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

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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)

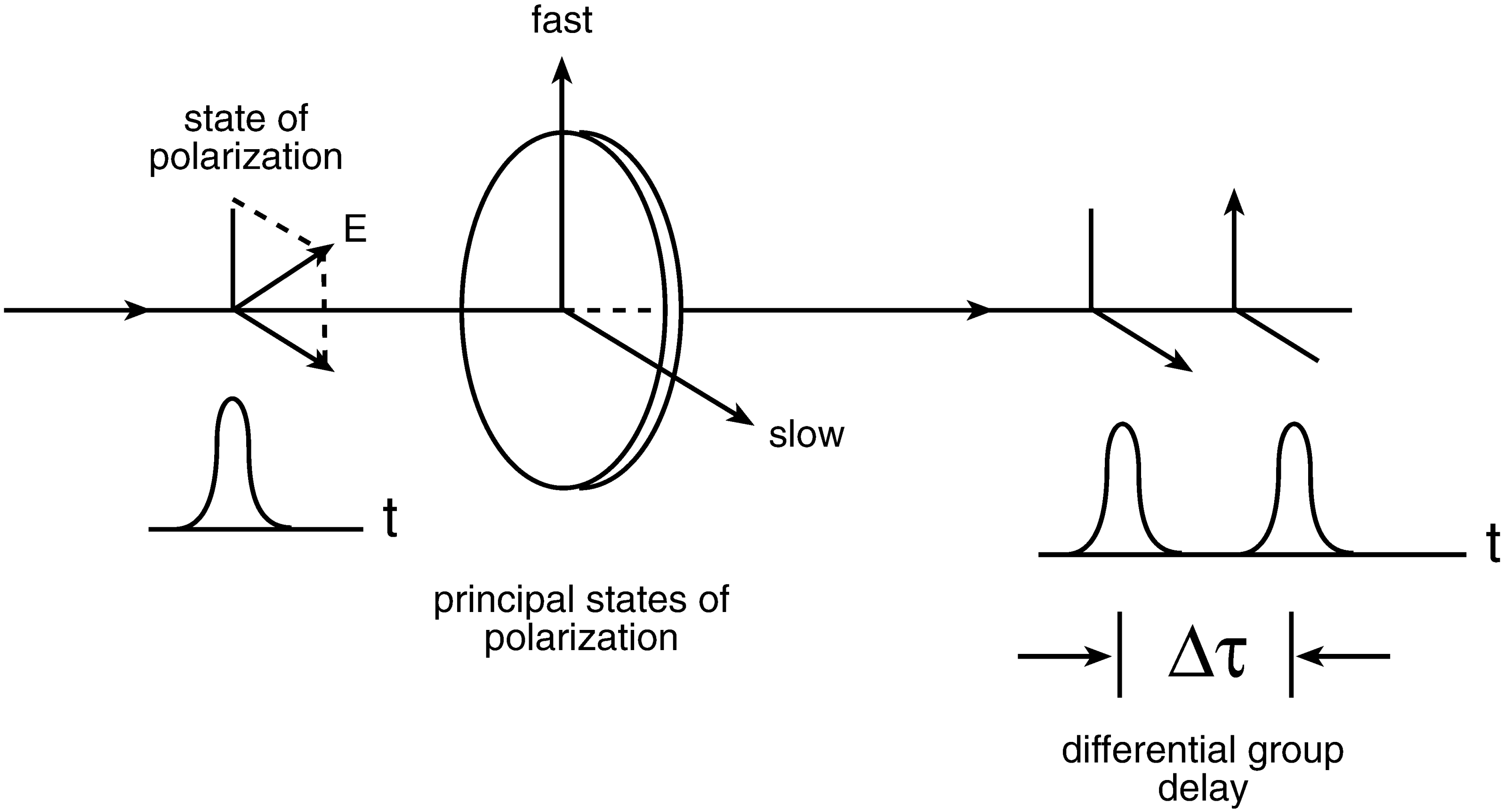
- phenomenon which results in pulse spreading on time axis
  - intersymbol interference in digital systems
  - distortion in analog system

- major limitation in high-bandwidth, long-haul systems

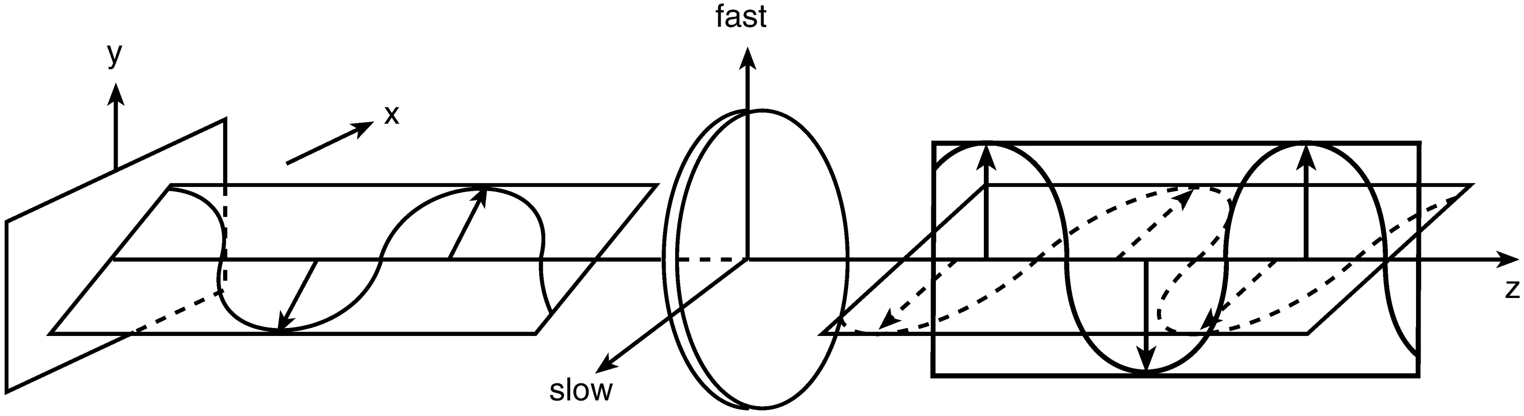
What is first-order PMD?

