The Abdus Salam International Centre for Theoretical Physics

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International Atomic Energy Agency

SMR: 1643/19

WINTER COLLEGE ON OPTICS ON OPTICS AND PHOTONICS IN NANOSCIENCE AND NANOTECHNOLOGY

(7 - 18 February 2005)

"Nonlinear Optical Waveguides" - II

presented by:

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These are preliminary lecture notes, intended only for distribution to participants.

Nonlinear Waveguides in Microstructured Media: Materials, Devices, and Applications

Optical Signal Processing

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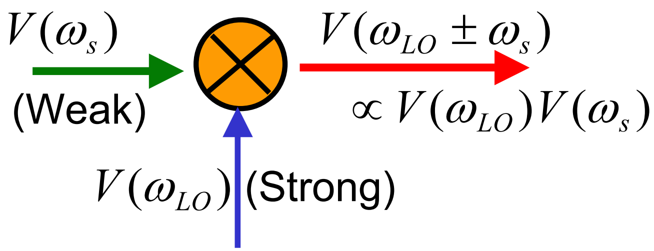
RF Mixers

Consider RF signal processing:

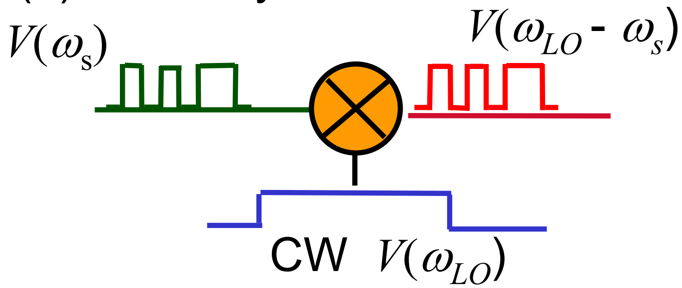
RF mixers



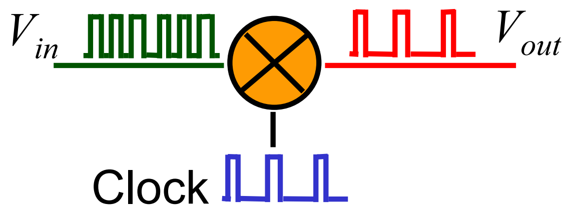
- Heterodyne mixer
  - shift carrier
- Gated mixer
  - sample
- Phase detection
- …

Typical RF Signal Processing Applications

(1) Heterodyne mixer



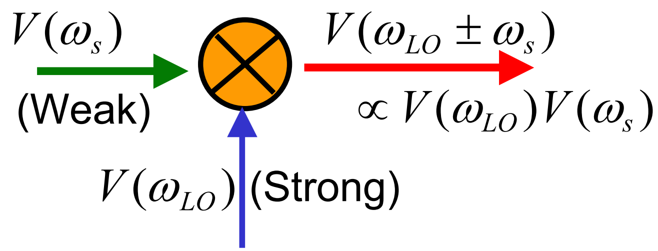
(2) Sampling/gating



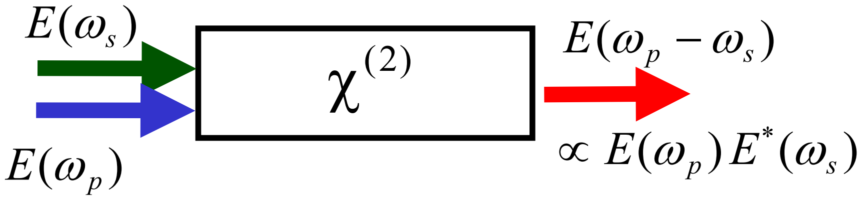
Optical Mixers

Consider RF signal processing:

RF mixers



Optical-Frequency Mixer



Closely analogous to RF mixer

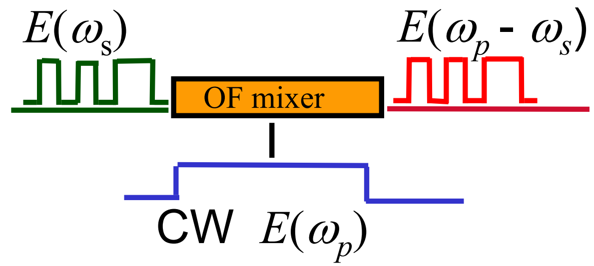
but more difficult to implement

Many communications applications

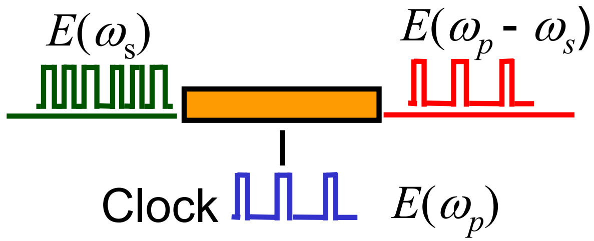
WDM: wavelength conversion
TDM: mux/demux
OCDMA: correlator
dispersion/nonlinearity correction
switching ...

Optical Signal Processing Applications

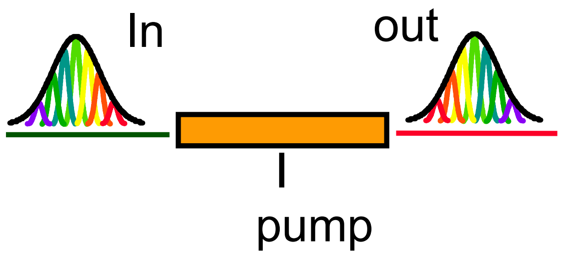
(1) Wavelength Converter



(2) MUX/Sampling



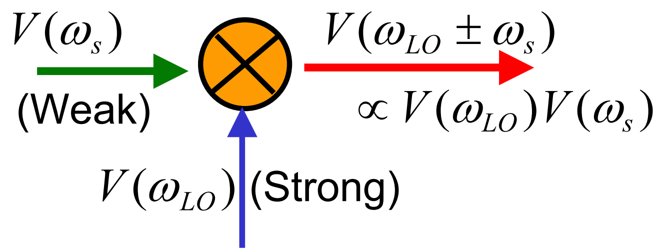
(3) Spectral Inverter/Phase Conjugator



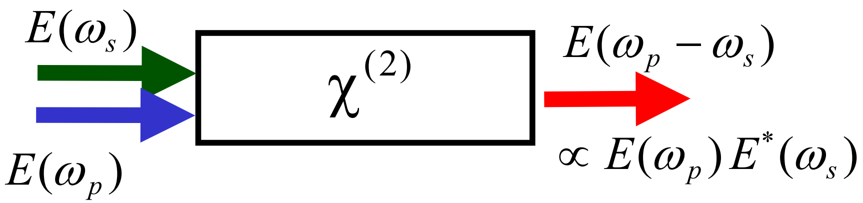
Optical Mixers

Consider RF signal processing:

RF mixers



Optical-Frequency Mixer



> 3000%/W conversion efficiency

> 70 nm conversion bandwidth

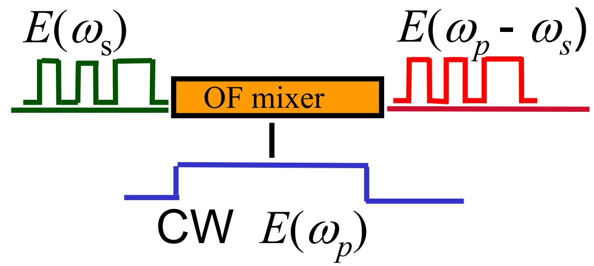
> 1 THz modulation bandwidth

> 50 dB dynamic range

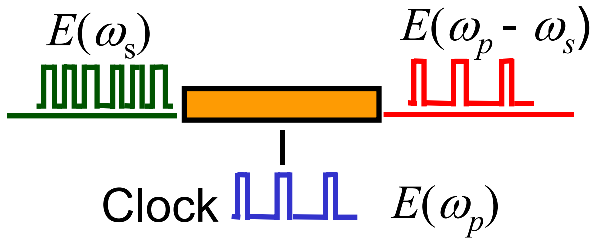
pump power 10 ~ 20 dBm

Optical Signal Processing Applications

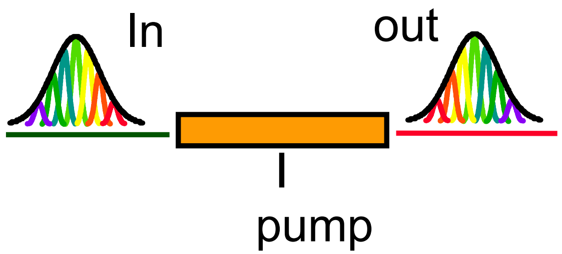
(1) Wavelength Converter



(2) MUX/Sampling

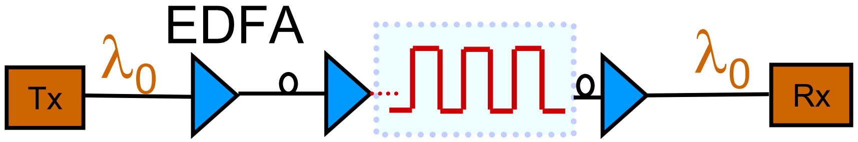


(3) Spectral Inverter/Phase Conjugator



Optical Fiber Communication Systems

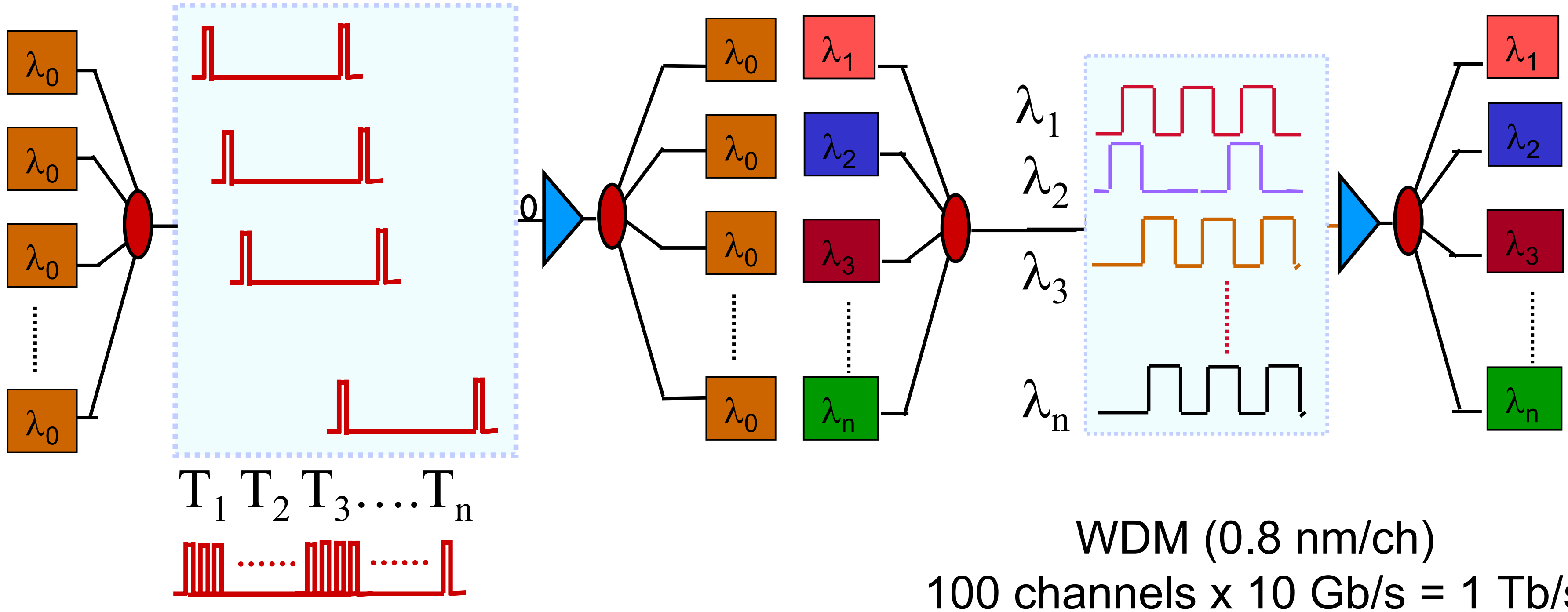
1550 nm



Single Channel
limited bit rate (10~40 Gb/s)

Low loss of optical fiber
Erbium Doped Fiber Amplifier (EDFA)

Time-Division-Multiplexing (TDM) Wavelength-Division-Multiplexing (WDM)

