Polarized Light in So-called "Singlemode" Fiber: Not As Simple As You May Think

Gregory W. Schinn and Normand Cyr
EXFO Electro-Optical Engineering Inc

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Outline

- Implications and interaction of polarization in fiberoptics for telecom applications
- What is PMD?
  - first-order
  - second-order
- Is PMF really polarization maintaining?
- A "topological" mechanism for altering SOP in fiber
- Polarization and the patchcord
- Conclusions
Implications of Polarization in Telecommunications

- coherent communications
- Mach-Zehnder modulators
- semiconductor optical amplifiers
- interaction with component PDL/ PDG $\Rightarrow$ intensity noise
- interaction with PD bandpass-filter wavelength
- interaction with fiber birefringence and mode coupling (1st-order PMD)
- interaction with PMD/ chromatic dispersion (2nd-order PMD)
- Effect on Brillouin, FWM, Raman amplitudes in long fibers.
How does polarized light interact with optical fiber?

- Physical interaction
  - birefringence
  - mode coupling

- Topological Interaction
  - geometric phase
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Polarization Mode Dispersion (PMD)

- phenomenon which results in pulse spreading on time axis
  - intersymbol interference in digital systems
  - distortion in analog system

- major limitation in high-bandwidth, long-haul systems
What is first-order PMD?

Key concepts:
- differential group delay
- principal states of polarization
- input and output states of polarization
Simple case: Discrete waveplate, discrete input pulse

- state of polarization
- principal states of polarization
- differential group delay
Simple case Discrete waveplate cw input

dehasing of two PSPs depends linearly on optical frequency ω
Many waveplates with different orientations and orders (DGDs)

Important result: for any given optical frequency, exists input SOP which corresponds to no spreading or distortion

$\Rightarrow \text{PSP } (\omega_0) \text{ of waveplate combination}$
More realistic case Long singlemode fiber

- can be modelled as concatenation of many, randomly-oriented, birefringent elements
- strongly mode coupled
  - many interfaces between elements
- on average, $\Delta \tau$ increases as $\sqrt{L}$ (diffusion-like)
- birefringence behavior (i.e. orientation of PSP for given $\omega_0$) is strongly dependent upon environmental factors
Concatenation of 20 randomly oriented waveplates with different DGDs

Note: Probability distribution of $\delta \tau$ is maxwellian

Definition: PMD1 is the rms value of $\delta \tau(\omega)$ averaged over $\omega$
The Polarization Dispersion Vector, $\Omega$

- useful concept for visualizing transformation of input to output SOPs through long fiber
- $\Omega$ lies along axis of fast (output) PSP with modulus equal to the DGD

$$\text{PMD 1} = \sqrt{\langle |\Omega|^2 \rangle}$$
Poincaré sphere representation of PMD 1: Polarization dispersion vector, $\Omega(\omega)$, and arc described by the output SOP, $s$, as a function of optical frequency, $\omega$. 
Second-Order PMD

- PMD 2 arises from the optical-frequency-dependent behavior of $\Omega(\omega_0)$, both in magnitude and in orientation.

$$\text{PMD} 2 = \frac{2\pi c}{\lambda^2} \sqrt{\langle |\Omega|^2 \rangle} \quad \text{(ref: Gisin)}$$

- units of ps/ nm
- grows as $L$
- effect on power penalty averages to zero, but yields large fluctuation
PMD2 as the link between PMD and the chromatic dispersion

- Chromatic dispersion \(\longrightarrow\) Chirped pulses (chirp growing with distance)
  
  Chirp: time-dependent slewing of the carrier optical frequency

- Chirp (frequency sweep) \(\longrightarrow\) Time-dependent polarization dispersion vector \((\Omega)\)
  (both DGD and PSPs)

- Time-dependent \((\Omega)\) \(\longrightarrow\) Time-dependent delay
  Pulse spreading
PMD - Induced Power Penalty

Mean Penalty

Standard deviation of penalty

✧ it is the PMD 2-induced fluctuations of the power penalty which lead to system degradation
Could PMD be a problem in your system?

- only problem at bitrates ≥10 Gbs (about 10x less for analog systems)
- possible problem if chromatic dispersion >500 ps/ nm (⇒ non-D SF L >30 km)

Proper CD management should virtually eliminate any deleterious PMD2 effects
Unresolved Question:

Do Bragg-grating dispersion compensators induce "uncorrectable" PMD 2?

- significant PMD measured in many Bragg compensators (ref. S. Bonino et al., OFMC'97)

- Deterministic nature of grating PMD and "stitching" errors may lead to deviations in relation between PMD 1 and PMD 2

⇒ Uncorrectable PMD 2?
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Polarization Maintaining Fiber

- large intrinsic birefringence applied via stressed elements in preform: "HiBi" fiber

- no transfer of energy launched along SLOW/FAST axes
  \[\implies\] no mode coupling
Beat length: Length over which light (at specified wavelength) along FAST axis accumulates $1\lambda$ of phase lead over light along SLOW axis.

PMF is only polarization maintaining for two "special" cases.
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An old experimentalists' trick...

Linear Polarization (semi-major axis of SOP) rotated by 90 degrees
Linear polarization (semi-major axis of SOP) rotated by 40 degrees
Polarization unaffected: planar topology
The Geometric Phase

(M.V. Berry, 1984)

- Topology of path can introduce phase factor in wavefunction (e.g. light, quantum mechanical wavepacket, etc.)
- An overlooked phase factor in QM formulation of Born, Dirac

⇒ Consequences in molecular spectroscopy: mysterious forbidden bands explained.
⇒ Aharanov - Bohm effect
The Geometric Phase in Action...

In absence of birefringence semi-major axis rotated by $\theta$. 
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Polarization and the Patchcord

Standard singlemode 1-m patchcord: Is SOP preserved?
Polarization and the Patchcord

Typical PMD: 1-5 fs, chiefly intrinsic

Orientation of birefringence: In general varying, can be modeled by 2 or 3 waveplates.

Geometric Phase: If patchcord in plane ⇒ no effect
If out of plane ⇒ evolution of SOP along patchcord.
Most variations in SOP through a patchcord are due to geometric phase effects directly, or interaction of the changing geometric phase with the axes of birefringence.
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Conclusions

- Singlemode fiber is not really singlemode!
- PMD is practically impossible to eliminate ⇒ must accurately evaluate its consequences on a statistical basis.
- PMD and CD interact via second-order PMD.
- Birefringence, mode coupling, and geometric phase are the main causes of changes in SOP.
- There is no such thing as true polarization-maintaining fiber.