Lecture 12: Wavelength Conversion and Optical Regeneration

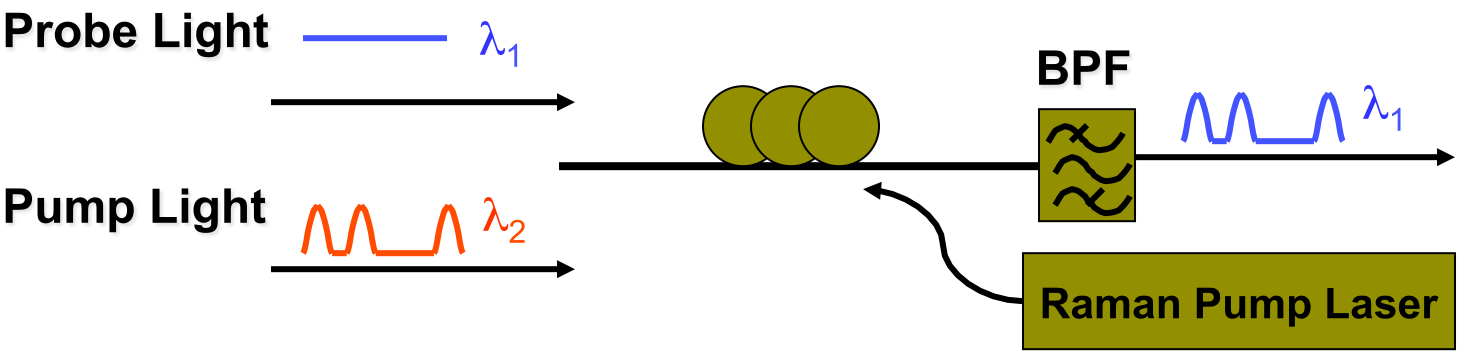
Kerr Effects

$$\frac{\partial A}{\partial z} = -\alpha A + j\frac{1}{2}\beta_2\frac{\partial^2 A}{\partial t^2} - \frac{1}{6}\beta_3\frac{\partial^3 A}{\partial t^3} - \boxed{j\gamma\left|A\right|^2 A}$$

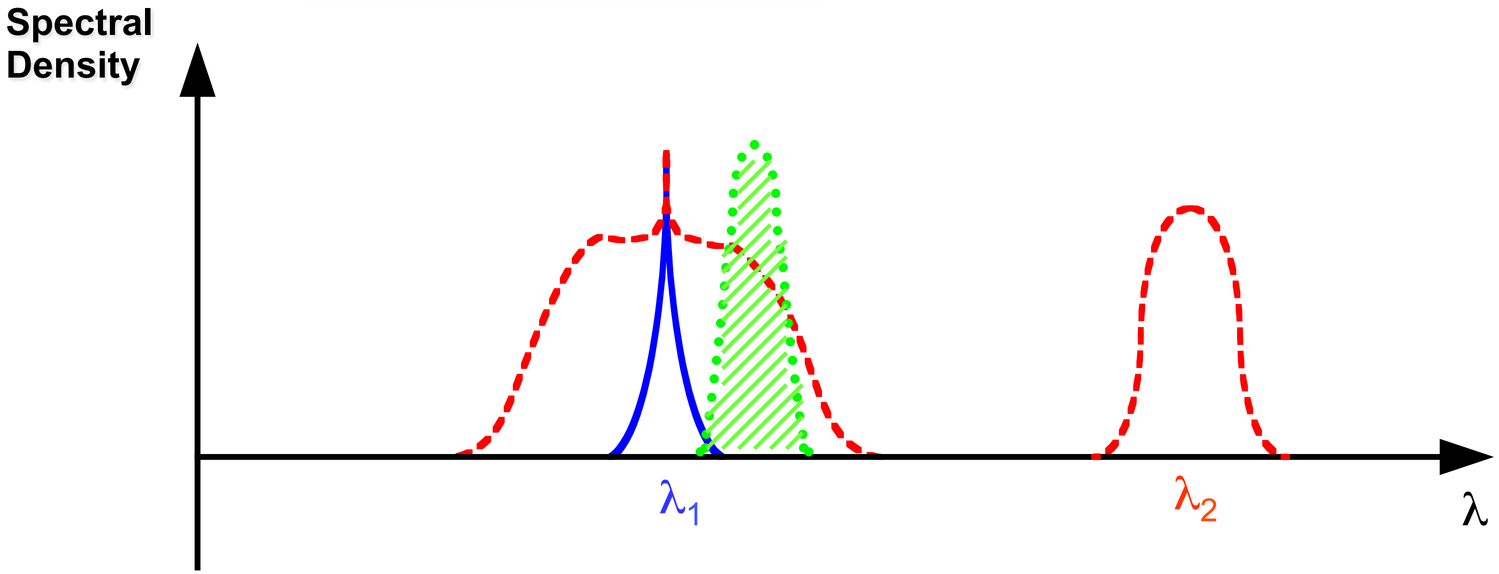
Kerr
Effect term

- Optical power in the fiber (Silica) can alter the index of refraction
- All the resulting effects are generically called as "Kerr effects"
- In general, Kerr effect induces a phase modulation on the signal that is proportional to its instantaneous power level
- The phase modulation is then converted to amplitude modulation by fiber dispersion
- Though its apparent simplicity in the above equation, Kerr effects are very difficult to be studied analytically

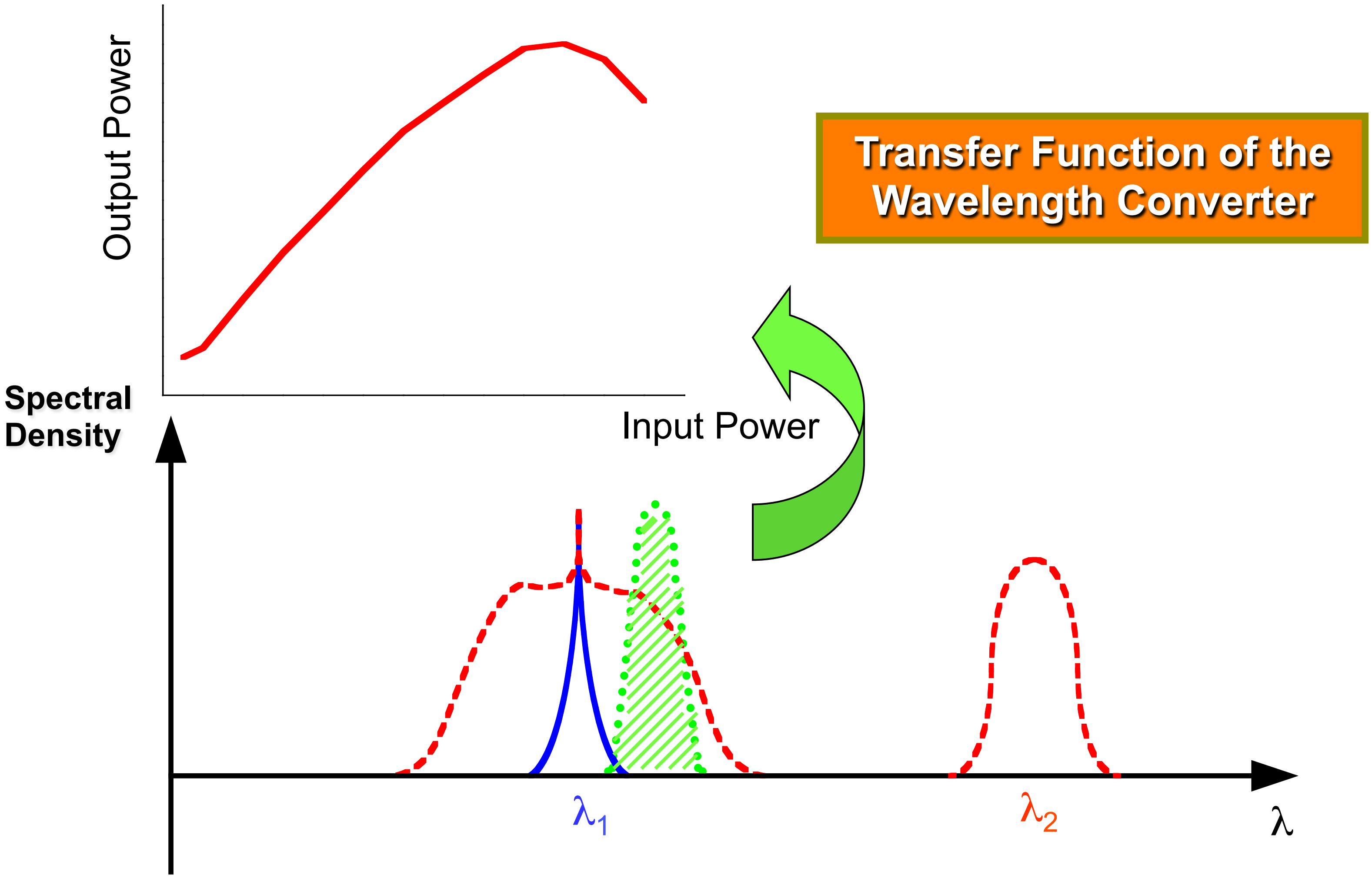
Fiber XPM using Raman Gain



Filter convert PM to AM

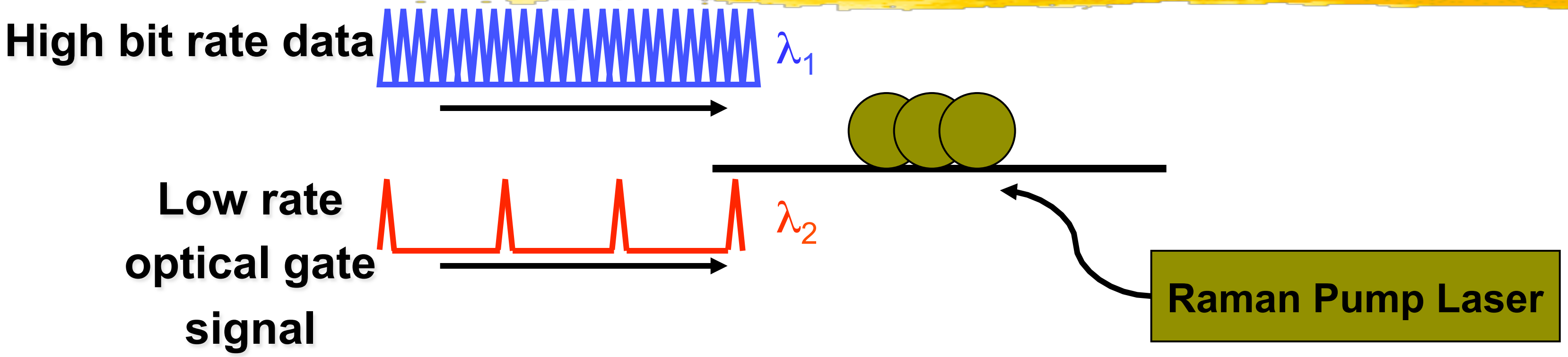


Fiber XPM with Raman Gain



Transfer Function of the Wavelength Converter

Fiber Four Wave Mixing (FWM)



