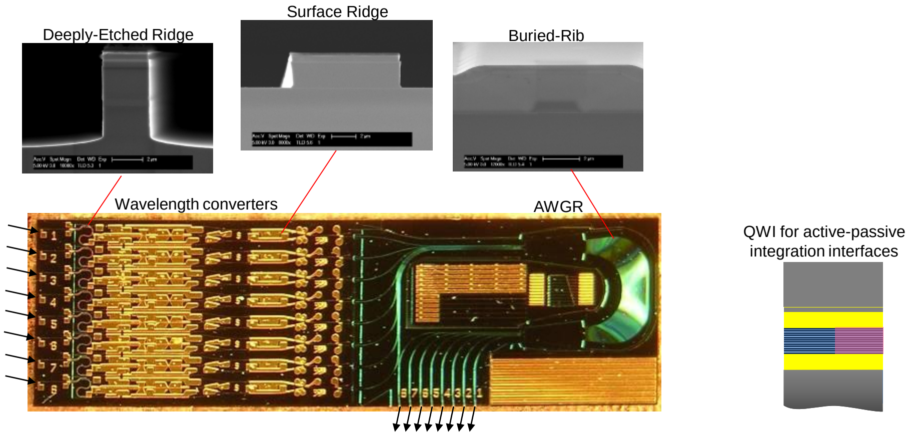
More functionality: 8 x 8 MOTOR Chip: (40 Gb/s per channel)

LASOR

- 8 x 8 'all-optical' crossbar switch
- SOA – Mach-Zehnder Wavelength Converters
- Quantum-well intermixing (QWI) to shift bandedge for low absorption in passive regions
- Three different lateral waveguide structures for different curve/loss requirements
- Single 'blanket' regrowth—Vendor growth, regrowth, & implants



Monolithic Tunable Optical Router

See S. Nicholes, et al, "Novel application of quantum-well intermixing implant buffer layer to enable high-density photonic integrated circuits in InP," *IPRM '09*, paper WB1.2, Newport Beach (May, 2009)

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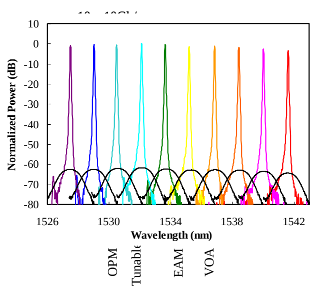
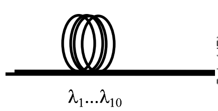
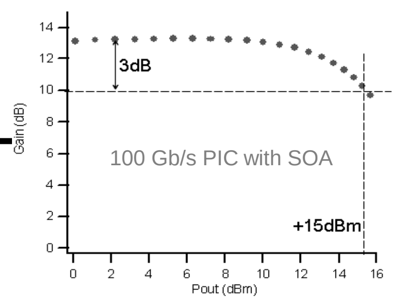
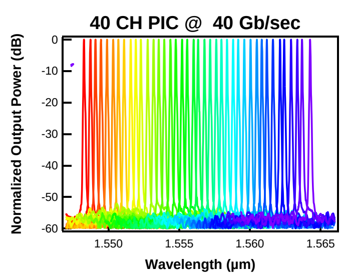
Infinera Commercial WDM PICs: Parallel Integration







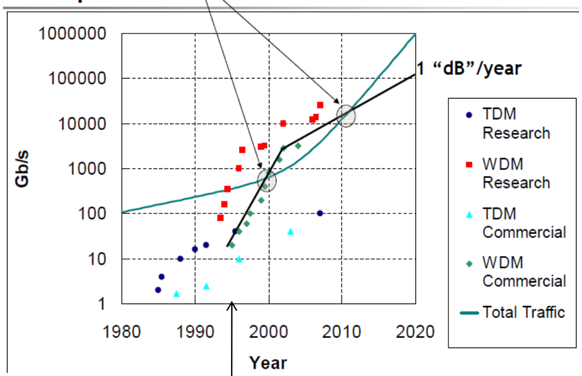


Courtesy C. Joyner

Fiber capacity not keeping pace with demand

- Spectral efficiency increases accompanying WDM not enough

Two Special Years 2000 and 2011



Introduction of EDFA and WDM
→ OEO repeaters vastly reduced

Courtesy Bob Tkach

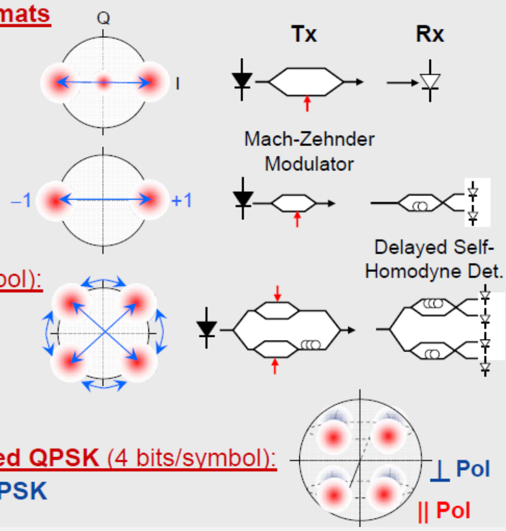
Coherent returns to extend spectral efficiency++

