OPTI510R: Photonics

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Announcements

- Homework #4 is due today, HW #5 is assigned (due April 8)
- Final exam May 1 (Tentative)
Passive fiber components

- Fiber spicing and connectorization
- Directional couplers
- WDM couplers
- Isolators
- Tunable filters, resonators, AWG… (homework)
Photonics crystal fibers

Standard fiber  PCF  HC-PCF

Limitation of standard fibers

**Loss**: amplifiers every 50–100km
  ...limited by Rayleigh scattering
  ...cannot use “exotic” wavelengths like 10.6µm

**Nonlinearities**: crosstalk, power limits
  *(limited by mode area ~ single-mode, bending loss)*
  also cannot be made with (very) large core for high power operation

**Radical modifications to dispersion, polarization effects?**
  ...tunability is limited by low index contrast
Interesting breakthroughs

Guiding @ 10.6µm (high-power CO₂ lasers) loss < 1 dB/m (material loss ~ 10⁴ dB/m)


Guiding @ 1.55µm loss ~ 13dB/km


OFC 2004: 1.7dB/km

BlazePhotonics


[ figs courtesy Y. Fink et al., MIT ]
Interesting breakthroughs

Endlessly single-mode

Polarization-maintaining

Nonlinear fibers

Low-contrast linear fiber (large area)
Interesting Applications

• Dispersion compensation
• Pulse compression and deliver
• Supercontinuum generation
• Gas, liquid sensing
• Telecommunication?
• …
Questions for thoughts

Can you come up with a new design of optical fiber that would work much better than existing ones?

New applications for optical fibers?

Do optical fibers exist in nature?
Optical elements are used to split/combine, filter, focus, amplify, attenuate… light

Traditional optics

Ti:sapphire laser
“Fiberization” in Optics

Ti:sa femtosecond laser

Femtosecond fiber laser
Passive fiber components

- Fiber coupler
- Variable fiber coupler
- WDM
- Isolator
- Attenuator
- Modulator
- Switches
- Pump/signal combiner
- Polarization splitter/combiner
- Collimator
- Fiber delay line
- Polarizer
- Tunable filter
- Circulator
- Faraday rotator mirror
- ...
Point-to-point WDM Transmission System - Building Blocks -
Erbium-doped fiber amplifier
Fiber laser

Mode-locked ring fiber laser
Fiber cable construction

Reinforcement needed to protect the fragile glass fiber
Corning® SMF-28® ULL Optical Fiber
With Corning® Ultra-Low Loss Technology
Product Information

Corning® SMF-28® ULL fiber with Corning® ultra-low-loss technology is a G.652-compliant fiber with the lowest attenuation and PMD in the industry, empowering networks to achieve longer spans and extended reach.

**Optical Specifications**

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Maximum Value* (dB/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1310</td>
<td>0.28 – 0.31</td>
</tr>
<tr>
<td>1550</td>
<td>0.17 – 0.18</td>
</tr>
<tr>
<td>1625</td>
<td>0.20 – 0.21</td>
</tr>
</tbody>
</table>

*Maximum specified attenuation value available within the stated ranges. Alternate attenuation offerings available upon request.

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>MFD (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1310</td>
<td>9.2 ± 0.5</td>
</tr>
<tr>
<td>1550</td>
<td>10.7 ± 0.5</td>
</tr>
</tbody>
</table>

**Cable Cutoff Wavelength (λ/ccf)**

\[ λ_{ccf} \leq 1260 \text{ nm} \]

**Mode-Field Diameter**

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Dispersion Value [ps/(nm·km)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1550</td>
<td>( \leq 18.0 )</td>
</tr>
<tr>
<td>1625</td>
<td>( \leq 22.0 )</td>
</tr>
</tbody>
</table>

**Dispersion**

Zero Dispersion Wavelength (\( \lambda_d \)):

\[ 1300 \text{ nm} \leq \lambda_d \leq 1324 \text{ nm} \]

Zero Dispersion Slope (\( S_0 \)):

\[ \leq 0.092 \text{ ps/(nm}^2\text{·km)} \]
Fiber connectorization

Fiber optics cable

Fusion splicer

Fiber optics connectors

Before splicing

After splicing
Fiber displacement

![Diagram of fiber displacement](image)

Loss due to radial misalignment [dB]

Radial misalignment / 
Core diameter

$R_E/C_D$
Longitudinal displacement

Graph showing the loss due to longitudinal separation in dB as a function of separation $L_s$ and core diameter $C_D$. The graph includes lines for different values of NA (numerical aperture): NA = 0.5, NA = 0.2, and NA = 0.15. The graph also shows the relationship between separation and core diameter.