- Key concepts:
  - differential group delay
  - principal states of polarization
  - input and output states of polarization

Simple case: Discrete waveplate, discrete input pulse

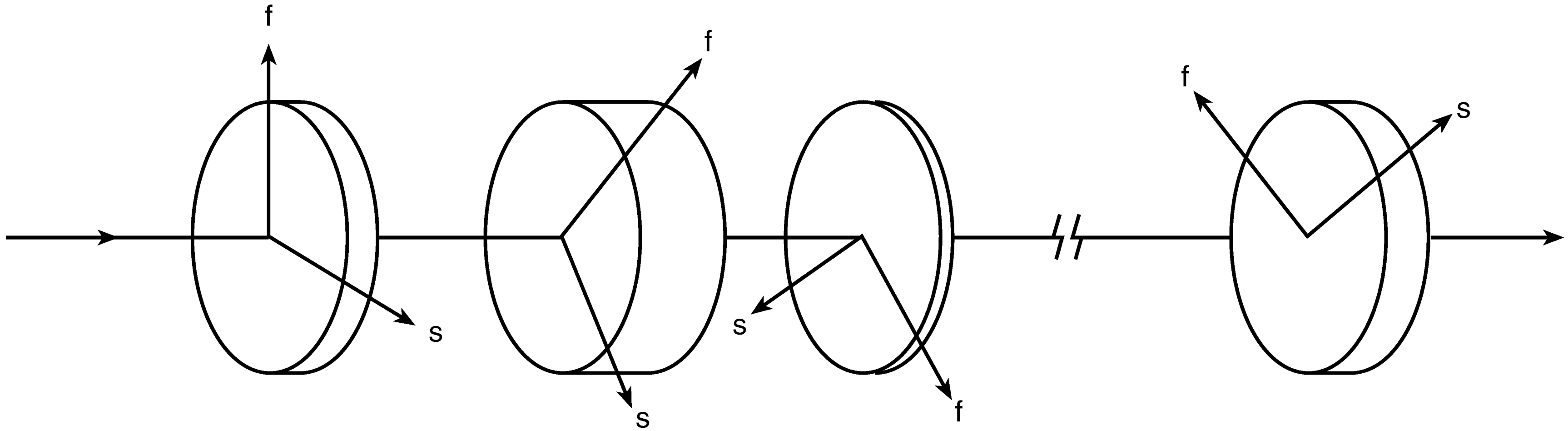


Simple case: Discrete waveplate, cw input



dephasing of two PSPs
depends linearly on
optical frequency ν

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

Þ *PSP* (ω_0) *of waveplate combination*

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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 ω_0) is strongly dependent upon environmental factors

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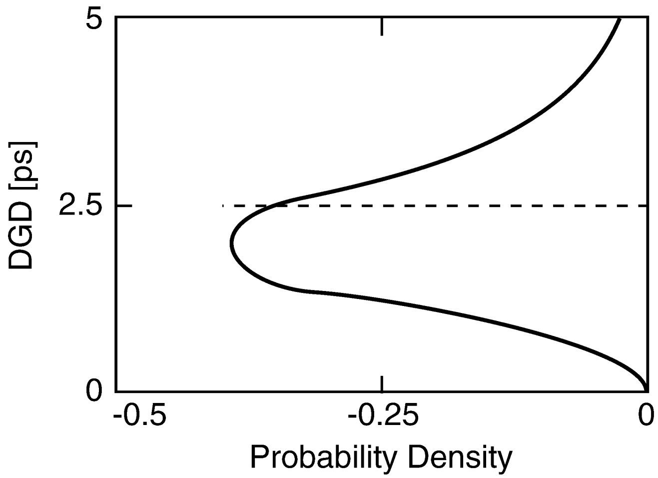
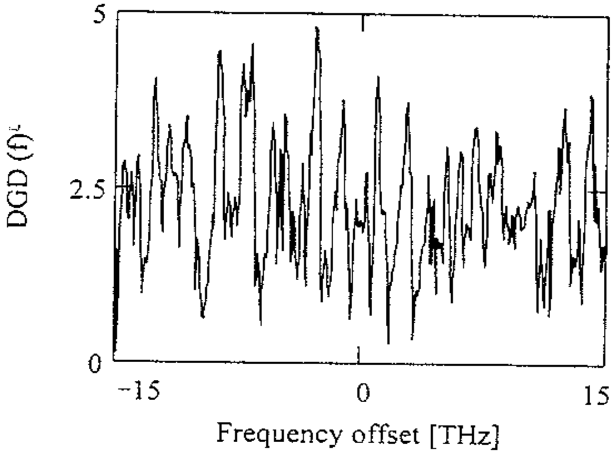
Concantenation of 20 randomly oriented waveplates with different DGDs