High bit rate data

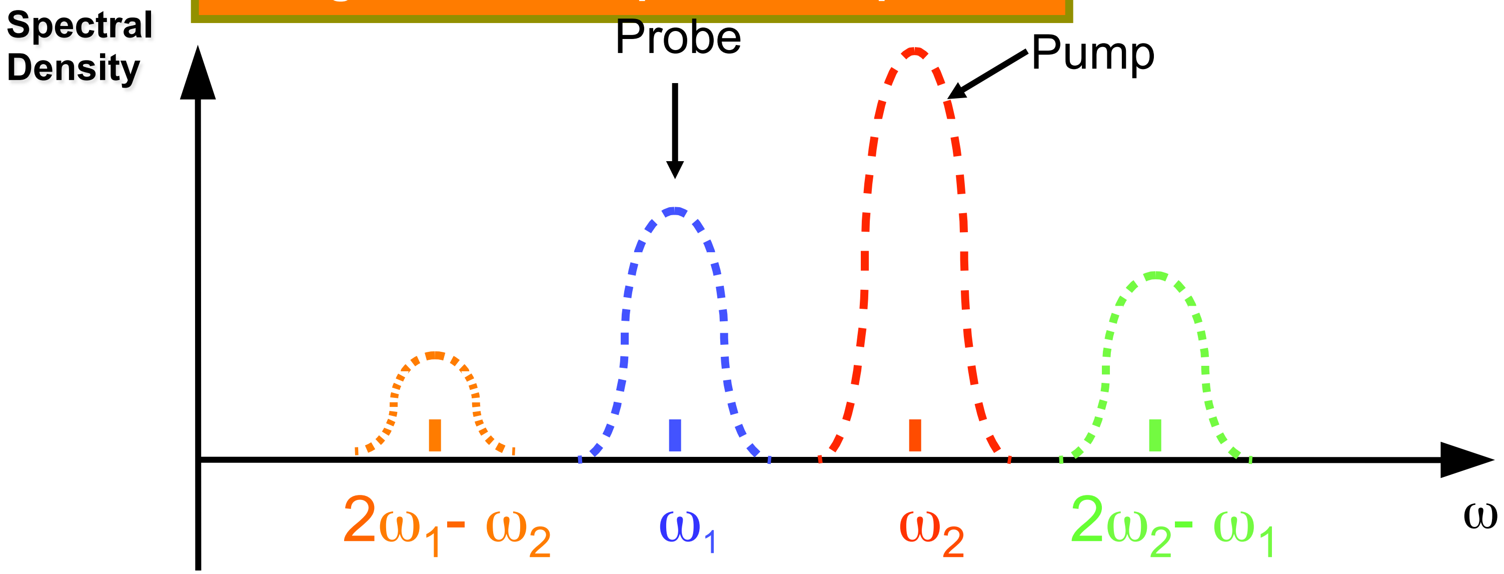
λ_1

Low rate optical gate signal

λ_2

Raman Pump Laser

FWM generate new spectral components



Spectral Density

Probe

Pump

$2\omega_1 - \omega_2$

ω_1

ω_2

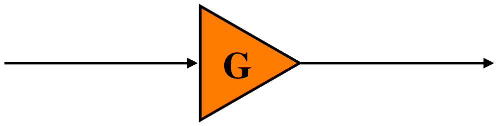
$2\omega_2 - \omega_1$

ω

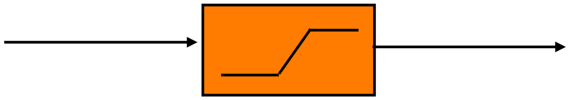
Optical Regeneration

- The success of digital electronics is based in the regenerative capabilities of transistor based gate logic.
- Current WDM optical networks are analog during the optical transport, routing and switching
- Devices are now demonstrated that show regeneration in the optical domain that can
  - Clean up ASE noise
  - Restore the extinction ratio of a digital intensity modulated signal

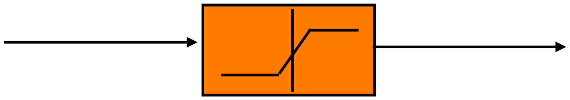
1R Regeneration: Analog amplification
Can provide gain but also adds noise. Noise accumulates during cascading



2R Regeneration: Nonlinear thresholding
Cleans up noise in the ones and zeros levels
Cascading these elements can lead to jitter accumulation



3R Regeneration: Thresholding with retiming
A completely regenerative technique. Will lead to cascadable optical digital systems



1R - Reamplification

- ⇨ We have already discussed optical amplification using a variety of approaches: SOAs, EDFAs, Raman Amplifiers, etc.
- ⇨ Important metrics include noise figure (NF), pulse distortion (leads to inter-symbol interference, pattern dependence), nonlinearities or crosstalk (which we have not discussed so far) and chirp.

2R - Reamplification and Reshaping

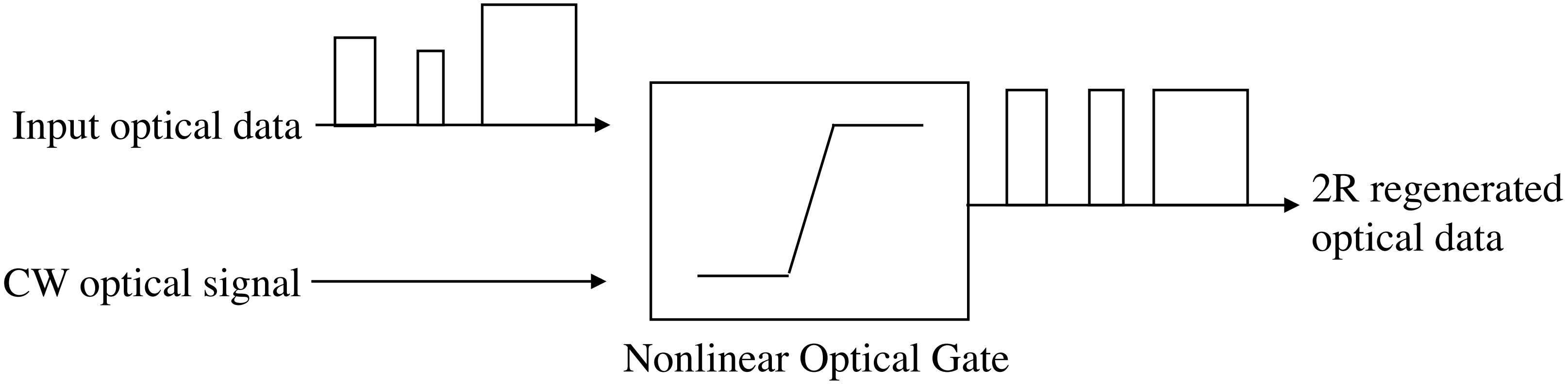
⇨ Reshaping requires some form of non-linearity operation on the signal to "redistribute" the noise and signal

⇨ It has to be done in a manner that improves the SNR

⇨ We will see that 2R alone can increase the "jitter" in the signal (Jitter will be defined later)

⇨In the end we want to decrease the number of bit-errors at the receiver. If the process of re-shaping creates errors, these are unrecoverable at the receiver (unless some type of error correction is performed. We will learn about error correction in ECE228C.

2R Regeneration



Signal Degradation

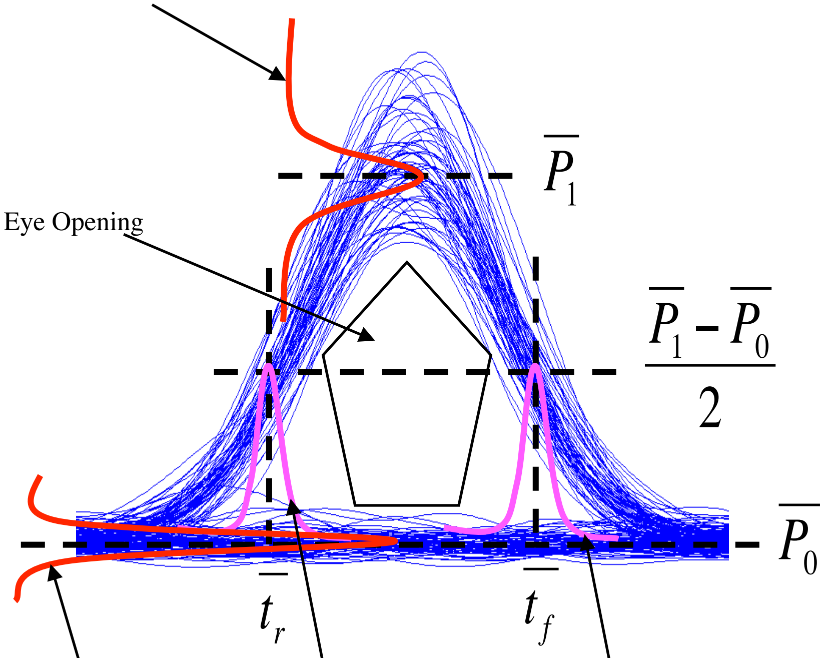
⇨ First we need to define the quality of a pulse, or bit of information.