Prof. Norwood
Angular deviation

The graph illustrates the loss due to angular deviation [dB] as a function of angular deviation $\alpha$ in degrees, for different numerical apertures (NA). The lines represent the loss for NA = 0.15, NA = 0.2, and NA = 0.5, respectively.
Fiber connectors
Fiber connectors

Insertion losses are generally
<0.2 dB typical
<0.5 dB max

Connectors can have a flat polish or they may have an 8° angle polish which reduces back reflections dramatically (< -60dB return loss) compared to flat polish (< -40dB return loss).
Fiber connectors, FC/PC
Fiber splicing

- Fiber stripping
- Surface cleaning
- Fiber cleaving
- Fiber alignment
- Pre-fusion heating
- Fusing
- Splice evaluation
- Protection, strain relief
  - Heat shrink sleeve
Fiber splicer
Fiber cleaver
Fiber stripper
Fiber optic couplers

- Optical couplers either split optical signals into multiple paths or combine multiple signals onto one path.
- The number of input (N)/ output (M) ports, (i.e. N x M) characterizes a coupler.
- Fused couplers can be made in any configuration, but they commonly use multiples of two (2 x 2, 4 x 4, 8 x 8, etc.)
Coupler applications

- Uses
  - Splitter: (50:50)
  - Taps: (90:10) or (95:05)
  - Combiners

- Couplers are key components in
  - Optical amplifiers
  - Fiber lasers
  - Optical switches
  - Mach Zehnder interferometers
  - Fiber-to-the-home networks
  - Optical fiber sensors
The coupling is wavelength dependent. Coupling occurs when the two fibers’ cores are very close to each other. Small changes effect the coupling ratio.

WDM coupler
- 100% of the 1.3 µm light couples to the core of fiber B, and then back to the core of fiber A to emerge at Port C
- 100% of the 1.55 µm light couples to the core of fiber B and emerges at Port D
- Simple coarse WDM filters can be made in this way
Single-mode coupler properties

- Couplers are made by tapering fibers down, thereby making the core very small, resulting in most of the light propagating in the "multimode' cladding in the taper region.

- If the adiabatic coupling regions vary slowly enough, then there is very little loss as the light propagates across the biconical taper.
Fused biconic taper fabrication

Fabrication of a biconical taper

- Heat fiber uniformly over a width $w$ to the glass melting point, $T_m$
- Stretch fiber a distance $L$ on both sides of the heated region
Fused biconic taper fabrication

or

example: experimental set-up

Typical parameters

(Bilodeau, et al., JLT, 26, 1476, '8)

Completely automated technology with high throughput

Coupling ratio, excess loss, PDL
Theory for directional couplers

- Four-port devices (two input and two output ports)
- Output can be split in two different directions; hence the name directional couplers
- Can be fabricated using fibers or planar waveguides
- Two waveguides are identical in symmetric couplers
- Evanescent coupling of modes in two closely spaced waveguides
- Overlapping of modes in the central region leads to power transfer
Theory for directional couplers

- Coupled-mode theory commonly used for couplers

- Begin with the Helmholtz equation: \( \nabla^2 \tilde{E} + \tilde{n}^2 k_0^2 \tilde{E} = 0 \)

- \( \tilde{n}(x,y) = n_0 \), everywhere except in the region occupied by two cores

- Approximate solution:
  \[
  \tilde{E}(r, \omega) \approx \hat{e} [\tilde{A}_1(z, \omega) F_1(x,y) + \tilde{A}_2(z, \omega) F_2(x,y)] e^{j\beta z}
  \]

