Hyperfine Spectral Phase Coded Optical CDMA: Component Technologies and Networking Applications

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Many Pieces to the Telcordia DARPA OCDMA Team

Program & vision:

- Shahab Etemad
- Janet Jackel

***Systems, hardware, software*:**

- Paul Toliver
- Anjali Agarwal
- Jeffrey Young
- Tom Banwell
- Mike Rauch

Simulation, coding:

- Ron Menendez
- Stefano Galli

Partners

- UCF/CREOL (Peter Delfyett): mode-locked laser source
- Little Optics: integrated OCDMA encoders/decoders
- Essex Corp: hyperfine free-space OCDMA encoders/decoders

Little Optics

Outline

- Why optical CDMA?
- Overview of spectral phase coded OCDMA
- Telcordia OCDMA approach:
  architecture & experimental implementation
- Key SPC-OCDMA technologies
  - Multi-wavelength laser source
  - Spectral phase encoder/decoder
  - Optical orthogonal coding
- Networking applications
  - Inter-band OCDMA+DWDM
  - Intra-band OCDMA+DWDM
  - All-optical code conversion
- Summary

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Why OCDMA?

- **Code empowered networking:**
  - Let the codes do the networking (as opposed to wavelength conversion)
  - Network provisioning & code assignment
  - Statistical multiplexing & efficient sharing of optical bandwidth

- **Physical layer "security":**
  - It is not encryption, but can provide some level of security through obscurity
  - How would one encrypt at 40Gb/s and higher? Could some form of optical CDMA help avoid electronic bottlenecks?

- **Exploiting available bandwidth (fiber or free-space):**
  - Could it help increase spectral efficiency?
  - Can it co-exist with existing DWDM techniques as an overlay?
  - Could it be used to fill in unused bandwidth?

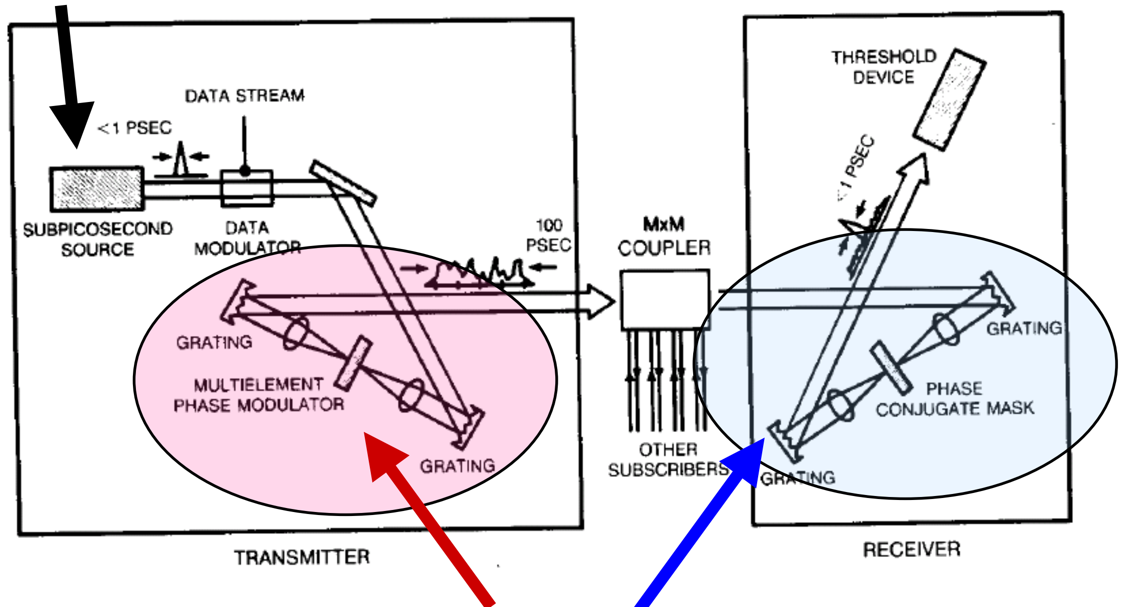
Relevant work on Spectral Phase Coded OCDMA

- **Prior work on *wideband* SPC-OCDMA:**
  – 1990: Salehi, Weiner, & Heritage
    "Coherent ultrashort light pulse CDMA comm. systems"
  – 2000: Weiner
    "Femtosecond pulse shaping using SLMs"
  – NTT & others

- **Current efforts:**
  – DARPA O-CDMA program
    - UC-Davis
    - Purdue
    - Telcordia (***narrowband*** SPC-OCDMA)

Bellcore's 1990 OCDMA

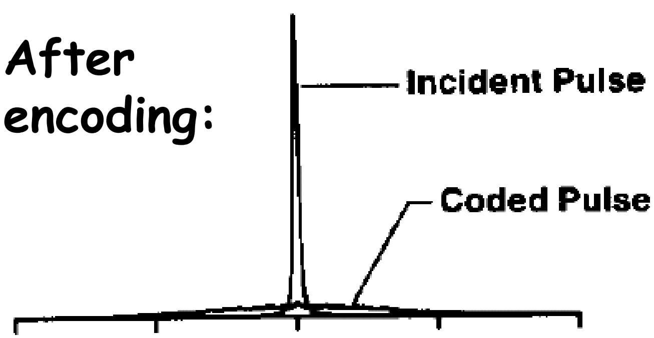
Ultrashort pulse source (wideband optical spectrum)



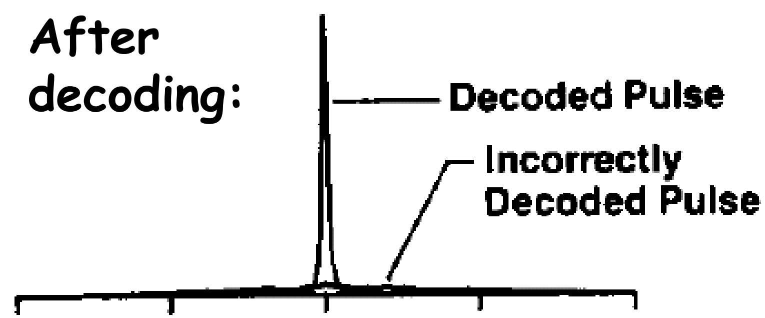
Very short optical pulses (<1 ps) containing many phase locked optical frequencies are spread in time according to a spectral phase code

Spectral phase encoder/decoder

After encoding:



After decoding:



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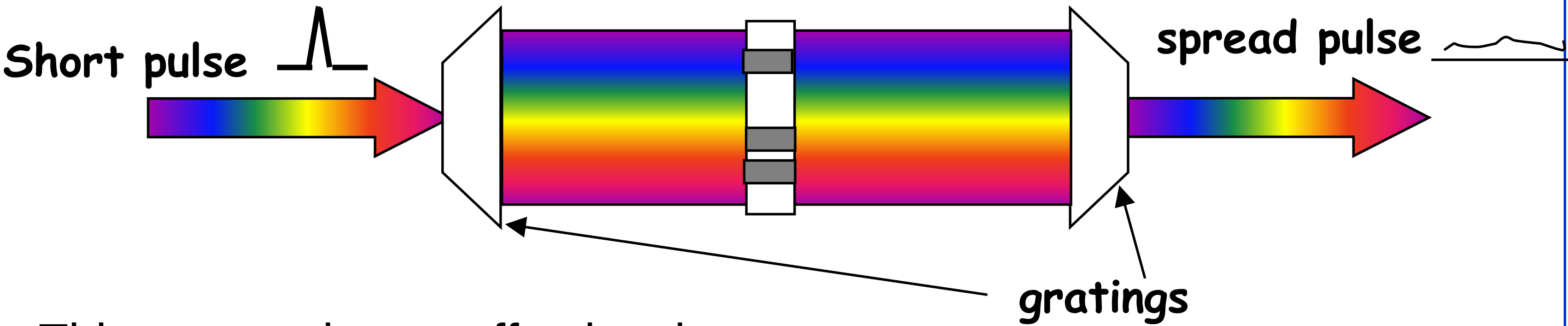
Bellcore's 1990 OCDMA continued….



This approach was effective, but

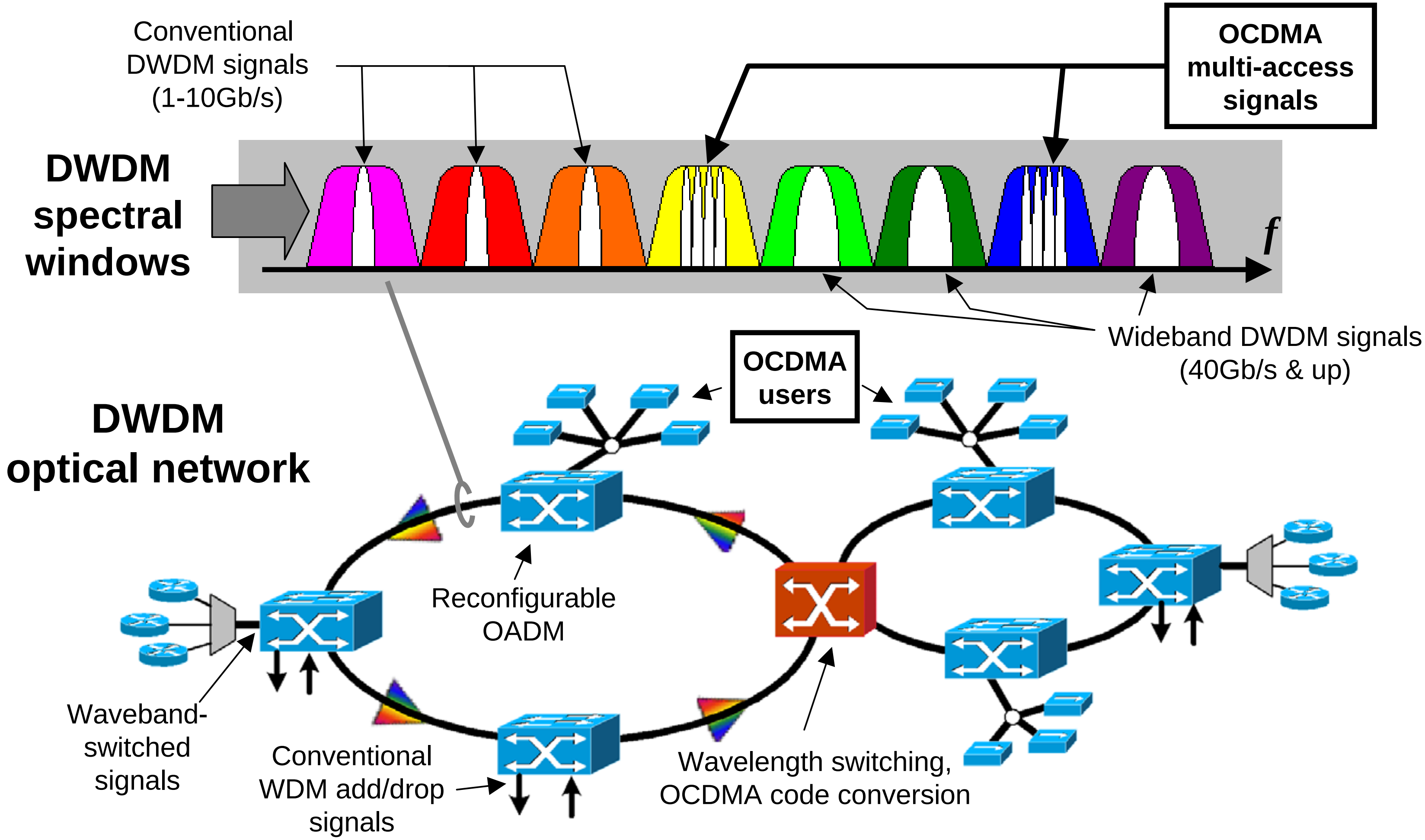
- The short pulses cover a huge amount of bandwidth, so this is not compatible with normal WDM
- The number of codes is limited, so the use of bandwidth is not efficient.
- It is built on an optical table – not very portable!

We wanted to find a way to be compatible with DWDM, and also use the bandwidth efficiently

And eventually we wanted to be able to create a compact coder and decoder for dynamic codes that can be changed on demand in a short time.

Vision for “Optical Network Compatible” OCDMA

- An overlay OCDMA architecture compatible with existing DWDM networks
- Spectral-phase-coded OCDMA using tightly spaced phase-locked laser lines within a tunable DWDM window



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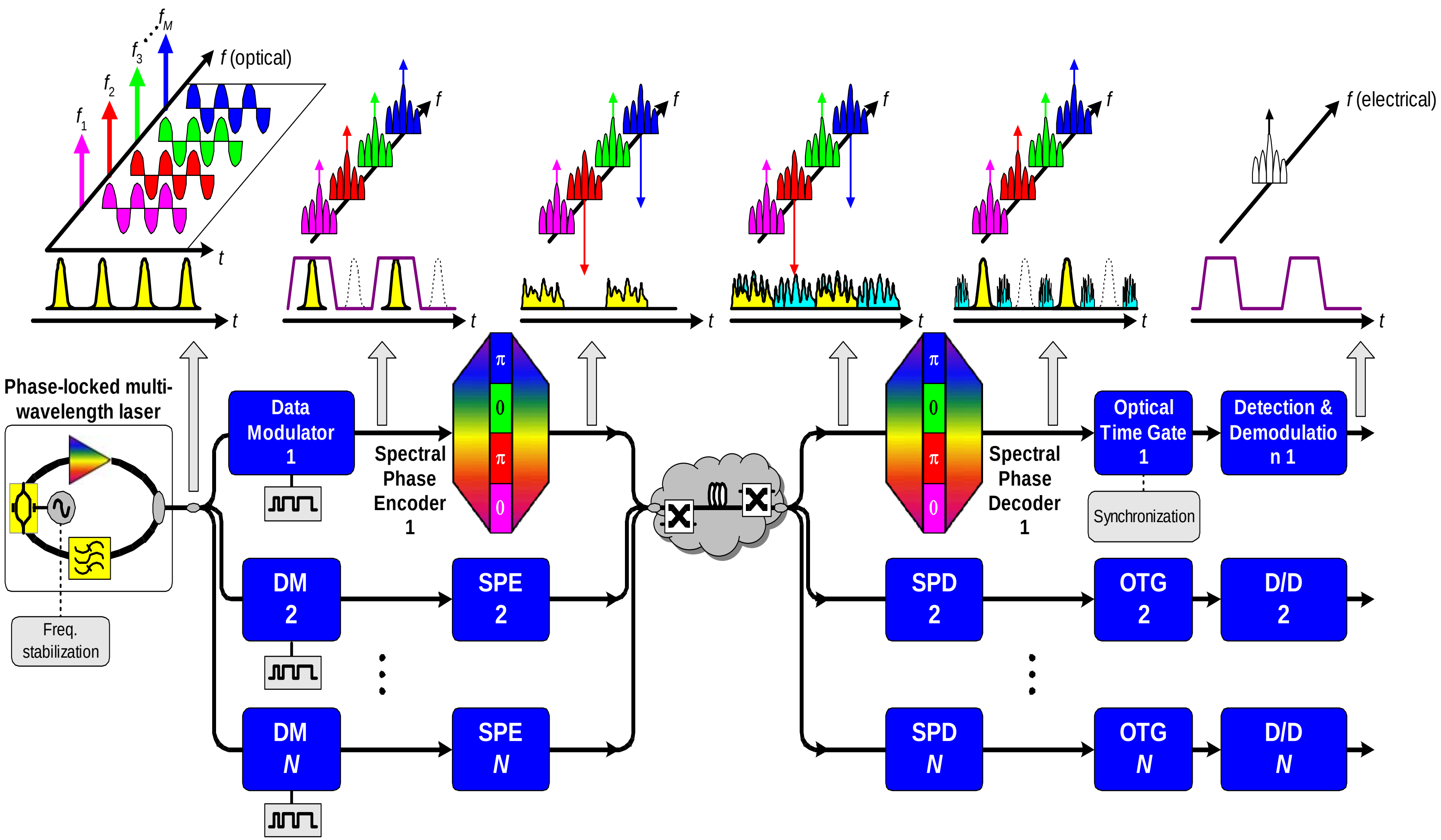
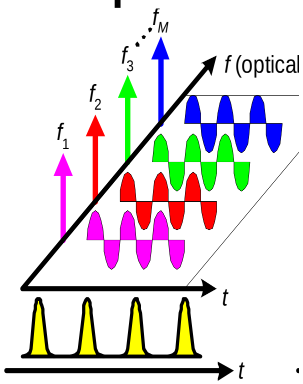
Telcordia OCDMA System Architecture and Signal Flow