⇨ At the right is an “eye diagram” that is an overlay of many pulses in a data stream.

⇨Note that from pulse to pulse there is variation in the “off” level, in the “on” level, and in the transitions from on-to-off and off-to-on

⇨When these variations are random and can be modeled by a random process, we call this “noise”

⇨When these variations are caused by specific events, e.g. a certain bit-pattern, we call this “deterministic”



Histogram representing probability of variations in “one” level

Eye Opening

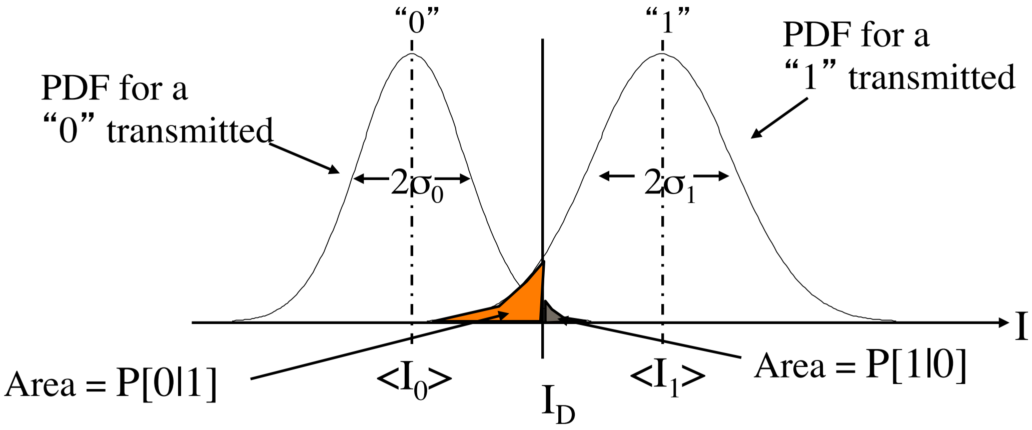
Histogram representing probability of variations in “zero” level

Histogram representing probability of location of transition from “zero” to “one”

Histogram representing probability of location of transition from “one” to “zero”

Bit Error Rate (BER)

- Probability of error = *P[0]P[1/0] + P[1]P[0/1]*
  - *P[0]* = Probability a “0” was transmitted
  - *P[1]* = Probability a “1” was transmitted
  - *P[1/0]* = Probability a “1” is received given that a “0” is transmitted
  - *P[0/1]* = Probability a “0” is received given that a “1” is transmitted



Under the Gaussian noise assumption:

$$P[1\,|\,0] = \frac{1}{\sigma_0\sqrt{2\pi}}\int_{I_D}^{\infty} \exp\left\{\frac{\left(\langle I_0\rangle - I\right)^2}{2\sigma_0^2}\right\} dI$$

$$P[0\,|\,1] = \frac{1}{\sigma 1\sqrt{2\pi}}\int_{\infty}^{I_D} \exp\left\{\frac{\left(\langle I_1\rangle - I\right)^2}{2\sigma_1^2}\right\} dI$$

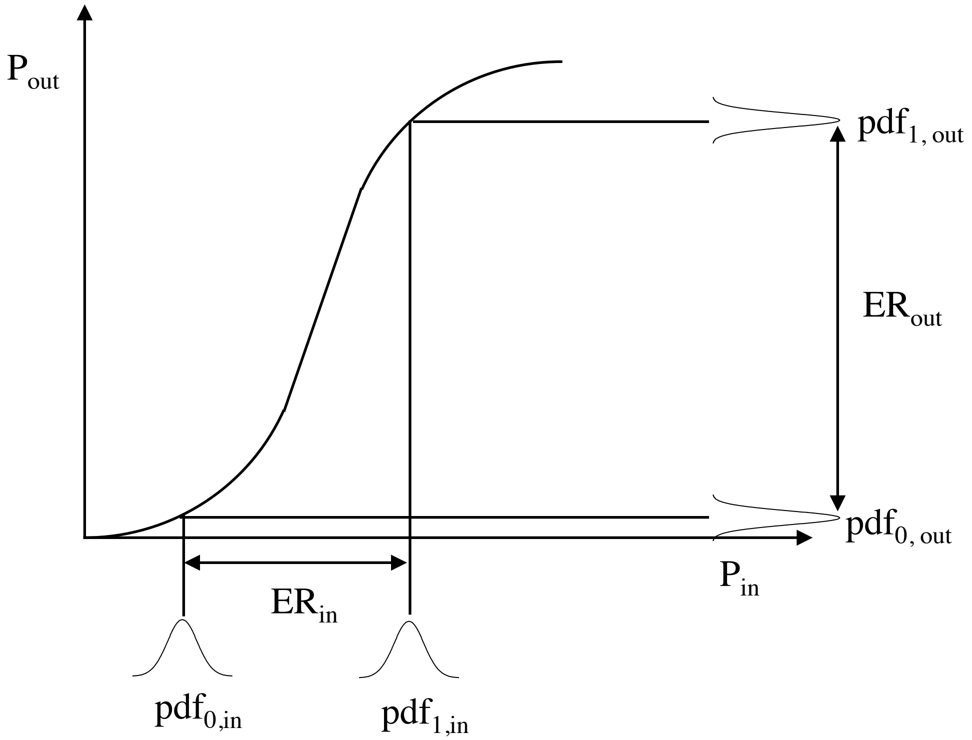
2R Noise Redistribution

⇛ Nonlinear transfer function re-distributes the noise at the input.

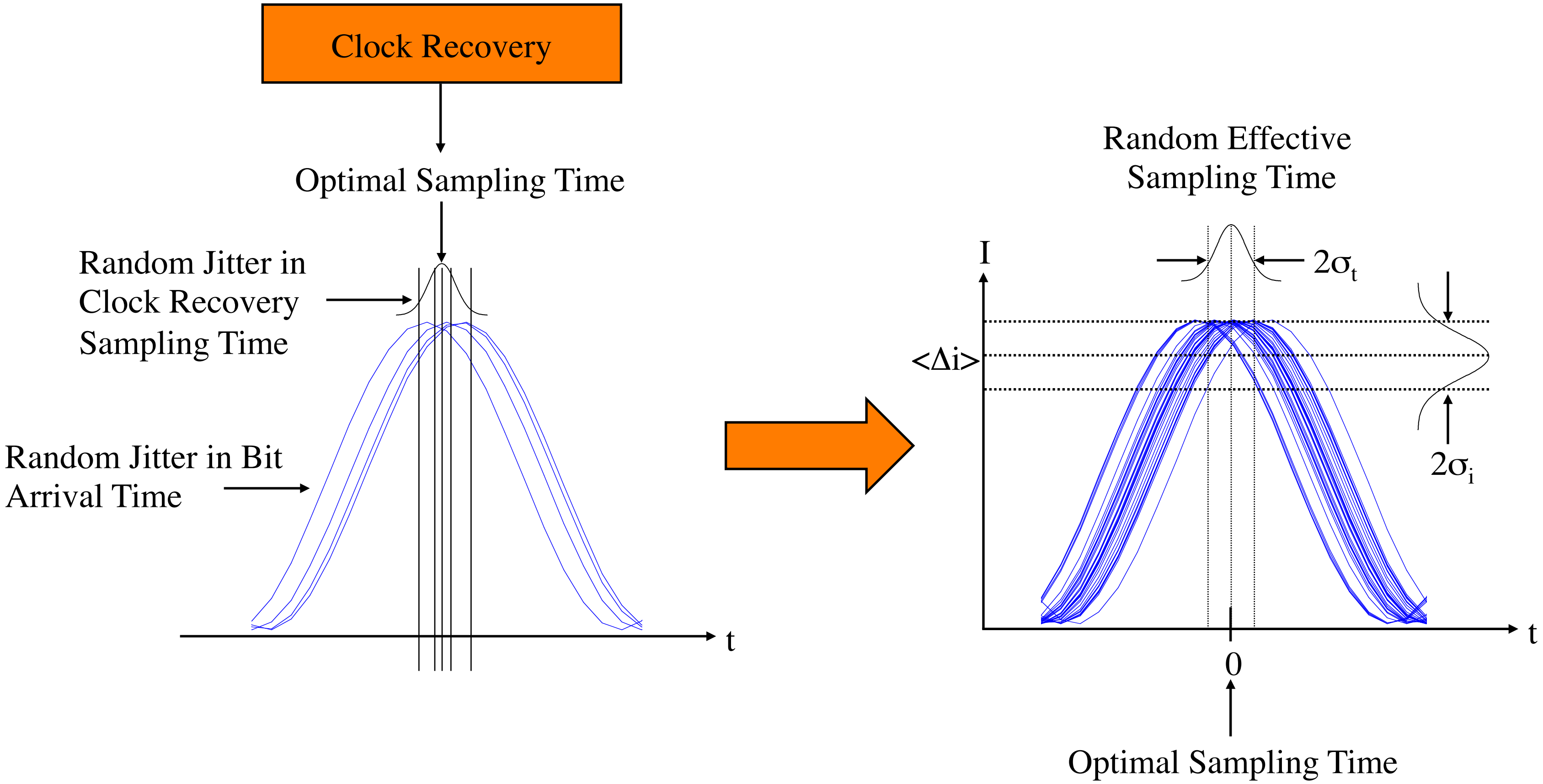
⇛Extinction ratio is expanded

⇛Important to note that apparent squeezing of noise distributions and expansion of ER does not translate to improved BER