- Vector modulation/coherent detection utilizes full complex field to enhance spectral efficiency
- Increase bit-rate without increasing baud rate

❑ Binary modulation formats (1 bit/symbol):
- Optical duobinary / PSBT
- NRZ- / RZ-DPSK (“bipolar” ASK)

❑ Quaternary (2 bits/symbol):
- NRZ- / RZ-DQPSK

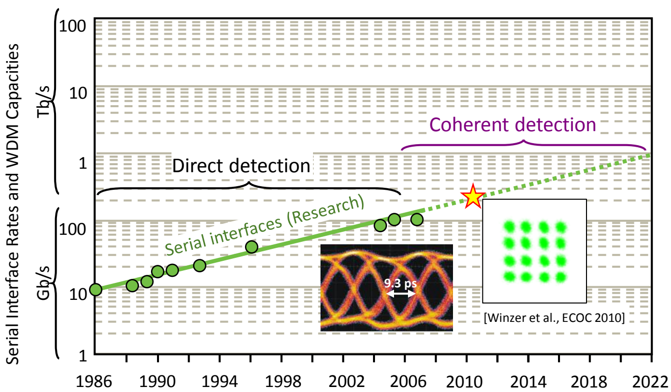
❑ Polarization-multiplexed QPSK (4 bits/symbol):
- Dual-Polarization QPSK



Other approaches for S.E. improvement include QAM (both amplitude and phase) and OFDM (Orthogonal Frequency Division Multiplexing →no guardbands)

Courtesy B. Mason

The evolution of high-speed optical interfaces



Optical interfaces switched to coherent detection at 100 Gbit/s

- Higher spectral efficiency
- More networking flexibility through digital signal processing (CD, PMD, filters)

400-Gbit/s interfaces have been demonstrated in research

(200 Gb/s per polarization)

CD: Chromatic dispersion
PMD: Polarization-mode dispersion

Courtesy P. Winzer

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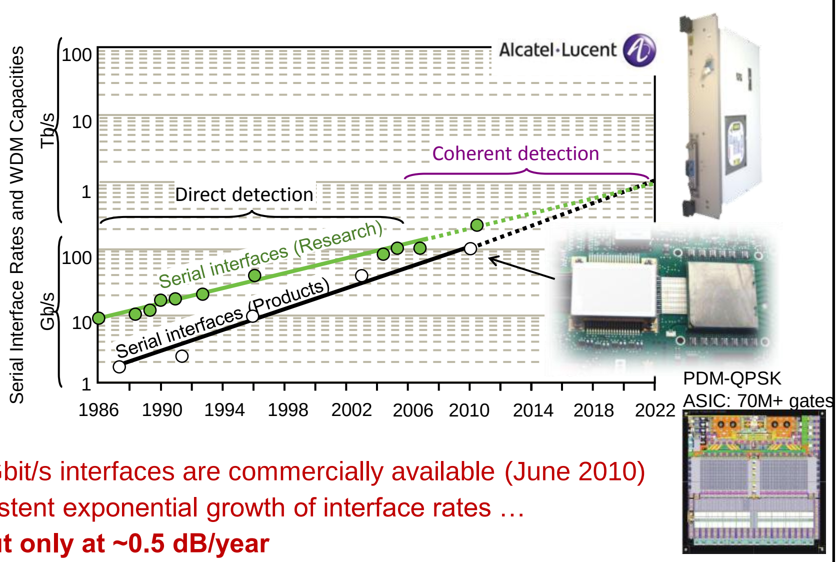
The evolution of high-speed optical interfaces



100-Gbit/s interfaces are commercially available (June 2010)

Consistent exponential growth of interface rates …

… but only at ~0.5 dB/year

Courtesy P. Winzer

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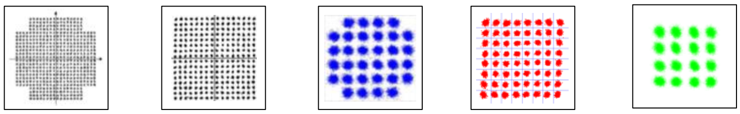
Increase modulation complexity or Baud rate?