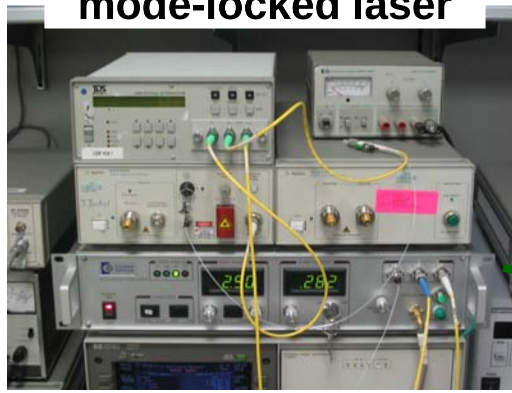
Key SPC-OCDMA Technologies

Phase-locked multi-wavelength laser source

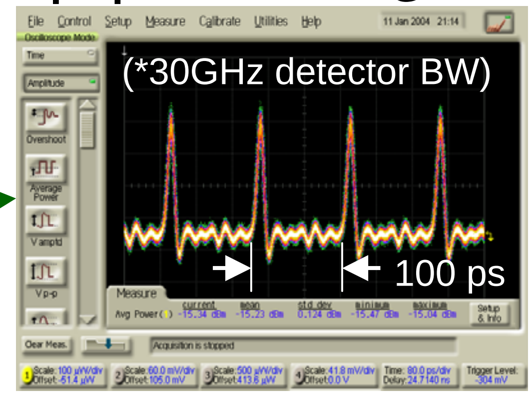
Conceptual picture



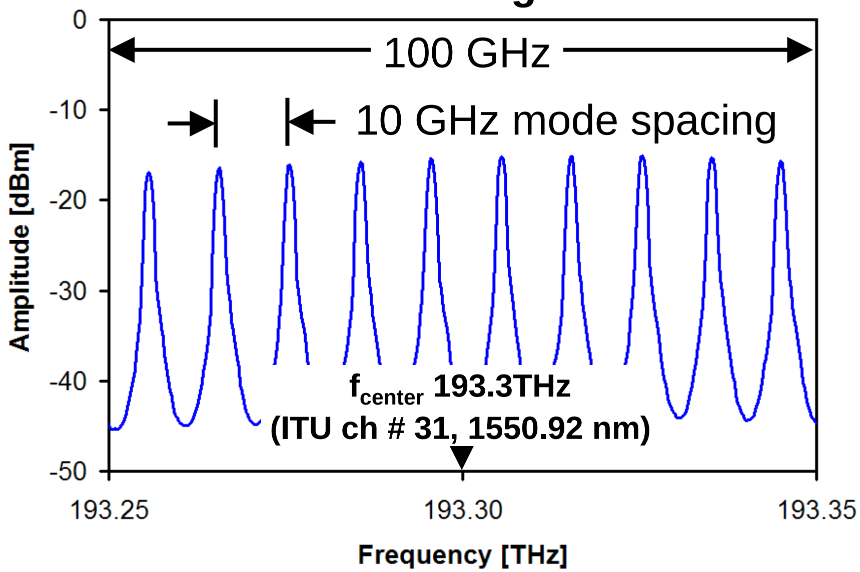
Implementation: mode-locked laser



Time-domain: ~2.5 ps pulse stream @ 10 GHz



Frequency domain: multi-wavelength comb



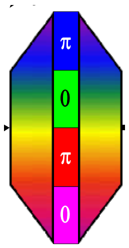
(*0.01 nm OSA BW)

<u>Key technical challenges:</u>

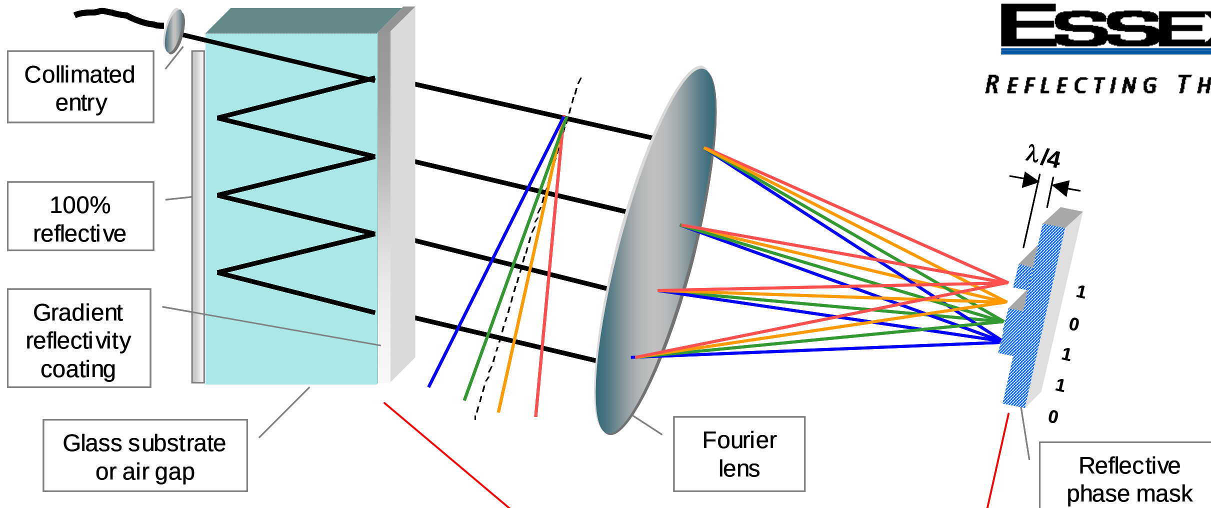
- **Comb frequency alignment**
- **Mode phase noise**
- **Size/power reduction**

Spectral Phase Encoder/Decoder: Phase 1

Conceptual picture



Implementation: Essex Hyperfine OCDMA encoder/decoder



REFLECTING THE FUTURE

- **Fixed 5 GHz spectral code bin spacing**
- **Static spectral phase mask**

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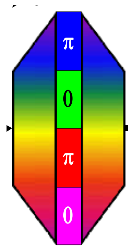
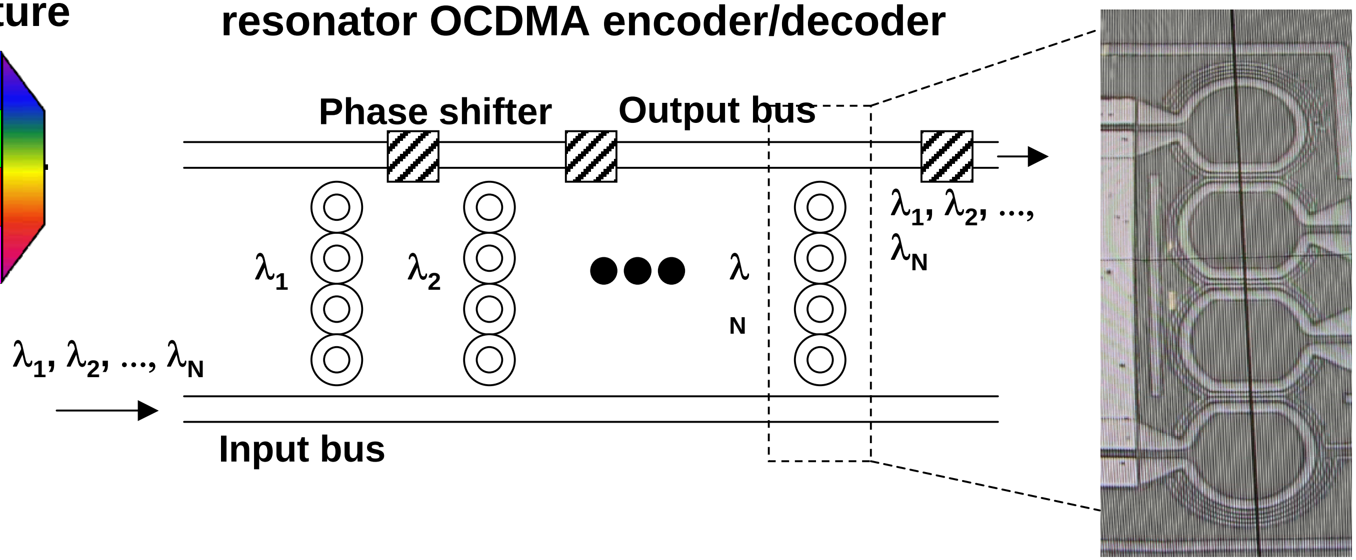
OPTICAL CODE-DIVISION MULTIPLE ACCESS O/CDMA

Spectral Phase Encoder/Decoder: Phase 2

Conceptual picture



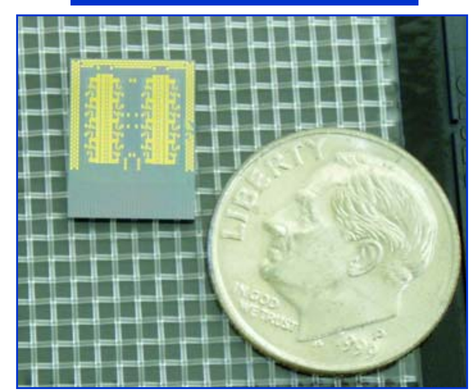
Implementation: Little Optics ring resonator OCDMA encoder/decoder



Little Optics

- **Programmable frequency bin position & programmable spectral phase mask**
- **Four ring resonators define each spectral frequency bin (~8 GHz wide, center tunable)**
- **Differential spectral phase shift between two adjacent frequency bins is programmable & controlled by a thermo-optic phase heater (accuracy to ~λ/10)**

16-bin encoder



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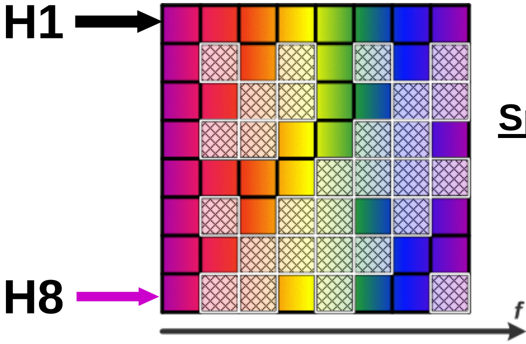
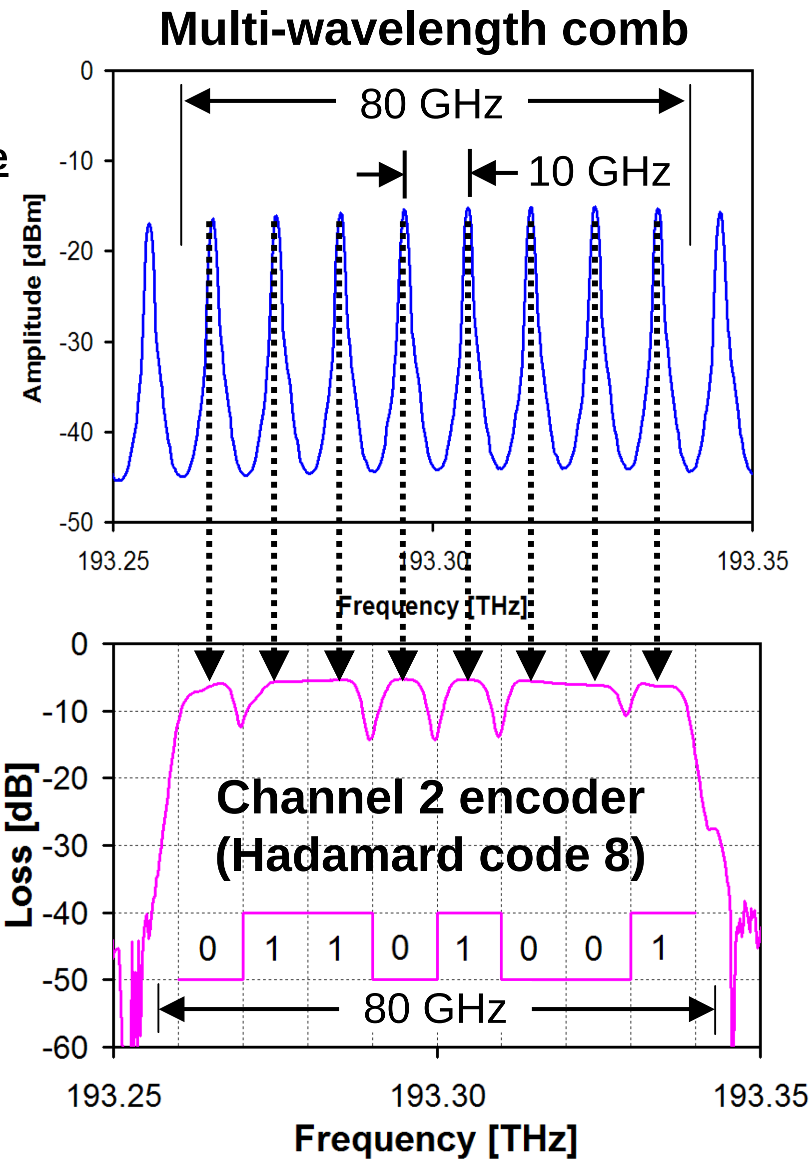
Optically Orthogonal Coding

Walsh-Hadamard-8 code set



Spectral phase code
Unchecked = 0
Checkered = π



- **True code orthogonality:** multi-access interference is theoretically **zero** at center of temporal signal …independent of number of simultaneous users
- Allows for much higher spectral efficiency (more users in given BW)
- Price paid for orthogonality: ***synchronization*** req'd between users

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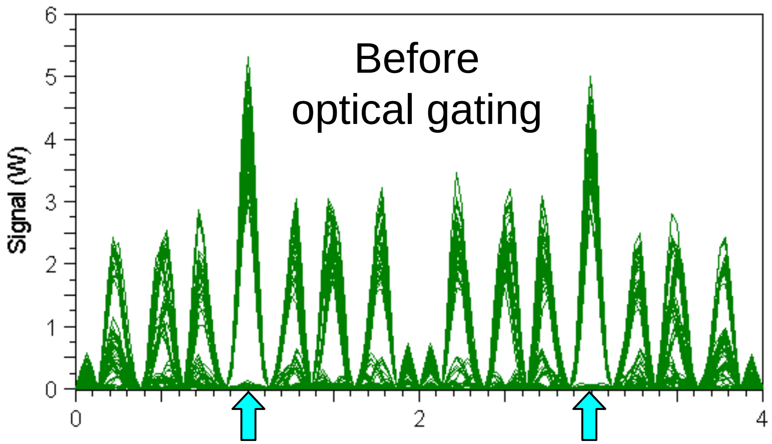
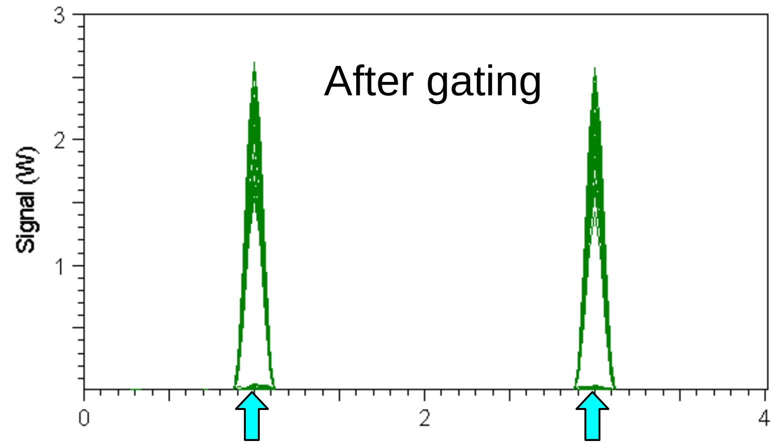
OPTICAL CODE-DIVISION MULTIPLE ACCESS O/CDMA