  ⇛If signals are moved from a 0 to a 1 or visa versa, an error will be generated



Timing Jitter



Clock Recovery

Optimal Sampling Time

Random Jitter in Clock Recovery Sampling Time

Random Jitter in Bit Arrival Time

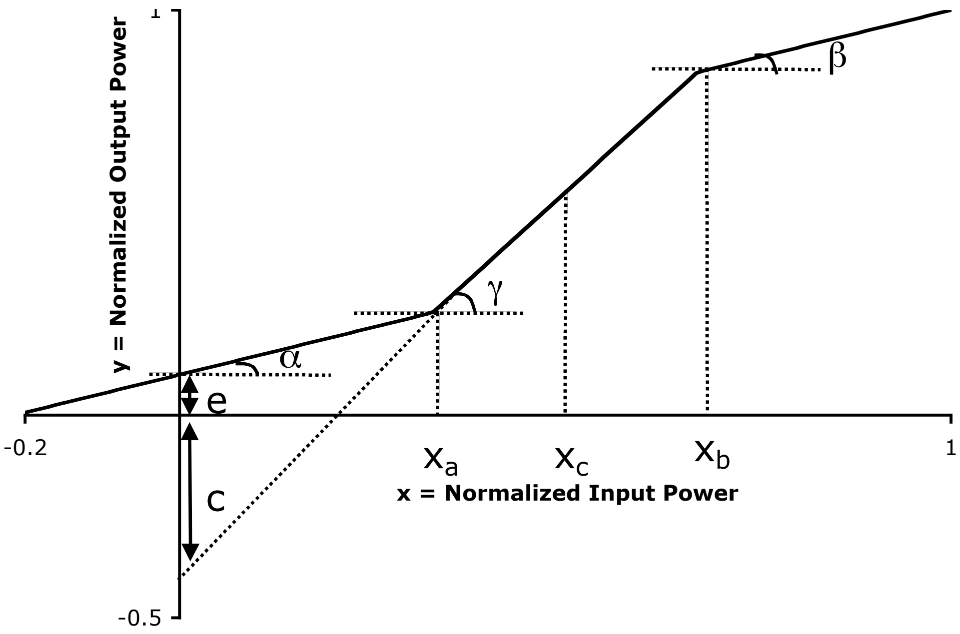
Random Effective Sampling Time

Optimal Sampling Time

Nonlinear Transfer Function

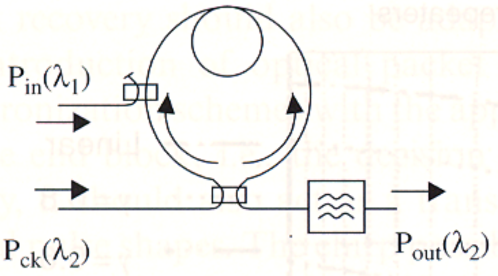
- The equation used to model the transfer function is where The degree of non-linearity is controlled by γ

$$T(x) = \begin{cases} x\tan\alpha + e & x < x_a \\ x\tan\gamma - c & x_a \le x \le x_b \\ 1-(1-x)\tan\beta & x_b < x \end{cases}$$

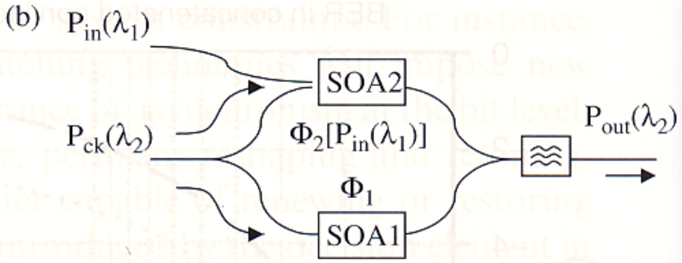


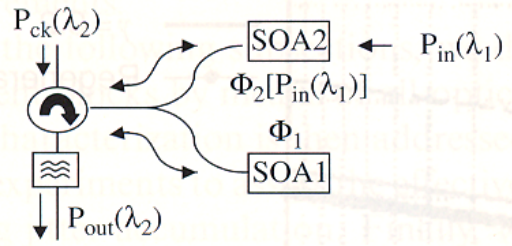
Nonlinear Optical Interferometric Implementations

Nonlinear Optical Loop
Mirror (NOLM)

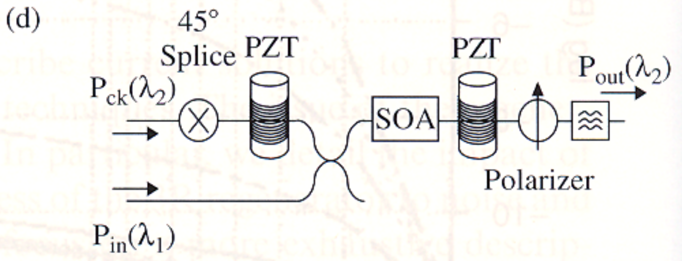


SOA Based Mach-Zehnder
Interferometer (SOA-MZI)





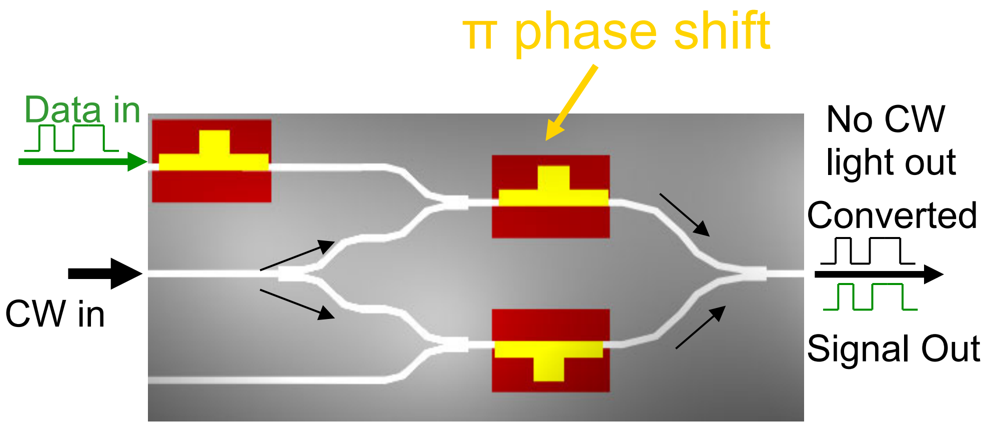
SOA Based Michelson Interferometer
(SOA-MI)

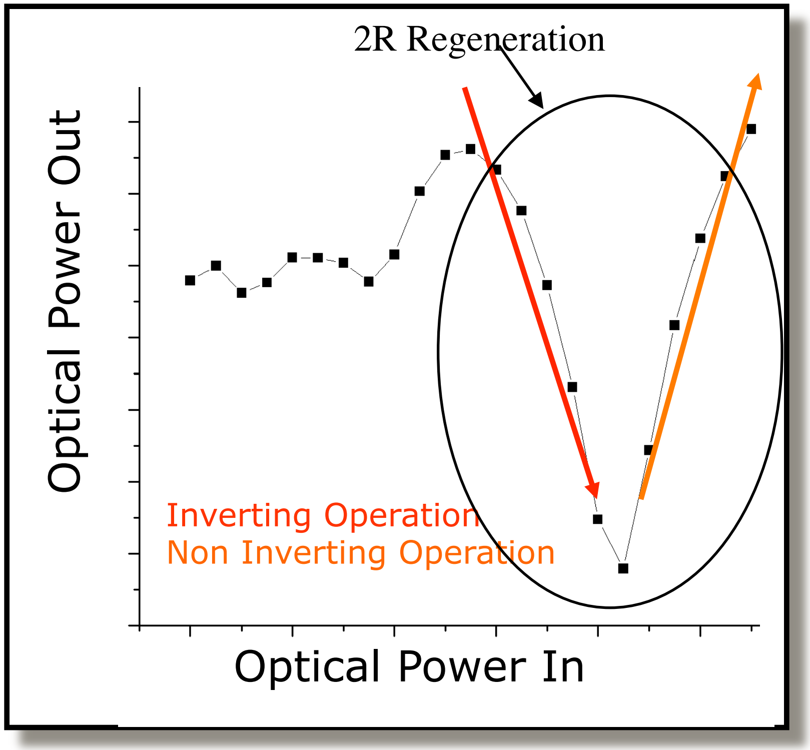


SOA Based Ultrafast Nonlinear
Interferometer (SOA-UNI)