Note: Probability distribution of δτ is maxwellian

Definition: PMD1 is the rms value of δτ(ω) averaged over ω

The Polarization Dispersion Vector, $\vec{\Omega}$

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

$$\text{PMD1} = \sqrt{\langle |\vec{\Omega}|^2 \rangle}$$

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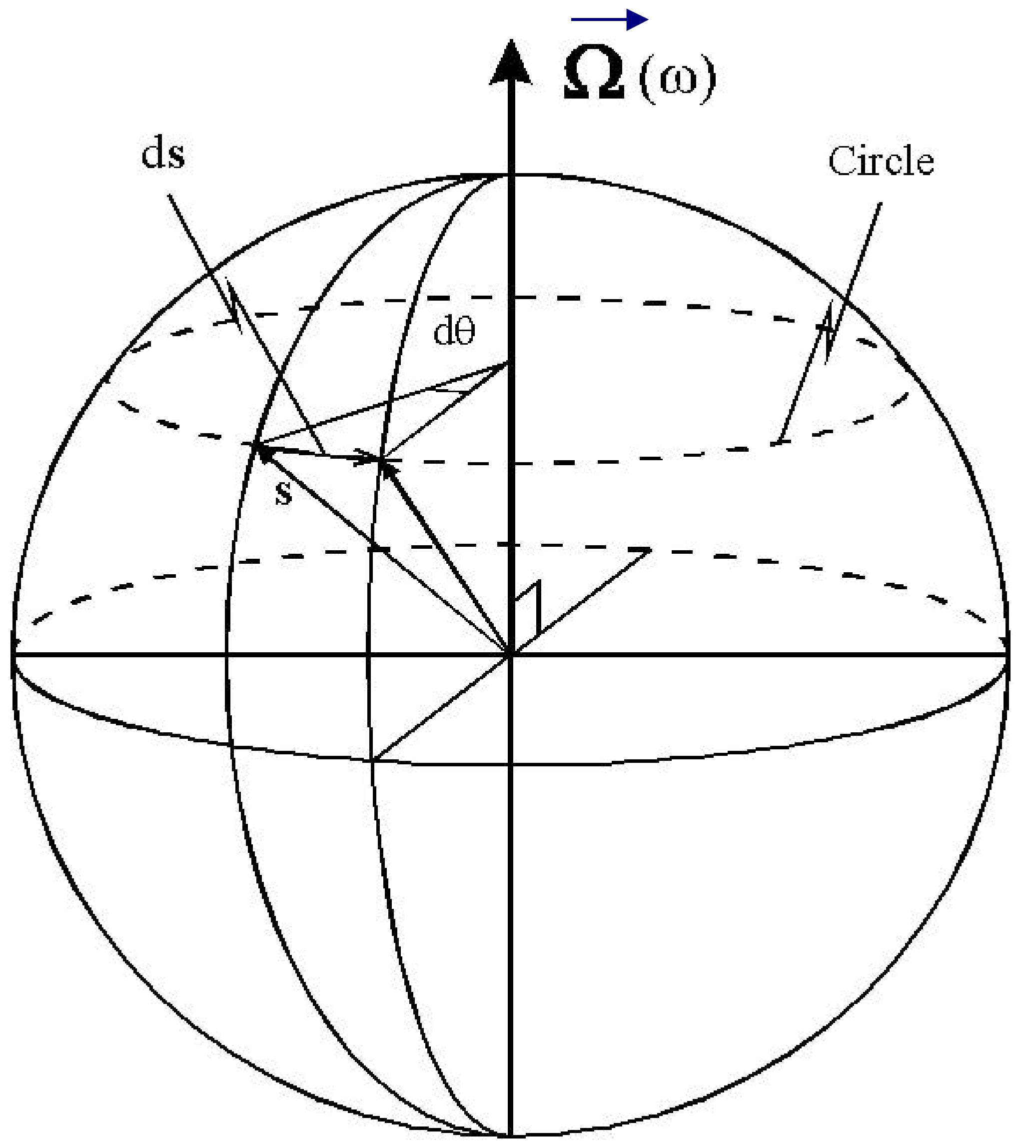

Poincaré sphere representation of PMD1: Polarization dispersion vector, $\vec{\Omega}(\omega)$, and arc described by the output SOP, ***s***, as a function of optical frequency, ω .

Second-Order PMD

- PMD2 arises from the optical-frequency-dependent behavior of $\vec{\Omega}(\omega_0)$, both in magnitude and in orientation

$$PMD2 = \frac{2\pi c}{\lambda^2} \sqrt{\overline{\langle |\vec{\Omega}|^2 \rangle}} \quad \text{(ref: Gisin)}$$

- units of ps/nm
- grows as L
- effect on power penalty averages to zero, but yields large fluctuation

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PMD2 as the link between PMD and the chromatic dispersion