- \( F_m(x,y) \) corresponds to the mode supported by the each waveguide:
  \[
  \frac{\partial^2 F_m}{\partial x^2} + \frac{\partial^2 F_m}{\partial y^2} + [n_m^2(x,y) k_0^2 - \beta_m^2] F_m = 0
  \]

- \( A_1 \) and \( A_2 \) vary with \( z \) because of the mode overlap

Credit: Agrawal
Coupled mode equations

- Coupled-mode theory deals with amplitudes $A_1$ and $A_2$

- We substitute assumed solution in Helmholtz equation, multiply by $F_1$ or $F_2$, and integrate over $x$-$y$ plane to obtain:

$$\frac{d\tilde{A}_1}{dz} = i(\tilde{\beta}_1 - \beta)\tilde{A}_1 + i\kappa_{12}\tilde{A}_2,$$

$$\frac{d\tilde{A}_2}{dz} = i(\tilde{\beta}_2 - \beta)\tilde{A}_2 + i\kappa_{21}\tilde{A}_1,$$

- The coupling coefficient is defined as:

$$\kappa_{mp} = \frac{k_0^2}{2\beta} \int \int_{-\infty}^{\infty} (n^2 - n_p^2) F_m^* F_p \, dx \, dy,$$

- Modes are normalized such that:

$$\int \int_{-\infty}^{\infty} |F_m(x, y)|^2 \, dx \, dy = 1$$
Time-domain coupled mode equations

- Expand $\bar{\beta}_m(\omega)$ in a Taylor series around the carrier frequency $\omega_0$ as:

$$\bar{\beta}_m(\omega) = \beta_{0m} + (\omega - \omega_0)\beta_{1m} + \frac{1}{2}(\omega - \omega_0)^2\beta_{2m} + \cdots,$$

- Replace $\omega - \omega_0$ by $i(\partial / \partial t)$ while taking inverse Fourier transform:

$$\frac{\partial A_1}{\partial z} + \frac{1}{v_g} \frac{\partial A_1}{\partial t} + \frac{i\beta_{21}}{2} \frac{\partial^2 A_1}{\partial t^2} = i\kappa_{12}A_2 + i\delta_a A_1,$$

$$\frac{\partial A_2}{\partial z} + \frac{1}{v_g} \frac{\partial A_2}{\partial t} + \frac{i\beta_{22}}{2} \frac{\partial^2 A_2}{\partial t^2} = i\kappa_{21}A_1 - i\delta_a A_2,$$

where $v_g \equiv 1/\beta_{1m}$ and

$$\delta_a = \frac{1}{2}(\beta_{01} - \beta_{02}), \quad \beta = \frac{1}{2}(\beta_{01} + \beta_{02})$$

- For a symmetric coupler, $\delta_a = 0$ and $\kappa_{12} = \kappa_{21} \equiv \kappa$

Credit: Agrawal
Consider first the simplest case of a CW beam incident on one of the input ports of a coupler.

Setting time-dependent terms to zero we obtain

\[
\frac{dA_1}{dz} = i\kappa_{12}A_2 + i\delta_a A_1, \quad \frac{dA_2}{dz} = i\kappa_{21}A_1 - i\delta_a A_2.
\]

Eliminating \(dA_2/dz\), we obtain a simple equation for \(A_1\):

\[
\frac{d^2A_1}{dz^2} + \kappa_e^2 A_1 = 0, \quad \kappa_e = \sqrt{\kappa^2 + \delta_a^2} \quad (\kappa = \sqrt{\kappa_{12}\kappa_{21}}).
\]

General solution when \(A_1(0) = A_0\) and \(A_2(0) = 0\):

\[
A_1(z) = A_0[\cos(\kappa_ez) + i(\delta_a/\kappa_e)\sin(\kappa_ez)], \\
A_2(z) = A_0(i\kappa_{21}/\kappa_e)\sin(\kappa_ez).
\]
Even though $A_2 = 0$ at $z = 0$, some power is transferred to the second core as light propagates inside a coupler.

Power transfer follows a periodic pattern.

Maximum power transfer occurs for $\kappa_e z = m\pi/2$.