PDM 512-QAM
3 GBaud (**54 Gb/s**)
[Okamoto et al., ECOC'10]

PDM 256-QAM
4 GBaud (**64 Gb/s**)
[Nakazawa et al., OFC'10]

PDM 32-QAM
9 GBaud (**90 Gb/s**)
[Zhou et al., OFC'11]

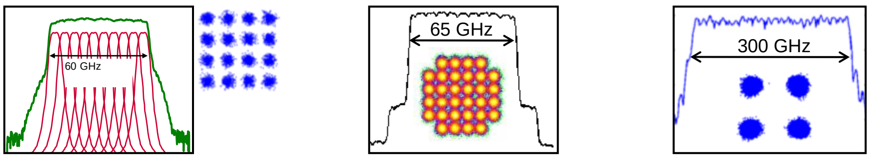
PDM 64-QAM
21 GBaud (**256 Gb/s**)
[Gnauck et al., OFC'11]

PDM 16-QAM
56 GBaud (**448 Gb/s**)
[Winzer et al., ECOC'10]

- More parallel channels
- More 'linear' electronics needed

- More dispersion/impairments
- Costly/non-existent electronics

Or, use superchannels??



448 Gb/s (10 subcarriers) 16-QAM
5 bit/s/Hz
2000 km transm.
[Liu et al., OFC'10]

606 Gb/s (10 subcarriers) 32-QAM
7 bit/s/Hz
2000 km transm.
[Liu et al., ECOC'10]

1.2 Tb/s (24 subcarriers) QPSK
3 bit/s/Hz
7200 km transm.
[Chandrasekhar et al., ECOC'09]

Courtesy P. Winzer

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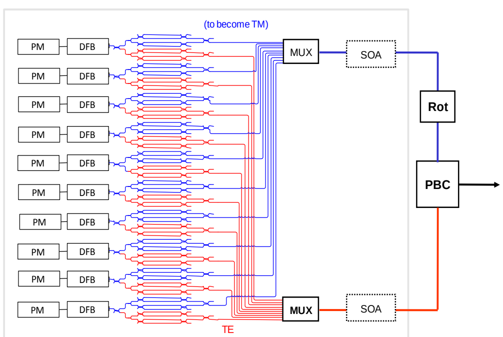
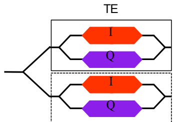
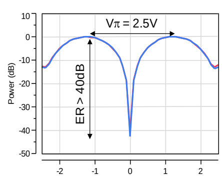
Infinera Coherent PIC Architecture: 400 Gb/sec PM-DQPSK Transmitter—parallel + serial integration



PM-DQPSK (10 x 40G)
10GBaud x 4 / λ
1.8 bits/Hz



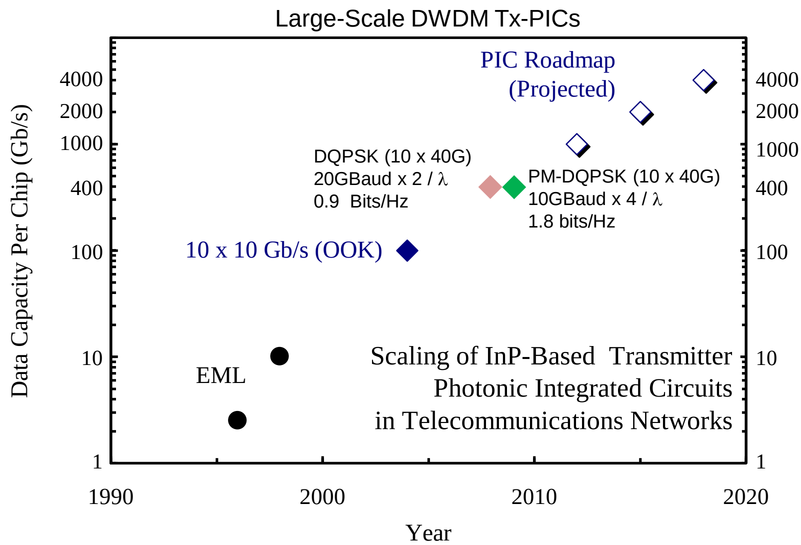


Vector Modulation

C. Joyner, P. Evans, S. Corzine, M. Kato, M. Fisher, J. Gheorma, V. Dominic, P. Samra, A. Nilsson, J. Rahn, A. Dentai, P. Studenkov, M. Missey, D. Lambert, R. Muthiah, R. Salvatore., S. Murthy, E. Strzelecka, J. Pleumeekers, A. Chen, R. Schneider, R. Nagarajan, M. Ziari, J. Stewart, F. Kish, and D. Welch, "Current View of Large Scale Photonic Integrated Circuits on Indium Phosphide," *OFC*, San Diego, CA, Mar. 21-25, 2010, OWD3.

