Optical Parallel Processing Approach to All-Order PMD Compensation

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Outline

• Introduction

• Pulse shaping and chromatic dispersion compensation

• Sub-ps pulse all-order PMD compensation experiment

• Extending to DWDM via hyperfine-resolution spectral dispersers

• Wavelength-parallel polarization sensor (parallel sensing at under 1 ms)
Polarization Mode Dispersion (PMD)

For broadband inputs, random birefringences lead to wavelength-dependent polarization scrambling and wavelength- and polarization-dependent delays.

“Anatomy of a real fiber”
First-Order PMD vs. All-Order PMD

**First-order PMD**
- Narrowband approximation, valid only for small DGD (compared to pulse width)

**Poole and Giles,** *Opt. Lett.* **13,** 155 (1988)

**All-order PMD**
- Series expansion rapidly breaks down for large bandwidth or DGD larger than pulse width

**Foschini, Jopson et al,** *JLT* **17,** 1560 (1999)
PMD Compensators

Mainstream approach: first-order PMD compensation (applies only to small PMD or narrow bandwidth; already difficult!)

All-order approaches beginning to receive attention:
- A.M. Weiner, U.S. Patent 20020060760 (pending) [Purdue]

This work: first demonstration of all-order compensation!
An All-Order Compensation Scheme

(1) Distorted pulse:
\[ E_{PMD}(\omega) = E_{in}(\omega)\{a(\omega)\hat{\alpha} + b(\omega)\hat{\beta}\} \]

(2) Sense and correct full spectrally dependent state of polarization
\[ E(\omega) = E_{in}(\omega)\exp\{j\Psi(\omega)\} \hat{\gamma} \]

(3) Sense and compensate full spectral phase (generalized chromatic dispersion)
\[ E(\omega) = E_{in}(\omega) \hat{\gamma} \]
Femtosecond Pulse Shaping

- **Fourier synthesis** via parallel spatial/spectral modulation

- **Diverse applications**: fiber communications and dispersion compensation, coherent quantum control, few femtosecond pulse compression, ...

- **Liquid crystal modulator (LCM) arrays**:
  - Typically 128 pixels (up to 640), millisecond response
  - Functionalities: phase-only, independent phase and intensity, now polarization

Programmable Fiber Dispersion Compensation Using a Pulse Shaper: Subpicosecond Pulses

- Coarse dispersion compensation using matched lengths of SMF and DCF
- Fine-tuning and higher-order dispersion compensation using a pulse shaper as a programmable spectral phase equalizer
- Similar ideas apply to DWDM tunable dispersion compensation and few femtosecond pulse compression.

\[ \tau(\omega) = -\frac{\partial \psi(\omega)}{\partial \omega} \]
Higher-Order Phase Equalization Using LCM

Input and output pulses from 3-km SMF-DCF-DSF link


Input pulse

Output pulse (without phase correction)
already compressed several hundred times

Output pulse (with quadratic & cubic correction)

• No remaining distortion!

Applied phase
460 fs transmission over 50 km SMF

Commercial DCF module (as is) with spectral phase equalizer

- ~ 5 ns after SMF
- 13.9 ps after DCF
- 470 fs after quadratic/cubic phase equalization

All-Order PMD-Compensator Implementation

- Concatenated polarization and phase pulse shapers
- Wavelength-parallel polarimeter for control of polarization pulse shaper
- Ultrashort pulse measurement approach for control of phase shaper

State-of-polarization (SOP) Pulse Shaper

2-layer liquid crystal design

- Rotate ARBITRARY POLARIZATION STATE into a FIXED LINEAR STATE

- In an LCM Array configuration, potentially 128 wavelengths can be SOP-rotated independently

Spectral Phase Retrieval

- Various ultrafast measurement techniques available
- We chose Gerchberg-Saxton algorithm
  - Uses $I(t)$, measured via cross-correlation, and power spectrum

![Algorithm Diagram]

1. Use initial guess to start algorithm
2. Apply power spectrum
3. Typically 70-250 iterations
4. Apply intensity data
5. (Iterated G-S algorithm)
6. Measure new intensity profile
7. Improved pulse
8. Apply phase to shaper
All-Order Compensation Experiment (1)

600 fs input pulse through PMD emulator (16 section PM fiber, mean DGD ~1.3 ps)

All-Order Compensation Experiment (2)

800 fs input pulse through PMD emulator (16 section PM fiber, mean DGD ~1.3 ps)

Potential Applicability for DWDM
Hyperfine Resolution Wavelength Demux

Virtually Imaged Phased Array (VIPA)

- At Purdue: Hyperfine WDM (3 GHz spacing!) Filters with 1000 dB/nm skirts, etc.

Eight-channel demux with ~700 MHz linewidth and 50 GHz free-spectral-range

Grating-VIPA spectral disperser in 2D geometry: potential for >1000 channels in the C band

VIPA spectral disperser (Parts donated by Avanex Corp.)

Programmable Hyperfine Resolution VIPA Pulse Shaper

Tunable Dispersion Compensation at 10 Gb/s over 120 km SMF
(now 240 km!)

Uncompensated

Compensated

Wavelength-Parallel Sensing

Requirement to sense frequency-dependent polarization data in milliseconds!
Current Practice: Single-Channel Polarimetry

To achieve frequency (wavelength) resolution:

- Multiple polarimeters (expensive)
- Frequency-swept measurements (slow)
The Wavelength-Parallel Polarization Sensor

Configured for:
- 256 channels
- 0.4 nm (50 GHz) spacing
- < 3° polarization error
- < 1 ms read-out time

0.1ms (FLC switching time)  
+ 0.053ms (camera line time for 256 pixels @ ~1.5μW/pixel)  
0.153ms  
× 4 (four different polarization components)  

0.612ms (total measurement time for 256 wavelengths)

High Resolution Spectral Polarimeter

Now able to resolve polarization variations within 10 Gb/s channel

- ~1GHz / pixel spacing
- ~1GHz 3dB resolution
- <1 ms read-out time
- < 3° polarization error

Wang, Weiner, Boroditsky and Brodsky, OFC 2006 (paper OFL6)

Live 10 Gb/s traffic in AT&T central office
2D Fast Wavelength Parallel Polarization Sensor

Application to PMD sensing and compensation – *Multiple λ’s in single instrument!*

High resolution 2D configuration:
- 32.8 nm span
- 1500 channels
- 2.8 GHz channel spacing (<20 dB crosstalk)
- 5 ms read-out time (potential)

Summary

• First reported all-order PMD compensation experiment (sub-ps pulses)

• Wavelength-parallel polarization sensor (parallel sensing at under 1 ms)

• Progress towards DWDM compatible implementations
  • 1D tunable dispersion compensator and spectral SOP sensor (10 Gb/s)
  • 2D spectral disperser geometry with potential to handle multiple DWDM channels within a single box

• Future challenges and opportunities:
  • Improved phase sensing compatible with robust real-time operation
  • Endless all-order compensation
  • PMD emulation

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