Simulation

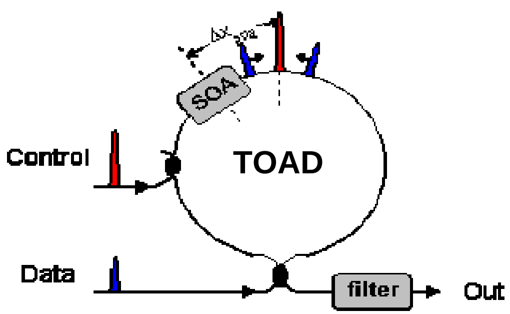
Optical Time Gating

- After spectral decoding, a pulse from a given channel must be separated from ***multi-user interference noise*** (resulting from other channels present)
- In a synchronous OCDMA system, multi-user interference can be effectively suppressed through the use of ***time gating*** at the receiver



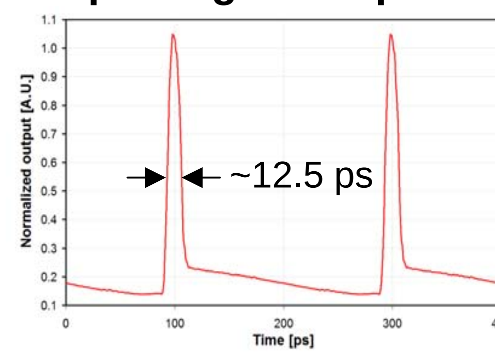


SOA-based optical gate



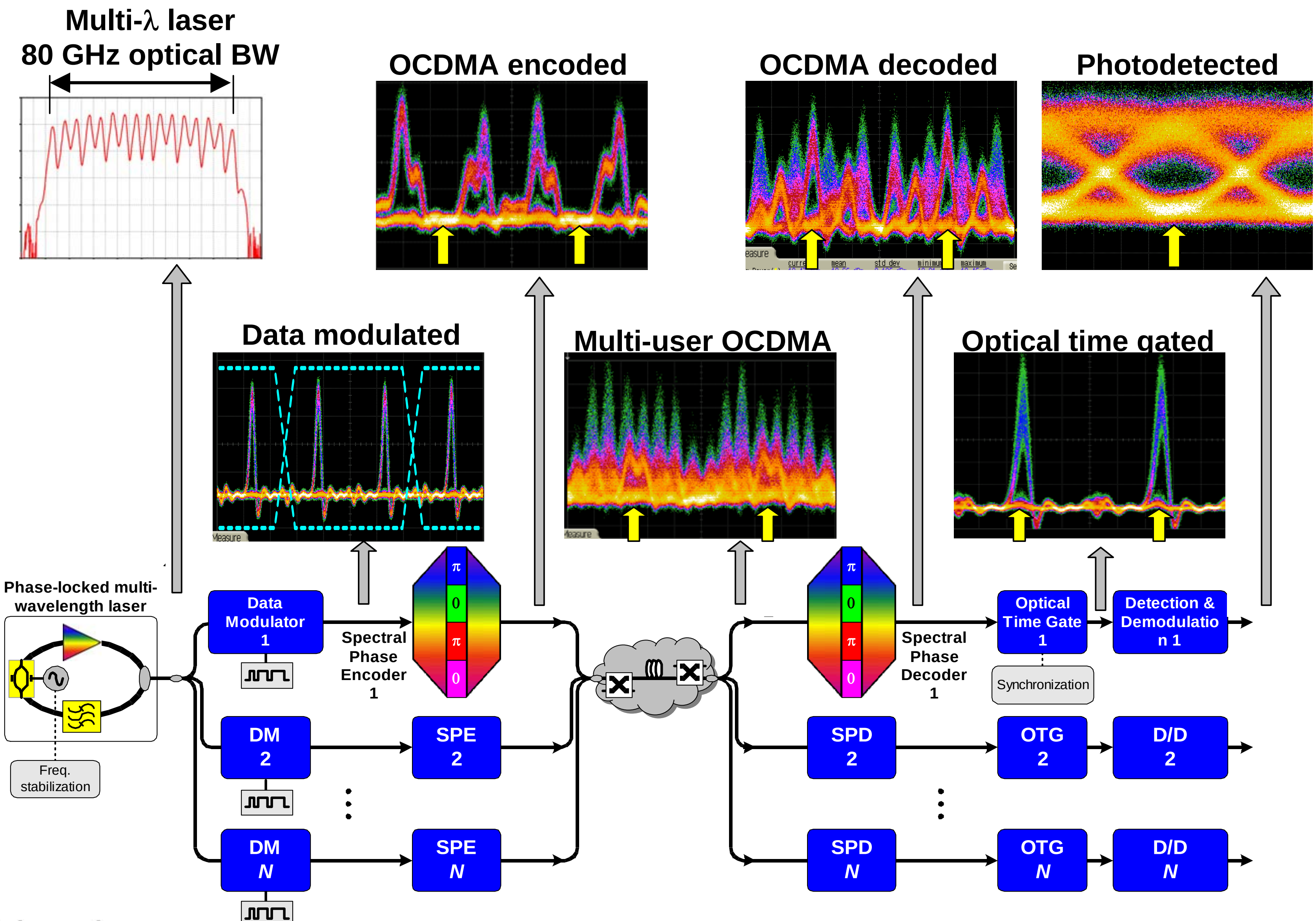
Lab setup

Optical gate response



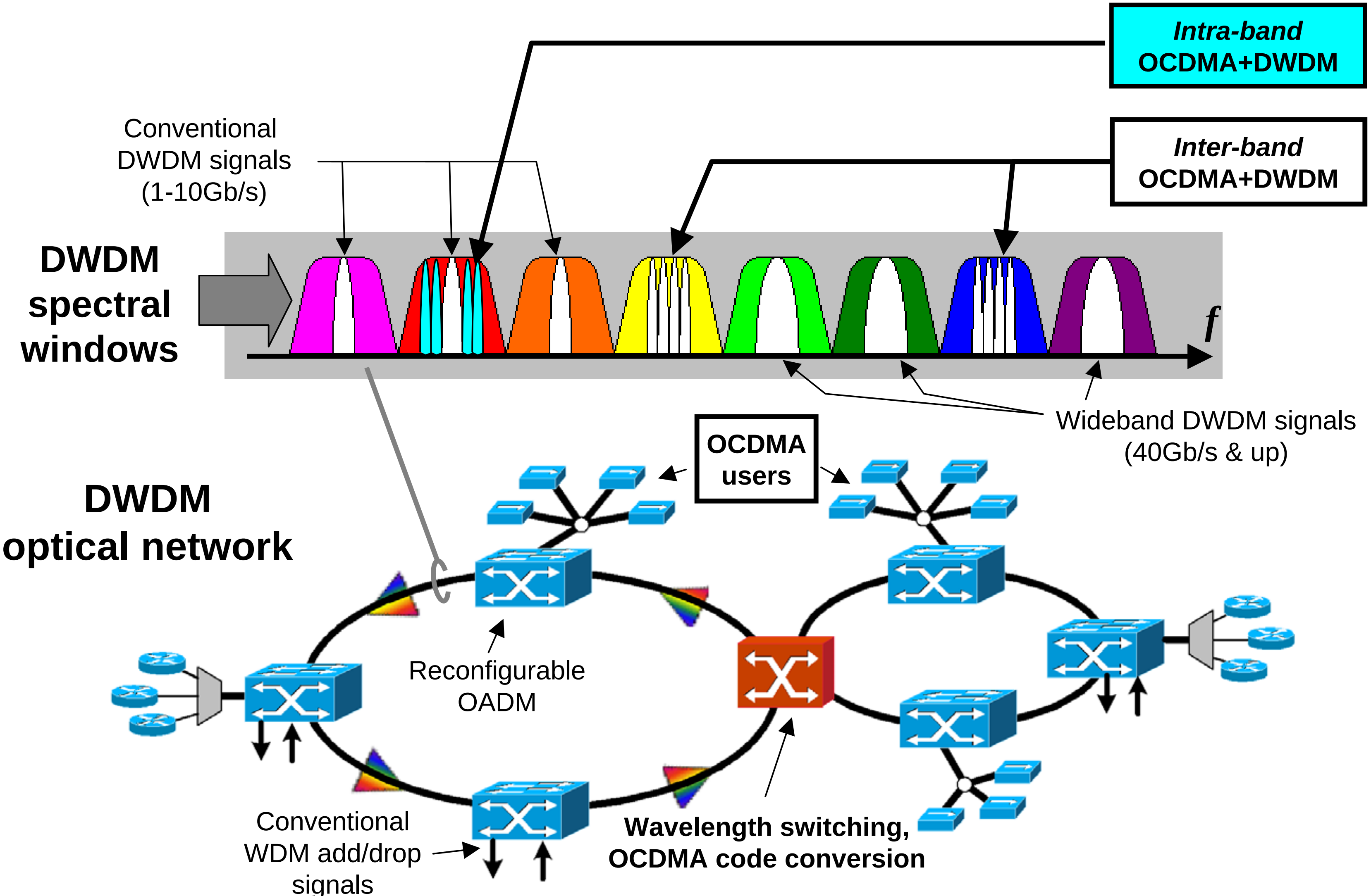
OCDMA system demonstration

Experimental demonstration: 4 users x 2.5 Gb/s



Optical network compatibility

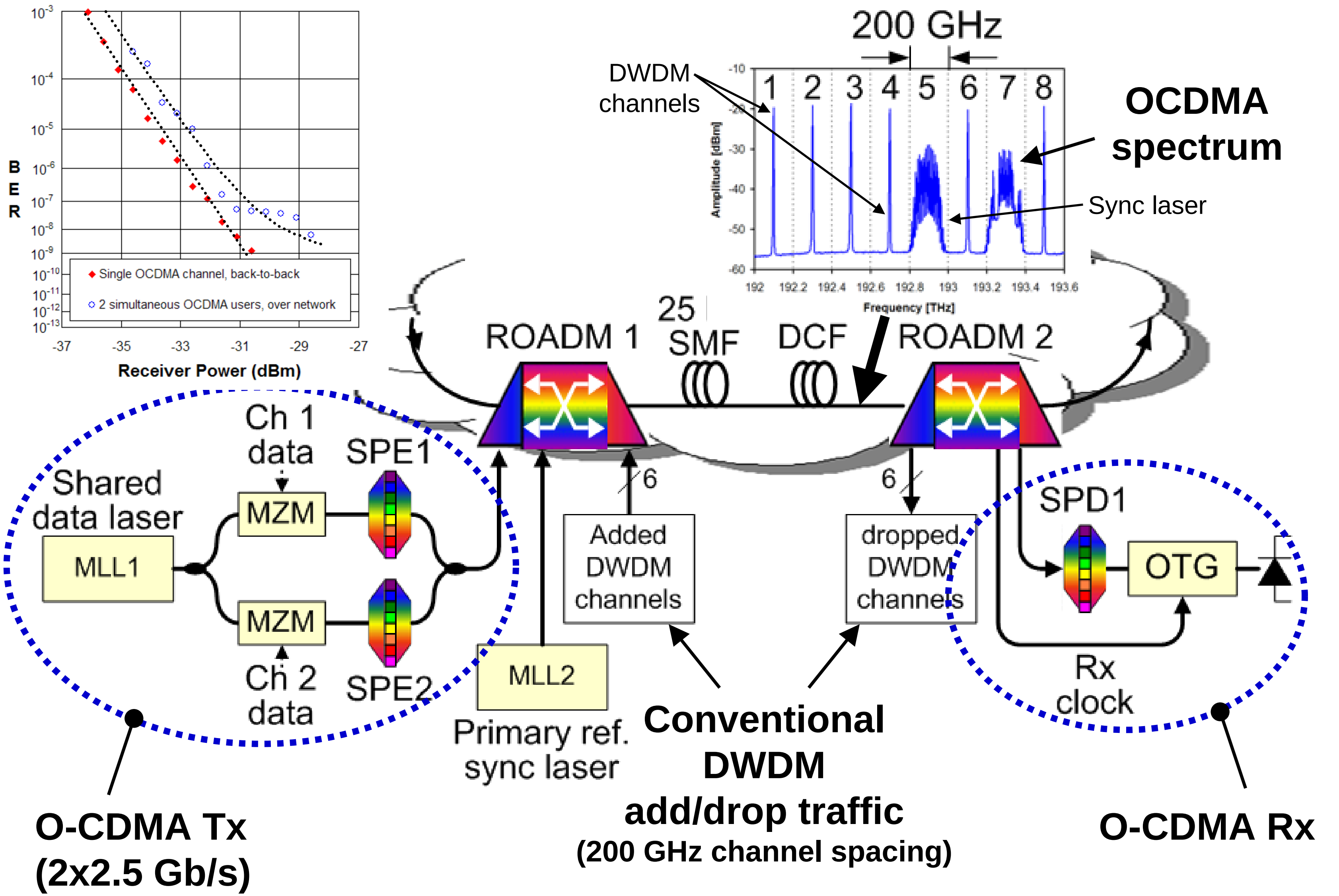
Compatibility with DWDM Optical Networking



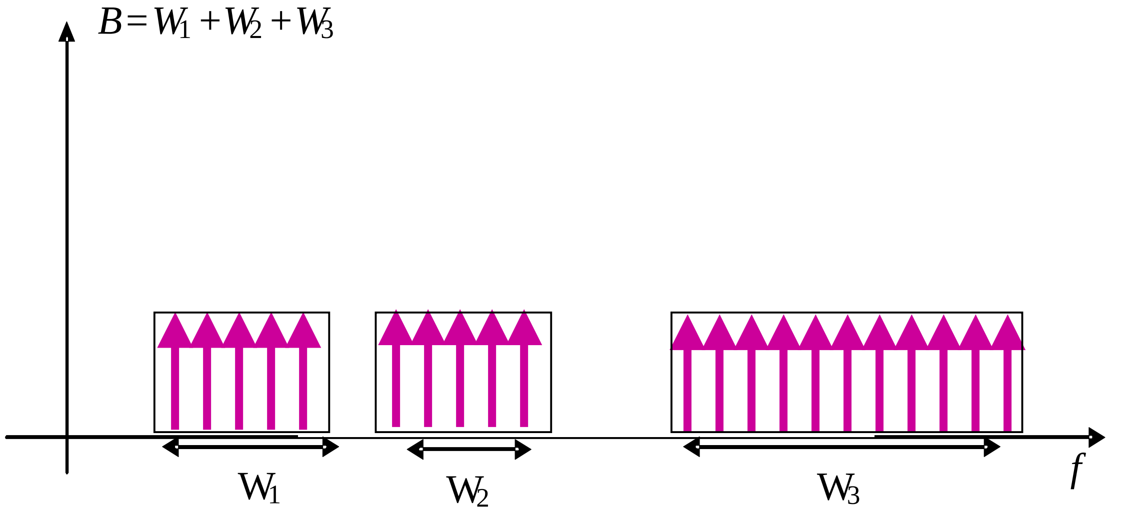
Toliver *et al.* LEOS'2004

Galli et al., OFC'05

Inter-band OCDMA+DWDM compatibility demonstration



Conveying broadband signals over disjoint frequency support.