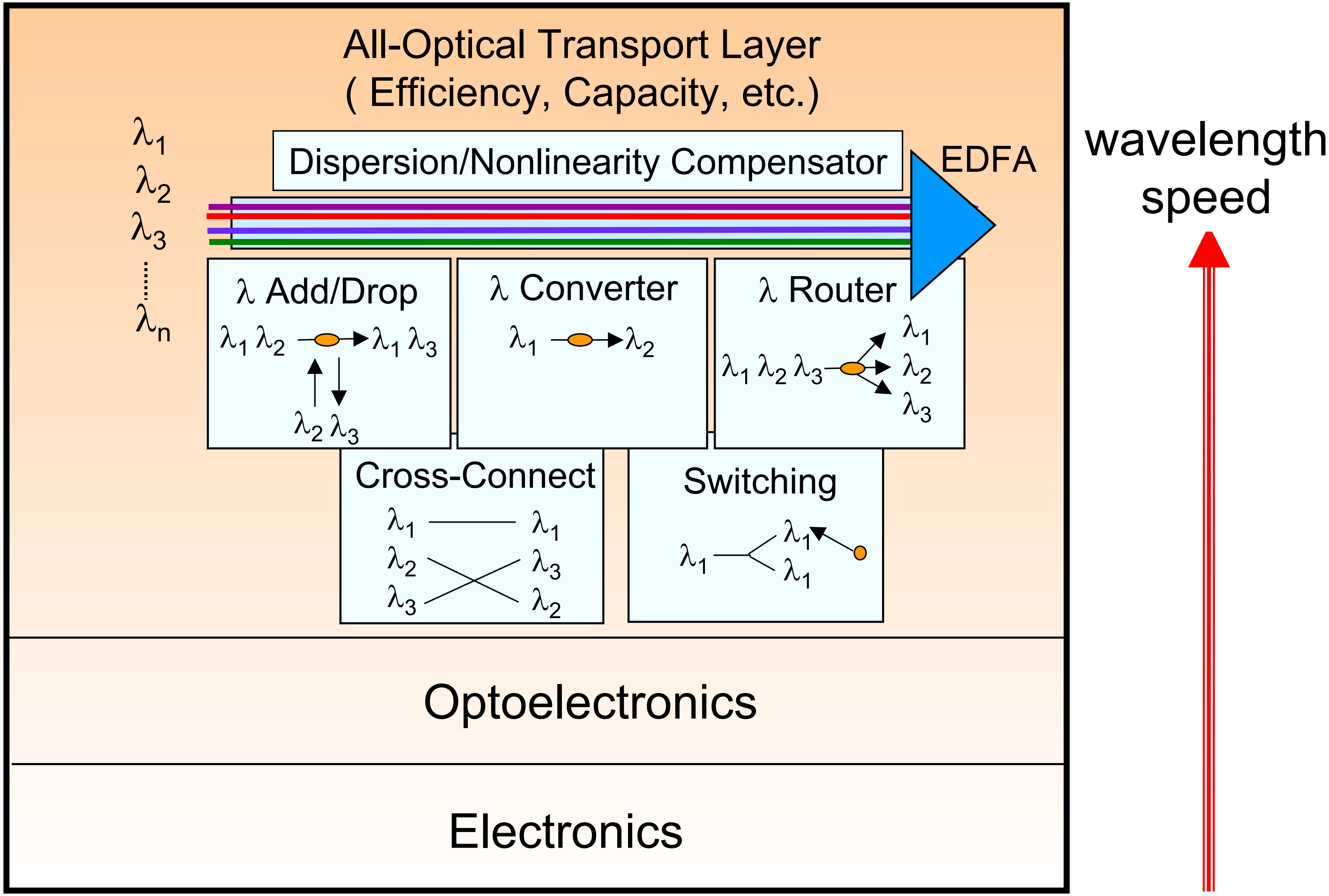


Single λ TDM 640 Gb/s

WDM (0.8 nm/ch)
100 channels x 10 Gb/s = 1 Tb/s

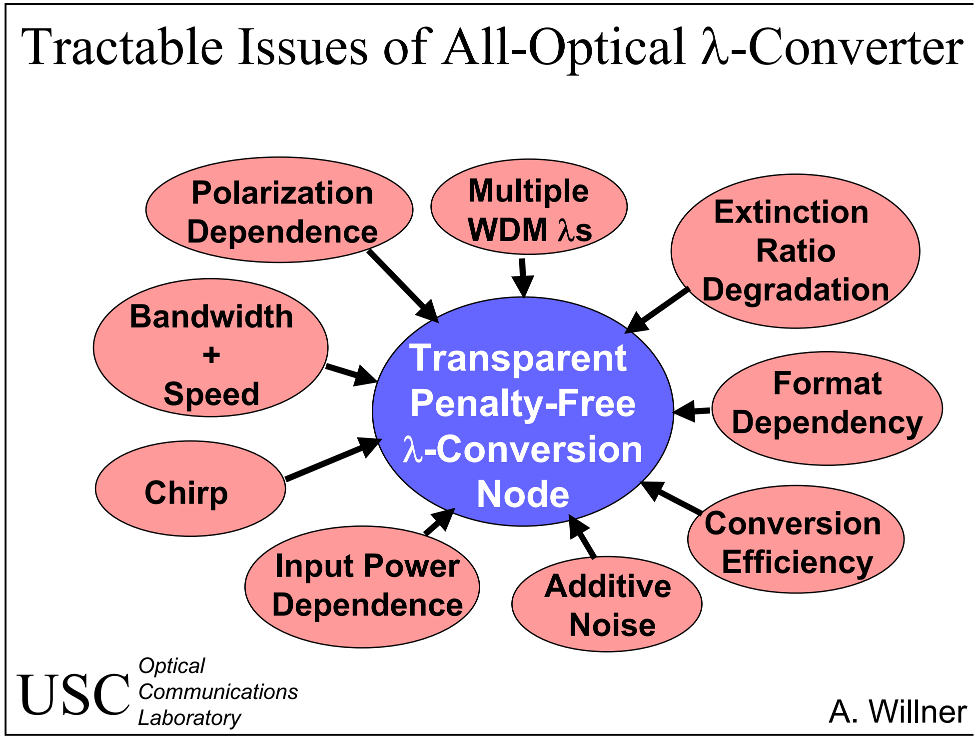
WDM+TDM: 19 Chs x 160 Gb/s = 3 Tb/s (NTT)

Demanding All-Optical Components



Wavelength Conversion Technologies

- Opto-electronic (O/E/O)
- Incoherent wave mixing (*SOA-based*)
  - Cross gain modulation
  - Cross phase modulation
- Coherent wave mixing
  - $\chi^{(3)}$: four-wave-mixing (*fiber, SOA*)
  - $\chi^{(2)}$: difference frequency mixing

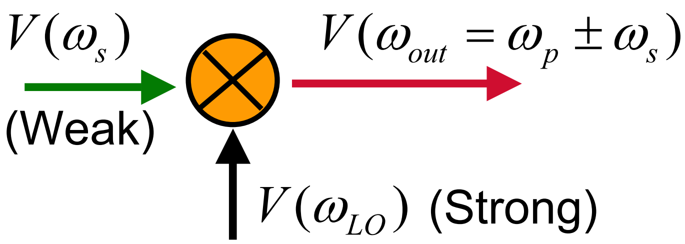


Has most of the parametric properties of FWM
No FWM crosstalk
and
with more flexibility by engineerable QPM structures

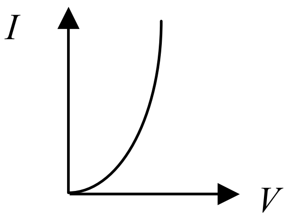
>> 100 GHz speed
> 60 nm bandwidth
format transparent
> 60 dB dynamic range

RF Mixers vs. OF Mixers

RF mixers

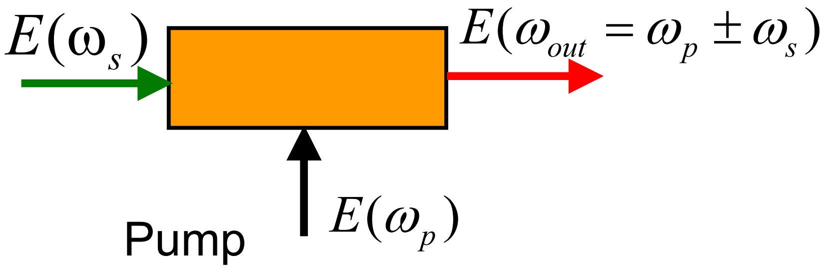


- Strongly nonlinear elements available
  - prototype: diode junction



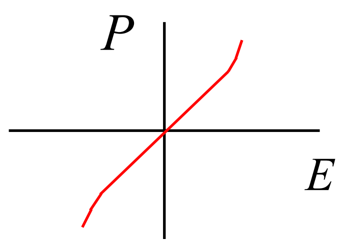
- Lumped mixers possible
  - $L << \lambda$
  - broadband and low conversion loss

OF mixers



- Only weak nonlinearities available

$$P_{NL} \propto \chi^{(2)} E_1 E_2 + \chi^{(3)} \cdots$$



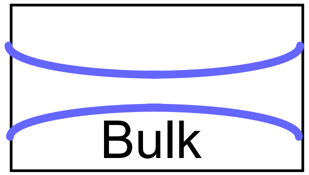
- Distributed mixers necessary
  - $L >> \lambda$
  - requires phase velocity matching

Previous lecture: QPM waveguide techniques to solve this problem

Outline

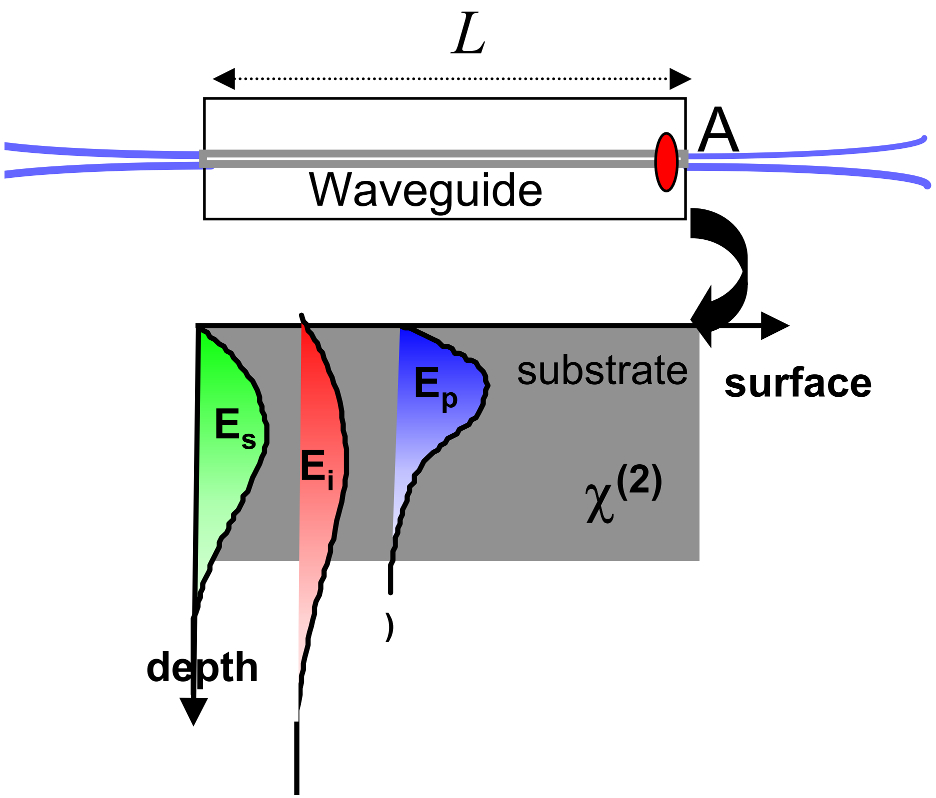
- Introduce optical mixer
- Physical implementation
  - QPM and waveguides
- Basic device properties
  - simple and cascaded operation
- Applications
  - WDM
  - OTDM
  - OCDMA
- Limitations on existing devices; advanced designs
  - engineered tuning behavior
  - distinguishability of input and output: balanced mixers
  - quasi-group velocity matching
  - polarization independent operation

