Dispersion and its Compensation

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• Optical communication
• Photonic crystal fiber
• Photonic crystal waveguide

Extreme of dispersion in…
• Slow Light / Stop Light

Dispersion properties in…
• Surface plasmon polaritons & meta-material

Concluding remarks
Newton

Isaac Newton
(1642-1727)


A sketch (left) from Newton’s 1672 notebook shows sunlight entering through the window at right, passing through a triangular prism, and splitting into a spectrum of colors. One of the earliest known studies of optics (the science of light and vision) was done by Islamic mathematician Ibn al-Haytham (965–1040), also known as Alhazen. His sketch of lenses is below.
Dispersion

- Dispersion: a phenomenon due to a dependence of the wave's speed on its wavelength that causes the separation of a wave into spectral components with different wavelengths.
  - Chromatic Dispersion
  - Material Dispersion
  - Waveguide Dispersion
  - Modal Dispersion

Spatial dispersion

Temporal dispersion
Control of dispersion

Dispersion compensation / mitigation – removing dispersion

• Optical communication
• Photonic crystal fiber
• Photonic crystal waveguide

Dispersion control – using dispersion

• Photonic crystal fiber
• Photonic crystal waveguides
• Slow light / stop light
• Pulse compression
• Surface plasmon polaritons & meta-material
Chromatic dispersion in optical fiber

\[ \nu(\lambda) = \frac{c_0}{n(\lambda)} \approx \frac{c_0}{n_0(\lambda_0)} + \frac{\partial n}{\partial \lambda} \delta \lambda + \frac{1}{2} \frac{\partial^2 n}{\partial \lambda^2} \delta \lambda^2 \]

\[ \frac{\partial n}{\partial \lambda} \sim \text{chromatic dispersion,} \frac{\partial^2 n}{\partial \lambda^2} \sim \text{dispersion slope} \]

\[ L_D = \frac{1}{D \cdot B \cdot \Delta \lambda} \propto \frac{1}{B^2} \]

\[ L_D : \text{dispersion limited distance,} B: \text{bit rate} \]

SMF D ~ +17 ps/(nm·km) at 1550 nm

\[ \Rightarrow \text{varies according to optical path and environment} \]
Optical communication

Dispersion engineering in optical fiber

Legacy fibers SMF-28 has dispersion of 17 ps/nm-km @ 1550 nm
For 40 Gb/s (or more) transmission,

- Communications link will not work if the compensation value does not exactly match the fiber within a few percent of the required dispersion value.

- Dispersion changes with temperature since the zero-dispersion wavelength of fiber changes with temperature at a typical rate of 0.03 nm/°C.

- Inventory management

- Reconfigurable optical networking

A. E. Willner, IEEE LEOS Annual Meeting, TuI1, 2002.
Dispersion Compensation with Chirped Fiber Bragg Gratings

CFBGs reflect different frequency components at different locations within the grating.

They can be used for dispersion compensation when the time delay for the grating is the inverse of the delay caused by dispersion of a transmission line.

Normalized reflectivity and time delay for a linearly CFBG. Oscillatory and random ripple should be minimized for the best system performance.

Optical communication

Commercialized Tunable CFBG for CD Compensation
- Highwave Optical Technologies

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<table>
<thead>
<tr>
<th>Optical Specifications</th>
<th>Units</th>
<th>HiLynx T10 (10 Gbit/s systems)</th>
<th>HiLynx T10/40 (10 and 40 Gbit/s systems)</th>
</tr>
</thead>
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<tr>
<td>Dispersion tuning range</td>
<td>ps/nm</td>
<td>700 to 1300</td>
<td>400 to 800</td>
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<tr>
<td>Channel Bandwidth (BW)</td>
<td>GHz</td>
<td>Up to 40</td>
<td>Up to 80</td>
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<tr>
<td>Insertion loss</td>
<td>dB</td>
<td>&lt; 2 dB</td>
<td></td>
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<tr>
<td>(including a circulator)</td>
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<tr>
<td>Insertion loss Ripple</td>
<td>dB</td>
<td>&lt; 0.5 dB</td>
<td></td>
</tr>
<tr>
<td>Raw Group Delay Ripple (over full T* range)</td>
<td>ps</td>
<td>&lt; +/-20 ps</td>
<td>&lt; +/-15 ps</td>
</tr>
<tr>
<td>Group Delay Ripple (100 pm smoothing avg.)</td>
<td>ps</td>
<td>&lt; +/- 5 ps</td>
<td>&lt; +/- 3 ps</td>
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<tr>
<td>PDL (averaged in BW)</td>
<td>dB</td>
<td>&lt; 0.1 dB</td>
<td></td>
</tr>
<tr>
<td>PMD (averaged in BW)</td>
<td>ps</td>
<td>&lt; 0.5 ps</td>
<td></td>
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</tbody>
</table>
Optical communication