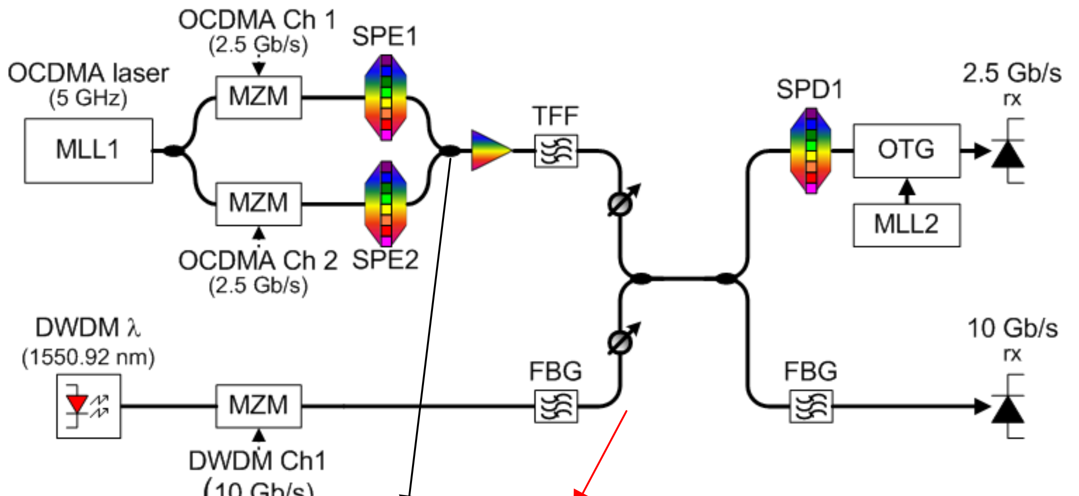


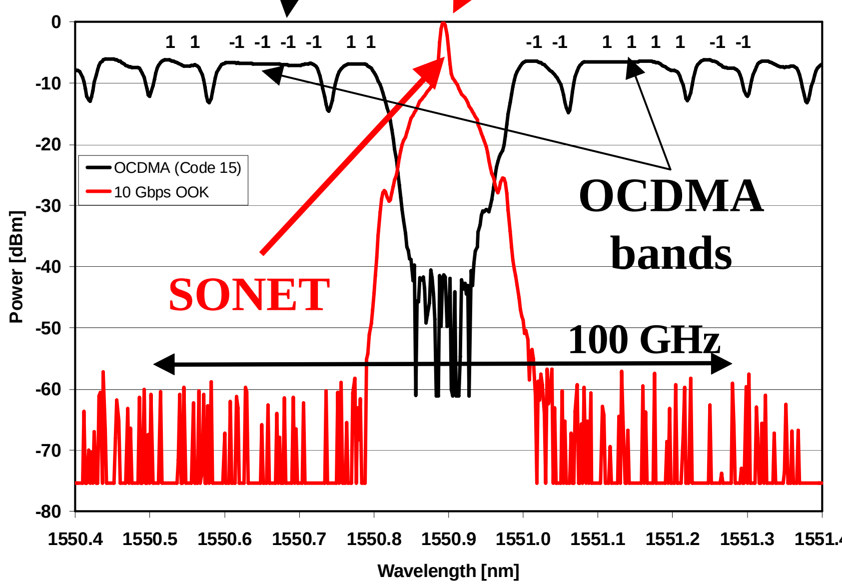
Code orthogonality **is maintained across *all* the utilized bandwidth *B*, even if disjoint!!**

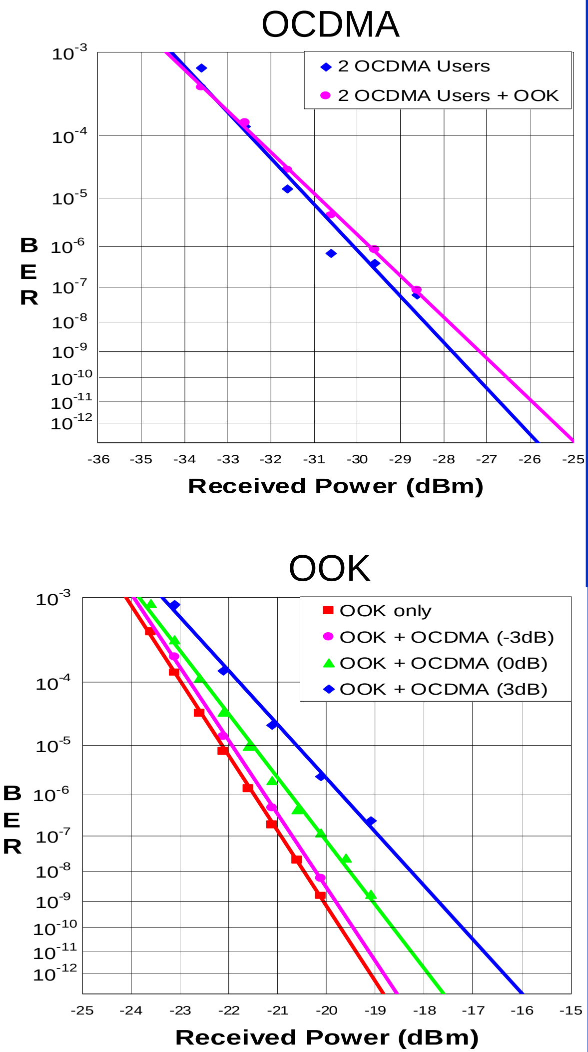
Zero-padded version of conventional Hadamard codes.

Intra-band OCDMA+DWDM compatibility demonstration

OCDMA + 10Gb/s DWDM: Filling the Unused Portion of a DWDM Window

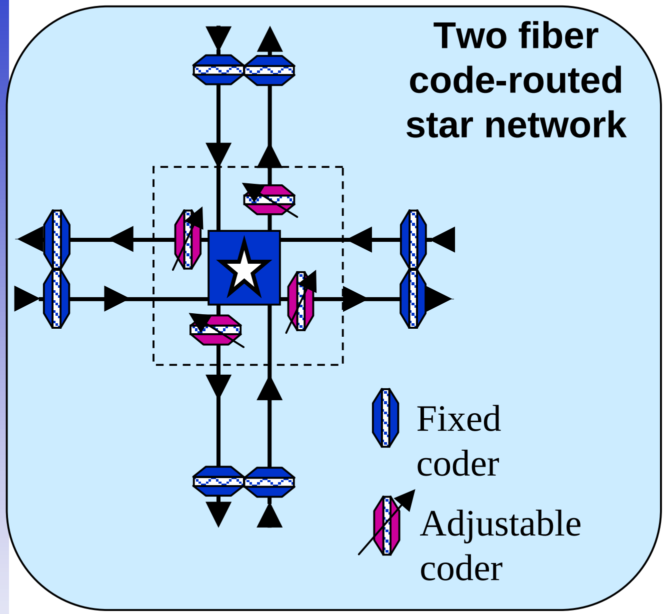


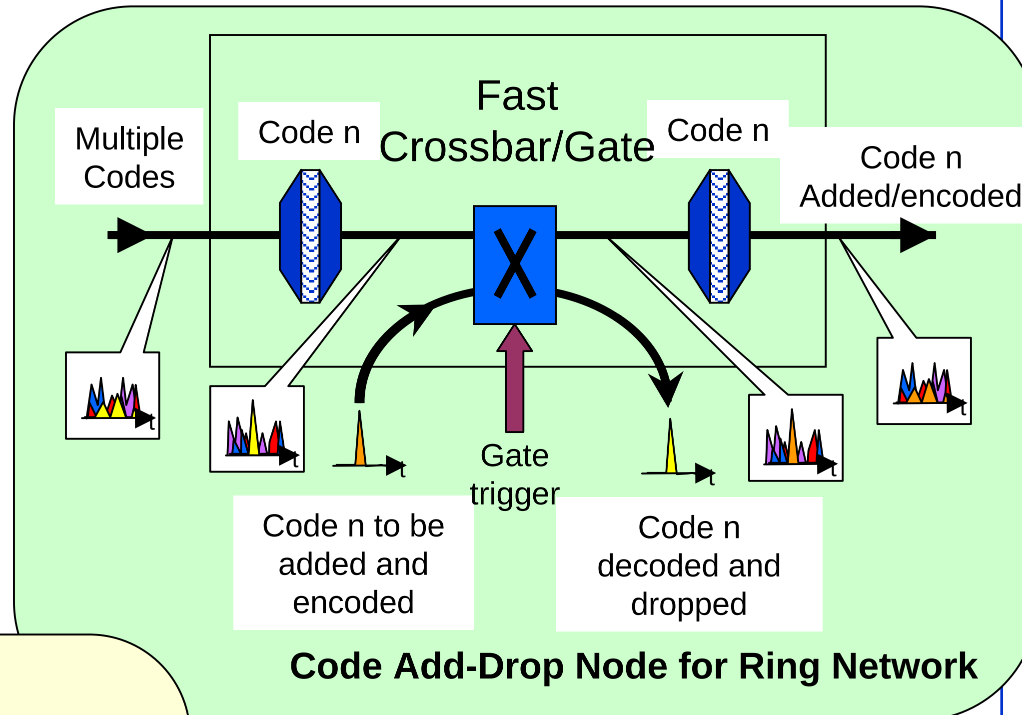


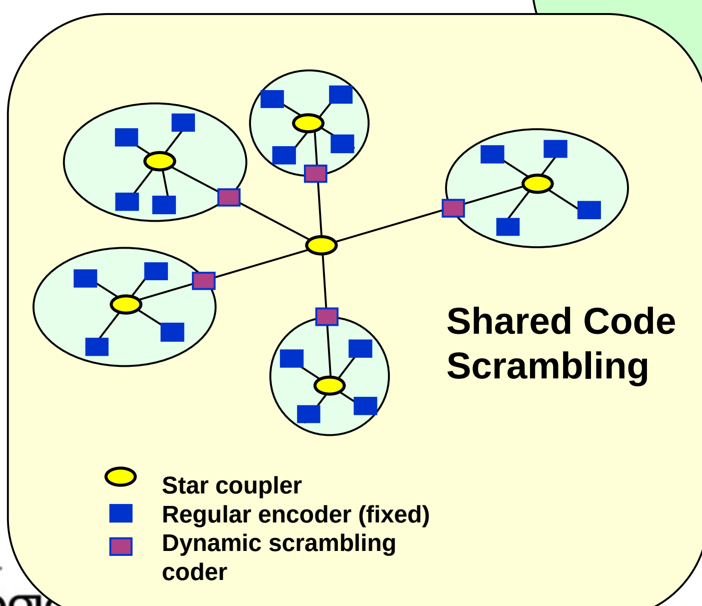


OCDMA Code Conversion

Code Based Networking Using Cascaded Code Translation

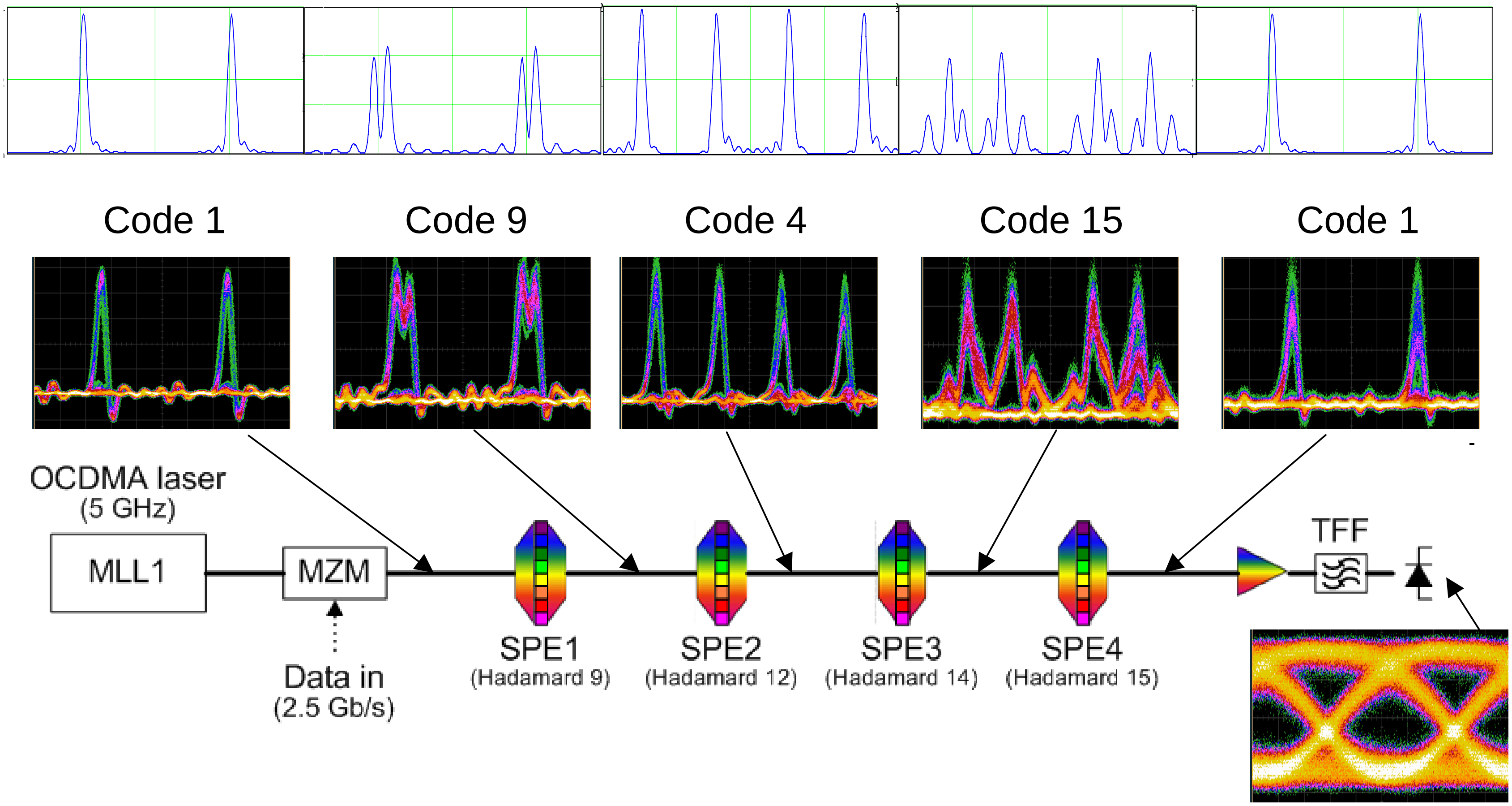






All of these architectures rely on the ability to reliably shift codes through a cascade of coders

Experimental Demonstration of Cascaded OCDMA Code Conversion



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OPTICAL CODE-DIVISION MULTIPLE ACCESS O/CDMA

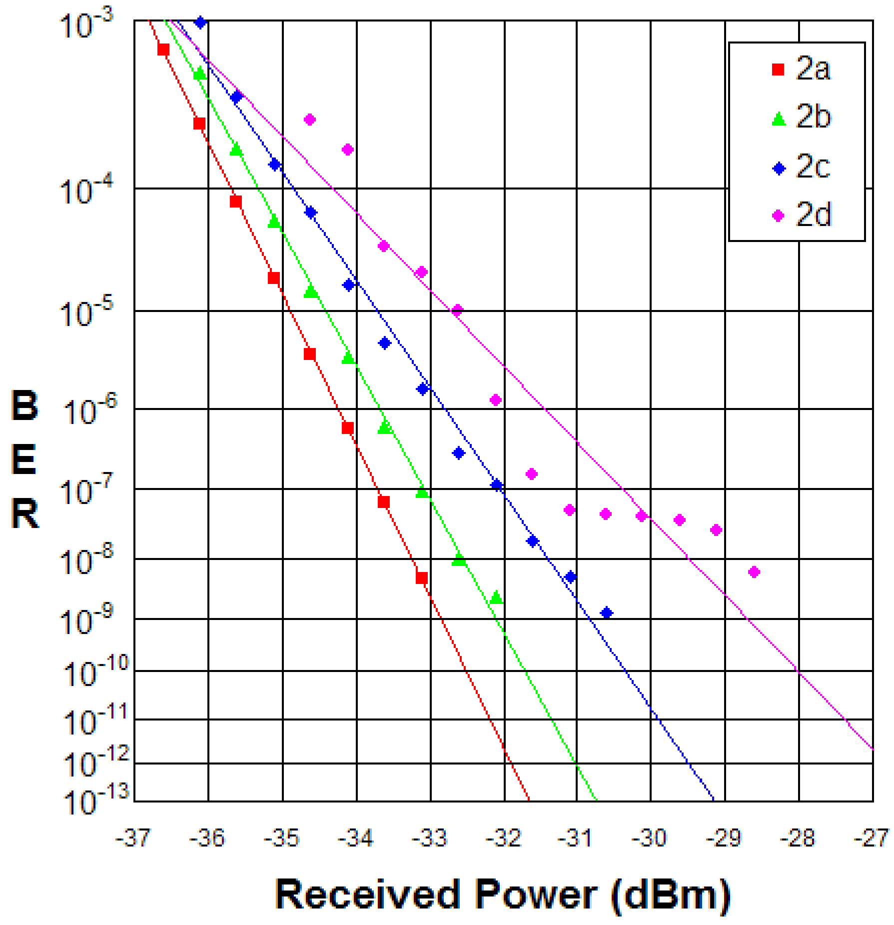
Summary

- High resolution encoder/decoder technology enables precise coherent phase manipulation of ***individual*** mode-locked laser spectral components
- Allows for higher ***spectral efficiency***: for a given code length and bit rate, spectral extent can be minimized
- True ***optically orthogonal*** codes; price paid is synchronous operation
- Multi-access ***obscurity***: coherent spectral & temporal overlap of incorrectly decoded channels
- Optical network ***compatibility***: inter-band and intra-band OCDMA+DWDM
- ***Code-empowered networking***: code translation enables powerful system architectures

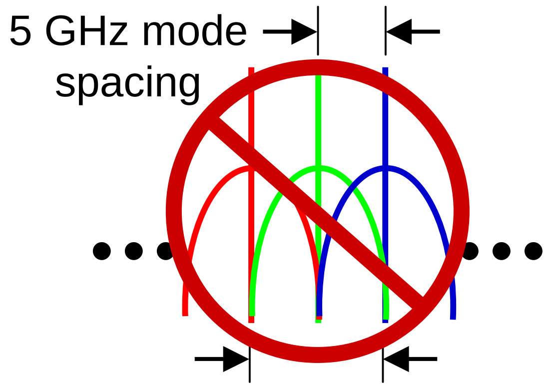
Thank you!