QPM Waveguide Interactions



Diffraction limits useful confinement
tradeoff spot size for interaction length

Waveguides eliminate this tradeoff

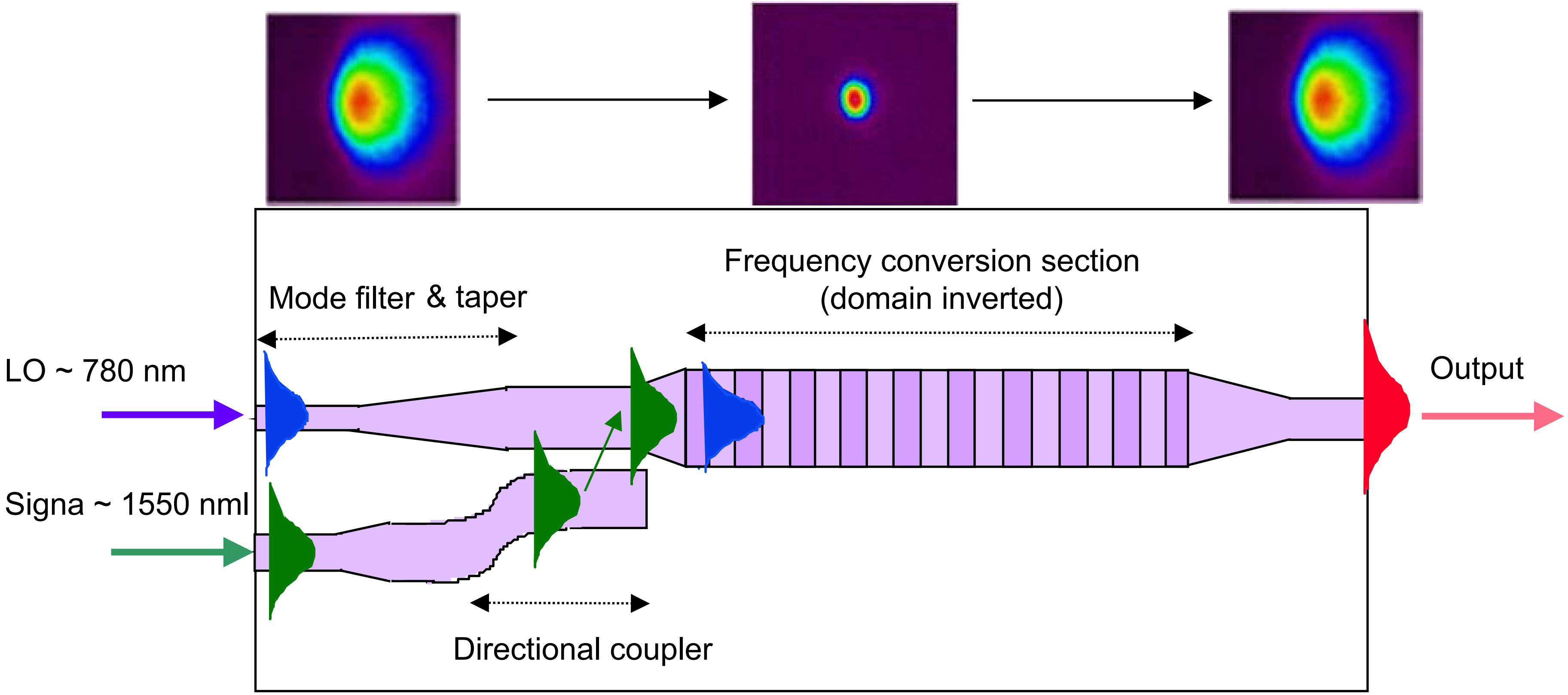


$$\frac{P_{out}}{P_s} = \eta[\%/\mathrm{W}]P_{LO}$$

$$\eta \propto \underbrace{\frac{\chi^{(2)\,2}}{n^2}}_{\text{Material properties}} \underbrace{\frac{L^2}{A}}_{\text{Device geometry}} \underbrace{\mathrm{sinc}^2\left(\frac{\Delta\,\mathrm{kL}}{2}\right)}_{\text{Dispersion}}$$

- η ~ 3000 %/W ; P_{LO}~100 mW
  - 100 % conversion efficiency
  - 10 log (P_{out}/P_s) = 0 dB
- Waveguide
  - Tightly confined mode $A\downarrow$
  - Longer interaction length $L\uparrow$
  - increase mixing efficiency > 10^3

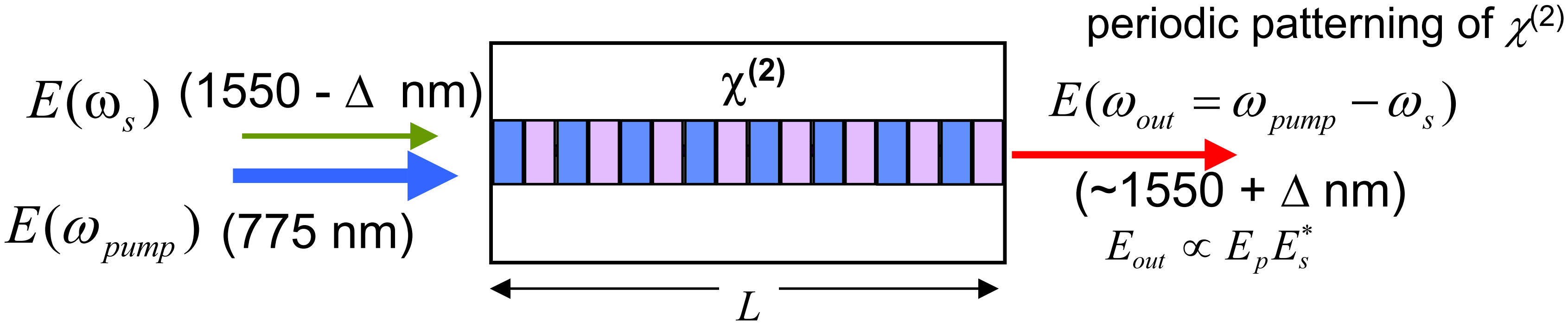
Integrated Waveguide Structures

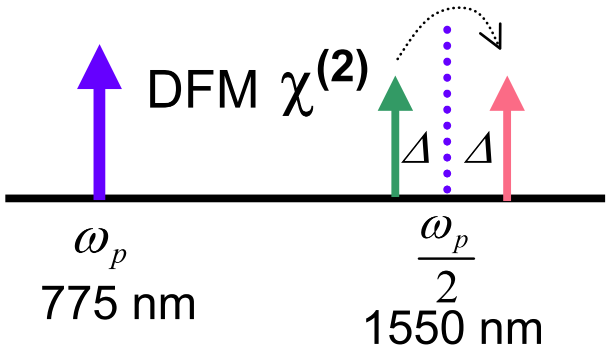


- Integrated mode coupling structure to couple 780 nm & 1550 nm
  - tapers for mode transformation
  - directional coupler for combining LO and signals
  - in & out for fiber pigtailing
  - independent optimization of each section
- < 3 dB fiber-to-fiber passive loss for 5 cm device

Difference Frequency Mixing (DFM)

Difference frequency mixing (DFM)





$P_{out} = \kappa L^2 P_p P_s$: Linear at fixed pump power

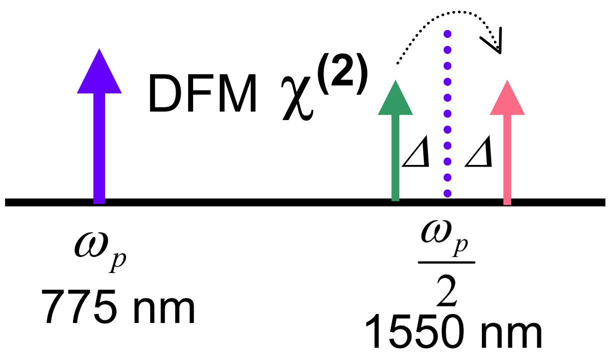
$= \eta_0[\%/\mathrm{W}] P_p P_s$ scales quadratically with L

$E_{out} \propto E_p E_s^*$: Phase conjugate output

$$\kappa[\%/\mathrm{W-cm^2}] \propto \chi^{(2)2} / A_{eff}$$

$$\eta_0[\%/\mathrm{W}] = \kappa L^2$$

Typical Mixing Efficiencies



$$P_{out} = \kappa L^2 P_p P_s$$
$$= \eta_0 [W^{-1}] P_p P_s$$

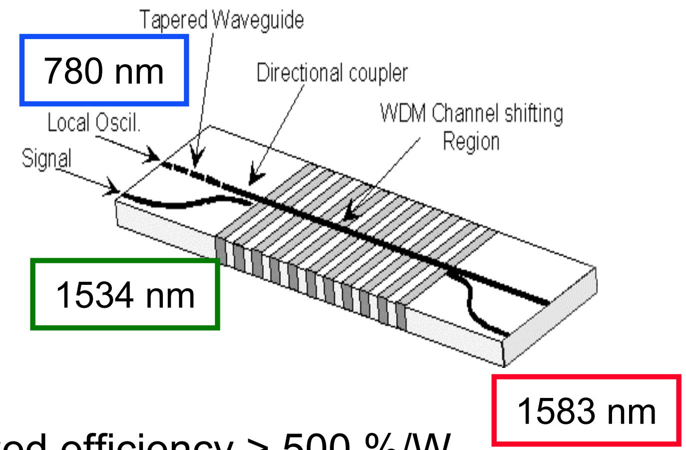
early work: η_0~5 W^{-1}
system expts: η_0~10--15 W^{-1}
current: η_0~35 W^{-1} (10^4 x bulk)
maybe: η_0>50 W^{-1}

- Efficiency has improved over last five years
  - application results based on various quality devices

