Lecture 12: Wavelength Conversion and Optical Regeneration
Kerr Effects

\[
\frac{\partial A}{\partial z} = -\alpha A + j \frac{1}{2} \beta_2 \frac{\partial^2 A}{\partial t^2} - \frac{1}{6} \beta_3 \frac{\partial^3 A}{\partial t^3} - j \gamma |A|^2 A
\]

⇒ 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

Probe Light $\lambda_1$

Pump Light $\lambda_2$

BPF

Filter convert PM to AM

Spectral Density

$\lambda_1$

$\lambda_2$
Fiber XPM with Raman Gain

Transfer Function of the Wavelength Converter
Fiber Four Wave Mixing (FWM)

High bit rate data

Low rate optical gate signal

Raman Pump Laser

FWM generate new spectral components

Spectral Density

ω

2ω₁ - ω₂  ω₁  ω₂  2ω₂ - ω₁
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

Input optical data

Nonlinear Optical Gate

CW optical signal

2R regenerated optical data
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”
Bit Error Rate (BER)

\[ \text{Probability of error} = P[0]P[1|0] + P[1]P[0|1] \]

\[ \Rightarrow P[0] = \text{Probability a “0” was transmitted} \]
\[ \Rightarrow P[1] = \text{Probability a “1” was transmitted} \]
\[ \Rightarrow P[1|0] = \text{Probability a “1” is received given that a “0” is transmitted} \]
\[ \Rightarrow P[0|1] = \text{Probability a “0” is received given that a “1” is transmitted} \]

Under the Gaussian noise assumption:

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

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

- Random Jitter in Clock Recovery Sampling Time
- Random Jitter in Bit Arrival Time
- Optimal Sampling Time

Clock Recovery

Random Effective Sampling Time

$<\Delta t>$

$2\sigma_t$

$2\sigma_i$

Optimal Sampling Time
Nonlinear Transfer Function

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

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

- **Nonlinear Optical Loop Mirror (NOLM)**
  - $P_{\text{in}}(\lambda_1) \rightarrow P_{\text{ck}}(\lambda_2) \rightarrow P_{\text{out}}(\lambda_2)$

- **SOA Based Michelson Interferometer (SOA-MI)**
  - $P_{\text{ck}}(\lambda_2) \rightarrow \Phi_1[\Phi_2[P_{\text{in}}(\lambda_1)]] \rightarrow P_{\text{in}}(\lambda_1) \rightarrow P_{\text{out}}(\lambda_2)$

- **SOA Based Mach-Zehnder Interferometer (SOA-MZI)**
  - $P_{\text{in}}(\lambda_1) \rightarrow P_{\text{ck}}(\lambda_2) \rightarrow \Phi_2[P_{\text{in}}(\lambda_1)] \rightarrow \Phi_1 \rightarrow SOA2 \rightarrow P_{\text{out}}(\lambda_2)$

- **SOA Based Ultrafast Nonlinear Interferometer (SOA-UNI)**
  - $P_{\text{ck}}(\lambda_2) \rightarrow 45^\circ$ Splice PZT $\rightarrow P_{\text{out}}(\lambda_2)$
SOA Interferometer Example

Cross-Phase Modulation Principle

\[ \pi \text{ phase shift} \]

- Data in
- CW in
- No CW light out
- Converted
- Signal Out
- Inverting Operation
- Non Inverting Operation

Optical Power In

2R Regeneration

Optical Power Out

Inverting Operation
Non Inverting Operation
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

Noisy input

Regenerated Output

Nonlinear Transfer Function
- Reduces intensity fluctuations
- Improves extinction ratio
Performance at 40Gbps (Wei Wang, UCSB)

- Conversion efficiency increase 18dB, \(P_{\text{Raman}} = 600\text{mW}\)
Performance at 80Gbps

Soliton Compression

BER for 80Gbps WC

- Ch1
- Ch2
- Ch3
- Ch4
- Ch5
- Ch6
- Ch7
- Ch8

10G Ring Laser B-T-B
10G Compressor B-T-B
80G Original DEMUX

Input $\lambda=1559\text{nm}$

Converted $\lambda=1545\text{nm}$
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

- Spectrum before SOA
- Spectrum after SOA
- Band-pass filter

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

Degraded Optical signal

1R

Optical Delay

OCR
Clock recovery Opt. pulse generator

Nonlinear Optical Gate
Optical Clock Recovery for Receivers and Optical 3R

- 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

Same output port

40Gb/s Optical signal @ $\lambda_1$

CW @ $\lambda_2$

TW-EAM-Based OCR

Reshaped optical signal @ $\lambda_1$

Pulsed optical clock @ $\lambda_2$

Separated wavelengths

Regenerative Wavelength Converter

40Gb/s 3R output @ $\lambda_2$
TWEAM Based OCR

40Gb/s OTDM Data @ $\lambda_1$

OPTDM @ $\lambda_1$

Optical clock @ $\lambda_2$

Minimized roundtrip delay time reduces locking time

To 3R wavelength converter

Optical

Electrical
OCR Operation

~40Gb/s input OTDM @ 1554nm

CW @ 1558nm

10ps

Polarization controller

OCR

EDFA

~40Gb/s output OTDM @ 1554nm

10ps

OBPF

~40GHz recovered optical clock @1558nm

Intensity (dBm)

1550 1555 1560

Wavelength (nm)