New Optical Functional Devices

• 1 - Interest in All Optical Signal Processing
• 2 - Physics Phenomena
• 3 - Wavelength Conversion
• 4 - Nonlinear Mirror Demultiplexing
• 5 - 3R Regeneration
• 6 - Conclusion

1 - Interest in All Optical Signal Processing

• Bandwidth requirement
• OTDM versus (D)WDM
• From Optoelectronic to « All Optical » Signal Processing

Bandwidth requirement

• Bandwidth: 1nm at 1.55 µm = 125GHz @ 10THz
• Overall optical fiber bandwidth: few 10THz between 1.3 & 1.5µ
• Erbium amplifiers bandwidth: few THz between 1.55 & 1.5µ
• Today needs: 100 Gbit/s to 1 Tbit/s per fiber
• Electronic bandwidth: few 10GHz

• Up to now:
  - Optical transmissions
  - Commutation, Routing & Processing in electronic domain
  - O/E & E/O conversions: slow, expensive (packaging), noisy, scrambling of the optical phase, lack of transparency...

• How to increase the bandwidth?

OTDM versus (D)WDM

• Wavelength Division Multiplexing (WDM)

• Optical Time Domain Multiplexing (OTDM)
From Optoelectronic to « All Optical » Signal Processing

- Transmission
  - OTDM versus (D)WDM
  - Pulse generation & pulse shaping
  - Dispersion compensation...
- Routing
  - Wavelength Conversion
  - Fix and programmable Optical Add & Drops (OAD)
  - Restoration
  - Optical Cross Connect (OXC)...
- Optical signal processing
  - Optical Demultiplexing
  - Address label reading
  - Clock (phase) Recovery
  - Optical Regeneration : Re-amplification, Re-timing, Re-shaping (3R)...
- Supervision: "wave watcher"

2 - Physical Phenomena

- Semiconductors Inter-band Dynamics
- Semiconductors Intra-band Dynamics
- Non-linearities in optical fiber

Semiconductors Inter-band Dynamics

- Gain and refractive index dependent on the carrier density
  - Gain saturation
    \[ G(N) = A(N - N_0) \]
    \( A \) : Differential gain
    \( G \) : Optical gain
    \( N_0 \) : Carrier density for transparency
  - Typical time constant from 0.1 to 1 ns determined by the effective carrier lifetime
  - Strong effect: power < 1 mw, interaction length ≈ few 100 \( \mu \)m
  - Phase-amplitude coupling : \( \alpha = \Delta n' \Delta n'' \) with \( n' = n'' = \Delta n' \)

Semiconductors Intra-band Dynamics

- A strong stimulated rate disturbs quasi-equilibrium
  \[ G(N, P) = A(N - N_0)(1 - eP) \]
  - \( e \) : gain compression factor
  - \( P \) : photons density
  - \( ps \) time constant determined by intra-band thermalizations
  - Gain compression (or compression)
    - \( 0 \%-10\% \) (heterostructure)
    - \( 10\% \) (quantum wells)

Chirping in a SOA

- When the optical Power increases :
  - The carrier density decreases
  - The refractive index increases (plasma effect)
  - The optical frequency decreases

Cross Gain Modulation (XGM)

Two beams with intensity \( I_1 \) and \( I_2 \) in the same SOA

When \( I_1 \) saturates the gain, \( I_2 \) experiments also a reduced gain : XGM

\[ E_1 = \sqrt{I_1} \exp i\varphi_1 \]
\[ E_2 = \sqrt{I_2} \exp i\varphi_2 \]
with \( I_2 \ll I_1 \)
Nonlinear Index and Cross Phase modulation (XPM)

- Carrier heating
  - Large bandwidth (<10nm), asymmetrical
  - High nonlinear index (α near 1)
- Spectral hole burning
  - Low bandwidth (<10nm), symmetrical
  - Low nonlinear index (α near 0)

\[ E_i = \sqrt{I_i} \exp j\varphi_i \]
\[ E_2 = \sqrt{I_2} \exp j\varphi_2 \]

Four Wave Mixing (FWM) in Semiconductor Optical Amplifier (SOA)