Additional support material

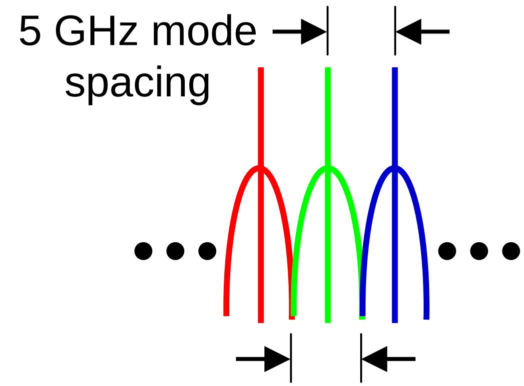
BER Performance



2.5 Gb/s Data Modulation



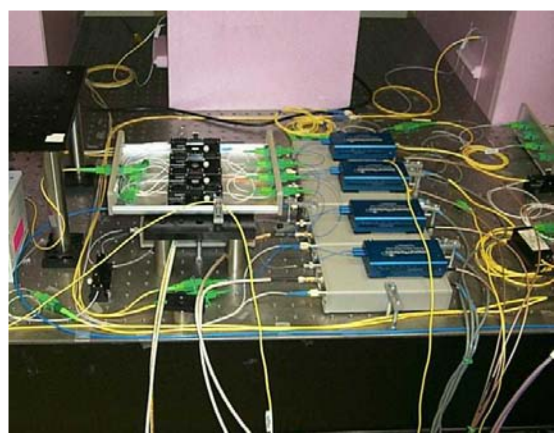
5 Gb/s OOK modulation:
significant spectral overlap!



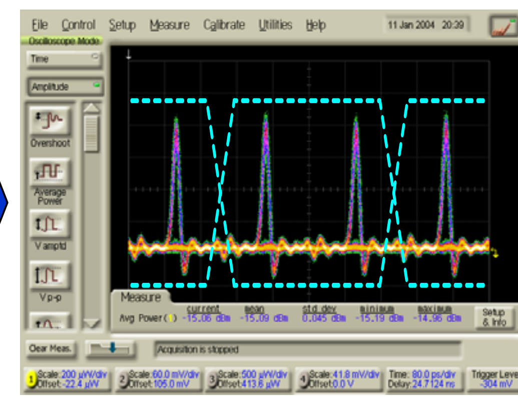
2.5 Gb/s OOK modulation:
minimal spectral overlap

2.5Gb/s pattern generator & 5GHz MLL

OOK data modulation: 4 independent user channels



"Double-pulse" modulation @ 2.5Gb/s



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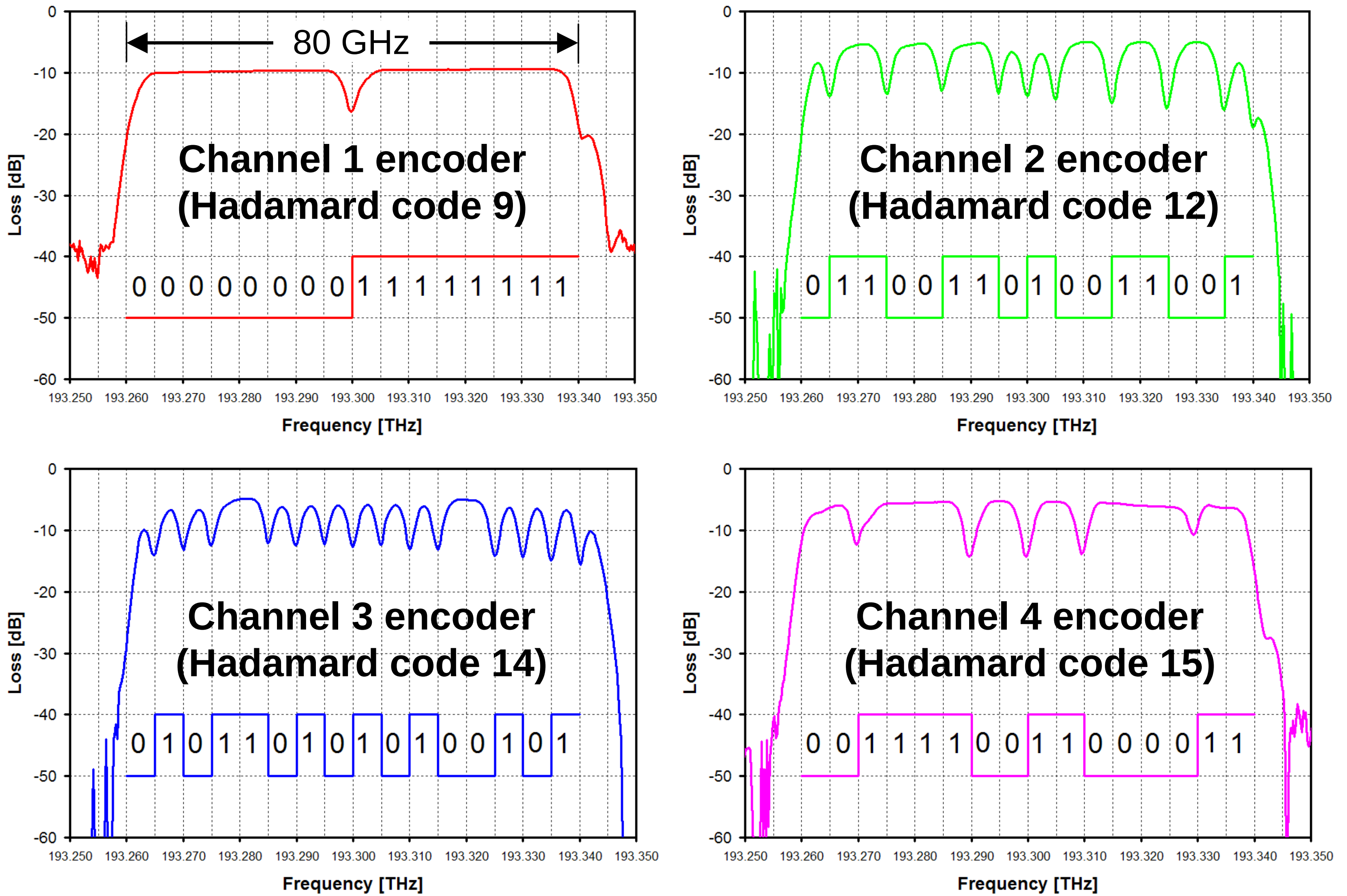
OCDMA Encoders: Experimental Spectral Response



(*characterized using broadband source + 0.01 nm OSA BW)

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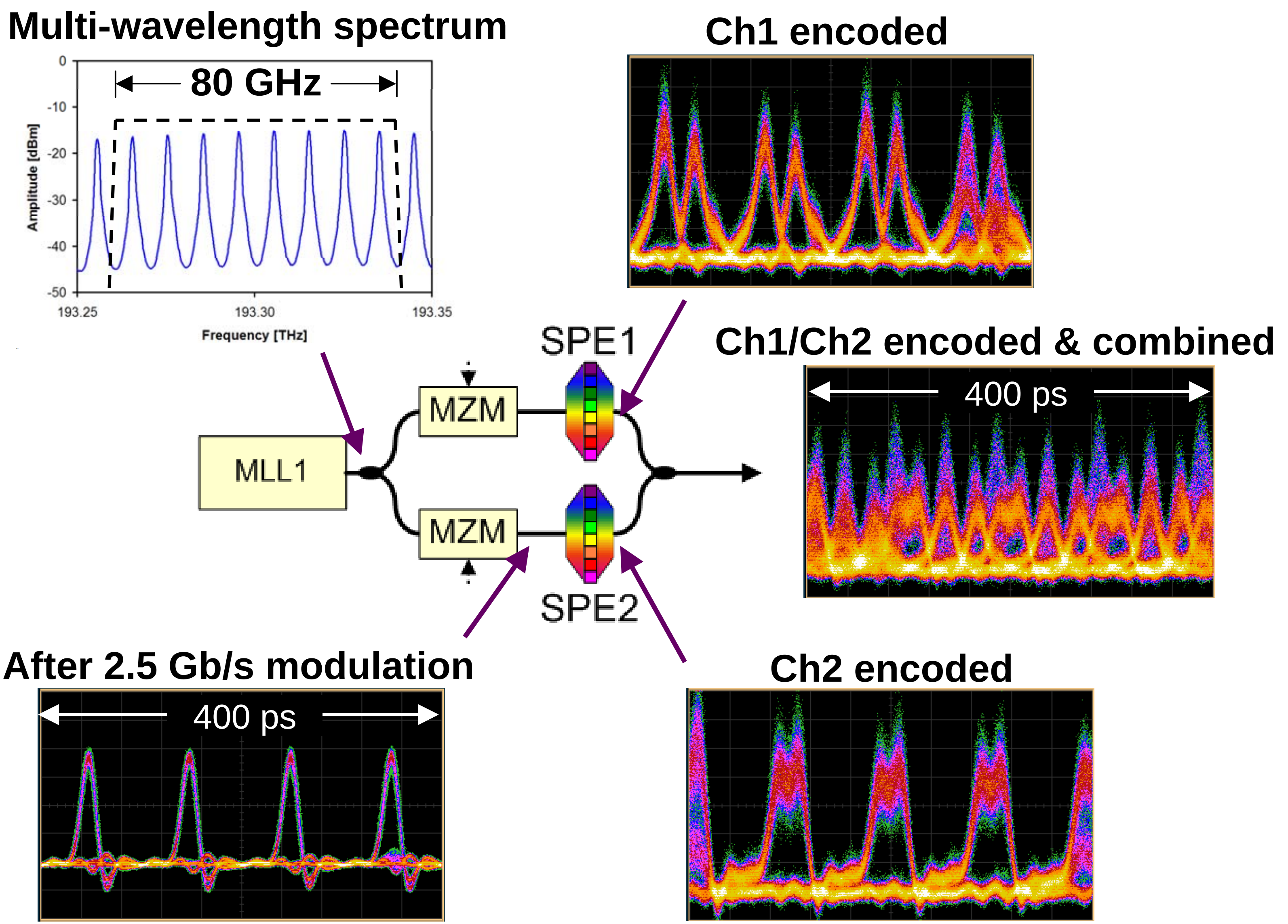
OPTICAL CODE-DIVISION MULTIPLE ACCESS O/CDMA

O-CDMA Tx: source, modulation, encoding, & combining



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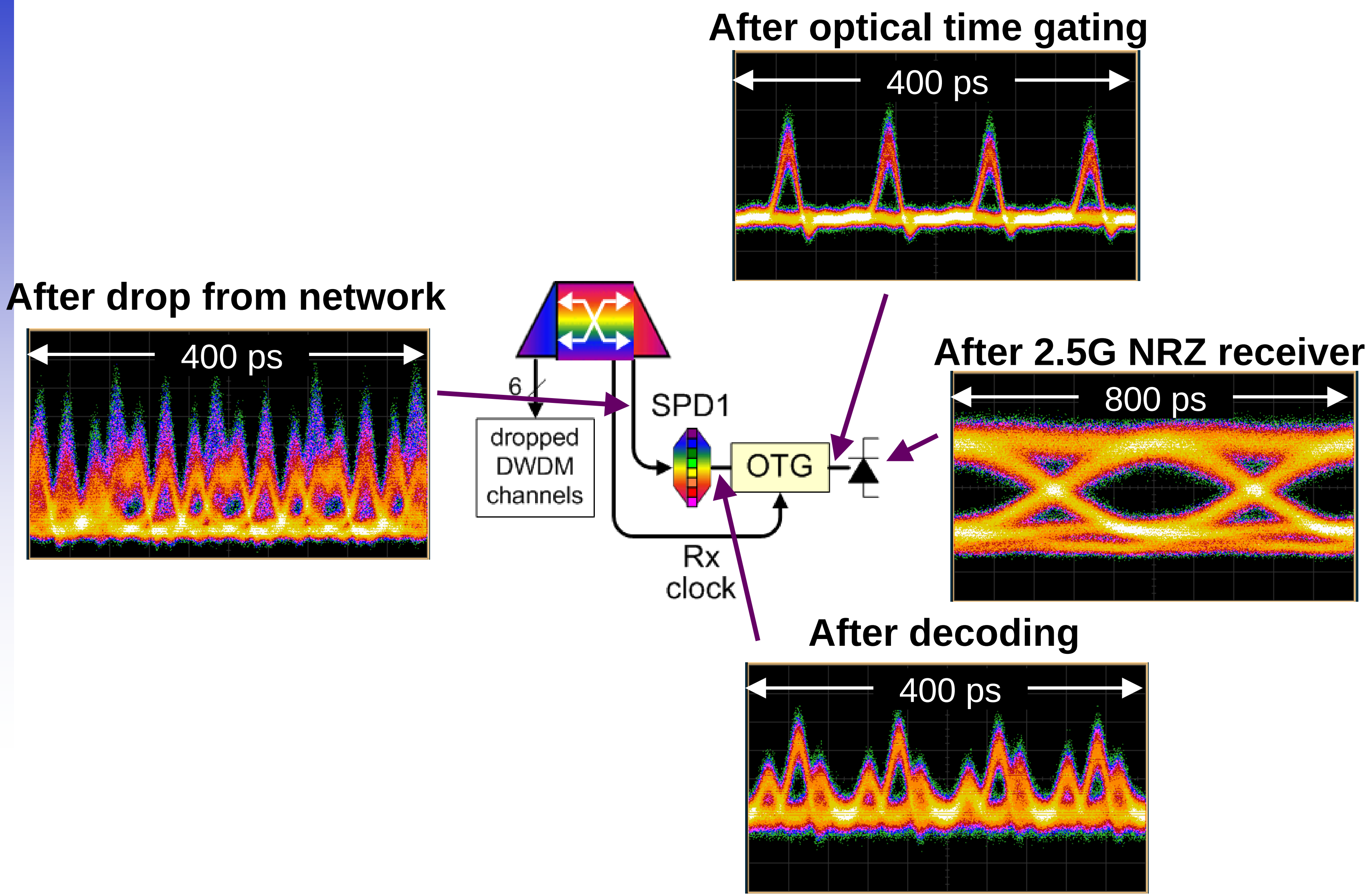
(*0.01 nm OSA BW, 30 GHz DCA BW)