- Chromatic dispersion → Chirped pulses

  (chirp growing with distance)

chirp: time-dependent slewing of the carrier optical frequency

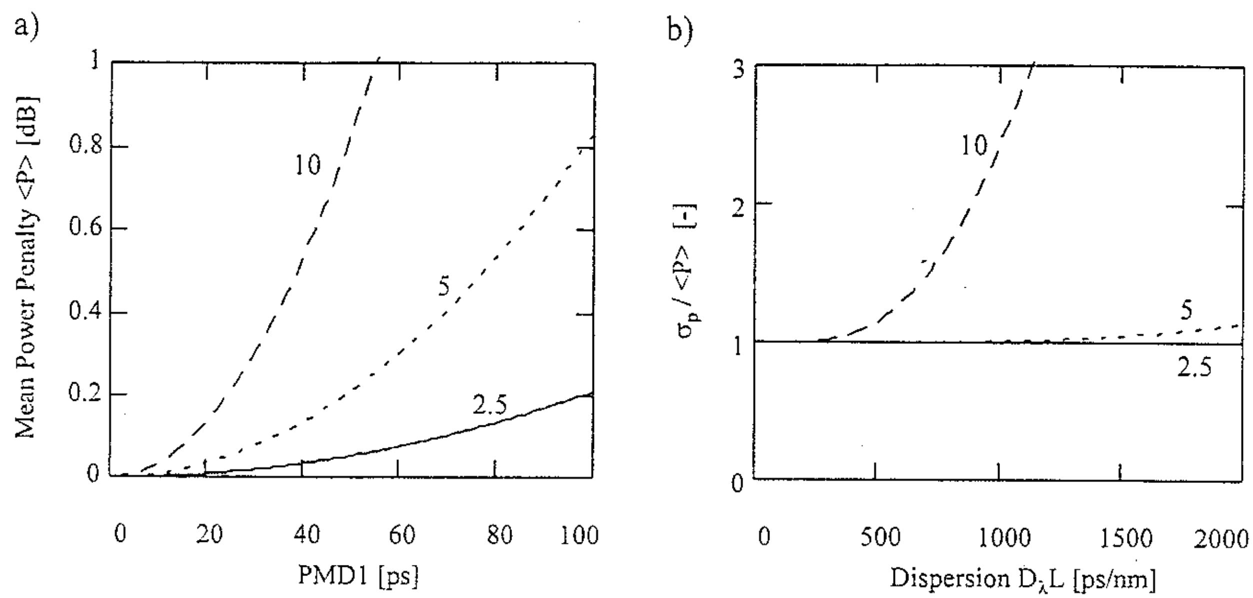
- Chirp (frequency sweep) → Time-dependent polarization dispersion vector ($\vec{\Omega}$)

  (both DGD and PSPs)

- Time-dependent ($\vec{\Omega}$) → Time-dependent delay

  Pulse spreading

PMD - Induced Power Penalty



Mean Penalty

Standard deviation of penalty

✦it is the PMD2-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 (Þ non-DSF L >30 km)

Proper CD management should virtually eliminate any deleterious PMD2 effects

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Unresolved Question:

Do Bragg-grating dispersion compensators induce "uncorrectable" PMD2?

- 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 PMD1 and PMD2

Þ uncorrectable PMD2?

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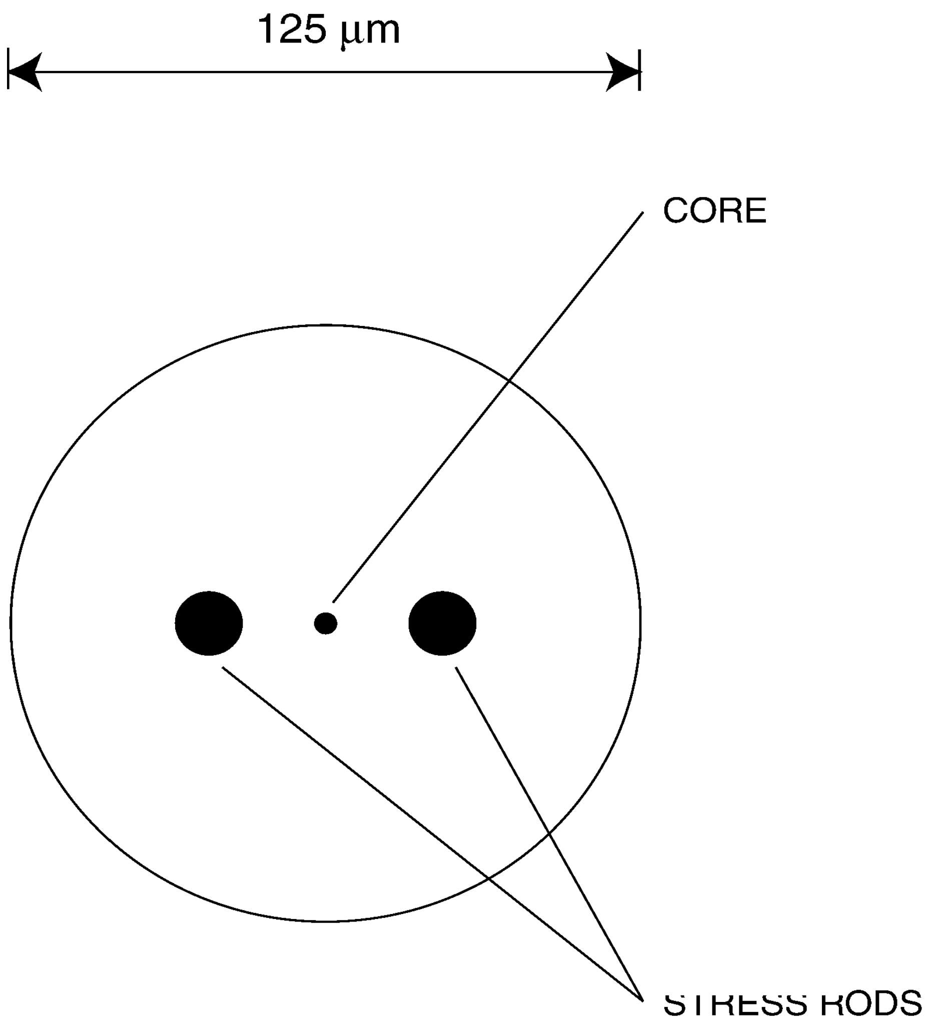
Polarization Maintaining Fiber