Electronic dispersion compensation (EDC)

5120-km RZ-DPSK transmission at 10 Gb/s without optical dispersion compensation


Electro-optic modulator in transmitter

Fig. 4. Eye diagrams at receiver after propagation on G.652 fiber: (a) back-to-back (0 ps/nm), (b) 1600 km (25.760 ps/nm), (c) 3200 km (51.520 ps/nm), and (d) 5120 km (82.433 ps/nm).

Fig. 5. BER as function of OSNR in 0.1-nm resolution bandwidth. Average launch power: (a) −5 and (b) −7 dBm.
EDC, without optical compensation

1500 km transmission over NZ-DSF without in-line or post-compensation of dispersion for 38 x 10.7 Gbps channels


Fig. 2 Accumulated dispersion and signal Q values at 800 and 900 km

900 km transmission w/o optical compensation

1500 km transmission with DCF compensation

Fig. 3 OSNR and Q values after transmission over 1500 km

~3350 ps/nm
pre-comp.
EDC, receiver dispersion slope compensation

Transmission of 40-Gb/s WDM signals over transoceanic distance using conventional NZ-DSF with receiver dispersion slope compensation


Fig. 6. Q-factors for 42.8-Gb/s RZ-DPSK (with slope compensation) and CSRZ-DPSK (without slope compensation) after 6250 km.

Fig. 18. Comparison of parallel and orthogonal launch (CSRZ-DPSK, 100-GHz channel spacing, 25 × 40 Gb/s over 6250 km).
Optical communication

Polarization mode dispersion (PMD)

1st Order PMD

Signal Distortion!!
Causes of birefringence

- **Intrinsic**: Oval waveguide
- **Extrinsic**: Mechanical stress

- **Non Symmetric Stress**
- **Elliptical Core**
- **Elliptical Cladding**
- **Ideal**

- **Geometrical Stress**
- **Stress**
- **Lateral Stress**
- **Band Twist**
Optical communication

Realistic model of fiber PMD

• Multiple concatenation of randomly oriented birefringent elements
Photonic crystal fibers

Photonic crystal fibers

Photonic crystal fibers

Dispersion compensation with PCF

A novel design for dispersion compensating photonic crystal fiber Raman amplifier


Highly-negative dispersion for the fundamental mode

Flattened gain by Raman amplification
Ultra-flattened chromatic dispersion controllability using a defected-core photonic crystal fiber with low confinement losses


Optimally-flattened-dispersion

Lattice constant variation

Cladding diameter variation

Core diameter variation
Group delay device: dispersion control

Dispersion-controlled optical group delay device by chirped photonic crystal waveguides


Delay device by slowing

$L_{\text{eff}} = 45 \mu m$
Real-space observation of ultraslow light in photonic crystal waveguides

Slow & stopping light

Stopping light all optically

Coupled photonic crystal resonator array (CPCRA)

\[
\omega_k^j \cong \Omega_l [1 - \frac{\Delta \alpha^j \lambda}{2} + \\
\kappa_{1,0}^j \cos Rk_x + \kappa_{0,1}^j \cos Rk_z + \kappa_{1,1}^j \cos R(k_x + k_z) + \kappa_{1,-1}^j \cos R(k_x - k_z)]
\]

\[
v_{g,x} = v_{g,z} = -\Omega_l R \kappa_{1,0} \sin Rk_x
\]

\[
v_{g,d} = -\Omega_l \frac{R}{\sqrt{2}} [\kappa_{1,0}^j \sin Rk_x + \kappa_{0,1} \sin Rk_z] \approx -\Omega_l \sqrt{2} R \kappa_{1,0}^j \sin Rk_x
\]