Courtesy C. Joyner

Infinera Transmitter PIC Roadmap



Courtesy C. Joyner

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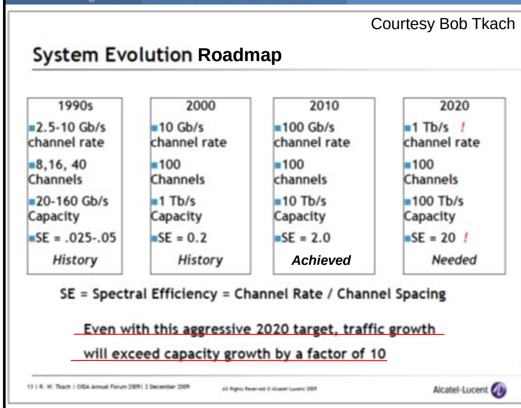
Another Complication in System Evolution—Dynamic Range


Courtesy Bob Tkach

System Evolution Roadmap

1990s	2000	2010	2020
2.5-10 Gb/s channel rate	10 Gb/s channel rate	100 Gb/s channel rate	1 Tb/s ! channel rate
8,16, 40 Channels	100 Channels	100 channels	100 Channels
20-160 Gb/s Capacity	1 Tb/s Capacity	10 Tb/s Capacity	100 Tb/s Capacity
SE = .025-.05	SE = 0.2	SE = 2.0	SE = 20 !
History	*History*	***Achieved***	*Needed*

SE = Spectral Efficiency = Channel Rate / Channel Spacing

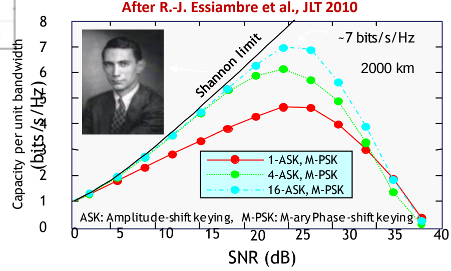
Even with this aggressive 2020 target, traffic growth will exceed capacity growth by a factor of 10

Alcatel-Lucent

- **Must make vast improvements in Spectral Efficiency (SE) → Bits/s/Hz of bandwidth to meet demand**
- **But, complex modulation formats are called for, and these require high-dynamic range**

- **Excess fiber capacity disappears after 2015→ lay more standard fiber, use multicore fiber, or multimode, or ??**
- **Going parallel may be better than continuing to evolve more complex modulation formats**

After R.-J. Essiambre et al., JLT 2010

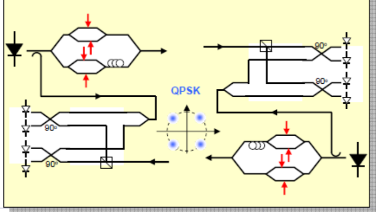


Only SE ~ 8 bits/s per Hz possible @ 500km

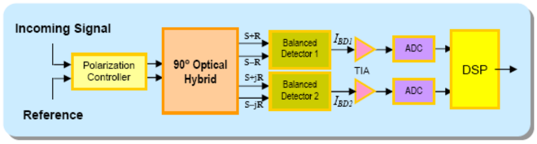
Intradyne or Heterodyne for generic sensor and short-reach communication applications?

Intradyne Coherent Detection

- Phase and polarization diversity
- Frequency-locked local oscillator
- Digital signal processing of received electrical signals
  - Electronic CD compensation
  - Electronic polarization demultiplex
  - Adaptive PMD compensation



Typical Intradyne receiver architecture

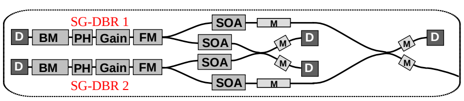


❖ Use 'Intradyne' without phase-locked LOs, or do we need true Heterodyne detection?

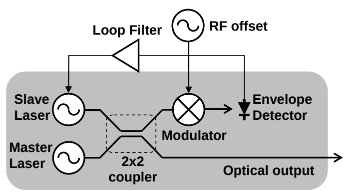
- Desire data-rate independent generic chips—when are phase-locked narrow-linewidth LOs desired?
- High-speed A/Ds & DSPs require lots of power and are expensive to design, especially as data rate increases
- Some impairments can be removed with much slower, lower-power, lower-cost signal-processing circuits

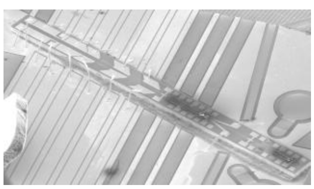
Integrated Optical Phase Locked Loops (OPLLs): provide a new stable control element