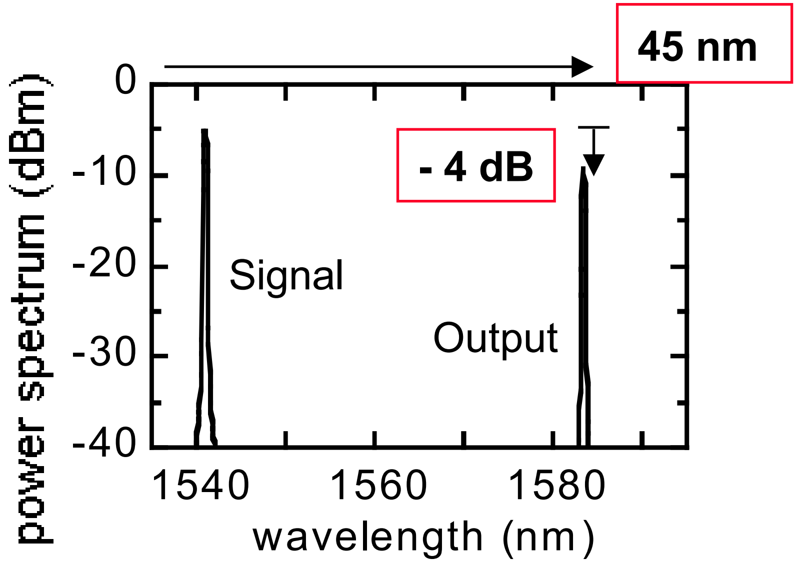
0 dB @ 20 -- 30 mW pump

parametric amplification for higher pump powers

1.5 μm band PPLN λ-Converters

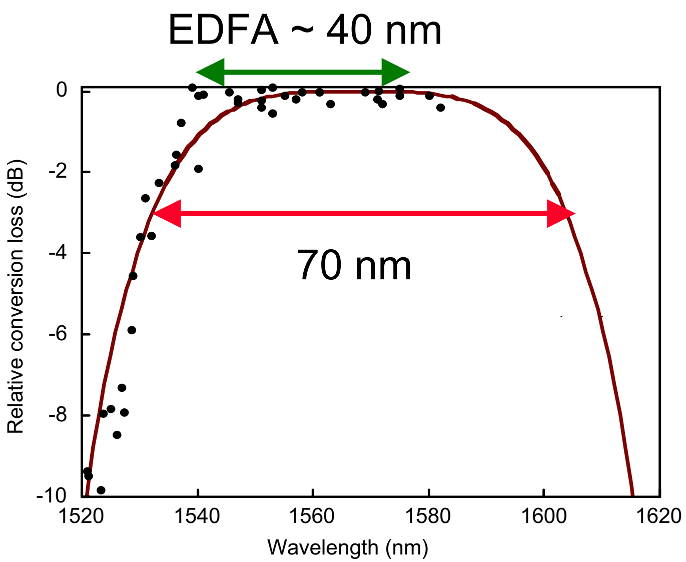


Normalized efficiency > 500 %/W
4-5 cm interaction length

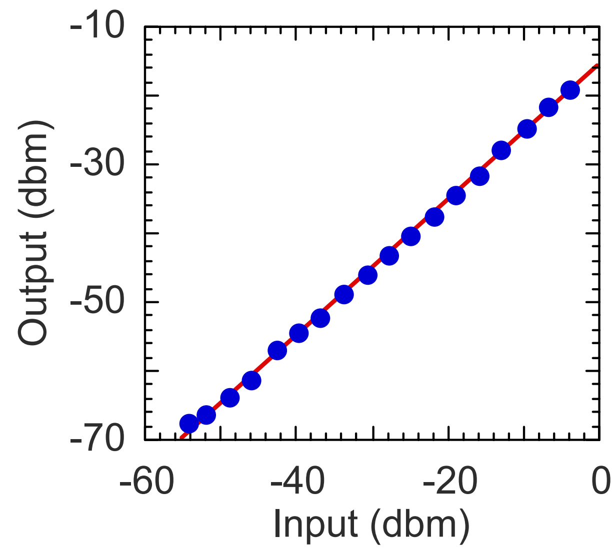


- 4 dB @ ~ 90 mW of 780 nm pump

Mixing bandwidth exceeds EDFA gain BW

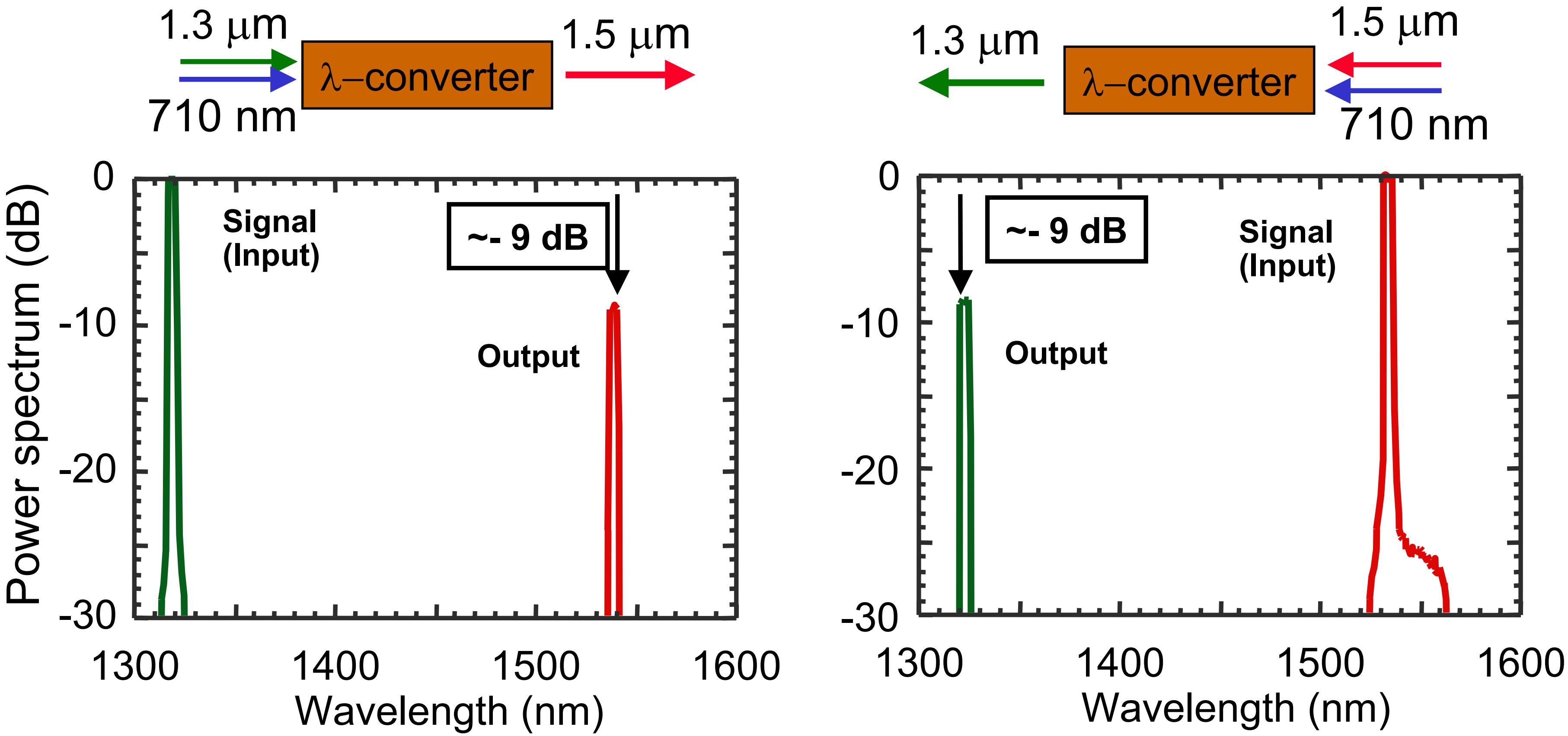


Linear over 50 dB measured range



Chou, Hauden, Arbore, Fejer, *Opt. Lett.* **23** 1004 (1998)

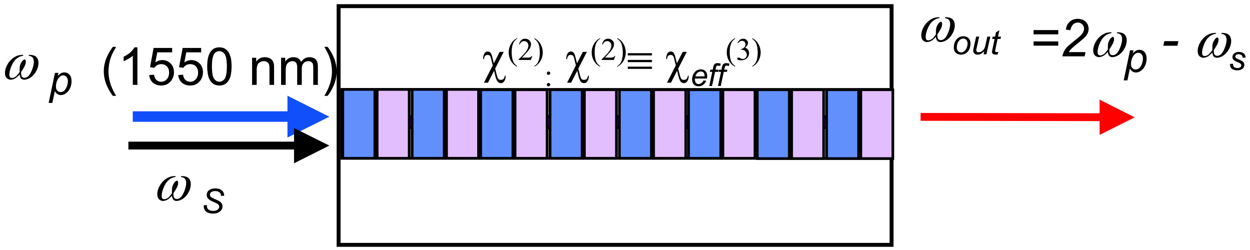
1.3-1.5 μm band bi-directional λ-conversion

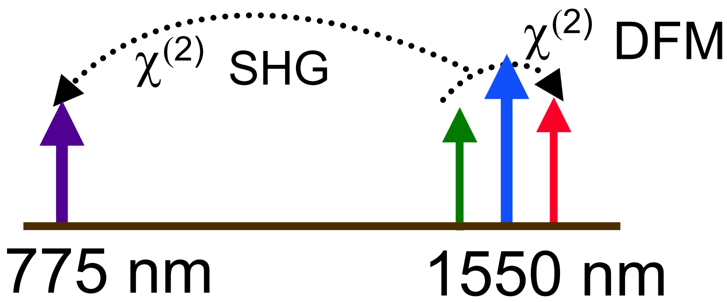


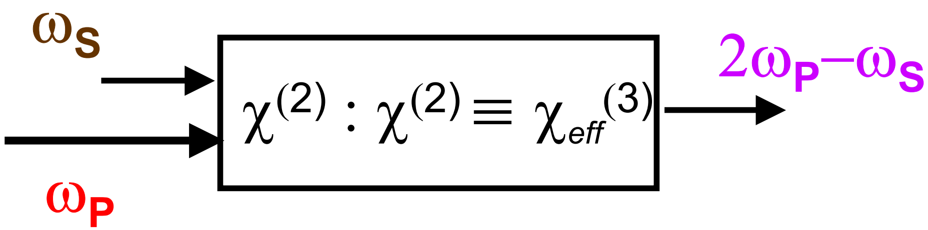
- Efficiency ~-9 dB with 40 mW pump at 710 nm
  - same for 1.5 μm -> 1.3 μm and for 1.3 μm -> 1.5 μm

M. H. Chou, K. R. Parameswaran, M. A. Arbore, J, Hauden, and M. M. Fejer, CLEO ’98

Wavelength Conversion: Cascaded $\chi^{(2)}$







behaves like FWM → "effective $\chi^{(3)}$"

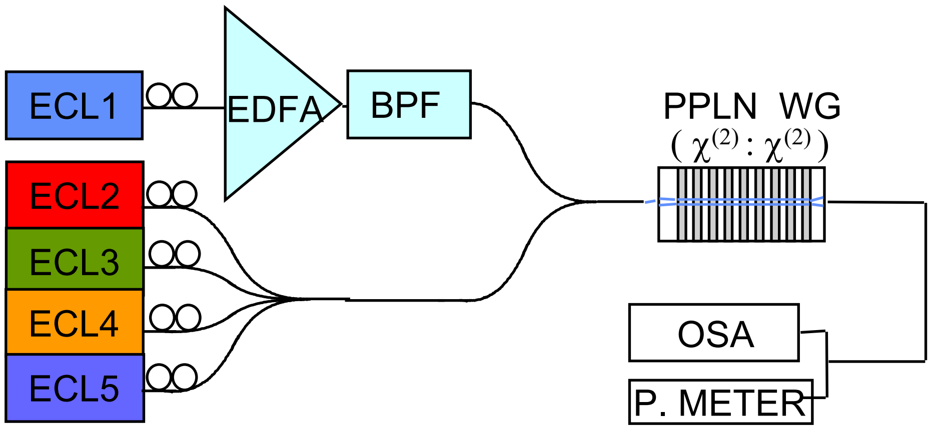
Use $\chi^{(2)}$ twice: SHG : $\omega_{SHG} = 2\,\omega_p$ $\qquad P_{2\omega} = \kappa L^2 P_p^2$

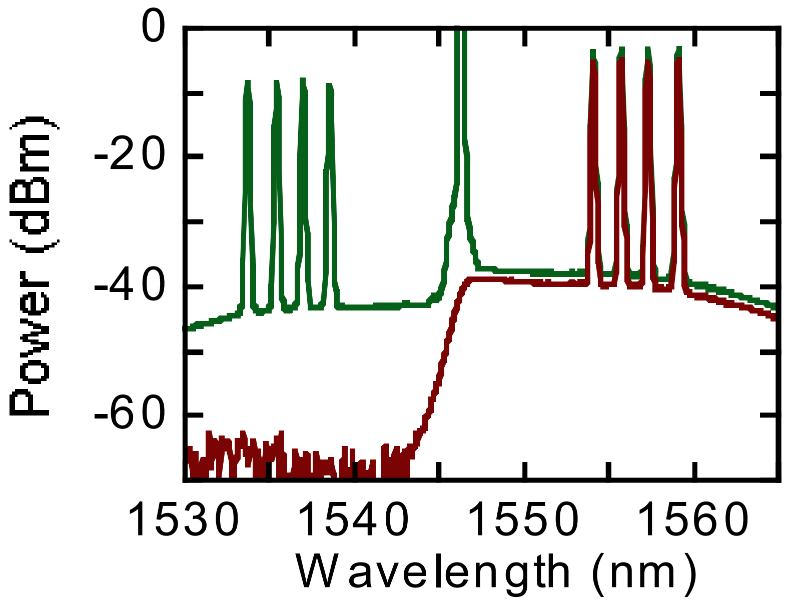
DFM : $\omega_{out} = \omega_{SHG} - \omega_s = 2\,\omega_p - \omega_s$ $\qquad P_{out} \sim \kappa L^2 P_{2\omega} P_s \sim \kappa^2 L^4 P_p^2 P_s$

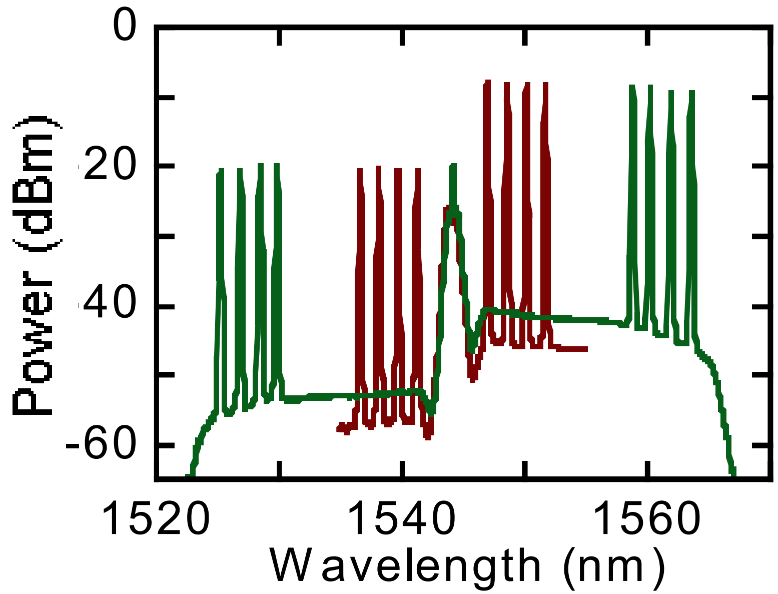
- High efficiency "pseudo" $\chi^{(3)}$ device:
  - all the advantages (switching speed, format transparency, etc)
  - compact, avoids SBS, unwanted FWM products, ...