SOA Interferometer Example

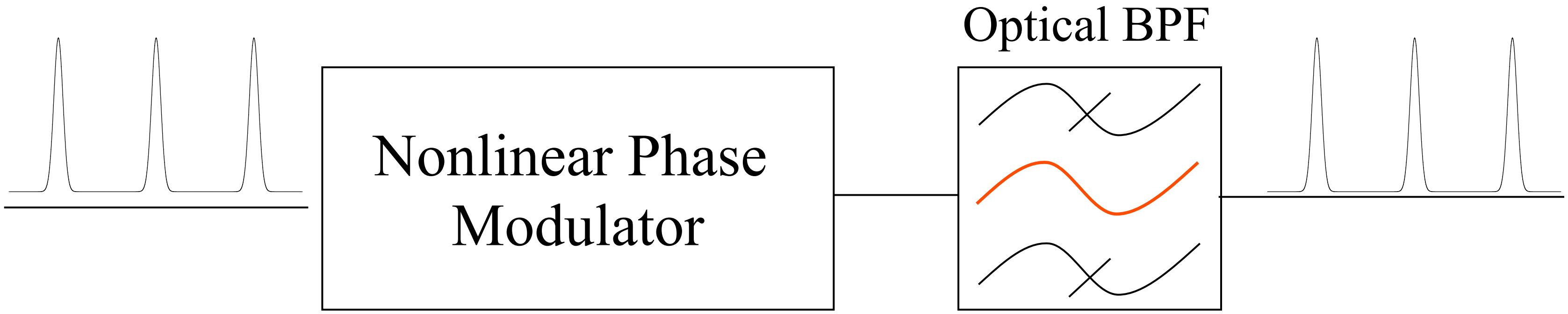
Cross-Phase Modulation Principle



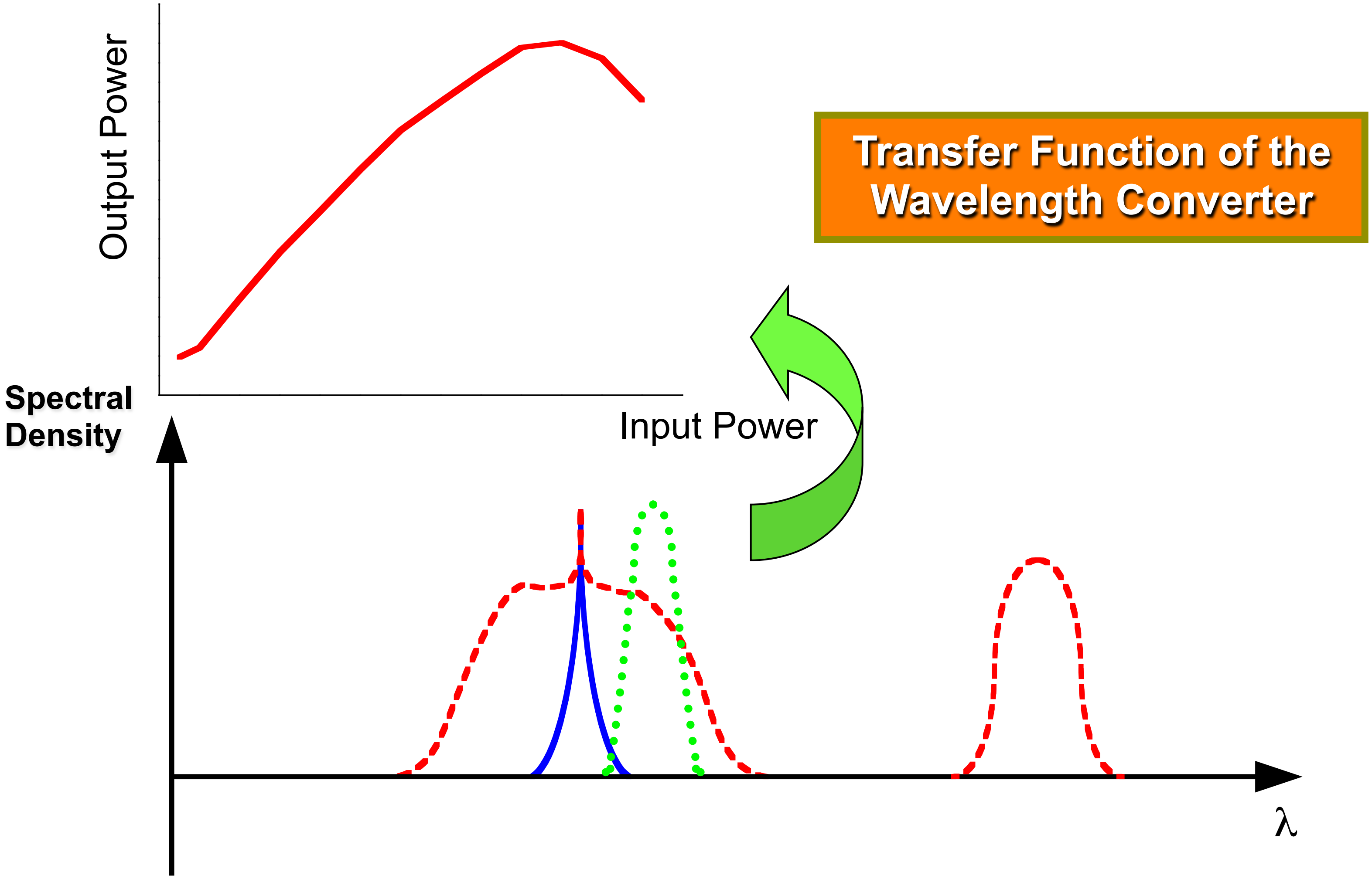


Nonlinear-Filter Based 2R Regenerators

- An optical nonlinearity that converts intensity change to phase change will induce a frequency shift.
- Using an optical bandpass filter converts the resulting frequency shift back to an intensity modulated signal
- The combined transfer function is step like (thresholding) and can 2R regenerate.