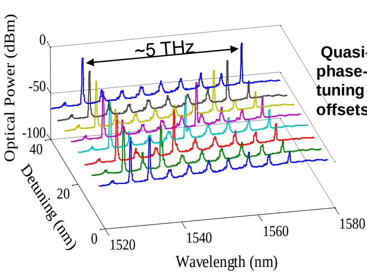
Offset locking of two SGDBRs→ viable using close integration of PICs with electronics in a OPLL



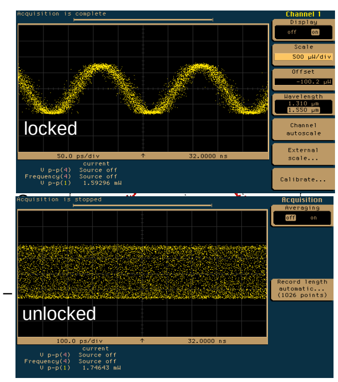
D Photodetector
M Modulator







Quasi-continuous phase-locked digital tuning up to 5 THz offsets possible



Ristic, *et al: JLT* v.28 no.4, pp526-8, Feb., 2010

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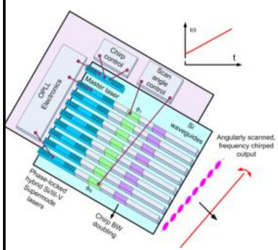
Photonic Integration for Coherent Optics *(PICO)*

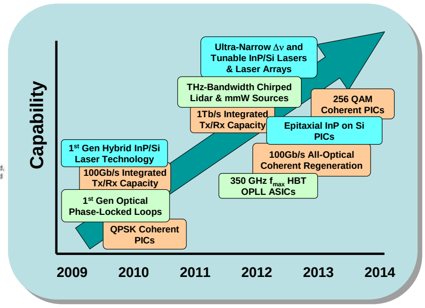
Coldren, Bowers, Rodwell, Johansson (UCSB),
Yariv (Caltech), Koch (Lehigh), Campbell (UVA), Ram (MIT)

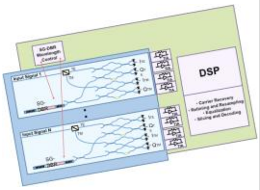
Goal: Create a new generation of photonic integration engines that provide unprecedented and practical control of optical frequency and phase, driving a level of sophistication that is routine today for RF into the optical domain.

- Enabling revolutionary capabilities in sensing & communications
- Advancing the intimacy of electronic and photonic integration with new monolithic and hybrid materials as well as integration platforms



LIDAR Tx





Ethernet Rx

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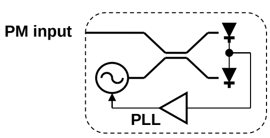
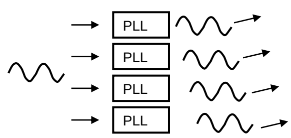
Applications/Challenges

Coherent receiver



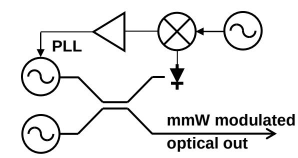
- Costa's Loop for BPSK, QPSK demodulation
- Complex DSP circuits not required, but simpler ones can be added for CD and PMD
- Challenge: Develop receivers for high speed (>100Gbaud) or high constellations (n-QAM)
- Matched with development of coherent sources

LIDAR



- Very rich/challenging area
- Locking tunable lasers
- Arrays of locked OPLLs
- Swept microwave reference
- Time / Phase encoding of directed output
- Need for rapid scanning and locking rates

mmW / THz generation

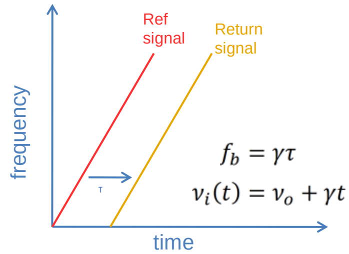


- Locking of two tunable lasers
- Requires high-speed, high-power UTC photodiode
- Speed determined by UTC photodiode and feedback electronics: Can be very high
- Combined with antenna designs for complete TRX links with free-space path

All require close integration of electronics with photonics

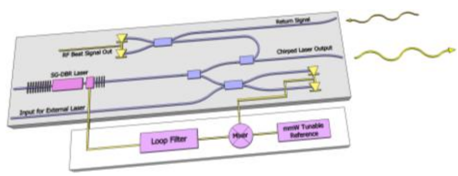
FMCW LIDAR

- Spatial Resolution related to Frequency Span
  - SG-DBR has 5 THz tuning range → 30 µm resolution
  - $\Delta z_r = \dfrac{c}{2 n_g \Delta \nu_s}$
- Range ~ c/(πΔv);
  - For 100 kHz linewidth, range could be 750m