[Stegeman, Banfi]

Cascaded Multiple Channel Conversion







- 4 channels same efficiencies
- High efficiency

  -7 dB fiber to fiber w/ pump 200 mW

  ~2 dB parametric signal gain
- S/N did not degrade
- wideband (70 nm)

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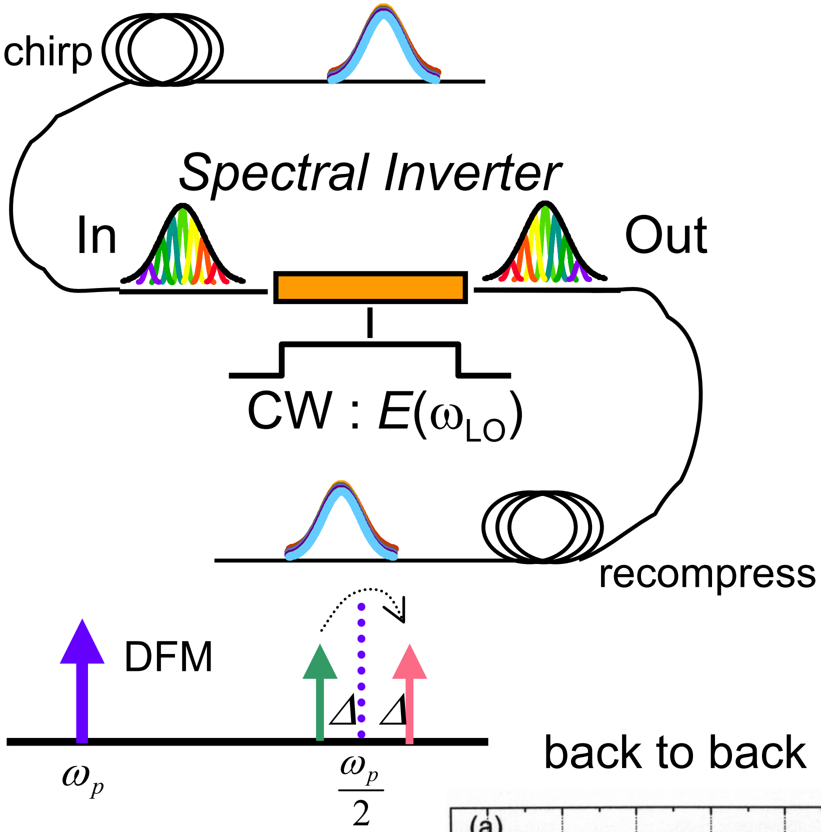
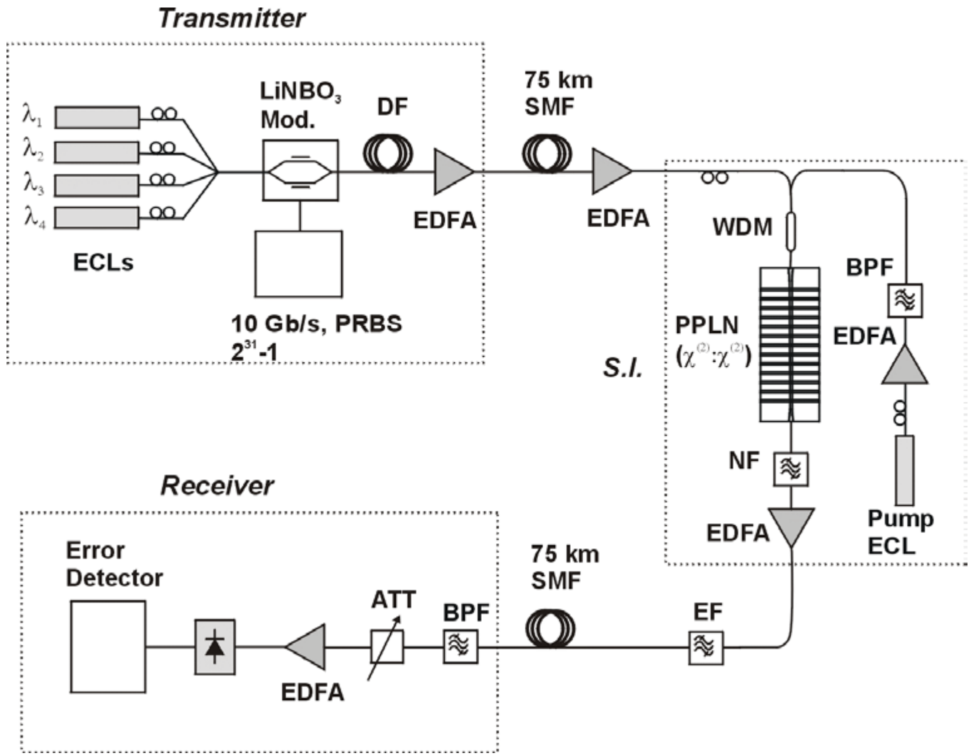
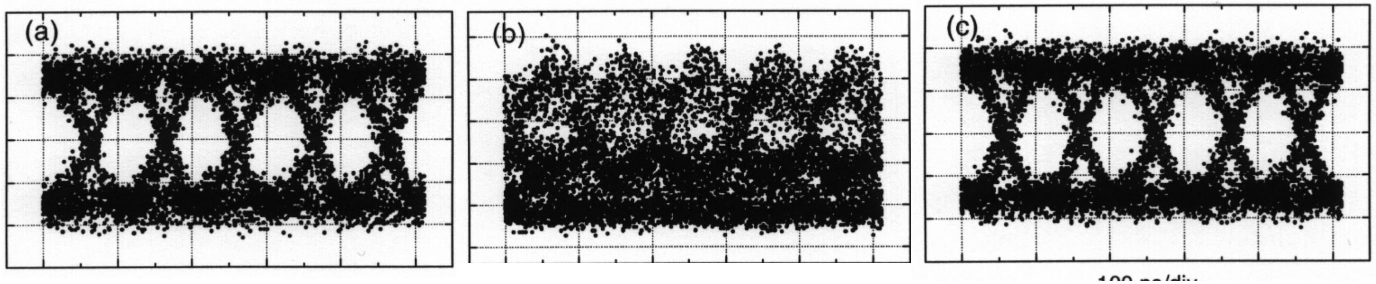
Dispersion Compensation by Mid-Span Spectral Inversion

Mid-span Spectral Inversion:
10 Gb/s, 100Gb/s system tests





back to back | after 75 km | 150 km & MSSI



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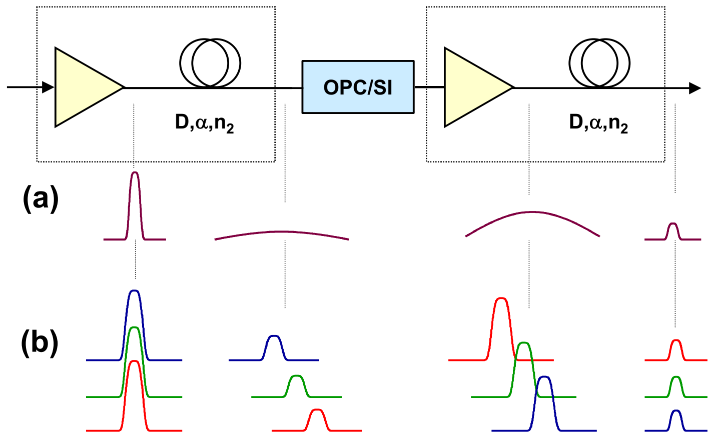
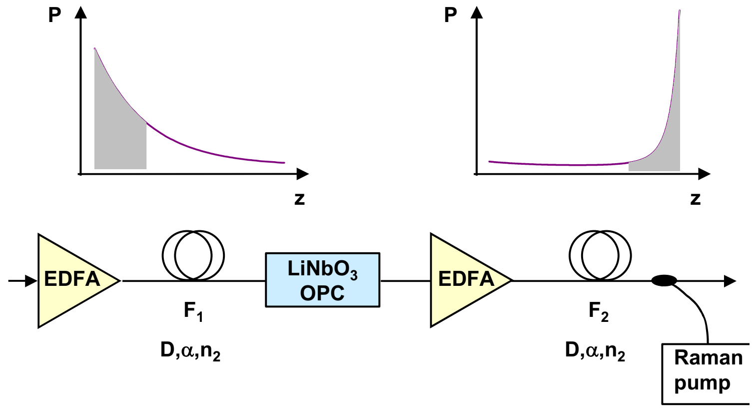
Cancellation of Four-Wave Mixing by MSSI

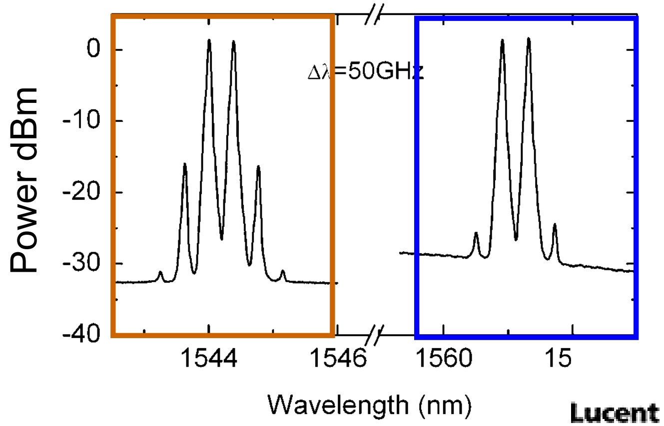
Simple MSSI does not work in lossy fiber
loss breaks the symmetry



MSSI + Raman amp will cancel Kerr efects
distributed gain symmetrizes the system

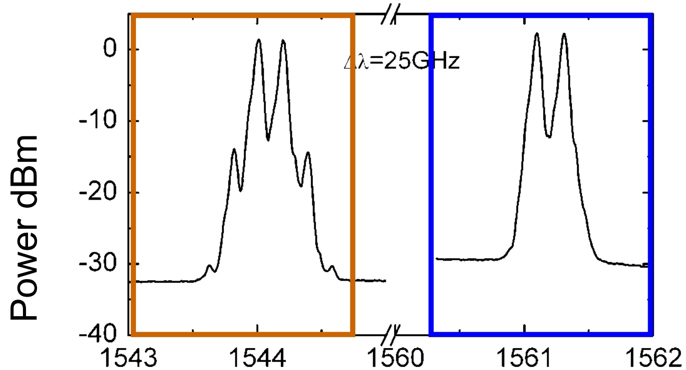


Two 75 km spools of Truewave fiber
launch 3 dBm at each of two wavelengths
17 dB Raman gain → 15 dB lower 4WM



Unconverted channel

Converted channel



$\Delta\lambda = 50\,\mathrm{GHz}$

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$\Delta\lambda = 25\,\mathrm{GHz}$

SPM and XPM Cancellation

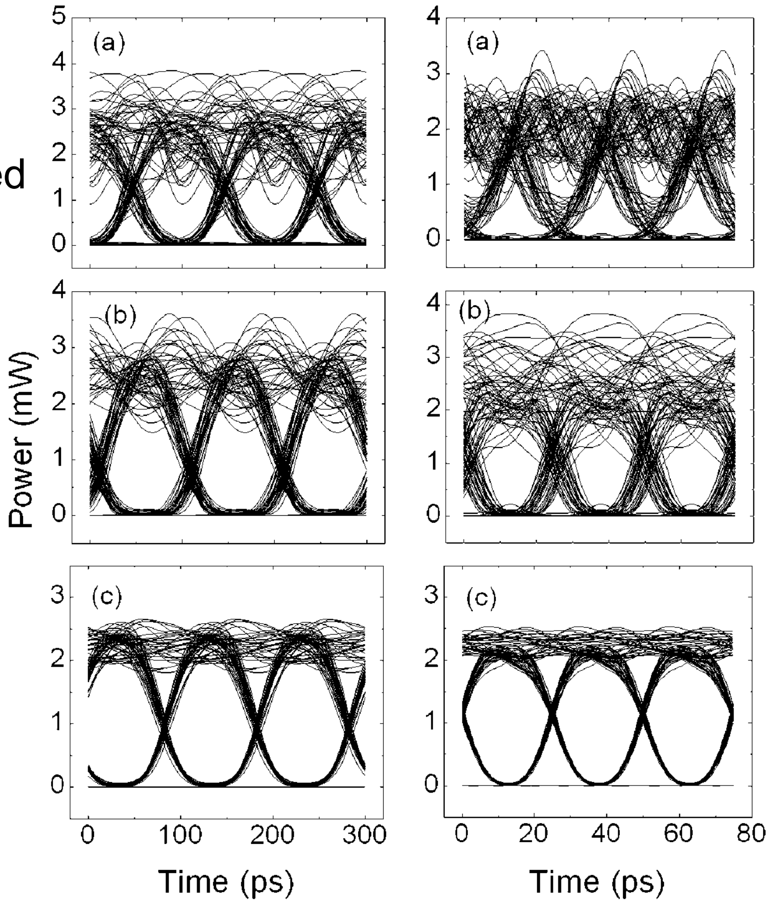
Simulation
10 x 80 km WDM network
5 channels, 4 dBm launched