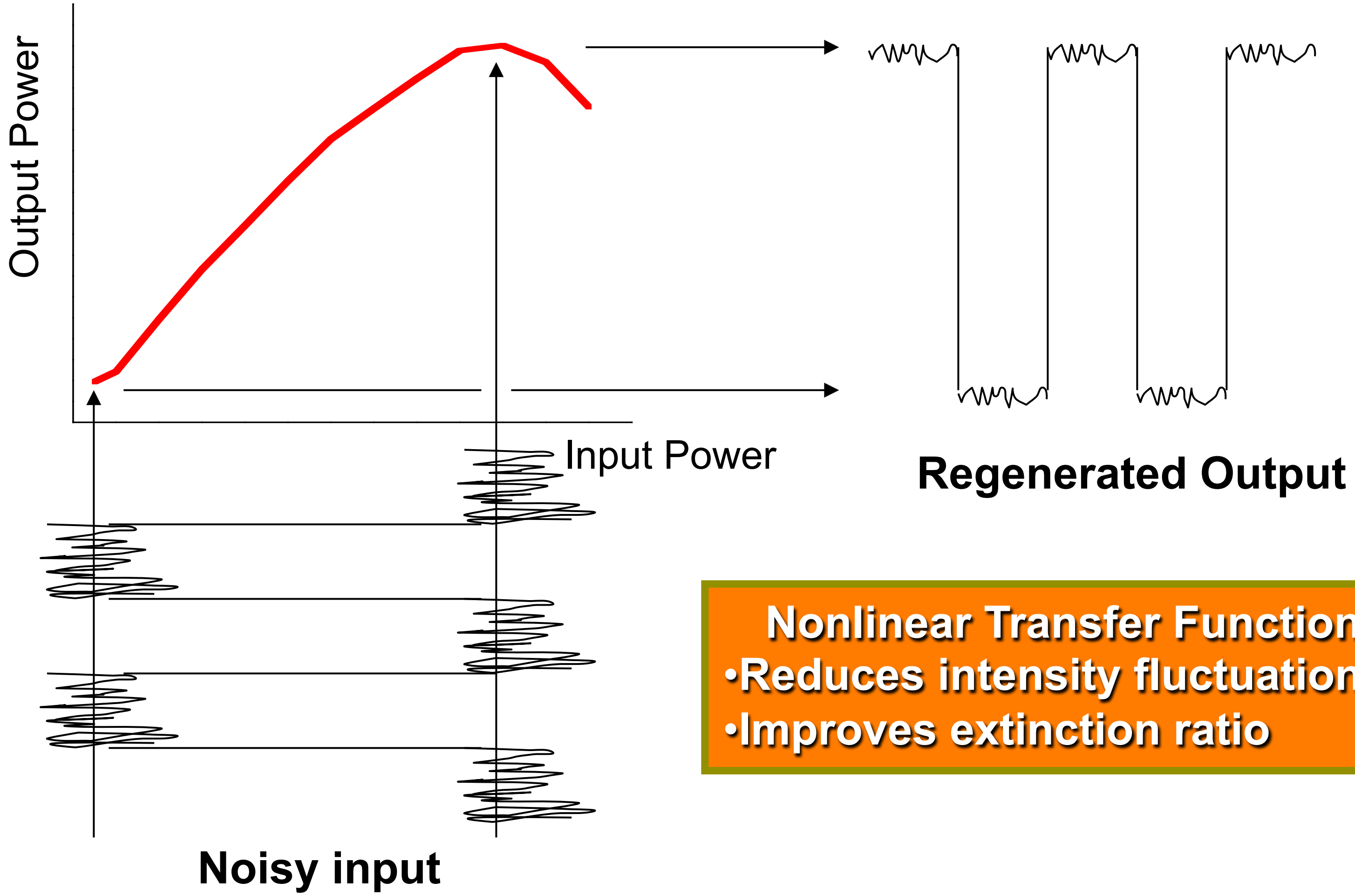


Raman Enhanced XPM Wavelength Converter



Transfer Function of the Wavelength Converter

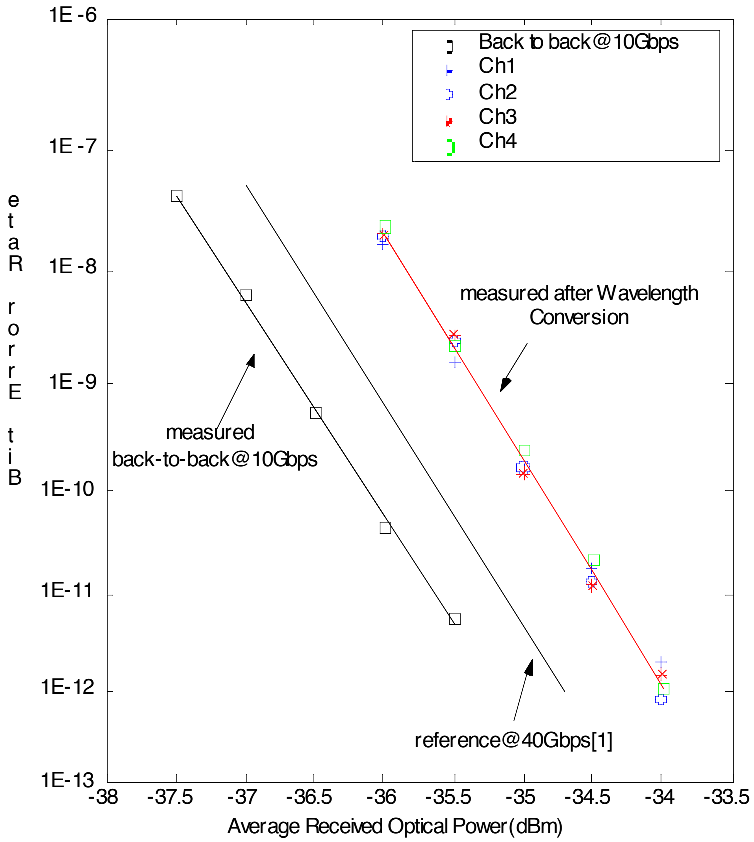
Regeneration property of the WC



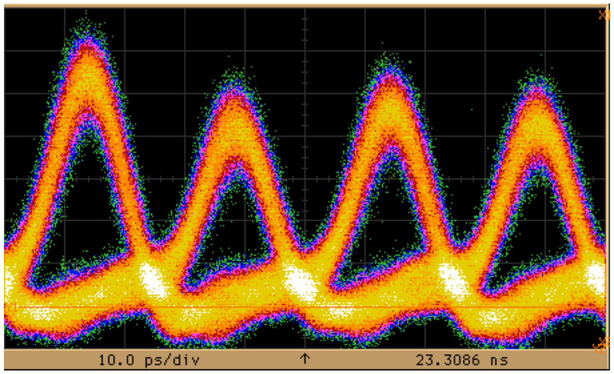
Nonlinear Transfer Function

- Reduces intensity fluctuations
- Improves extinction ratio

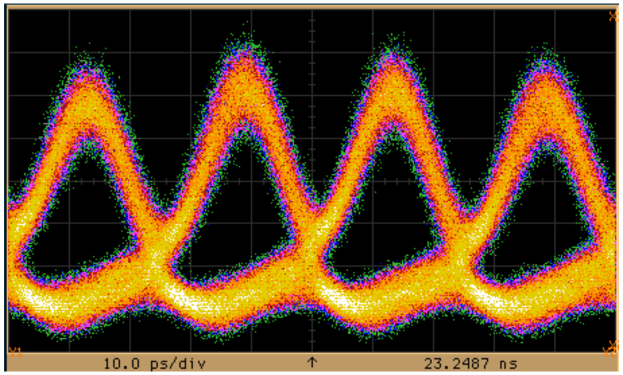
Performance at 40Gbps (Wei Wang, UCSB)



Input 40G eye diagram@1559nm

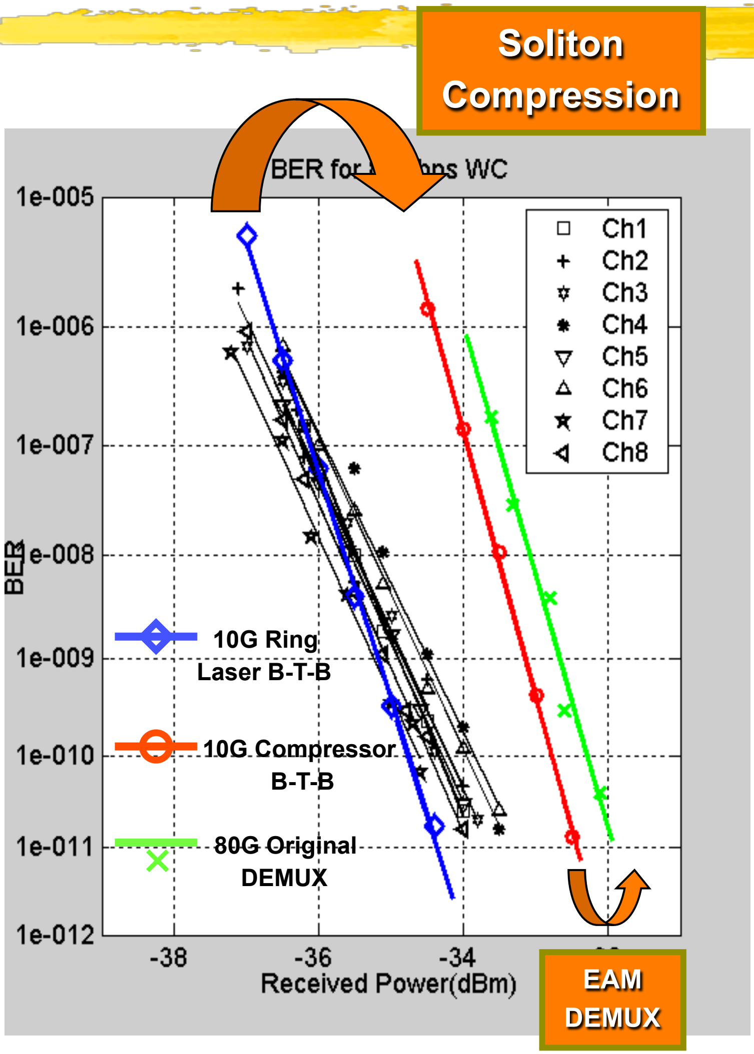


Converted 40G eye diagram@1554nm



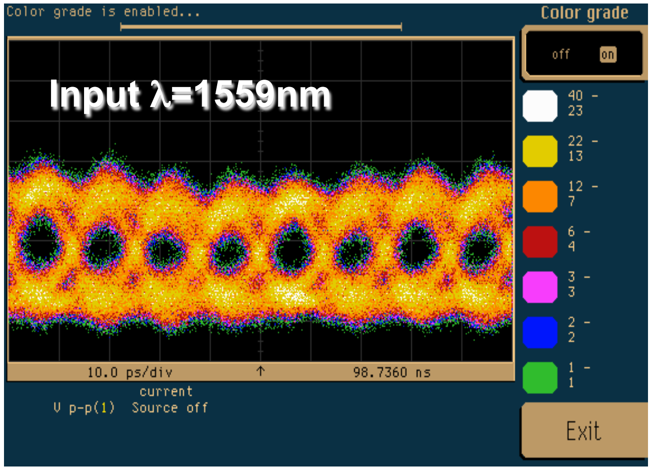
⇨ Conversion efficiency increase 18dB, (P_{Raman} =600mW)

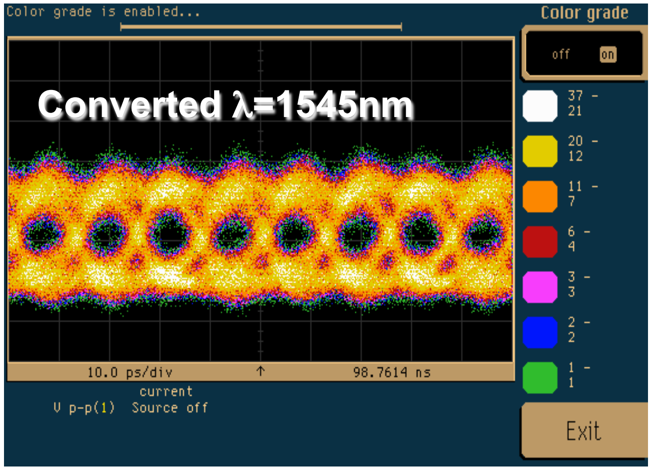
Performance at 80Gbps



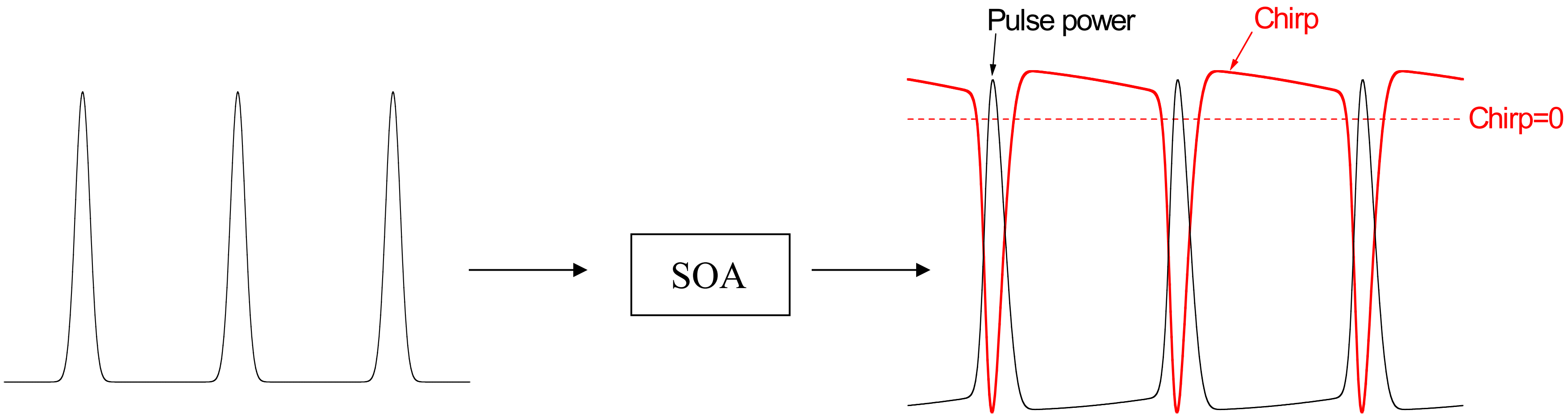
Soliton Compression

EAM DEMUX





Self-phase modulation in SOA

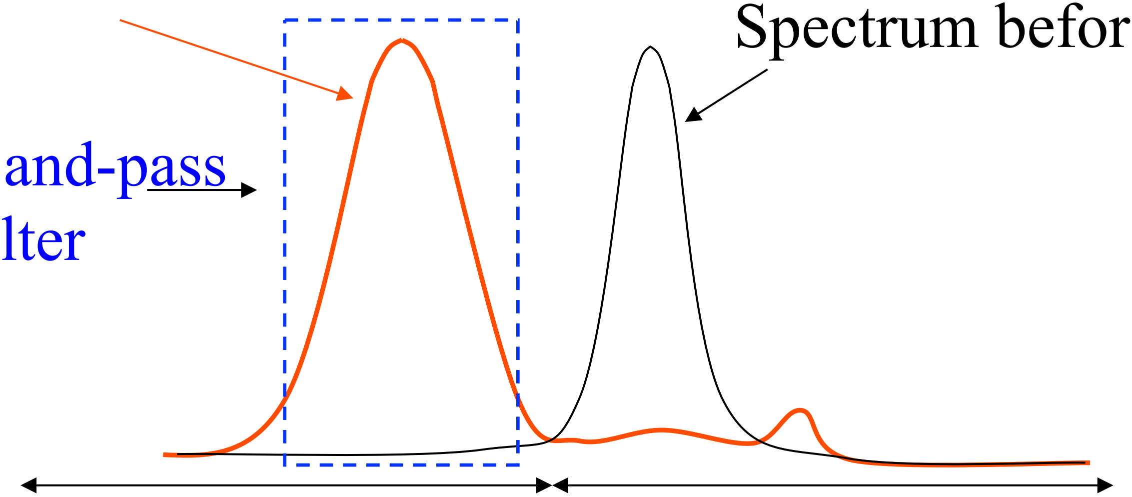


High power: Gain saturation (fast) → Index modulation: Frequency chirp (red shift)

Low power: Gain recovery (slow) → Index modulation: Frequency chirp (blue shift)

- High and low power contents separated in frequency.