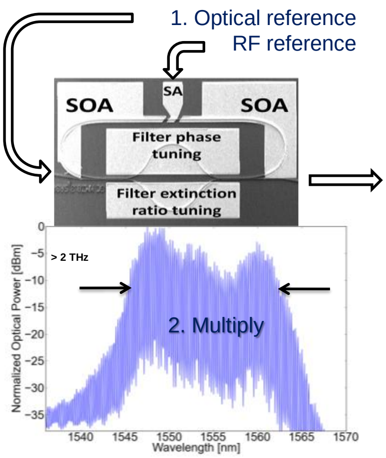
Integrated LIDAR Transmitter

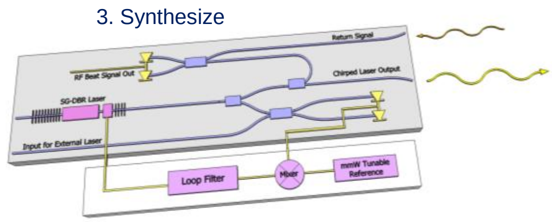
- SG-DBR Laser
- Balanced Detectors
- MMI Couplers
- Modulators
- 90 Degree Hybrid
- Transmission Lines

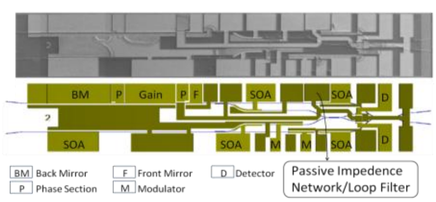


Optical waveform synthesis *LIDAR Transmitter*

- *Multiply RF reference to >2THz (5 THz projected) using gain-flattened mode-locked laser (MLL)*
- *Phase-lock widely tunable LIDAR transmitter with sub-Hz relative accuracy*
- *>2 THz Swept LIDAR or pulse-compression LIDAR waveforms available*







Tuning Across the Comb

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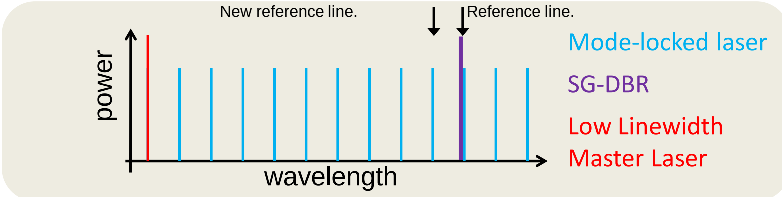
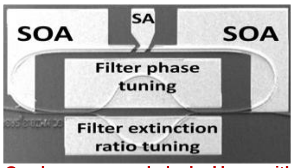


- ❑ **Frequency offset is increased until adjacent reference line can be locked at DC.**
- ❑ **Process is repeated for continuous tuning.**



Comb source: mode-locked laser with gain flattening filter.

Integrated Covega DFB. <100 kHz optical linewidth.

Narrow linewidth master laser.

RF Driver

SG-DBR laser with balanced detectors for OPLL.

Broadband Comb Generation

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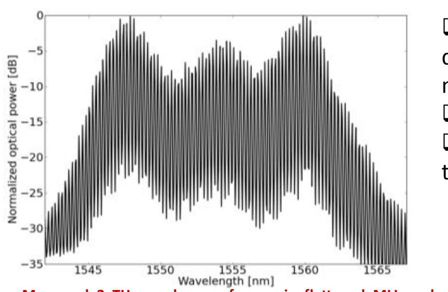
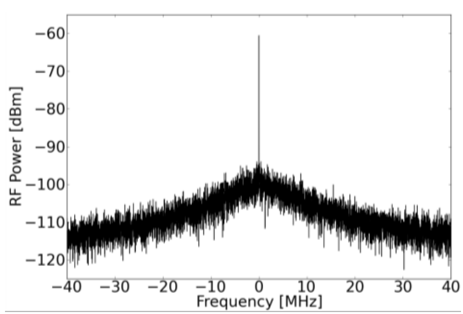


Measured 2 THz comb span from gain flattened MLL under hybrid mode-locking.

- ❑ Comb spans over 2 THz have been demonstrated with the current gain flattened mode-locked laser.
- ❑ There are 70 lines spaced by ~29.6 GHz.
- ❑ This far exceeds the spans available without the use of the gain flattening filter.

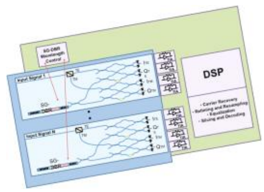
- ❑ With hybrid mode-locking (using an RF reference) the RF linewidth is < 10 Hz.
- ❑ This corresponds to the frequency error over the entire comb.
- ❑ < 10 Hz error over a 2 THz range.



Measured RF power at 29.6 GHz, from a high-speed photodiode with electrical signal analyzer (ESA). FWHM < 10 Hz. (RBW = 30 KHz).