- Physical origins:
  - Interband for low frequencies: carrier density modulation,
  - Intraband for high frequencies: nonlinear gain i.e. carrier heating, spectral hole-burning, 2 photon absorption, Kerr effect
- Application to Wavelength conversion, 3R regeneration, Spectrum inversion
- Spurious effect in WDM systems

FWM New Frequencies Generation in WDM Systems

Nonlinearities in optical fiber

- Optical Kerr effect
  - Polatization: \( P(E) = \chi^{(2)} E + \chi^{(3)} E^2 + \chi^{(4)} E^4 + \ldots \)
  - Index: \( n(E) = n_0 + \frac{j}{2} \chi^{(3)} I \)
- Self Phase Modulation (SPM) & Cross Phase Modulation (XPM)
- Low effect but transverse confinement and longitudinal integration

\[ \varphi = \frac{2\pi}{\lambda_0} n_2 I L \]
\[ \varphi = \frac{\pi}{2} \text{ for }PL = 1 \text{ W.km} \]
- Very fast effects but:
  - Walk off problems
  - Other concurrent nonlinear effects

Self Phase Modulation (SPM) & Cross Phase Modulation (XPM)

- Self Phase Modulation (SPM)

\[ E = \sqrt{I} \exp j\varphi \]

- Cross Phase Modulation (XPM)

\[ E_i = \sqrt{I_i} \exp j\varphi_i, \quad E_2 = \sqrt{I_2} \exp j\varphi_2, \quad \text{with } I_2 \ll I_1 \]

Nonlinear Propagation: Soliton

- Linear Propagation:

- Nonlinear Propagation:
3 - Wavelength Conversion

- Wavelength converter
- Cross Gain Modulation (XGM) in an SOA
- Cross Phase Modulation (XPM) in an SOA
- Gain Modulation in Semiconductor Laser (SCL)
- Wavelength conversion in bistable Laser Structure
- Four Wave Mixing (FWM) in a SOA

Wavelength Converter

- Wavelength routing
- Wavelength re-use
- WDM network reconfiguration
- Optical circuit & packet (ATM…IP) switching

Expected Properties

- All optical device:  
  - Transparent to modulation format  
  - Bit rate independent: 155Mb/s à 10 Gb/s…40Gb/s
- No clock recovery requirement
- Flexible implementation  
  - Speed (10 Gb/s and more)  
  - Wide conversion range  
  - Up conversion & down conversion allowed  
  - Polarization independent  
  - Input wavelength rejection
- No BER penalty (cascability)  
  - High extinction (on/off) ratio  
  - No jitter  
  - No chirp  
  - Amplification of the signal level  
  - Pulse reshaping...

All of them together?

Optoelectronic conversion vs. all optical conversion

- Optoelectronic conversion
  - No bit rate transparency  
  - Bit rate bottleneck  
  - Noise  
  - Cost (packaging)
- All optical conversion
  - Bit rate transparency  
  - High bit rate  
  - Possible pulse regeneration  
  - Integration low cost

Cross Gain Modulation (XGM) in an SOA

(TU Denmark)

The carrier depletion induced by \( \dot{\phi}_c \) modulated signal amplification reduces the available gain for the CW signal \( \dot{\phi}_c \) amplification.
Performances for XGM in an SOA

- Large conversion range:
  - Few GHz, i.e. few 1000GHz
  - Gain bandwidth limited
- Modulation bandwidth:
  - Few 10 GHz
  - Carrier lifetime limited
- Low chirp
- But:
  - Inverted modulation (even cell number required)
  - External output carrier generation
  - High driving signal level: 0 to -10 dBm
  - Low on/off ratio: 5 to 10 dB

Cross Phase Modulation (XPM) in an SOA Mach Zehnder Interferometer (MZI) Conversion

- Cross Phase Modulation (XPM)
- Low control power (only a phase shift $\pi$ is required)
- Accurate control power
- Polarization independent
- Possible up conversion and down conversion
- Low chirp
- 40 GHz operation already demonstrated