10 Gb/s   40 Gb/s

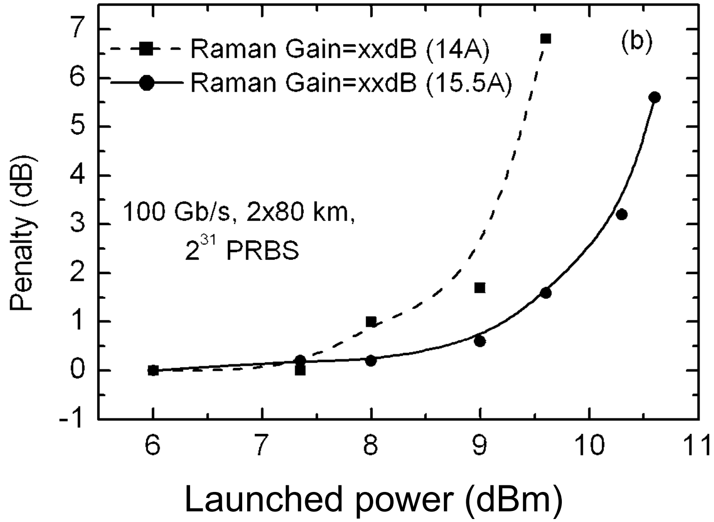
Dispersion compensated

MSSI

MSSI + Raman



Experiment
2 x 80 km WDM network
1 channel, 100 Gb/s



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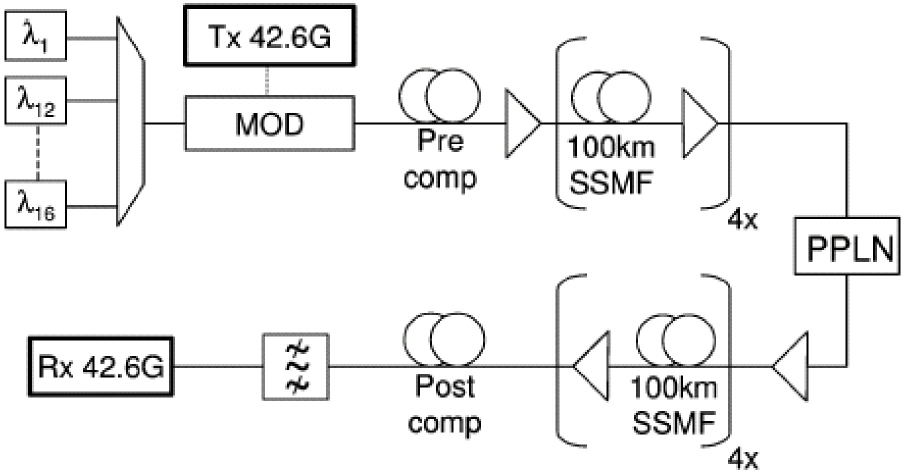
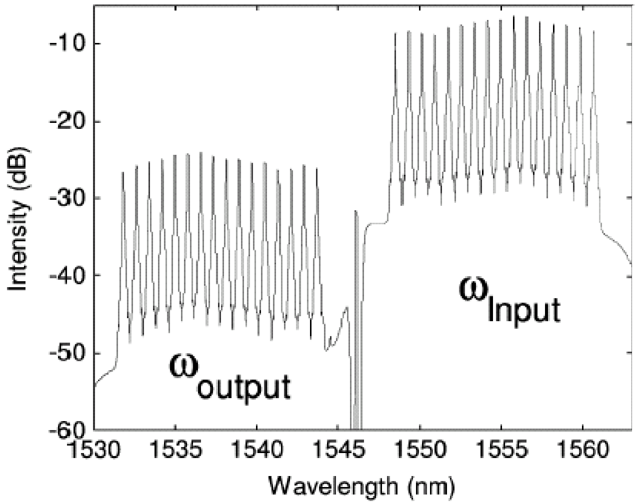
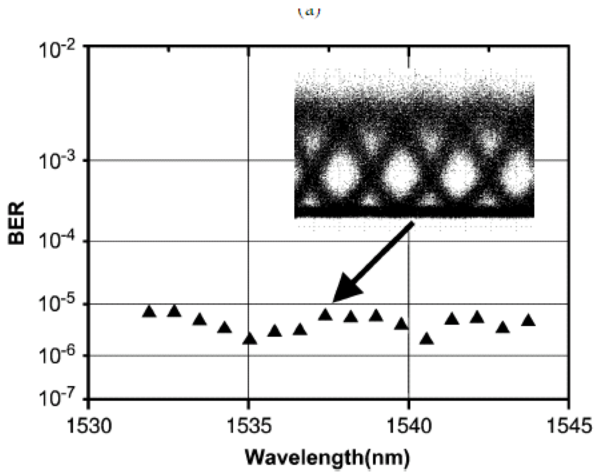
Commercial Units in System Tests

- 640 Gb/s (16 x 40 Gb/s) over 800 km SSMF
- No in-line dispersion compensation
  - only pre- and post-compensation





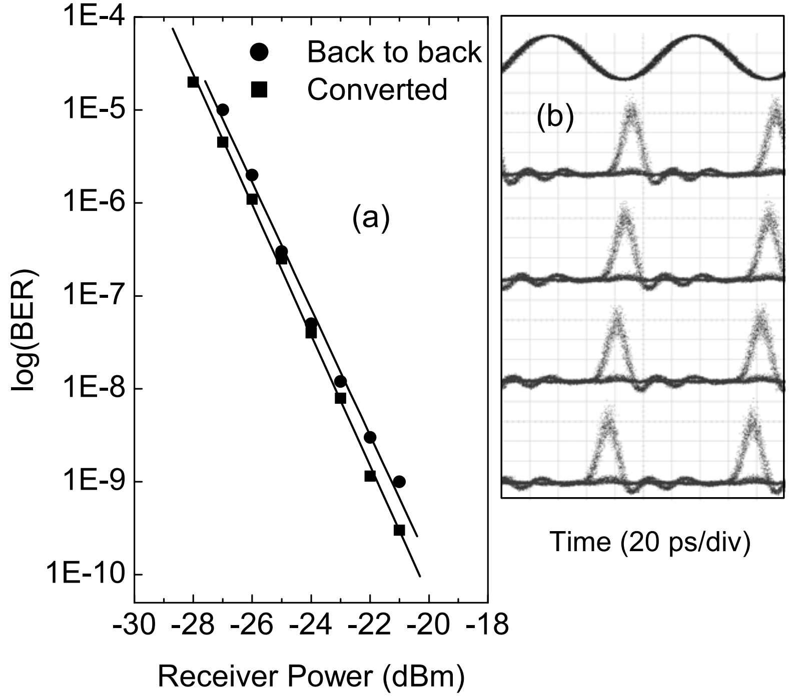


Khoe, Eindhoven TU
Spalter, Siemens
Sher, Lightbit

Higher Speed Operation of Wavelength Converter

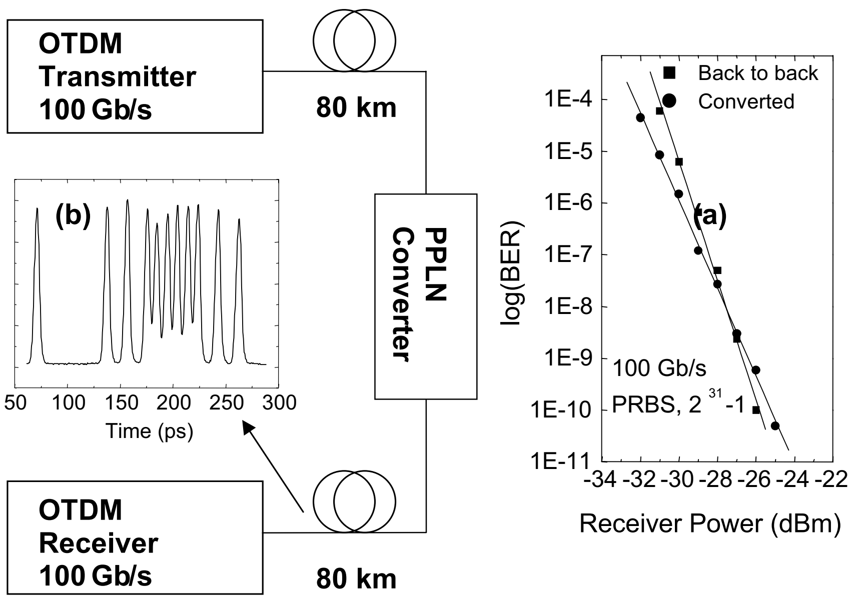
- Theoretical speed >> 1 THz
  - tested to 160 Gb/s

160 Gb/s back-to-back



<0.5 dB penalty

100 Gb/s MSSI



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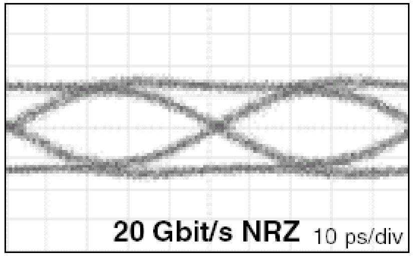
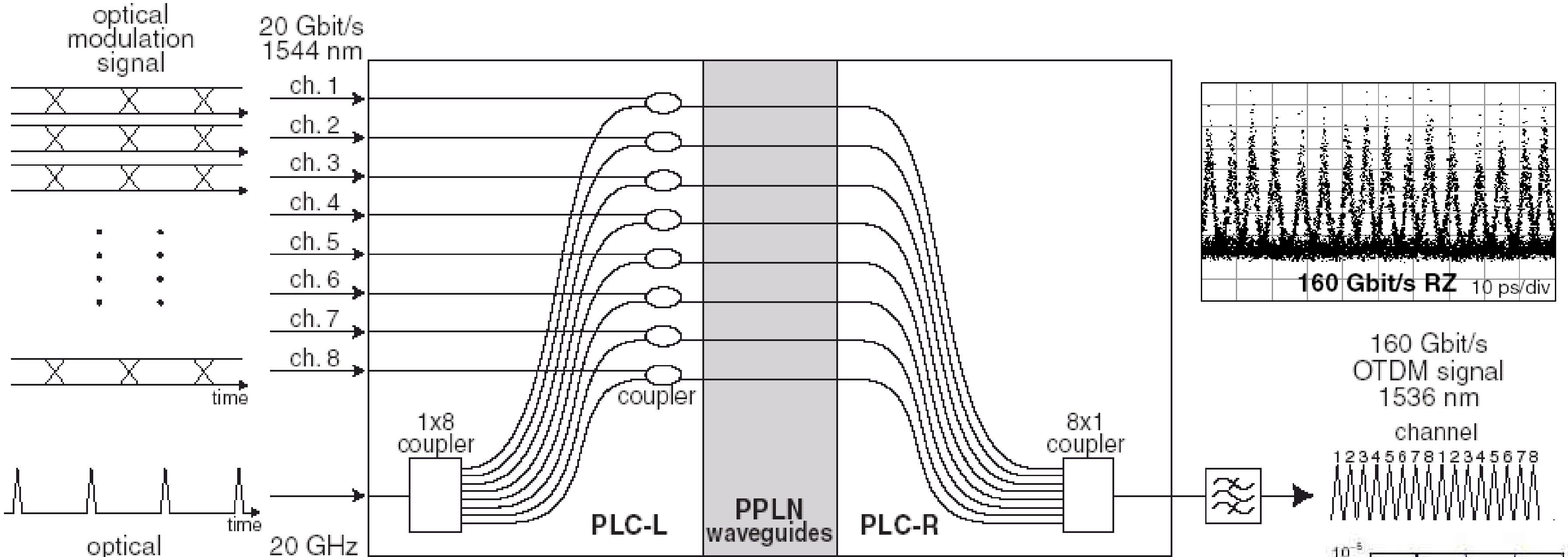
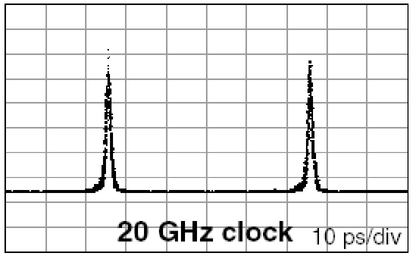
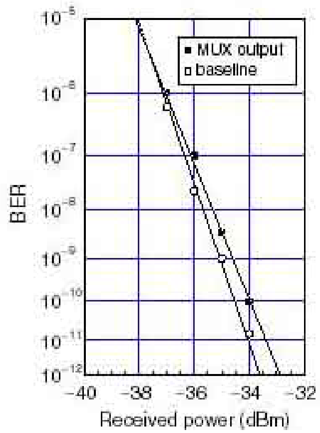
160 Gbit/s OTDM Mux