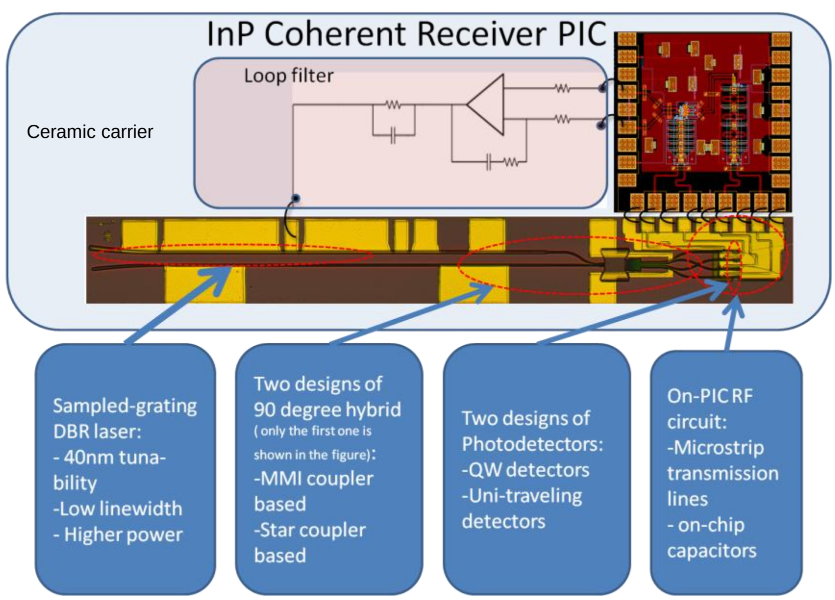
Coherent Receivers

- Advantages of coherent receivers
  - Tolerance to noise
  - Compatibility with different modulation formats
  - No optical filter needed to demultiplex WDM channels
- Typical limitations and drawbacks
  - Phase noise limitation -- LO laser linewidth
  - For Intradyne, high-speed DSP is required
    - High power consumption
    - High design and production cost
    - Limited speed



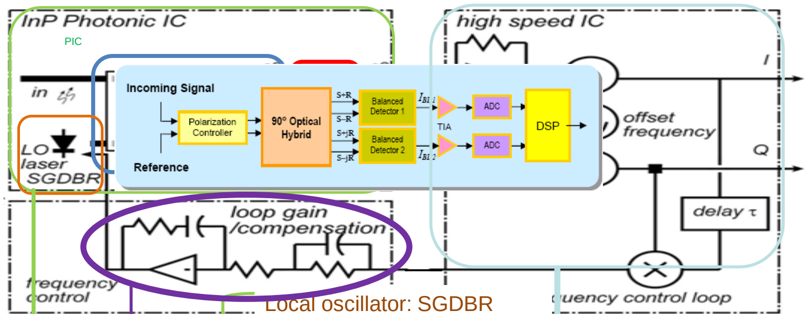
- Alternative -- Coherent receivers with OPLL (Costa's loop)
  - No phase and frequency tracking and correction
  - Lower relative LO phase noise
  - Low power, high-efficiency solution
  - Cannot pre-correct for large impairments

OPLL Receiver Layout



Coherent Receiver Architectures

Coherent receiver with a free-running LO (Intradyne):



Local oscillator: SGDBR laser
90 degree Hybrid
Balanced detectors

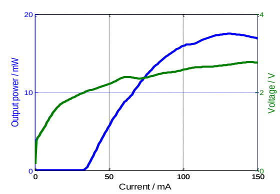
High speed Mixers, amplifiers

Loop filter

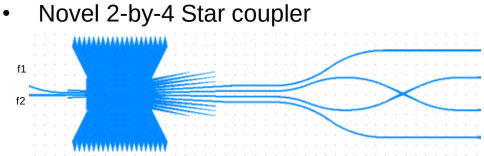
Optical Phase-Locked Loop (OPLL) with frequency lock (data removal also designed in)

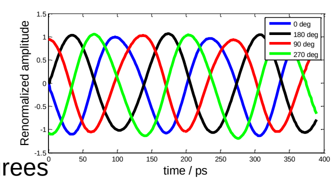
PIC Characterization

- SG-DBR laser
  - 20mW output power
  - 40 nm tuning range
  - 40mA threshold current



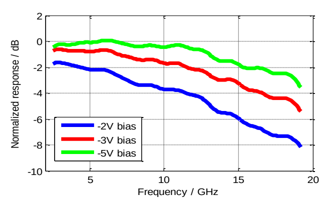
- Novel 2-by-4 Star coupler





  - Phase error between I and Q is within 3 degrees

- QW photodetector (same as gain regions)
  - 18 GHz 3-dB bandwidth with -5V bias