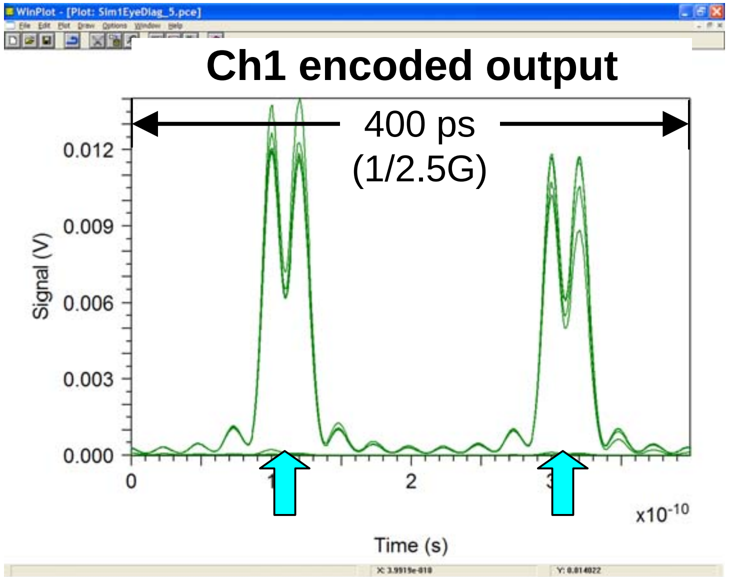
O-CDMA Rx: decoding, gating, and detection

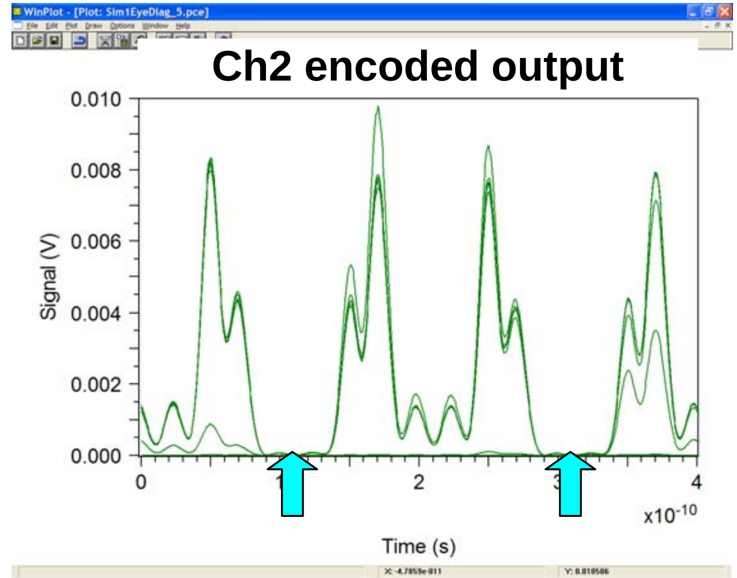


(*0.01 nm OSA BW, 30 GHz DCA BW)

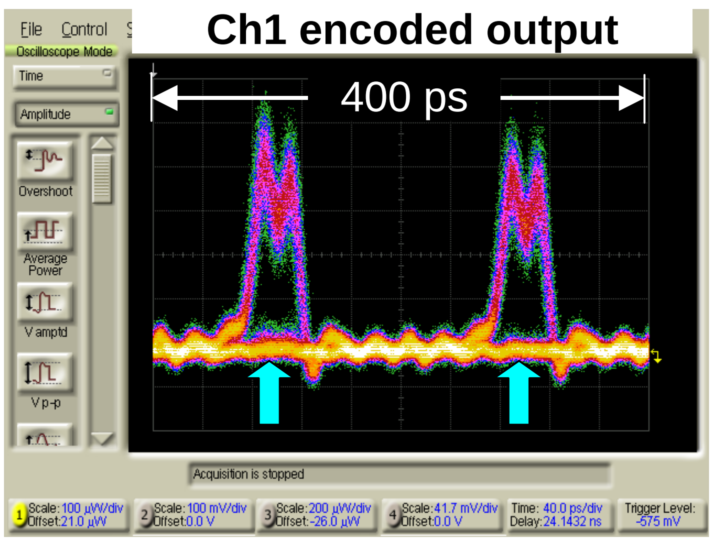
OCDMA Encoders: Temporal Response Ch1 & Ch2

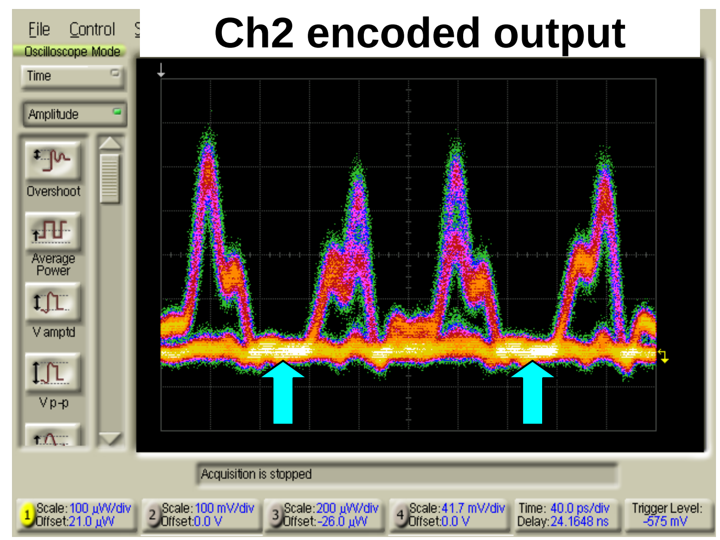
Simulation
(30GHz photodetector)





Experiment
(30GHz photodetector)





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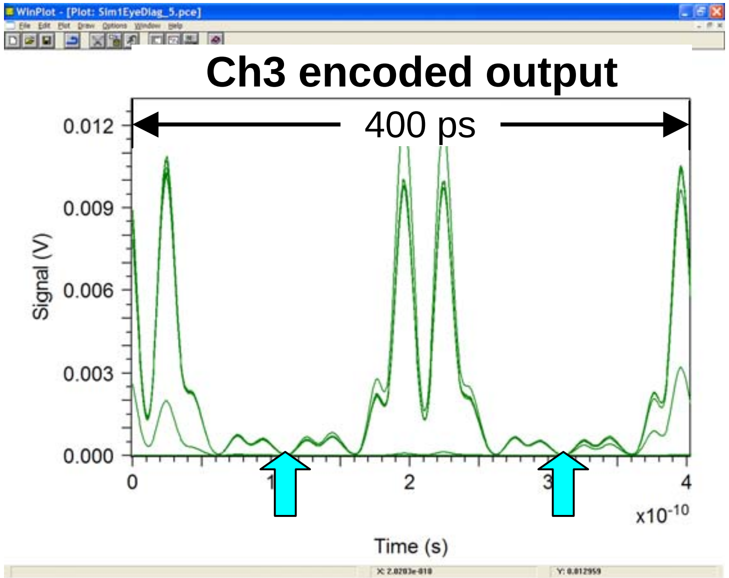
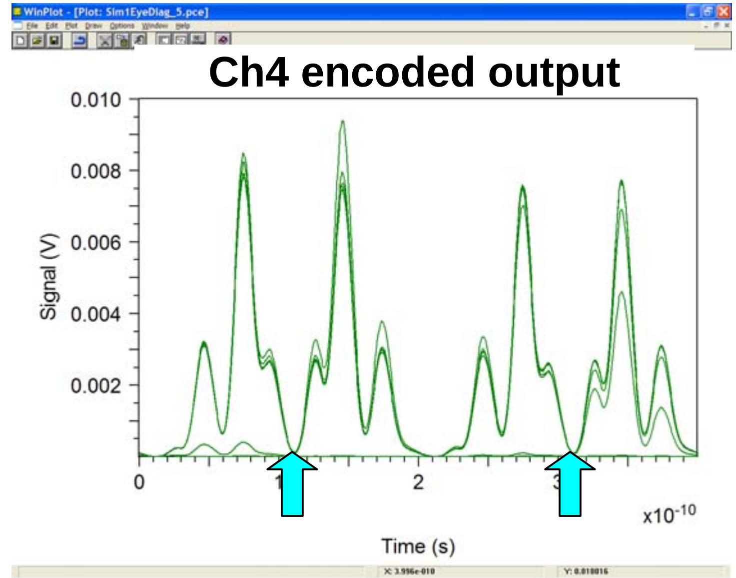
OPTICAL CODE-DIVISION MULTIPLE ACCESS O/CDMA

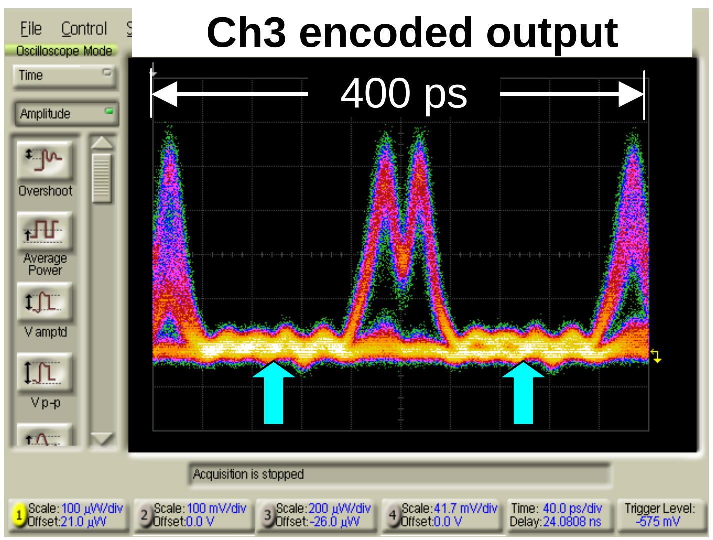
OCDMA Encoders: Temporal Response Ch3 & Ch4

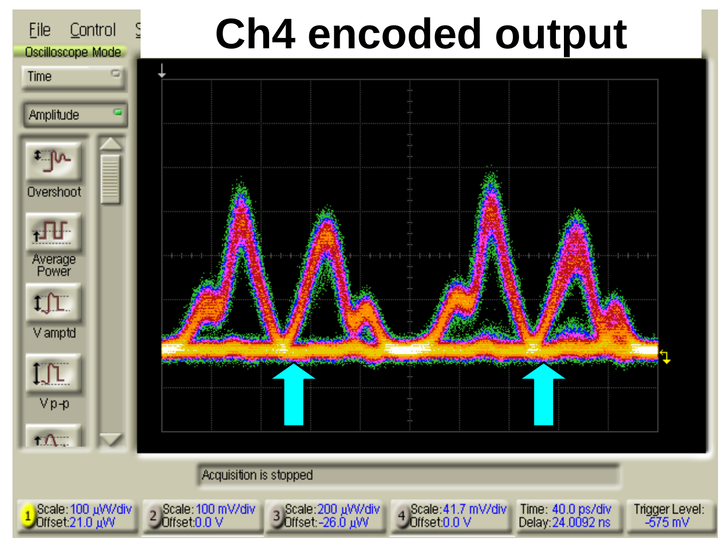
Simulation
(30GHz photodetector)





Experiment
(30GHz photodetector)





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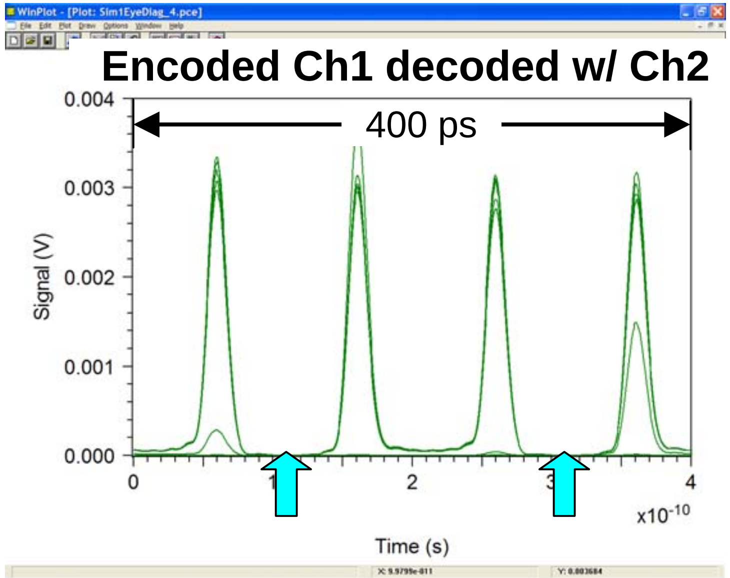
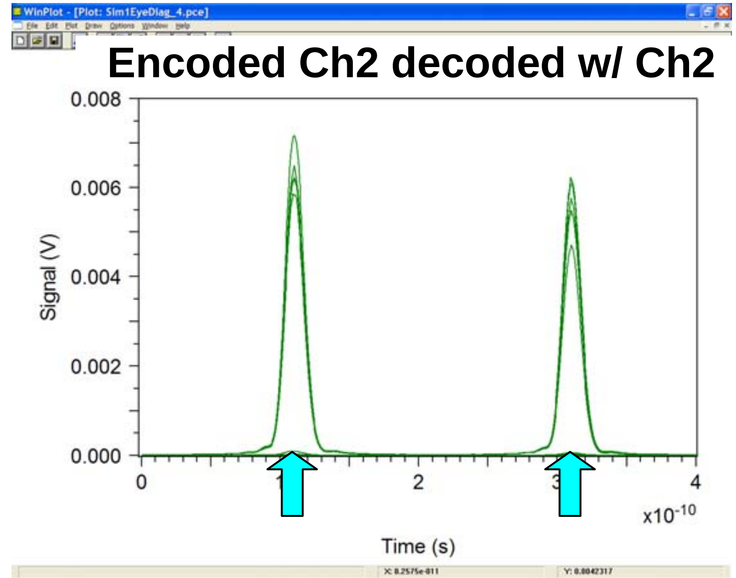
OCDMA Decoder: Temporal Response Ch1 & Ch2

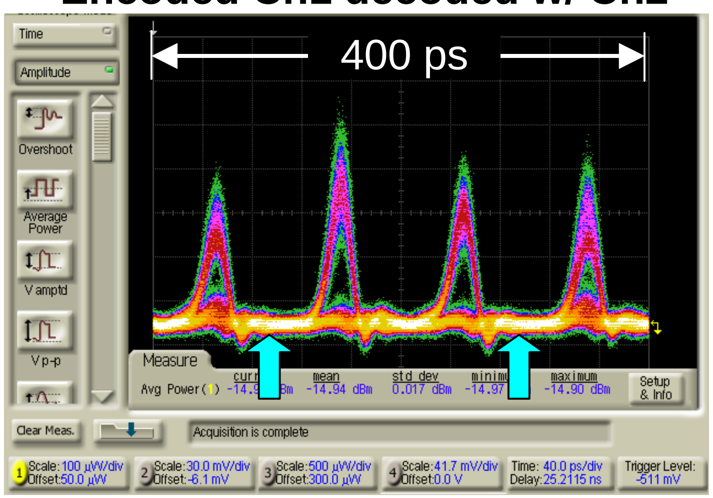
Simulation
(30GHz photodetector)



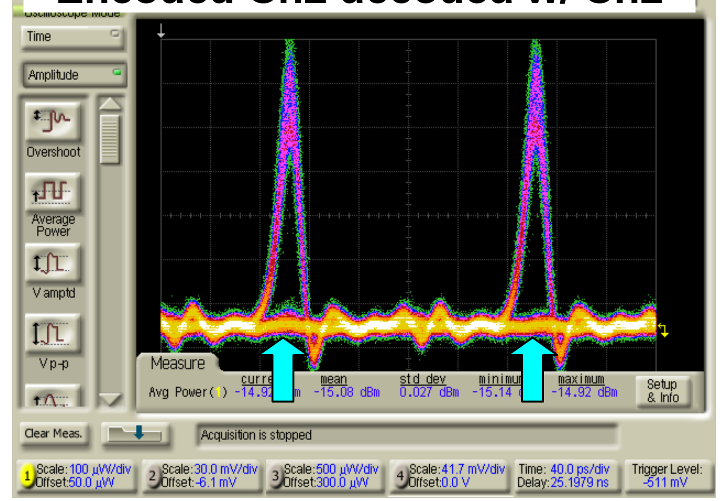


Experiment
(30GHz photodetector)