Filtering



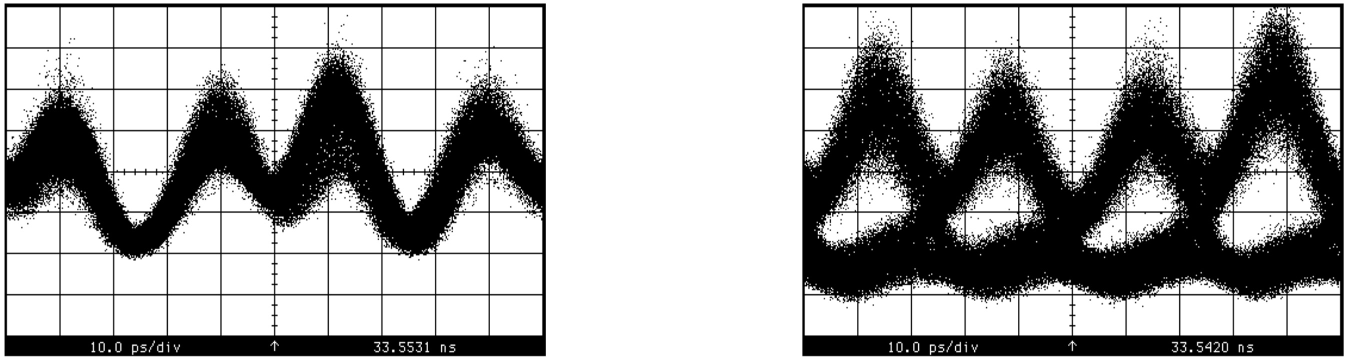
Frequencies corresponding
to pulse peaks

Frequencies corresponding
to background intensity

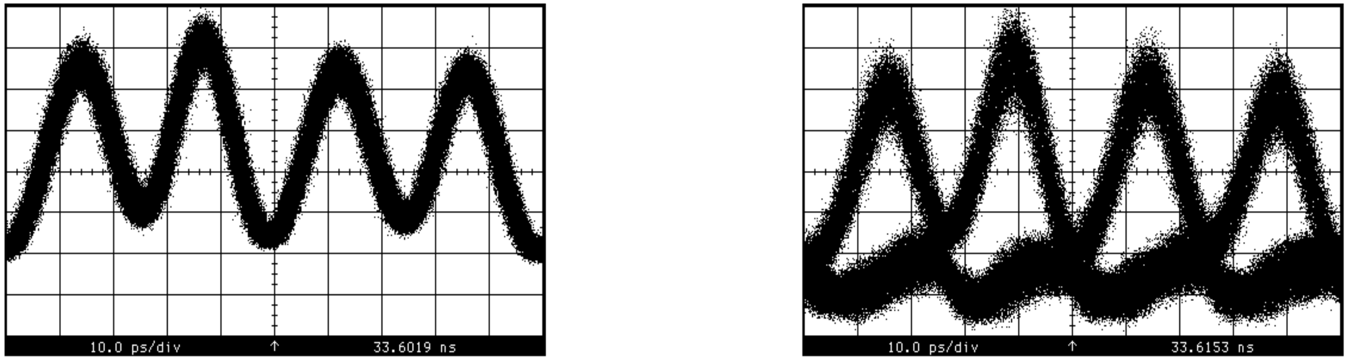
- Background intensity reduced

40Gb/s eye diagrams

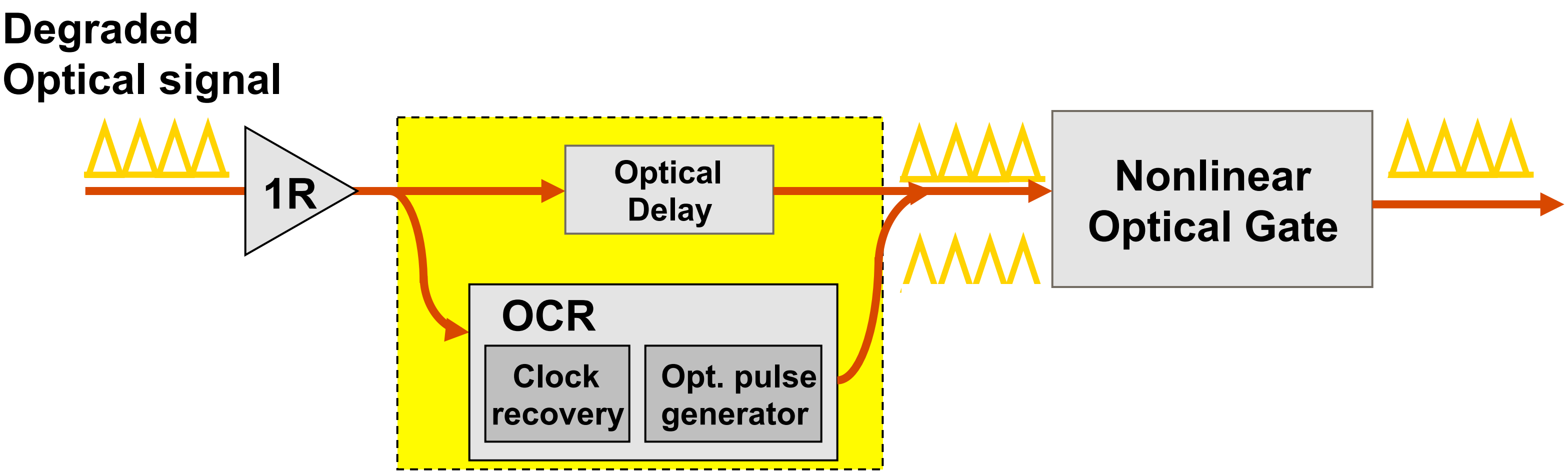
40GHz pulse train and 40Gb/s eye diagram
after degradation and multiplexing



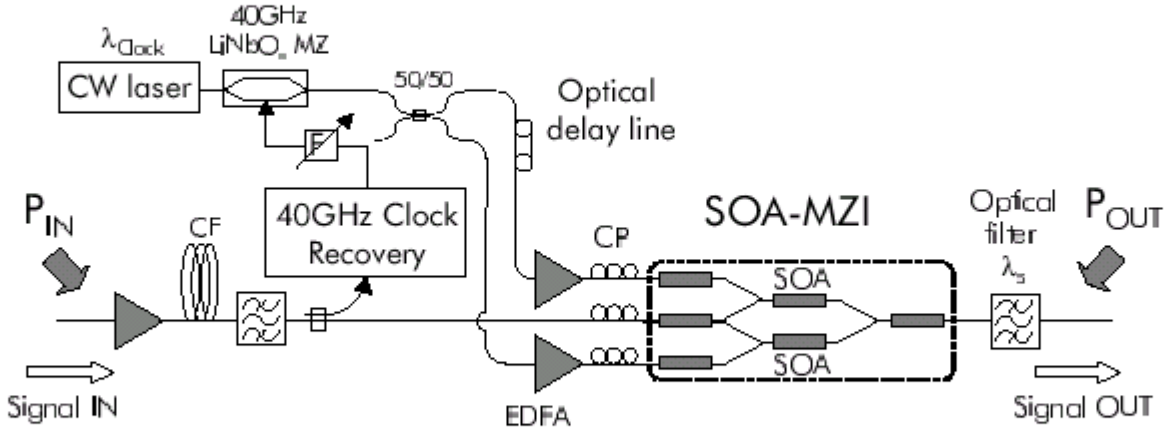
40GHz pulse train and 40Gb/s eye diagram
after degradation, ER-improvement, and multiplexing



3R- Retiming, Reshaping and Reamplification



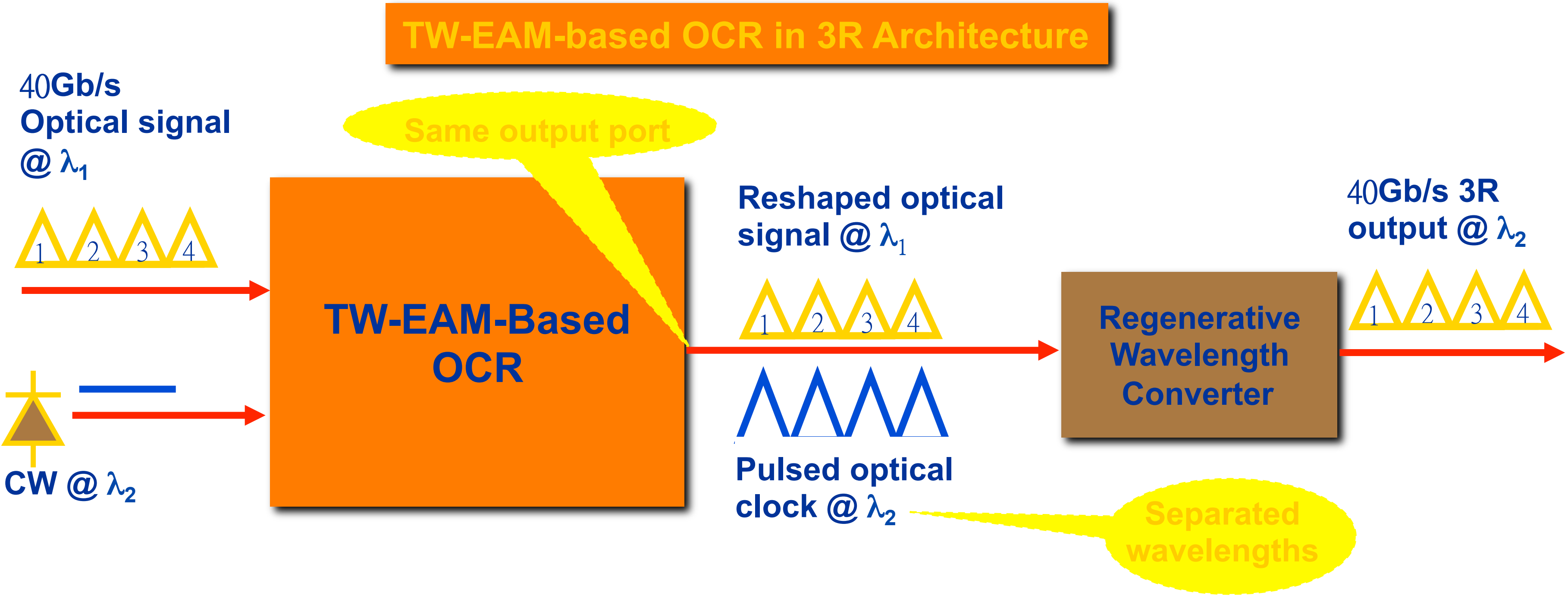
Optical Clock Recovery for Receivers and Optical 3R



Alcatel

- Non-integrated Electronic clock recovery + Optical WC demonstrated
- All-optical clock recovery techniques like self-pulsation have been demonstrated (HHI, CREOLE). Planar integration with complex circuits an issue.