Gain Modulation in Semiconductor Laser (SCL) Oscillator

- The carrier depletion induced by $\lambda_1$ signal injection reduce the available gain for the CW lasing $\lambda_2$ operation
- Gain and index changes result in simultaneous AM and FM (i.e. chirped) output
- Few 10 Gbit/s, On/Off Ratio > 10 dB, $P_{control} =$ few dBm

Wavelength Conversion in Bistable Laser Structure

- Saturable absorption
  - Non injected (i.e. unpumped) region
  - Vanish out under light injection
- Operation up to 40 Gbit/s demonstrated
- Possible re-timing operation by simultaneous optical or electrical clock modulation

Output Wavelength Tuning

- Mode hopping
- Progressive index saturation results in tuning efficiency (slope) reduction

Optical Bisability

The bistability improve the on/off ratio
Reshaping possibility
Low degradation (or small improvement!) of the BER allows large scale cascadability.

Four Wave Mixing (FWM) in a SOA

Applications:
- Wavelength conversion
- All-optical clock recovery
- Spectrum inversion
- Spurious effect:
  - Diaphotie in WDM systems

Applications:
- Interband for low frequencies: carrier density modulation,
- Interband for high frequencies: nonlinear gain i.e. carrier heating, spectral-hole-burning, 2 photon absorption, Kerr effect
- Takes benefit of built-in gain

4 - Optical Demultiplexing by Nonlinear Mirror

- Optical Linear Mirror Loop
- Optical Nonlinear Mirror Loop
- Nonlinearity realization
- SLALOM
- 4x10GBit/s Demultiplexing

Conversion efficiency

\[ \eta = \frac{P_{\text{CONJUGATED}}}{P_{\text{IN}} \times P_{\text{PROBE}} \times P_{\text{SIGNAL}}} \]

\[ P_{\text{SOA}} = -15.2 \text{ dBm/signal} \]

\[ \text{Efficiency (dB)} \]

\[ \text{Detuning (GHz)} \]

FWM Performances

- Transparency for the modulation format
- High bit rate
- Wide conversion range (65nm) by multiple conversion
- Polarization dependent

SOA Four Wave Mixing Efficiency

- Intra-band
- Inter-band

\[ \text{Efficiency (dB)} \]

\[ \text{Detuning (GHz)} \]

Simulation vs experiment

- Physical origins:
  - Interband for low frequencies: carrier density modulation,
  - Interband for high frequencies: nonlinear gain i.e. carrier heating, spectral-hole-burning, 2 photon absorption, Kerr effect
- Takes benefit of built-in gain
Functional Devices, P.G., ENST37

Optical Linear Mirror Loop (LOLM)

- Incident
- Reflected
- Transmitted

- Repartition coefficients for intensity: $A_i = (1 - \alpha)$ and $A_r = \alpha$
- Repartition coefficients for amplitude: $a_i = (1 - \alpha)\alpha^{-1/2}$ and $a_r = \alpha^{1/2} j \alpha^{1/2}$
- Transmitted reflected fields for $E_0 = 1$:
  \begin{align*}
  A_i &= (1 - \alpha) \quad \text{and} \quad A_r \times \alpha \\
  a_i &= (1 - \alpha)^{1/2} \quad \text{and} \quad a_r \times \alpha^{1/2} \cdot j \alpha^{1/2}
  \end{align*}
- In linear regime output port is the input port (mirror)

Nonlinear Optical Loop Mirror (NLOLM)

- Incident
- Reflected
- Transmitted

- Clockwise & unclockwise equal intensities: NL phase shift are identical
- Tuning for a nonlinear phase difference of phase equal to $\alpha$
- Tradeoff between contrast ($\alpha \approx 1/2$) & sensitivity ($\alpha \neq 1/2$)
- High level signal (1) transmission (NL regime)
- Low level signal (0) reflection (NL effects are negligible)

Non linearity realization
Fiber or semiconductor amplifier

1. Cross phase Modulation (XPM) in a fiber (NOLM)
   - Very fast (>100GHz)
   - High optical driving signal level (10 to 30dBm)
   - Long length (1km)
2. Cross phase Modulation (XPM) in SC amplifier (SLALOM)
   - Very fast (>20GHz, inter-band & 100GHz inter-band)
   - Low optical driving signal level (<-10 to 10dBm)
   - Compact (<1mm)

- Utilizations:
  - Intensity Filter
  - Correlator
  - Demultiplexer...