Encoded Ch1 decoded w/ Ch2

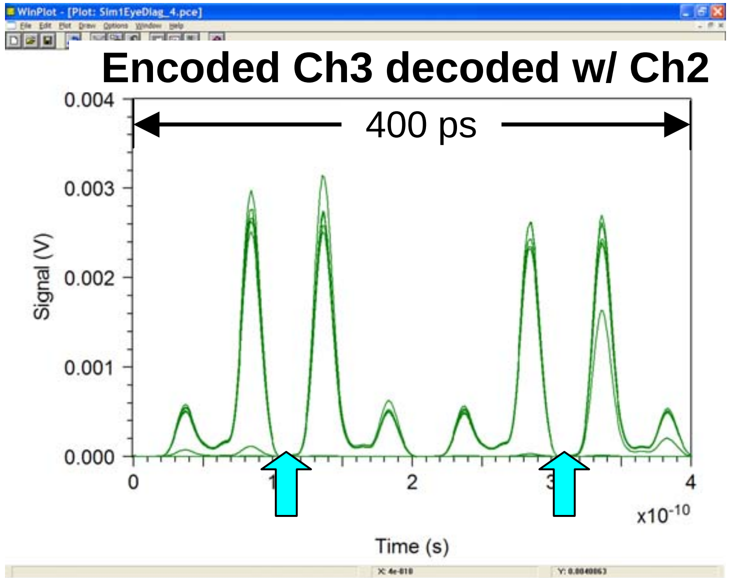


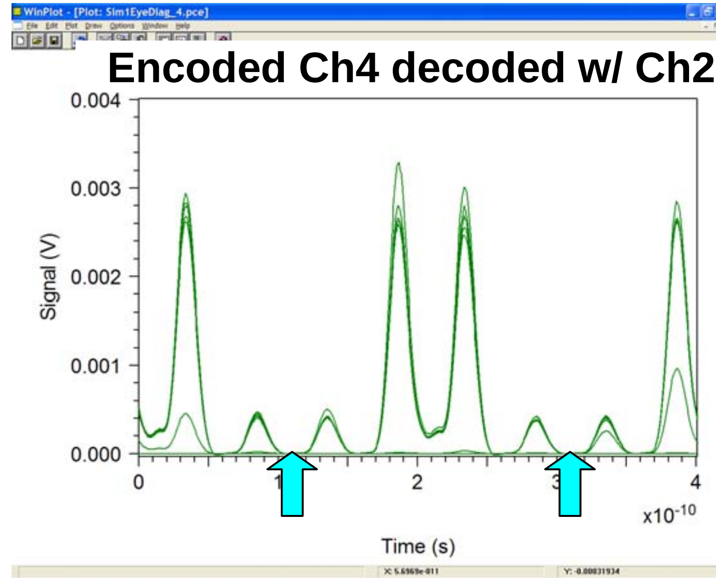
Encoded Ch2 decoded w/ Ch2



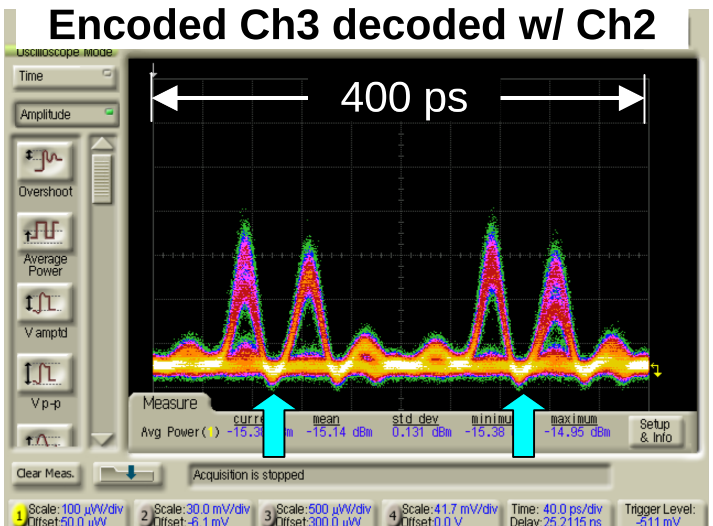
OCDMA Decoder: Temporal Response Ch3 & Ch4

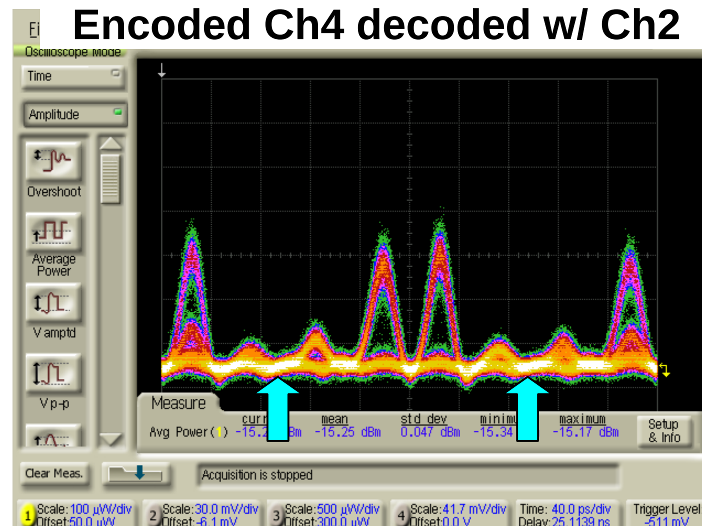
Simulation (30GHz photodetector)





Experiment (30GHz photodetector)





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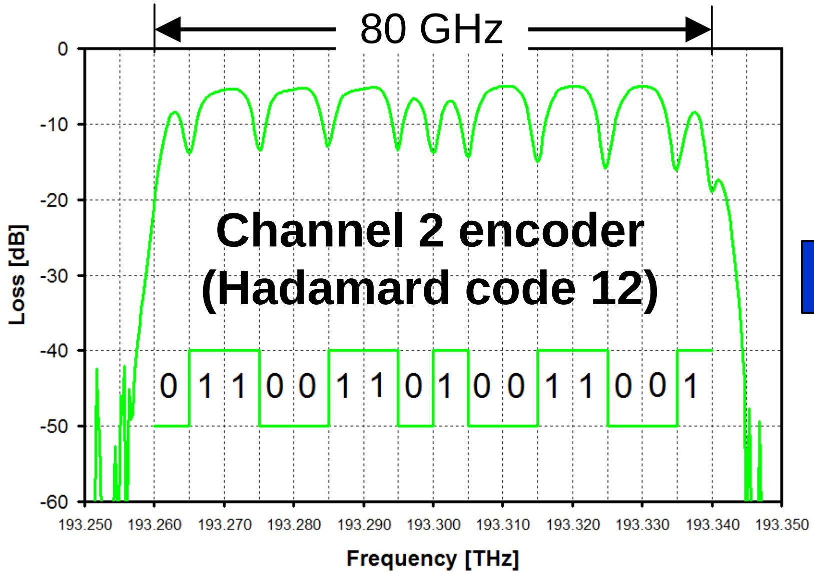
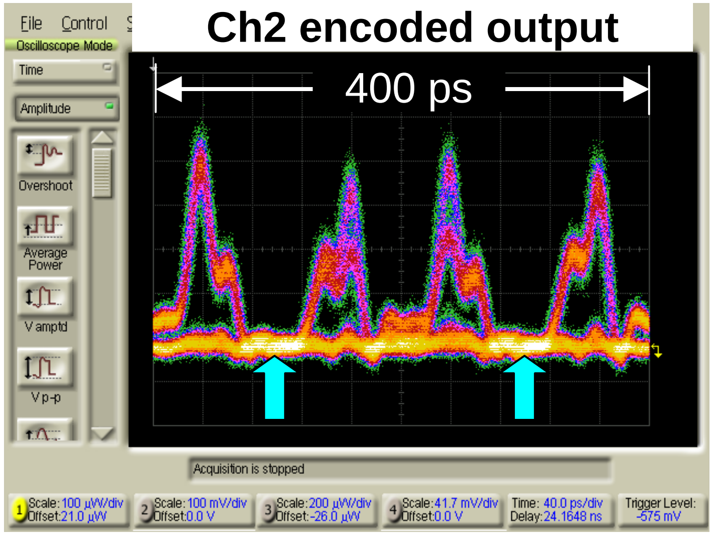
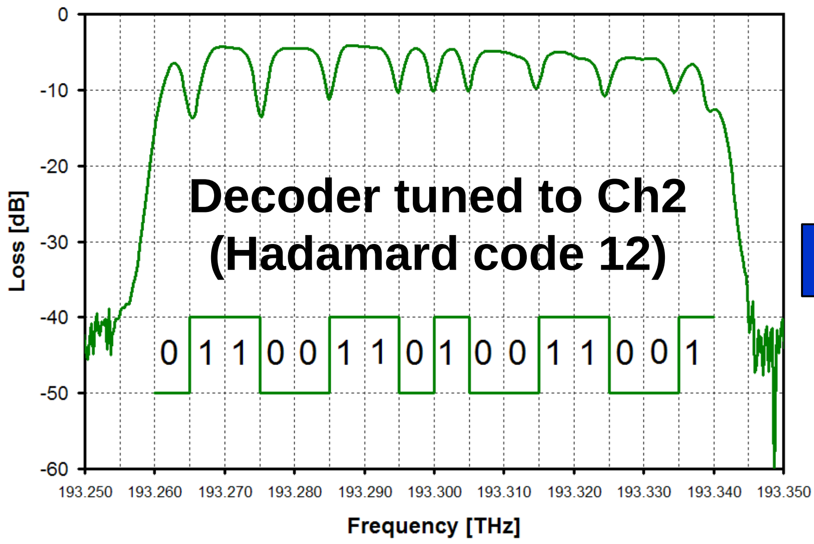
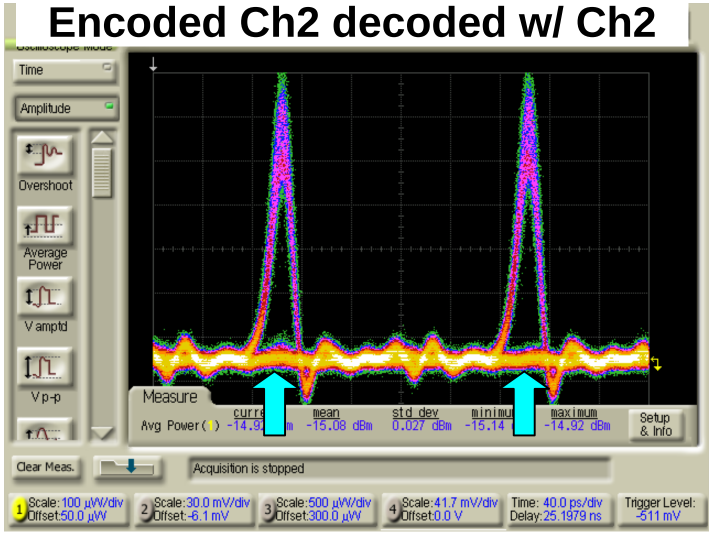
Summary of Experimental Characterization for 1 User





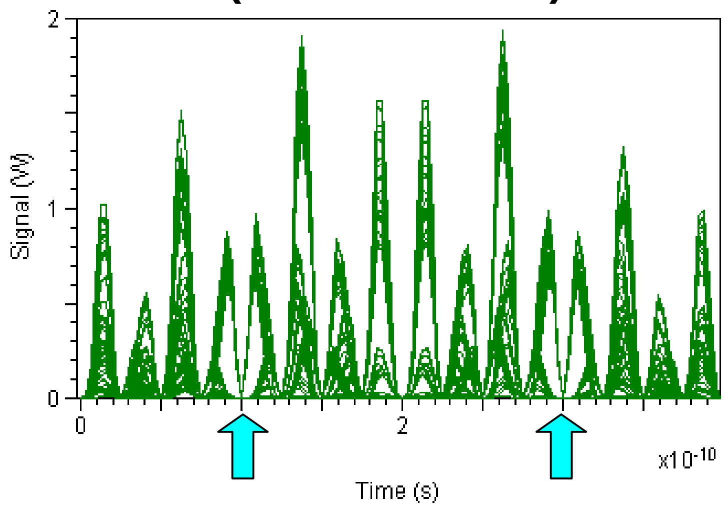




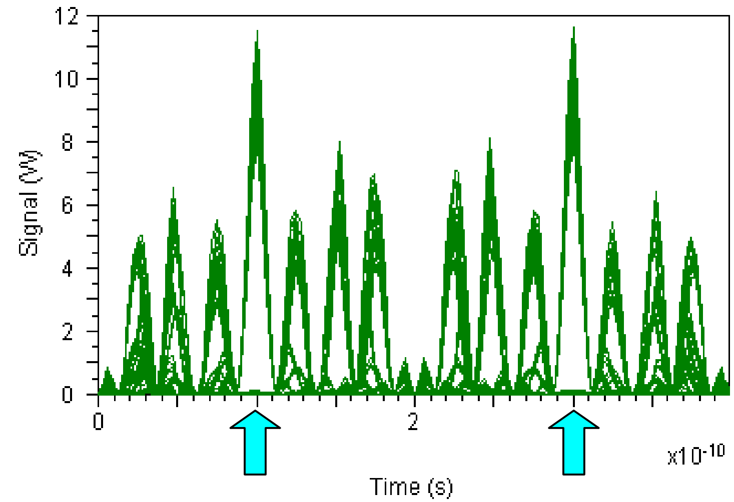
4 Simultaneous OCDMA Channels

Simulation
(infinite BW photodetector)

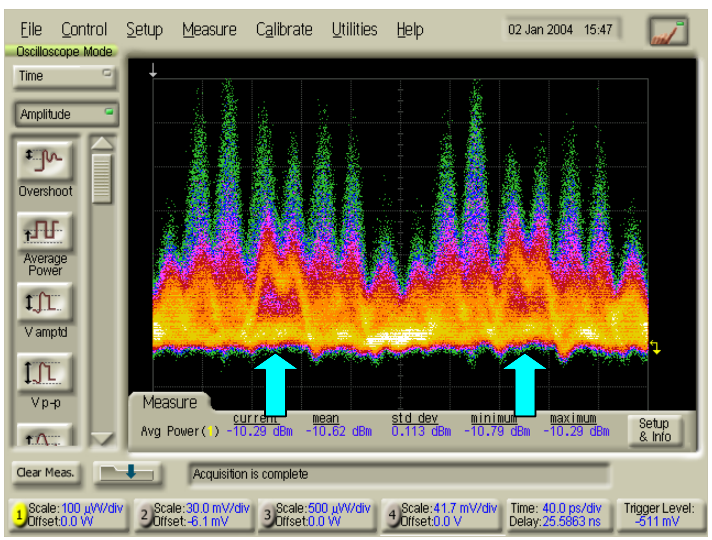
Encoded and Combined (before decoder)

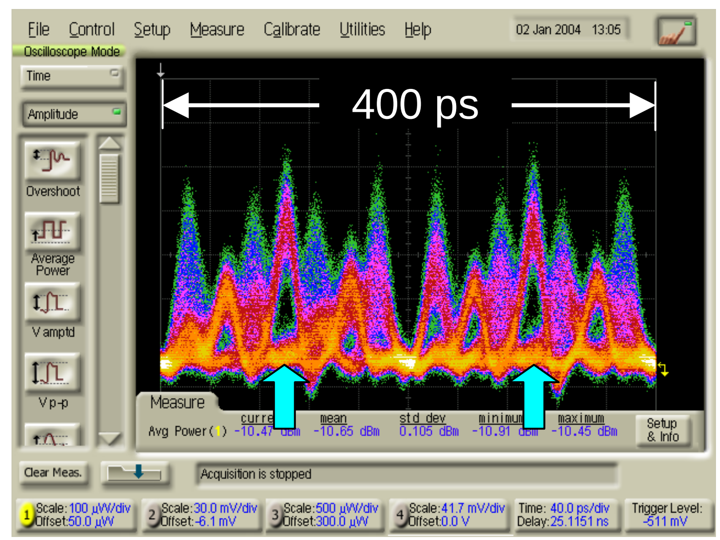


After Ch2 Decoder



Experiment
(30GHz photodetector)