TWEAM Based OCR and 3R (H. Chou and Z. Hu)



TW-EAM-based OCR in 3R Architecture

40**Gb/s Optical signal @ λ_1**

CW @ λ_2

TW-EAM-Based OCR

Same output port

Reshaped optical signal @ λ_1

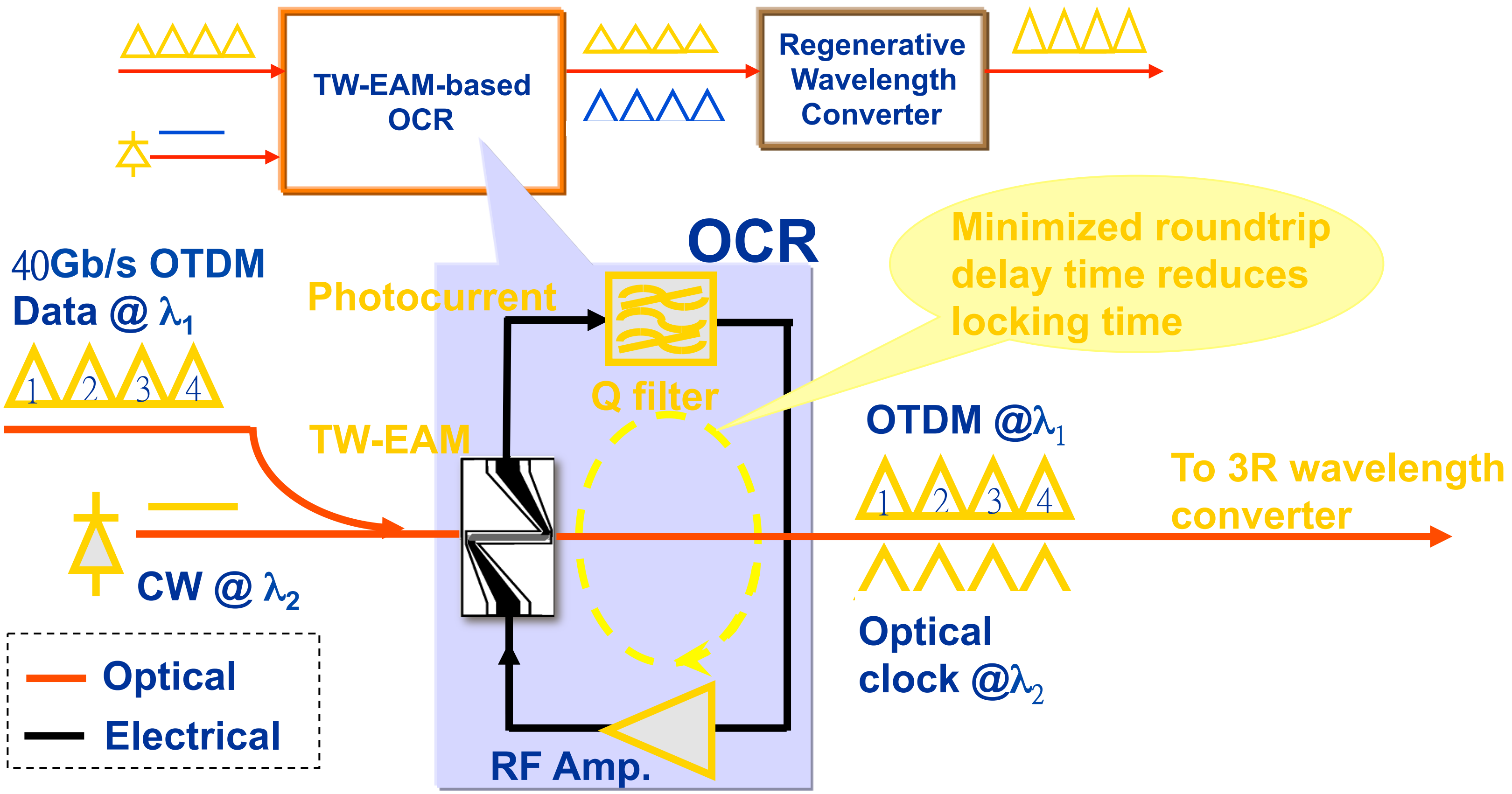
Pulsed optical clock @ λ_2

Separated wavelengths

Regenerative Wavelength Converter

40**Gb/s 3R output @ λ_2**

TWEAM Based OCR



TW-EAM-based OCR

Regenerative Wavelength Converter

OCR

40Gb/s OTDM Data @ λ_1

1 2 3 4

Photocurrent

Q filter

TW-EAM

Minimized roundtrip delay time reduces locking time

OTDM @λ_1

1 2 3 4

To 3R wavelength converter

CW @ λ_2

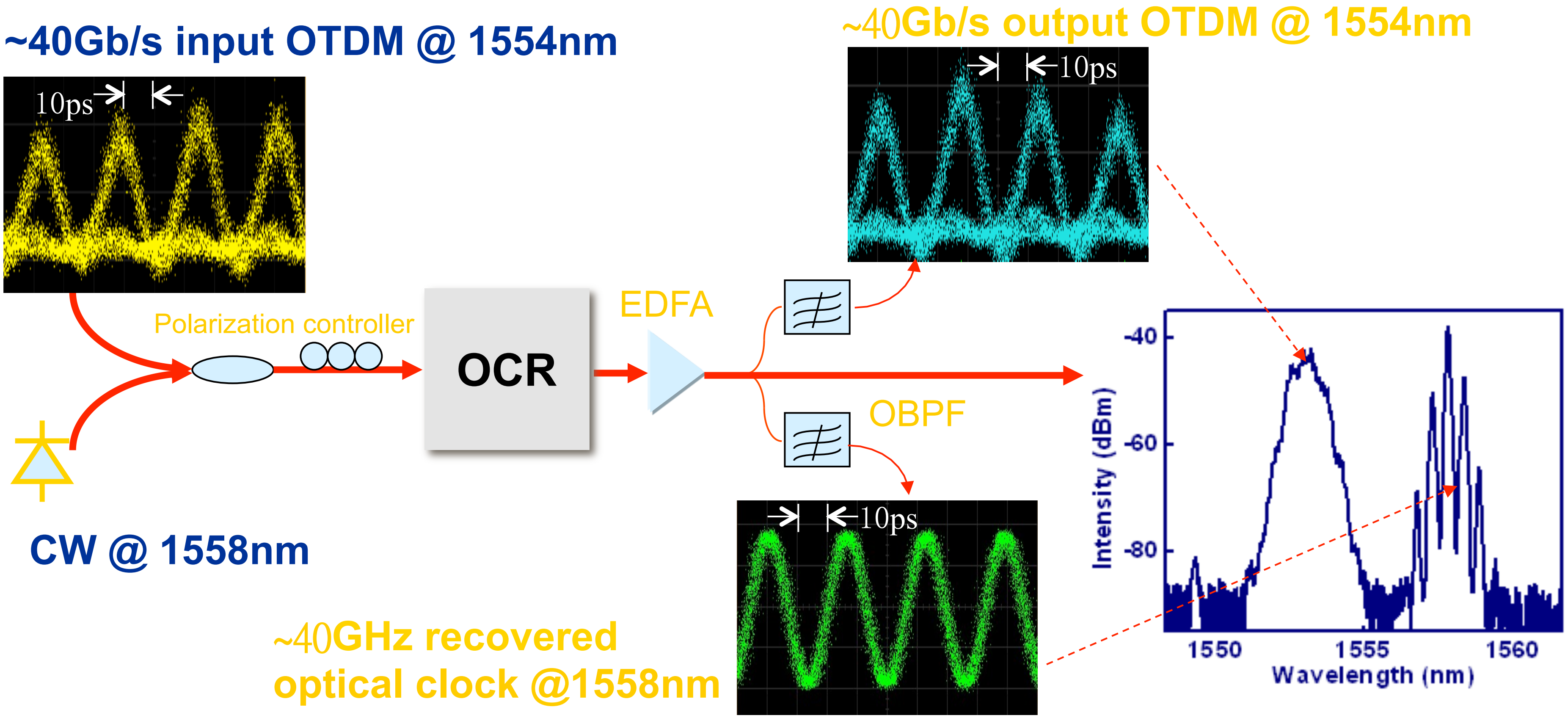
Optical clock @λ_2

RF Amp.

Optical

Electrical

OCR Operation


~40Gb/s input OTDM @ 1554nm

CW @ 1558nm

Polarization controller

OCR

EDFA

OBPF

~40Gb/s output OTDM @ 1554nm

~40GHz recovered optical clock @1558nm