Simple arrangement

Modified arrangement

Ultra-flattened dispersion
Transmission of slow light through photonic crystal waveguide bends

Dispersion surface

Energy propagation

\[ v_g = \frac{\partial \omega}{\partial \vec{k}} \]
Superprism phenomena in photonic crystals

Experimental evidence for superprism effects in three-dimensional polymer photonic crystals

All-angle negative refraction without negative effective index


\[ \frac{\partial^2 \omega}{\partial k_i \partial k_j} \]

superlens
Negative refraction in meta-material

\[
\cos(\alpha_0 d) = \cos[\gamma_1 (1-f) d] \cos[\gamma_2 f d] + \frac{1}{2} \left( \frac{\sigma_2 \gamma_1}{\sigma_1 \gamma_2} + \frac{\sigma_1 \gamma_2}{\sigma_2 \gamma_1} \right) \sin[\gamma_1 (1-f) d] \sin[\gamma_2 f d]
\]
What is a plasmon?

- “Plasma-oscillation”: density fluctuation of free electrons

**Surface plasmon polaritons**

1. **Bulk plasmon**
2. **Surface plasmon**
3. **Confined plasmon in nanoparticle**

- **The Lycurgus Cup (glass)**
  - British Museum
  - 4th century A.D.
  - Green when illuminated from outside and red when illuminated from within the cup due to very small amounts of gold powder (about 40 parts per million)

- **“Labors of the Months”**
  - Norwich, England
  - ca. 1480
  - The ruby color is attributed to gold nanoparticles.
Surface plasmon polaritons

Dispersion relation of surface plasmon polariton

- Dispersion of SP

\[ k_{SP} = k_0 \sqrt{ \frac{\varepsilon_d \varepsilon_m}{\varepsilon_d + \varepsilon_m} } = \frac{\omega}{c} \sqrt{ \frac{\varepsilon_d \varepsilon_m}{\varepsilon_d + \varepsilon_m} } \]

ex) for silver-air interface, \( k_{SP} = 1.03k_0 \)

- Propagation length, \( \delta_{SP} \)

\[ \delta_{SP} = \frac{1}{2k_{SP}'} = \frac{c}{\omega} \left( \frac{\varepsilon_d' + \varepsilon_m'}{\varepsilon_m'} \right)^\frac{3}{2} \left( \frac{\varepsilon_d'}{\varepsilon_m'} \right)^2 \]

ex) for silver-air interface, \( \delta_{SP} = 20 \mu m \)

Surface charges, evanescent fields, and dispersion curve for SP mode
Surface plasmon polaritons

Surface plasmon

\[ \delta_m, \delta_d, \lambda, \delta_{sp} \]

- Aluminium at 0.5 \( \mu m \)
- Silver at 1.5 \( \mu m \)
Surface plasmon polaritons

Surface plasmon applications

- SPP Applications
  - Surface sensitive techniques, SPR microscopy
  - SPR technologies and a wide range of photonic ICs.
    - Waveguides of surface plasmons
    - Surface plasmon Bragg reflectors
    - Bio- and flow-sensors using SPR
    - Light transmission enhancement
    - Laser beam shaping

Ag Film with hole arrays
(Period = 300, 450, 550nm
Hole diameter=155,180,225nm)


Surface plasmon polaritons

Plasmonic nanolithography


Surface plasmons
1. Much shorter wavelength compared to the excitation light wavelength
2. E-field intensity of surface plasmons can be boosted by several orders of magnitude compared to the excitation light

Metal mask: 90nm holes, 170nm period
Resonant surface plasmon couplings (SuperLens)

Superlens-based nanopatterning
- A flat plane of NRM behaves as superlens and amplifies evanescent waves in near-field through a series of plasmon resonances.
- This allows super-resolutions below diffraction limit.
- Experimentally achieved improvements in UV range: 5-10x beyond the operating wavelength
- Applicable for direct imaging of evanescent modes, thus for immediate recognition of analytes
- Also applicable for nanopatterning through subwavelength contact lithography