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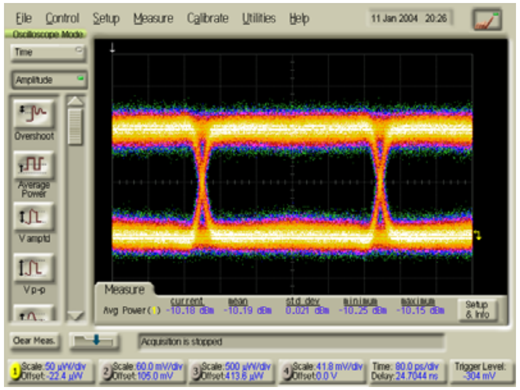
OPTICAL CODE-DIVISION MULTIPLE ACCESS O/CDMA

2.5 Gb/s NRZ Rx Characterization w/ Pulsed Input Signal

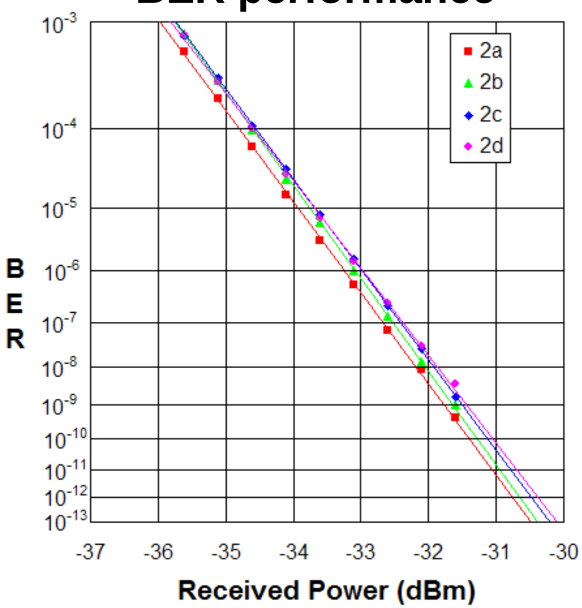
NRZ modulation (CW DFB laser source)



Conventional OC-48 Rx

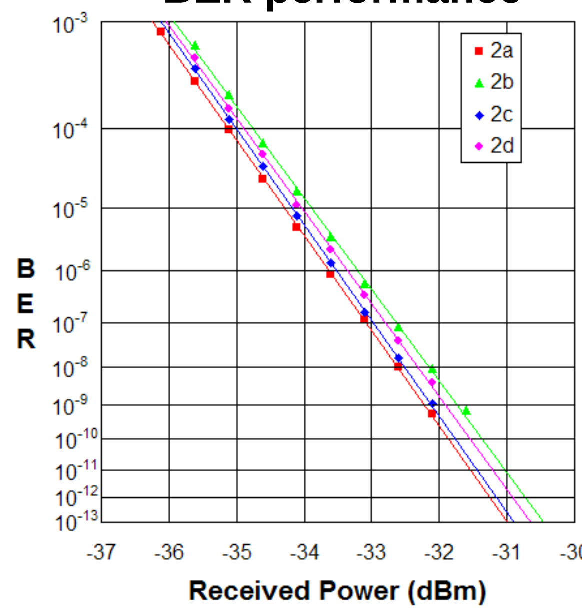
Double-pulse RZ modulation (5GHz MLL laser source)

BER performance



No receiver power penalty for "double-pulse" modulation

BER performance



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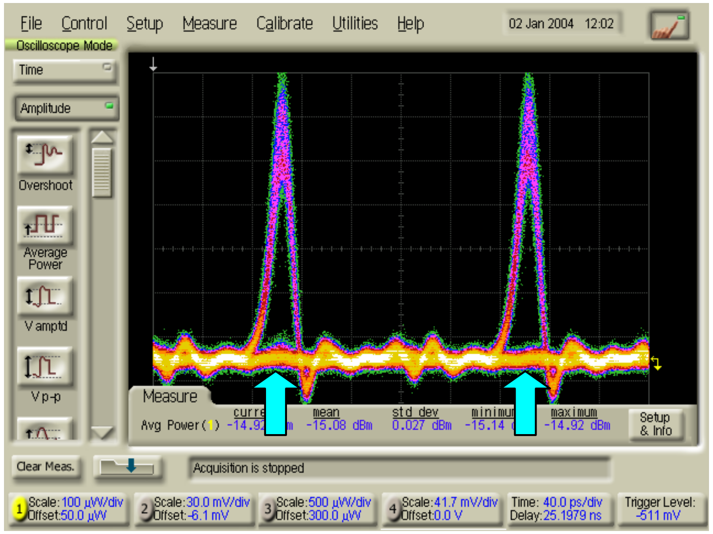
OPTICAL CODE-DIVISION MULTIPLE ACCESS O/CDMA

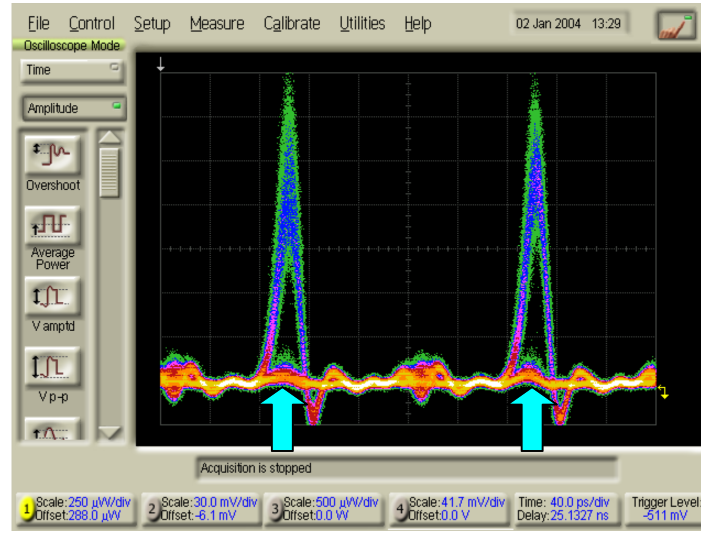
OCDMA system testing

System Experiments: Single OCDMA User (Ch2 only)

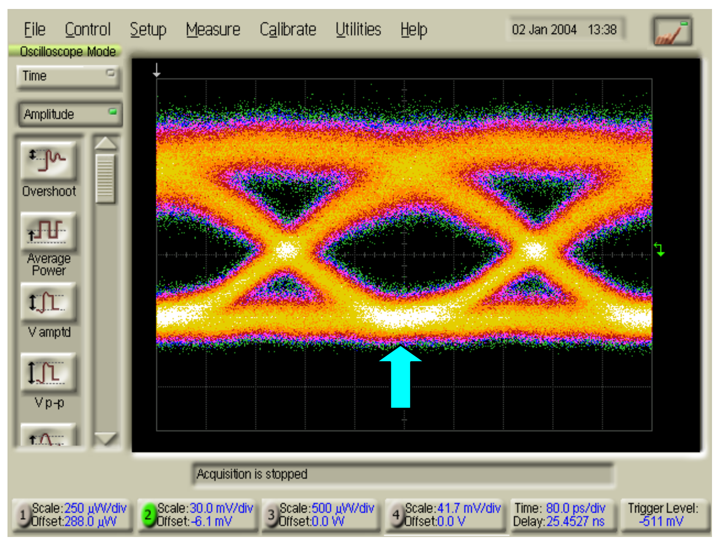
Optical gate input



Optical gate output



2.5 Gb/s NRZ Rx output (electrical)



Able to achieve error-free operation

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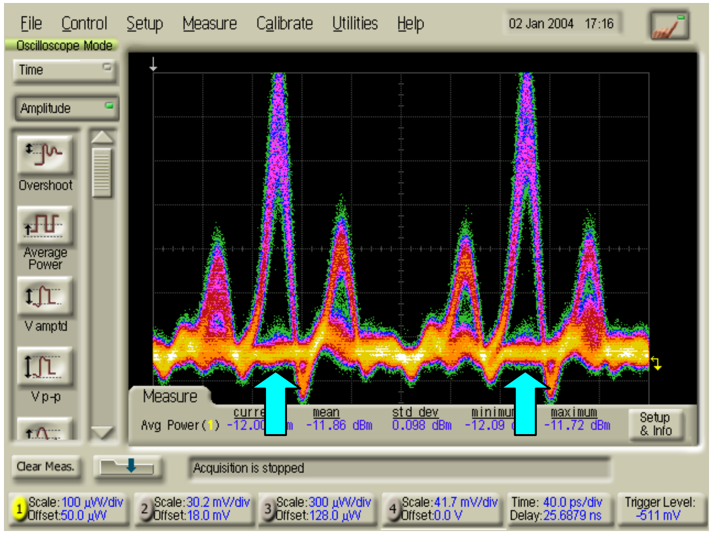
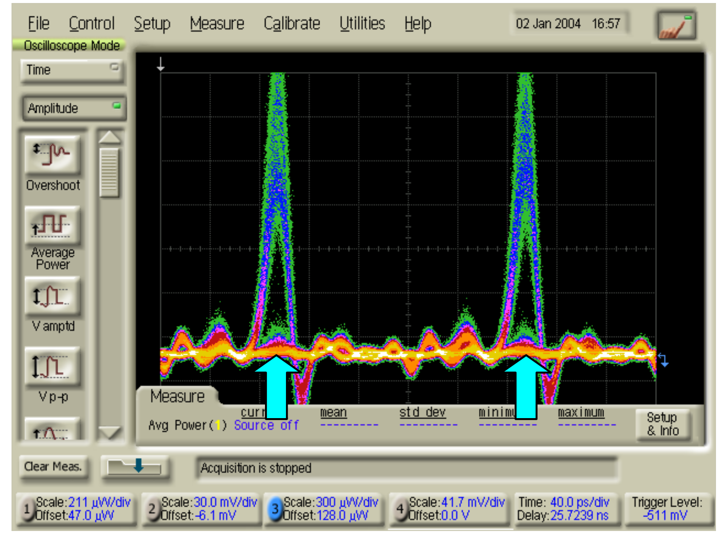
OPTICAL CODE-DIVISION MULTIPLE ACCESS O/CDMA

System Experiments: 2 OCDMA Users (Ch2 & Ch1)

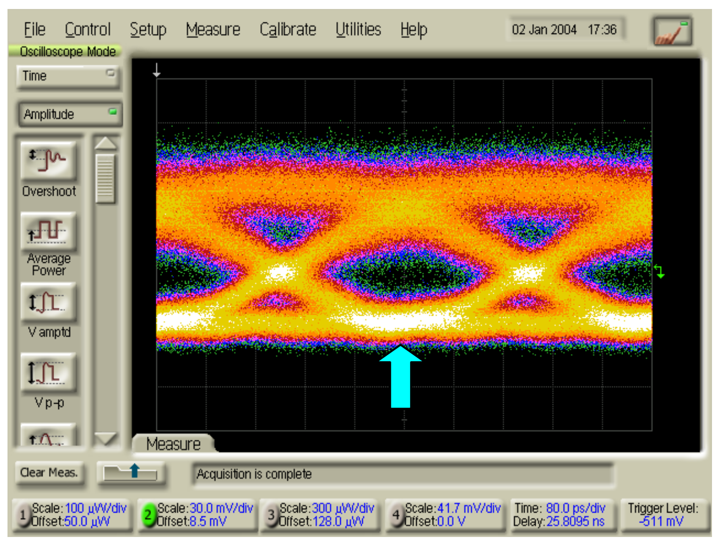
Optical gate input



Optical gate output



2.5 Gb/s NRZ Rx output (electrical)



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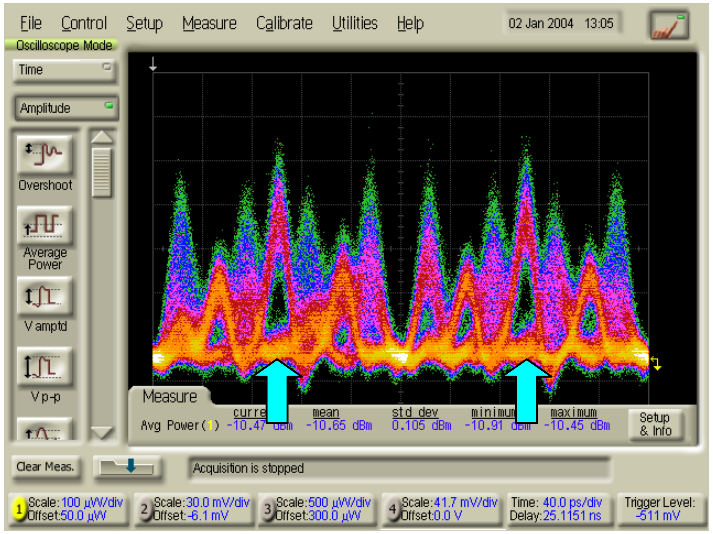
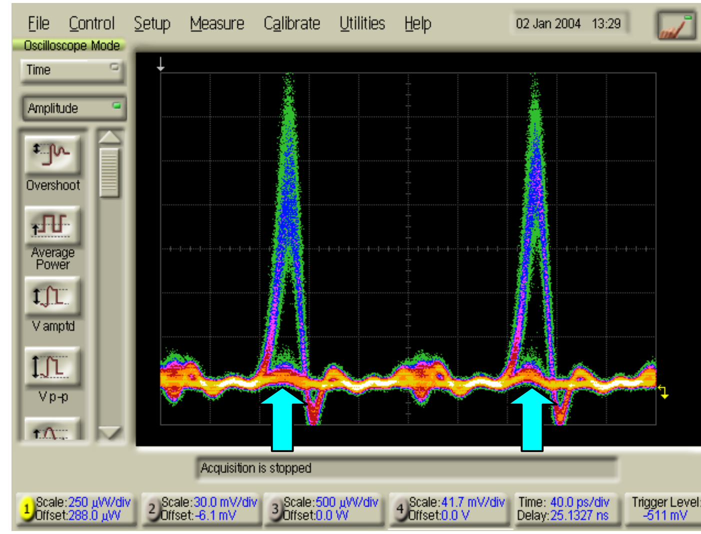
OPTICAL CODE-DIVISION MULTIPLE ACCESS O/CDMA

System Experiments: 4 OCDMA Users (Ch2 & 1,3,4)

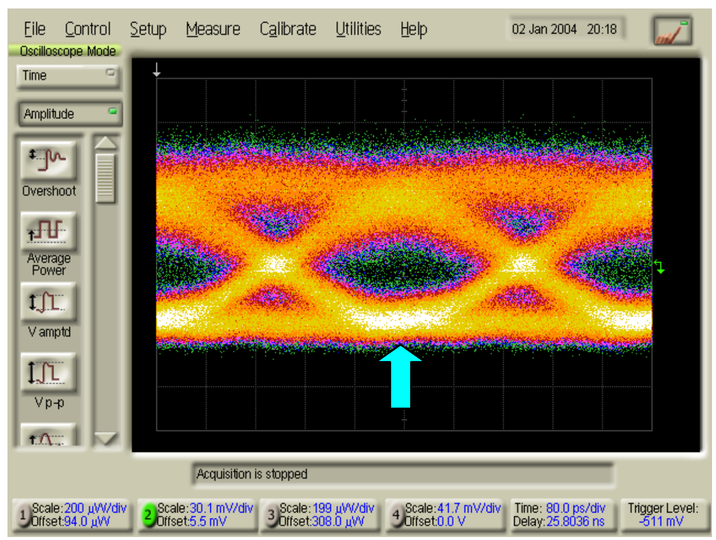
Optical gate input



Optical gate output



2.5 Gb/s NRZ Rx output (electrical)



Able to achieve BER as low as ~10^{-8} *without FEC*

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OPTICAL CODE-DIVISION MULTIPLE ACCESS O/CDMA