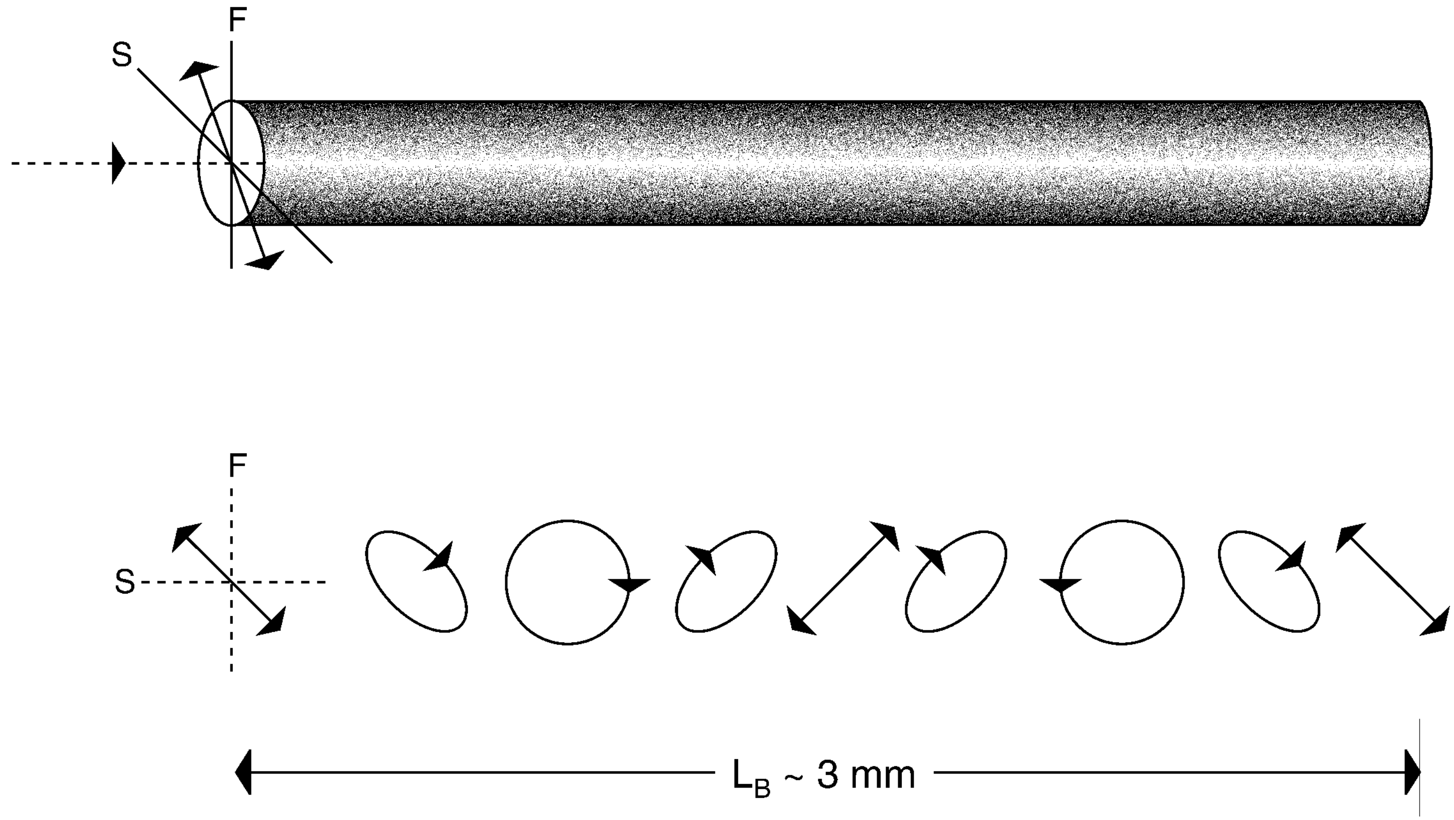
- large intrinsic birefringence applied via stressed elements in preform: "HiBi" fiber



- no transfer of energy launched along SLOW/FAST axes

Þ no mode coupling

Beat length: Length over which light (at specified wavelength) along FAST axis accumulates 1l of phase lead over light along SLOW axis