UV exposure (365nm)
Femto-second surface plasmon

Propagation of femtosecond surface plasmon polariton pulses on the surface of a nanostructured metallic film, space-time complex amplitude characterization


transmittance from nanohole array
Surface plasmon biosensor

Optical biosensor with dispersion compensation

# Comparison of simulation methods

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<thead>
<tr>
<th></th>
<th>FDTD</th>
<th>RCWA</th>
<th>PFMA</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Domain</strong></td>
<td>Space</td>
<td>Frequency</td>
<td>Frequency</td>
</tr>
<tr>
<td><strong>Field representation</strong></td>
<td>Finite-difference method</td>
<td>Piles of truncated 2D-pseudo-Fourier series</td>
<td>Truncated 3D-pseudo-Fourier series</td>
</tr>
<tr>
<td><strong>Structure modeling</strong></td>
<td>Mesh-structure</td>
<td>Staircase approximation &amp; piles of 2D-Fourier series</td>
<td>3D-Fourier series (no staircase approximation)</td>
</tr>
<tr>
<td><strong>Aperiodic structure Analysis</strong></td>
<td>Yes</td>
<td>No (If using PML, yes)</td>
<td>No (If using PML, yes)</td>
</tr>
<tr>
<td><strong>Evanescent field analysis</strong></td>
<td>No (Cannot separate)</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Modal analysis</strong></td>
<td>No</td>
<td>No</td>
<td>Yes</td>
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<tr>
<td><strong>Computation cost</strong></td>
<td>Very huge</td>
<td>Large</td>
<td>Huge</td>
</tr>
</tbody>
</table>
Simulations

RCWA examples

3D micro-metal-sphere structure (15 level staircase approximation)
Simulations

**Surface plasmon excitation**

**Finite metal slab structure**

Surface plasmon excited by Gaussian beam

Surface plasmon excited by Gaussian pulse beam

At metal surface

Surface plasmon excited by Gaussian beam

Surface plasmon excited by Gaussian pulse beam

At metal surface
Surface plasmon excitation by grating coupler

Simulations

Regenerated surface plasmon

Air
n=2

Ag 40nm
n=0.7

50μm
Metal-gap waveguide with bottom surface grating

\( \lambda = 532 \text{ nm}, \ TM \)

Ag clad

Grating period / width / height

= 500 nm / 250 nm / 80 nm

Reflection is decreased

Flat surface
Metal-gap waveguide

Metal-gap waveguide with upper surface grating

λ = 532 nm, TM

grating period / width / height
= 500 nm / 250 nm / 80 nm

n = 1.52

Ag clad

Surface grating

Flat surface
Holographic lithography

- TIR holography simulation – rigorous electromagnetic analysis

Recording

- Recording (TM Polarization)
- Recording (TE Polarization)

Reconstructing

- Reconstructing (TM Polarization)
- Reconstructing (TE Polarization)
Simulations

RCWA analysis of near field around a tip

- Dielectric tip structure

$n_{\text{clad}} = 1.46$

$n_{\text{core}} = 1.76$

500 layers
RCWA analysis of near field around a tip

- Metal coated tip structure

500 layers staircase approximation

Without metal coating

With metal coating
Perspectives: Plasmonics

- Transistor gate size: ~50 nm, Light wavelength: ~1,000 nm
- Plasmonics? – Surface plasmon-based photonics

- Demonstrate optical frequency subwavelength metallic wired circuits with propagation loss comparable to conventional waveguides
- Develop highly efficient plasmonic organic and inorganic LEDs with tunable radiation properties
- Achieve active control of plasmonic signals by implementing electro-optic, all-optical, and piezoelectric modulation and gain mechanisms to plasmonic structures
- Demonstrate 2D plasmonic optical components, including lenses and grating couplers, that can couple single mode fiber directly to plasmonic circuits
- Develop deep subwavelength plasmonic nanotolithography over large surfaces
Concluding remarks

- Brief review on recent research trends on the dispersion and its compensation

![Graph showing SCI/SCIE Publications Related on Dispersion from 1993 to 2005.](image)