SLALOM
Semiconductor Laser Amplifier in a Loop Optical Mirror

Control data (pump)

- Input data
- Output data

- 5 - 3R Regeneration

Re-amplification, Re-timing, Re-shaping (3R)

- Re-amplification
- Pulse reshaping by nonlinear filtering
- Re-timing (Re-synchronization)
- Clock (phase) recovery
- 3R Regeneration
- MZI all optical regeneration
- All optical regeneration using FWM in SOA
Re-amplification

- Re-amplification is limited by accumulated ASE and limited amplifier output power
- On/off ratio improvement by nonlinear response
- Different processing for weak (0) & strong (1) signals
- Act as digital electronics

Amplified Spontaneous Emission (ASE) Suppression (France Telecom)

Noise Suppression & Intensity Modulation
(Tokyo Institute of Technology)

- Intensity noise of a spectrum-sliced incoherent source
- Gain saturated SOA with current modulation
- Beat noise reduction
- Noise error floor observed with LiNbO3 linear modulation is removed

Pulse reshaping by nonlinear filtering

- Intensity noise of a spectrum-sliced incoherent source
- Gain saturated SOA with current modulation
- Beat noise reduction
- Noise error floor observed with LiNbO3 linear modulation is removed

Re-timing (Re-synchronization)

- Large wavelength deviation (13 nm)
- Low time jitter (11 ps)
- High bit-rate (3.8 GHz)

Clock (phase) recovery

- Mode-locked laser
- Self-Pulsating laser
Self Pulsating Laser

Self pulsation origins:
- Instabilities in longitudinal carrier or field distributions (Spatial-Hole Burning)
- Dispersive self Q-switching associated to the negative slope of the Bragg grating

\[ T_{UP} = \frac{1}{f_{AP}} \]

Synchronization time (HHI)

- 10 Gbit/s
- 1 ns (10 “one” bits) locking time
- Synchronization resist to > 100 “zero” bits
- Compatible with IP packet switching

Jitter & Amplified Spontaneous Emission (ASE) Suppression (France Telecom)

3R Regeneration

- Amplification
- Power Control
- Clock Recovery
- Optical Gate
- Non-linear Filter
- Reshaping

MZI all optical regeneration - 1

- XPM is the key phenomena
- Up to 40Gbit/s operation demonstrated

MZI all optical regeneration - 2

- 2 cascaded MZI to improve nonlinear response
- 20 and 40 Gbit/s operation
- 1.2 dB penalty
- Polarization insensitivity and 10 dB power dynamic range
All optical regeneration using FWM in SOA (ENST)

- PUMP = SIGNAL
- PROBE = CLOCK
- The squaring improved the On/off ratio
- The pulse overlap is the correlation process between clock and signal

![Graph showing optical regeneration using FWM in SOA](image)

- $P_{BM} \propto P_{PUMP}^2 P_{PROBE}$
- $P_{PUMP} = P_{SIGNAL} P_{PROBE}$

<table>
<thead>
<tr>
<th>Input extinction ratio (dB)</th>
<th>Output extinction ratio (dB)</th>
<th>0 dB improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>20 dB</td>
<td>10 dB</td>
<td></td>
</tr>
</tbody>
</table>

**Conclusion - 1**

Integration Possibility

- Nonlinear Fiber Devices
- Semiconductor Optical Devices (Intraband dynamics)
- Semiconductor Optical Devices (Interband dynamics)
- Fast Electronic Devices
- High Integration Electronic Devices

**Conclusion - 2**

- Nonlinearity allows light with light interaction
  - They are the key phenomena for all optical devices
- Nonlinearity is spurious in analog devices and systems
- Digital electronics takes benefit if it at each step
  - They are the key phenomena for optical regeneration
- The all-optical processing do not exist!
  - It is a user (system) point of view
  - Electrons play a key role in light-matter interaction
  - The speedy user have no time left to look at it
- Wide range of functional devices is today available
- Are these grapes too unripe? (Jean de La Fontaine)