- PMF is only polarization maintaining for two "special" cases

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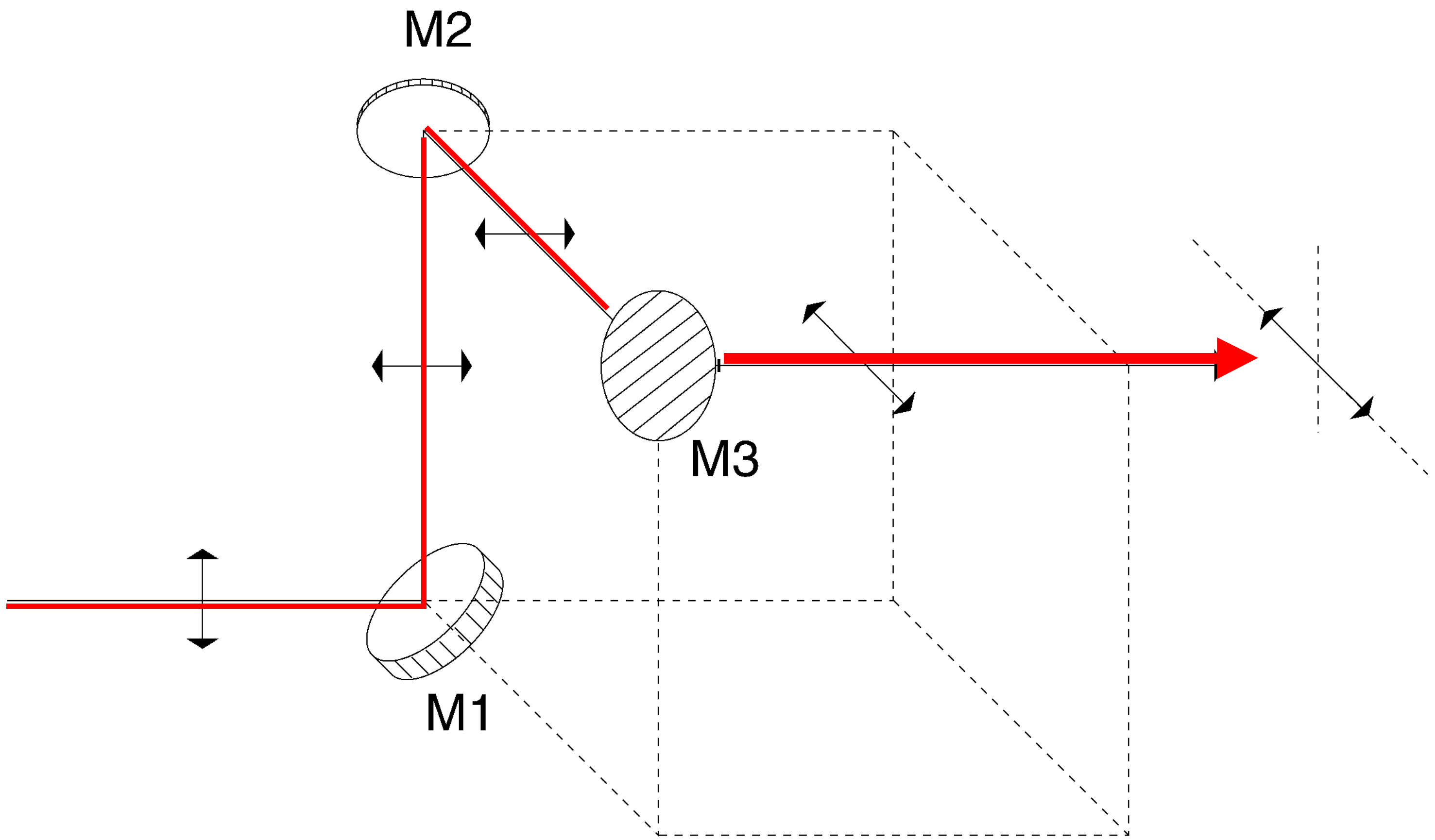