PIC Testing (no feedback)

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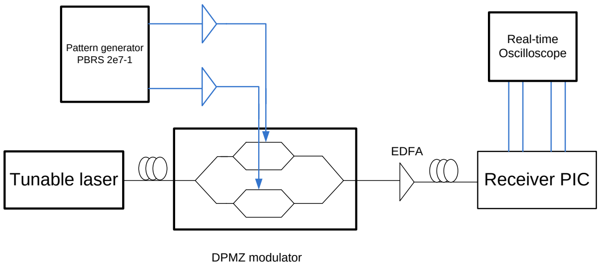
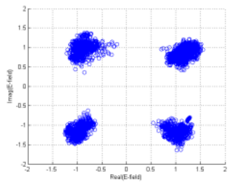
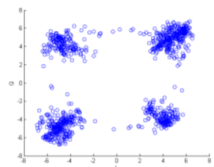
- As a QPSK coherent receiver
  - Back-to-back measurement
  - 10 Gbit/s and 20 Gbit/s signals were demodulated





10 Gbit/s QPSK data demodulation



20 Gbit/s QPSK data demodulation

Homodyne Locking (Loop filter only)

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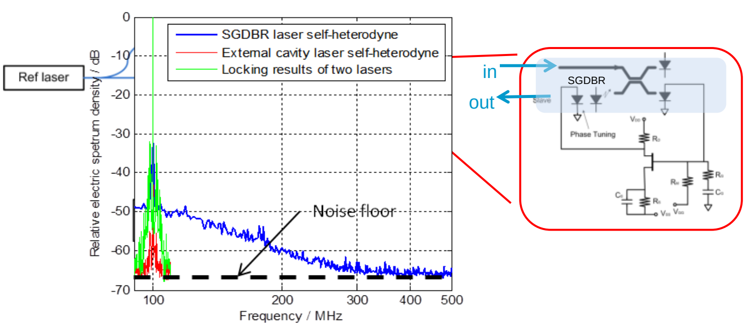
- Phase-lock SG-DBR L.O. laser to reference laser
  - Design loop bandwidth: ~ 1GHz
  - Using HEMT based active loop filter



- Issue: For high input signal levels, injection locking observed due to intra-chip reflections

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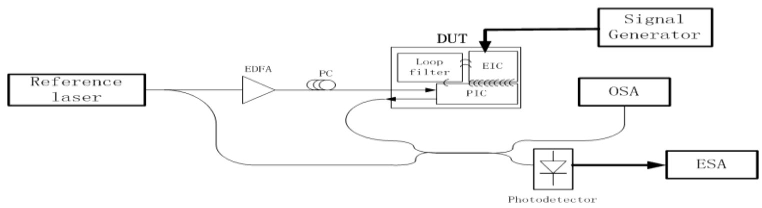
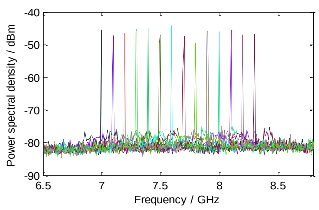
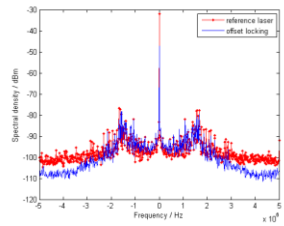
SSB Offset Locking

- Test setup



- Preliminary offset locking results
  - Successfully lock at 3.5 -11 GHz offset frequency range (identical linewidth to reference)
  - Illustrate frequency sweeping between 7-8.3 GHz





- **5.5 GHz offset locking**
- **SGDBR completely 'clones' reference—even its sidelobes**
- **Δλ < 100 kHz**

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Summary

- **Active InP-based Photonic ICs can be created with size, weight, power and system performance metrics superior to discrete solutions in many situations. If produced in some volume, the cost can be much lower.**
- **Coherent approaches will be greatly improved by the use of Photonic Integration, and numerous sensor applications may be enabled in addition to higher-spectral-efficiency communications.**
- **Efforts to increase the spectral efficiency of communication systems employing coherent approaches using vector modulation and reception with increasingly complex formats have yielded significant advances; however, the cost is significant, and we appear to be approaching practical limits. Parallel paths may be a practical alternative to higher levels of QAM.**
- **Close integration of control/feedback electronics will be desirable in many future PIC applications—it is required for Optical Phase Locked Loops (OPLLs) with conventional semiconductor lasers, but efficiency can be high.**
- **OPLL-based transmitters and receivers, incorporating all of the photonics on a single PIC, have demonstrated Hz-level relative frequency accuracy, and duplication of the linewidth and noise levels of the reference source.**