- 8 x 20 Gb/s operation with 8 parallel PPLN devices and 2 PLCs shown
- recently silmilar 4 x 40 Gb/s

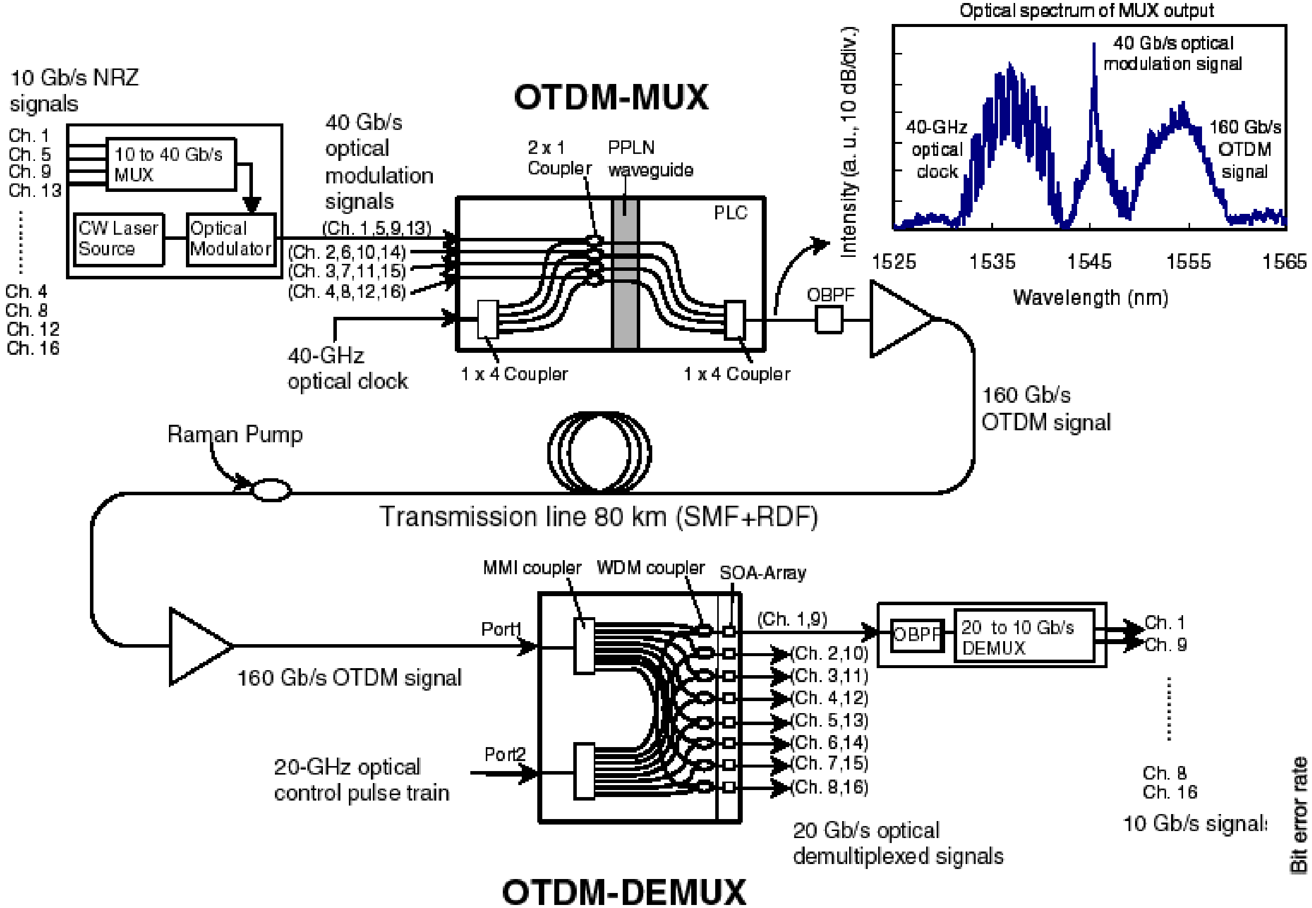


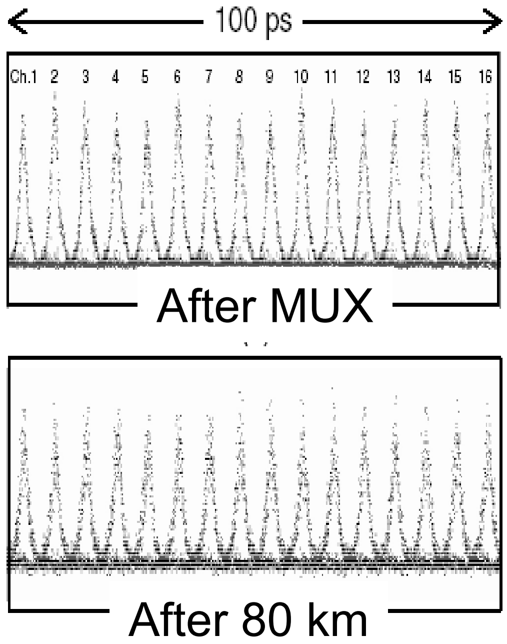


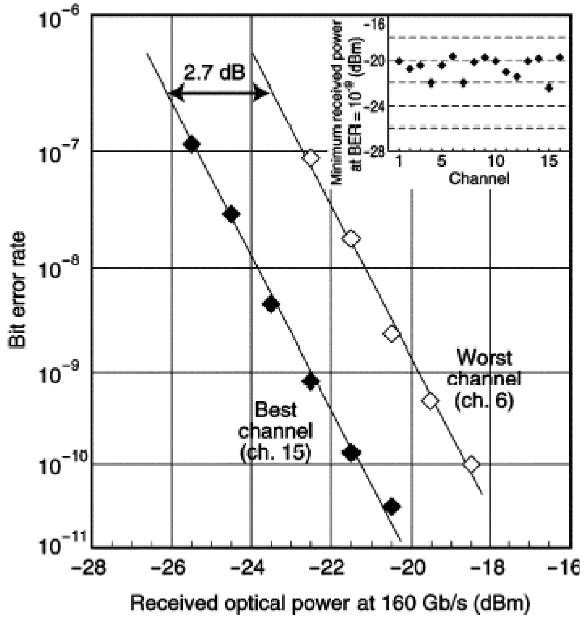


Ohara et al, CLEO 2002

160 Gb/s Transmission





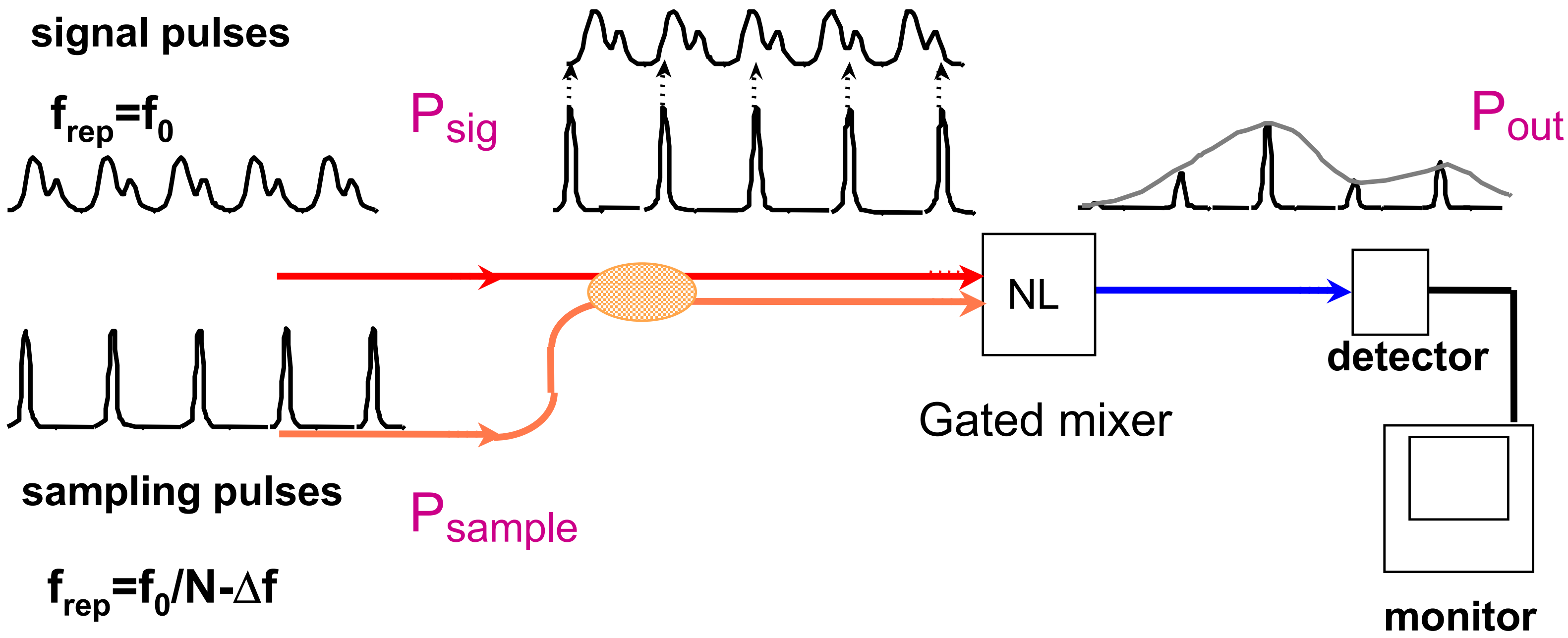


Principle of Optical Sampling

Sampling oscilloscope

traditionally electrical sampling of electrical signal

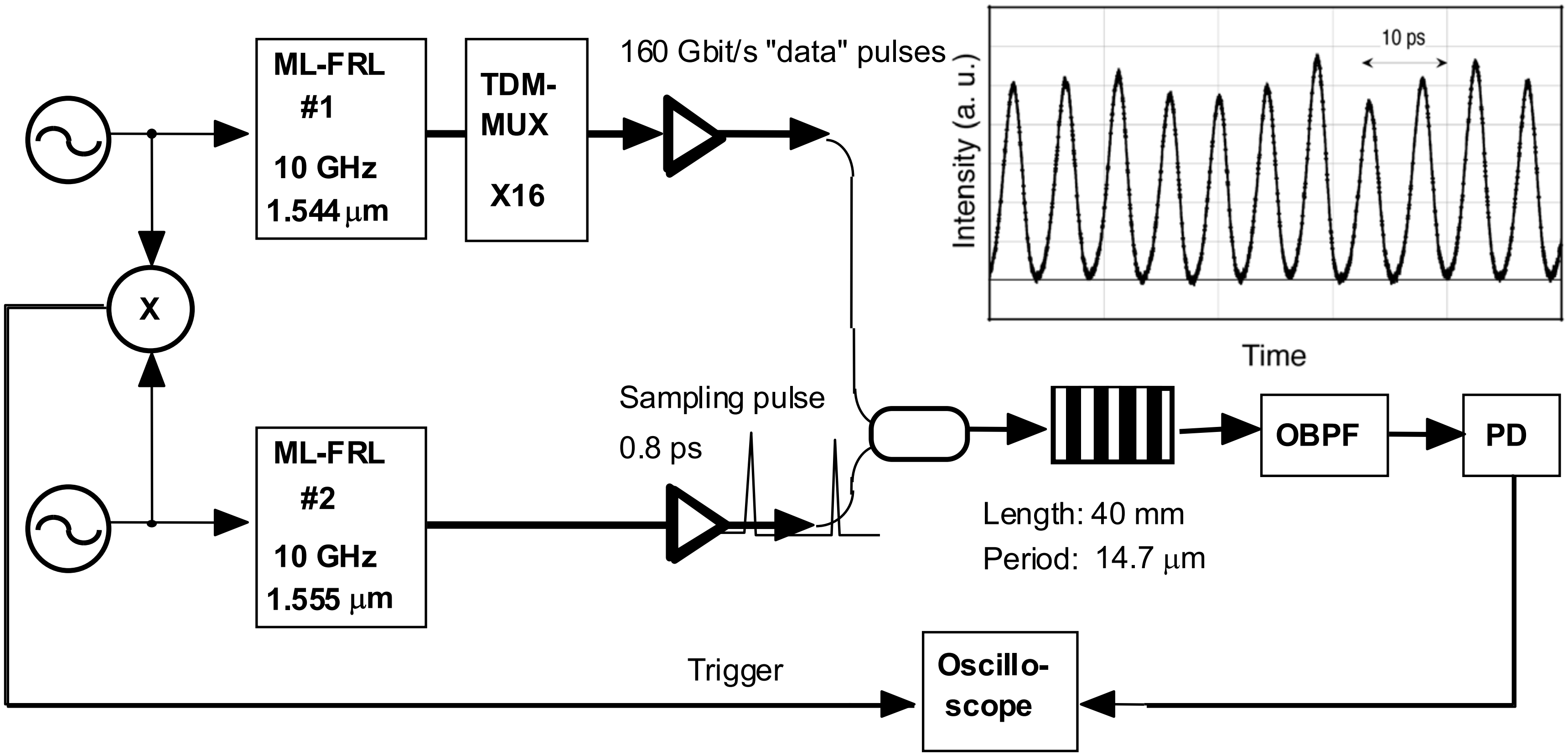
faster operation: Optical sampling of optical signal



NTT

Optical Sampling of 160 Gb/s signal

PPLN waveguide as nonlinear mixer:



Issue:

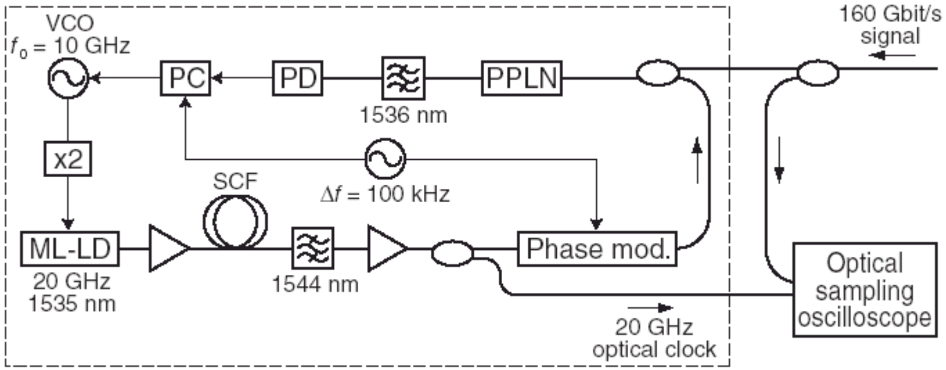
Temporal resolution $\propto$ 1/Length: 13 mm $\Rightarrow$ 1 ps

Sensitivity $\propto$ Length^2

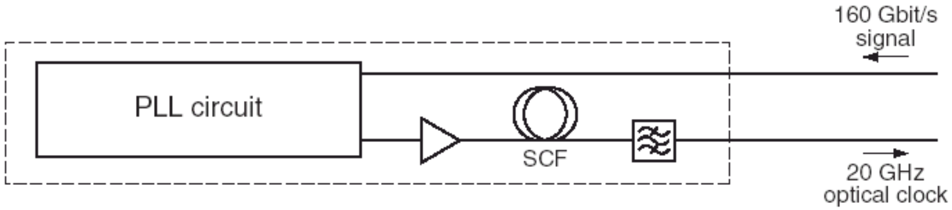
Discuss "quasi-group velocity matching" later

NTT

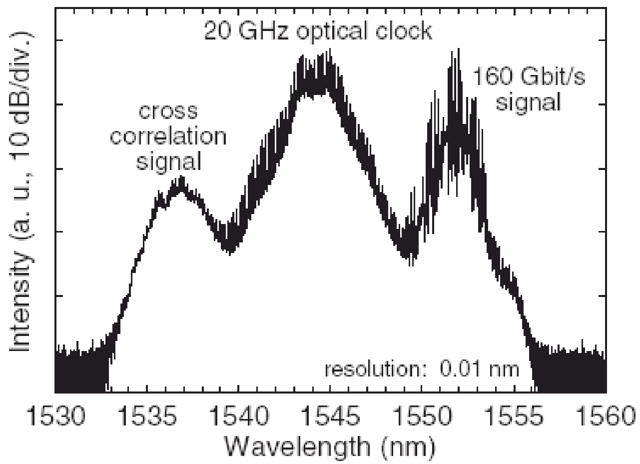
PLL