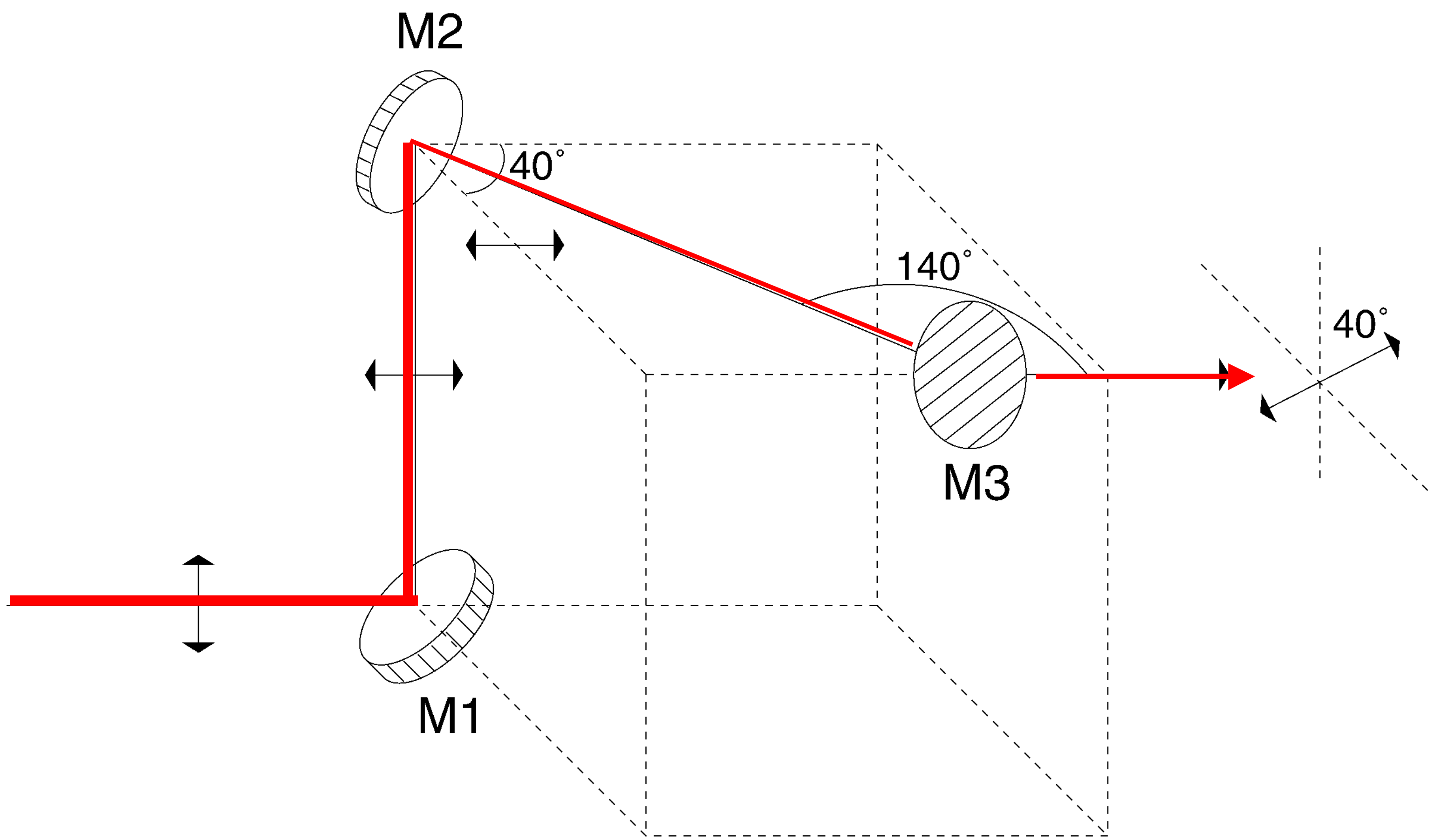
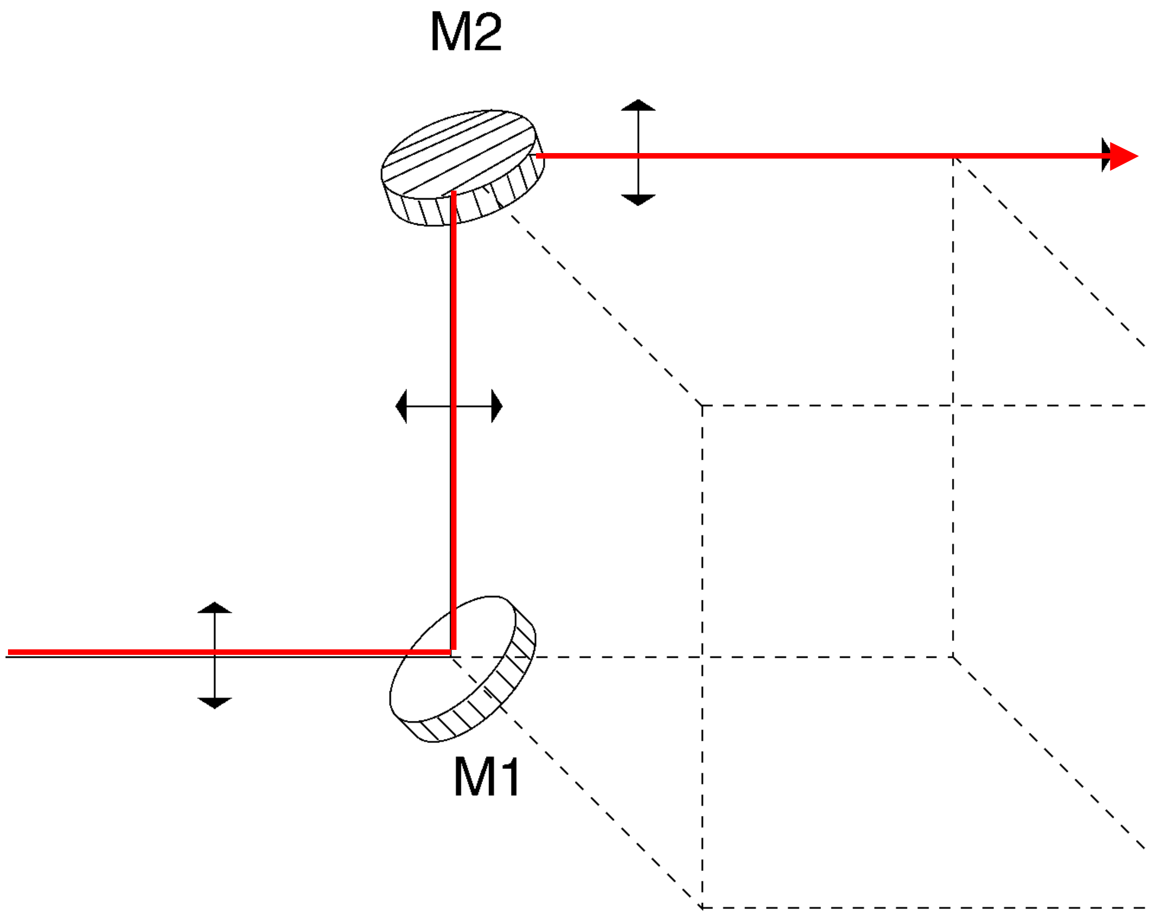
An old experimentalists' trick...



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

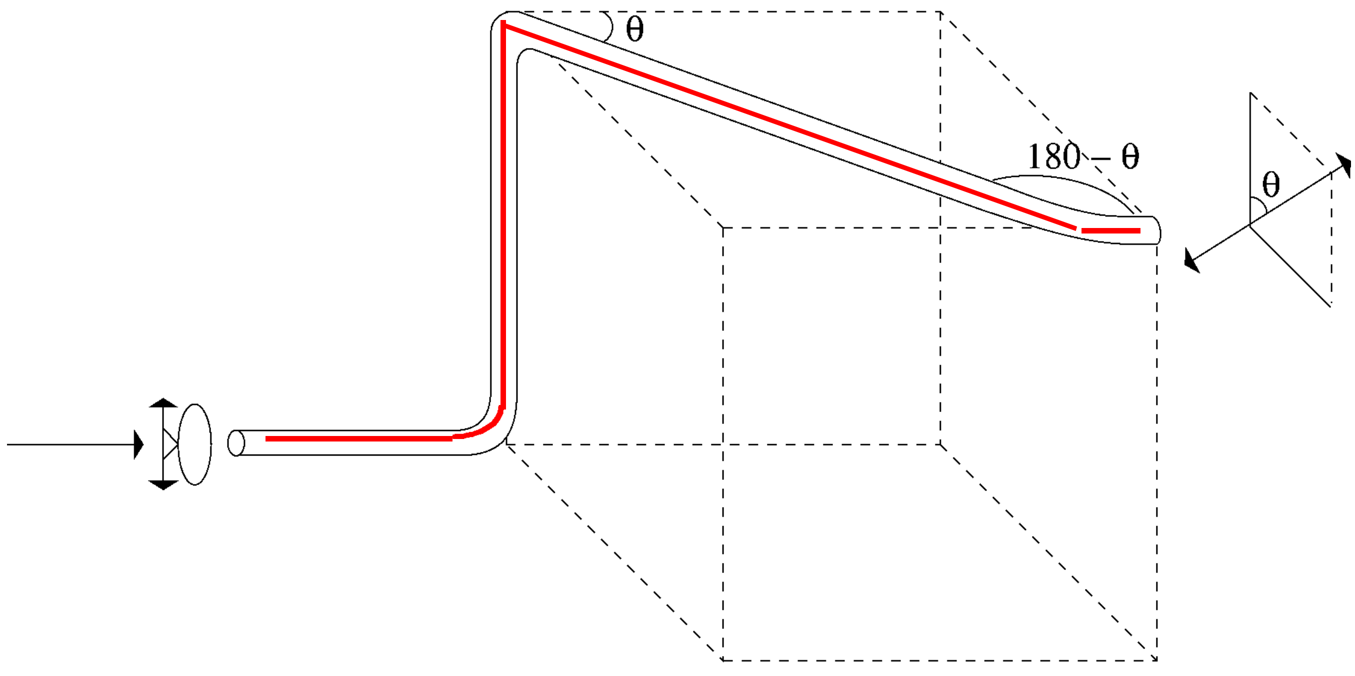
(M.V. Berry, 1984)

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

  Þ Consequences in molecular spectroscopy : mysterious forbidden bands explained.

  Þ Aharanov - Bohm effect

The Geometric Phase in Action...



In absence of birefringence semi-major axis rotated by θ.

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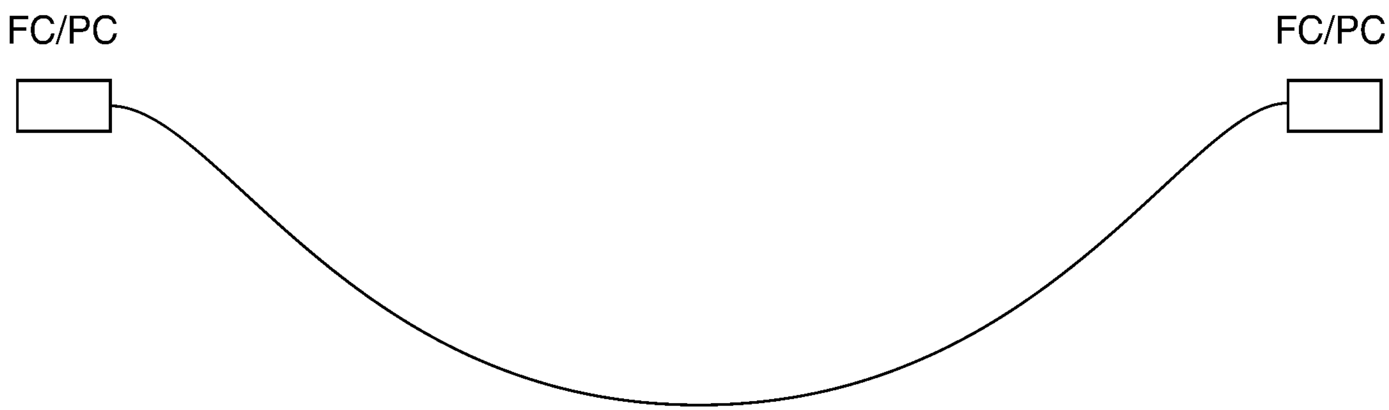
Polarization and the Patchcord



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 $\Rightarrow$ no effect

If out of plane $\Rightarrow$ 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 $\Rightarrow$ 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.