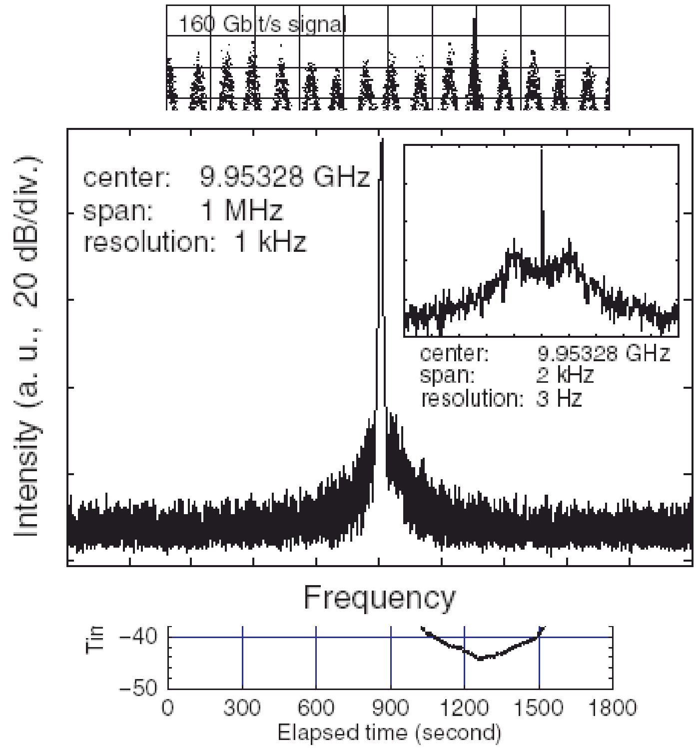


a



b





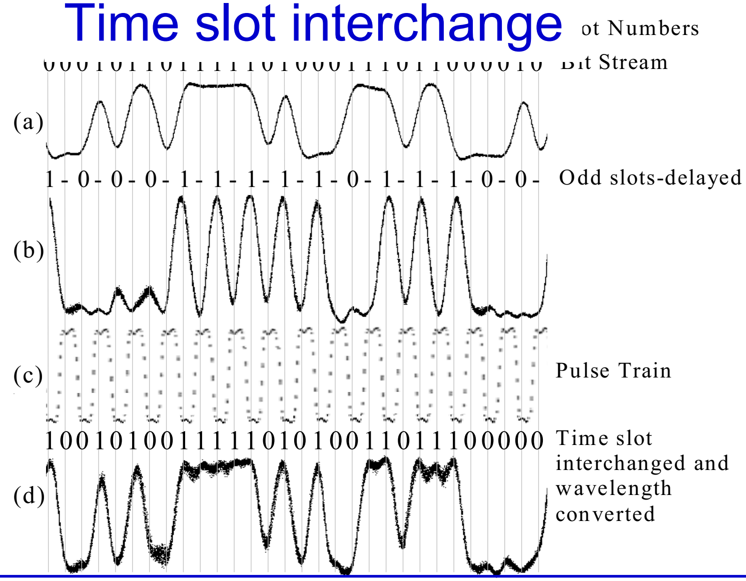
b

- PLL to lock 20 Gb/s optical clock to 160 Gb/s optical signal
  - 150 fs jitter (10 Hz--10MHz), 400 fs drift
  - PPLN high efficiency, low noise optical correlator

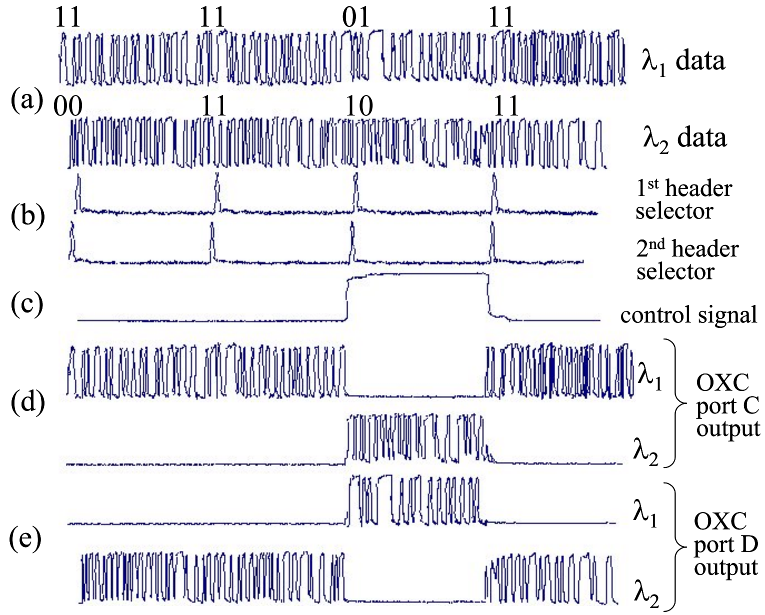
More Complex Processing Functions

- OFM enable time-gating and λ-switching
- Add time delays via FBG
  - enables more complex functions

Time slot interchange



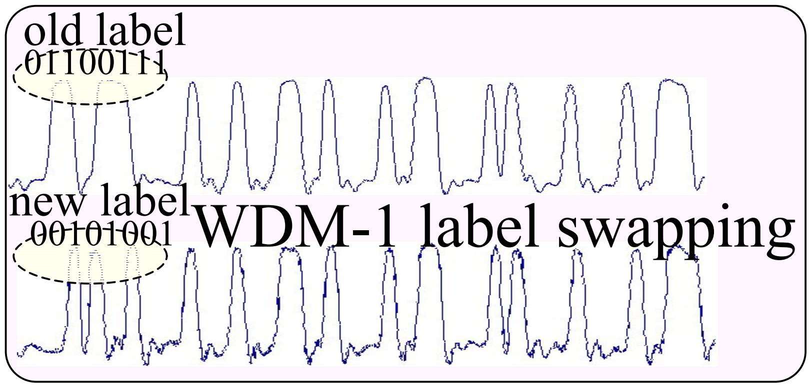
Multi-wavelength-channel header recognition

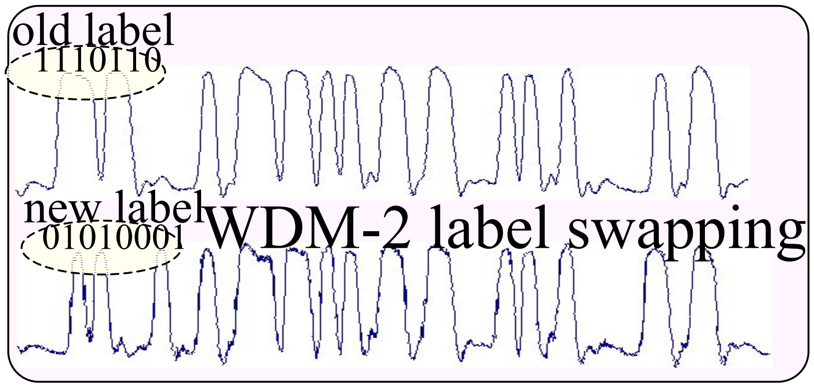


Optical Label Swapping

INPUT

OUTPUT





USC

Issues and Approaches

- Limited allowed pump tuning range
  - engineered QPM gratings
- Separation of output from input without spectral filtering
  - for operation near degeneracy
  - balanced optical mixer
- Limit on allowed pump modulation bandwidth
  - quasi-group velocity matching