Coupling length is defined as $L_c = \pi/(2\kappa_e)$. 

Symmetric couplers

- Maximum power transfer occurs for a symmetric coupler ($\delta_a = 0$)
- General solution for a symmetric coupler of length $L$:
  
  $A_1(L) = A_1(0) \cos(\kappa L) + iA_2(0) \sin(\kappa L)$
  
  $A_2(L) = iA_1(0) \sin(\kappa L) + A_2(0) \cos(\kappa L)$

- This solution can be written in a matrix form as
  
  $\begin{pmatrix} A_1(L) \\ A_2(L) \end{pmatrix} = \begin{pmatrix} \cos(\kappa L) & i \sin(\kappa L) \\ i \sin(\kappa L) & \cos(\kappa L) \end{pmatrix} \begin{pmatrix} A_1(0) \\ A_2(0) \end{pmatrix}$.

- When $A_2(0) = 0$ (only one beam injected), output fields become
  
  $A_1(L) = A_1(0) \cos(\kappa L)$, \quad $A_2(L) = iA_2(0) \sin(\kappa L)$

- A coupler acts as a beam splitter; notice $90^\circ$ phase shift for the cross port.

Credit: Agrawal
Symmetric couplers

- Simplest application of a fiber coupler is as an optical tap.

- If $\rho$ is close to 1, a small fraction of input power is transferred to the other core.

- Another application consists of dividing input power equally between the two output ports ($\rho = \frac{1}{2}$).

- Coupler length $L$ is chosen such that $\kappa L = \pi/4$ or $L = L_c/2$. Such couplers are referred to as 3-dB couplers.

- Couplers with $L = L_c$ transfer all input power to the cross port.

- By choosing coupler length appropriately, power can be divided between two output ports in an arbitrary manner.
Coupler performance parameters (I)

- **Coupling ratio or splitting ratio:**

  \[ CR = \frac{\text{Power from any single output}}{\text{Total power out to all ports}} = \frac{P_t}{P_{T\text{ out}}} \]

  \[ CR = 10\log_{10} \frac{P_2}{P_1 + P_2} \quad \text{2 x 2 case in dB} \]

- **Excess loss:**

  \[ L_e = \frac{P_{in}}{P_{T\text{ out}}} \]

  \[ L_e = 10\log_{10} \frac{P_{in}}{P_1 + P_2} \quad \text{2 x 2 case in dB} \]
Coupler performance parameters (II)

- **Insertion loss:**

  \[ L_i = \frac{\text{Power from any single output}}{\text{Power input}} = \frac{P_t}{P_{in}} \]

  \[ L_i = 10 \log_{10} \left( \frac{P_t}{P_{in}} \right) \quad \text{In dB} \]

- **Isolation or crosstalk:**

  \[ L_{iso} = \frac{\text{Input power at one port}}{\text{Reflected power back into other input port}} \]

  \[ L_{iso} = 10 \log_{10} \left( \frac{P_{in}}{P_3} \right) \quad \text{In dB} \]
Fiber star coupler

Combines power from $N$ inputs and divided them between $N$ outputs

Coupling ratio

$$CR = 10 \log_{10} \frac{1}{N} = 10 \log_{10} N$$

Excess loss

$$L_e = 10 \log_{10} \frac{P_{in}}{N} \frac{1}{P_{out,i}}$$
Wavelength-dependent couplers

- Wavelength-division multiplexers (WDM) types:
  - 3 port devices (4th port terminated)
  - 1310 / 1550 nm (“classic” WDM technology)
  - 1480 / 1550 nm and 980 / 1550 nm for pumping optical amplifiers
  - 1550 / 1625 nm for network monitoring

- Insertion and rejection:
  - Low loss (< 1 dB) for path wavelength
  - High loss (20 to 50 dB) for other wavelength
Wavelength-dependent couplers

- Fused biconic taper is made and monitored as it is being pulled.
- When 1550nm is in the bar state and 1310nm is in the cross state, pulling is stopped - - a coarse WDM filter results.
WDM couplers

Fused coupler type WDM

- Low loss (<0.5dB)
- Small size (35x5.5mm)
- Low cost (~$200)

Thin film type WDM

- Low loss (<0.5dB)
- Small size (35x5.5mm)
- Low cost (~$200)
The Singlemode Wavelength Division Multiplexers combine or separate light at different wavelengths. They offer very low insertion loss, low polarization dependence, high isolation and excellent environmental stability. These components have been extensively used in EDFA, CATV, WDM networks and fiber optics instrumentation.

### Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center Wavelength ($\lambda_c$)</td>
<td>nm</td>
<td>980/1550</td>
</tr>
<tr>
<td>Operating Wavelength</td>
<td>nm</td>
<td>$\lambda_c \pm 15$</td>
</tr>
<tr>
<td>Min. Isolation</td>
<td>dB</td>
<td>20</td>
</tr>
<tr>
<td>Max. Insertion Loss</td>
<td>dB</td>
<td>0.15</td>
</tr>
<tr>
<td>Max. Polarization Dependent Loss</td>
<td>dB</td>
<td>0.1</td>
</tr>
<tr>
<td>Thermal Stability</td>
<td>dB/°C</td>
<td>$\leq 0.002$</td>
</tr>
<tr>
<td>Min. Return Loss</td>
<td>dB</td>
<td>60</td>
</tr>
<tr>
<td>Min. Directivity</td>
<td>dB</td>
<td>60</td>
</tr>
<tr>
<td>Max. Optical Power (Continuous Wave)</td>
<td>mW</td>
<td>300</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>°C</td>
<td>-40 to +75</td>
</tr>
<tr>
<td>Storage Temperature</td>
<td>°C</td>
<td>-40 to +85</td>
</tr>
</tbody>
</table>

*IL is 0.5 dB higher, RL is 5 dB lower for each connector added.*

*Test at central wavelength only.*
Isolators

- **Polarization sensitive isolator**
  - Low loss (<0.5dB)
  - Small size (35x5.5mm)
  - Low cost (~$200)

- **Polarization insensitive isolator**

Forward
- Faraday crystal
- 0° polarizer
- 45° polarizer
- Pass

Block
- Faraday crystal
- 90° polarizer

Backward

Polarization sensitive isolator

Polarization insensitive isolator

- **Birefringent Wedge**
- **Faraday Rotator**
- **Birefringent Wedge**
Isolators

The Polarization Insensitive Isolator is designed and manufactured according to Telcordia standard. The unique manufacturing process and optical path epoxy-free design enhance the device high power handling capability. The device is characterized with high performance, high reliability and low cost. It has been widely used in EDFAs, Raman amplifiers, DWDM systems, fiber lasers, transmitters and other fiber optics communication equipments to suppress back reflection and back scattering.

**Specifications**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Single Stage</th>
<th>Dual Stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center Wavelength ($\lambda_c$)</td>
<td>nm</td>
<td>1310, 1480 or 1550</td>
<td></td>
</tr>
<tr>
<td>Typ. Peak Isolation</td>
<td>dB</td>
<td>42</td>
<td>58</td>
</tr>
<tr>
<td>Min. Isolation, $\lambda_c \pm 10$ nm, 23 °C, all polarization states</td>
<td>dB</td>
<td>30</td>
<td>46</td>
</tr>
<tr>
<td>Typ. Insertion Loss, $\lambda_c$, 23 °C; all polarization states</td>
<td>dB</td>
<td>0.35</td>
<td>0.4</td>
</tr>
<tr>
<td>Max. Insertion Loss, $\lambda_c \pm 20$ nm, all temperature, all</td>
<td>dB</td>
<td>0.5</td>
<td>0.6</td>
</tr>
<tr>
<td>polarization states</td>
<td></td>
<td></td>
<td>0.9</td>
</tr>
<tr>
<td>Min. Return Loss (Input/Output)</td>
<td>dB</td>
<td>60/55</td>
<td>60/55</td>
</tr>
<tr>
<td>Max. Polarization Dependent Loss, 23 °C</td>
<td>dB</td>
<td>0.05</td>
<td>0.15</td>
</tr>
<tr>
<td>Max. Polarization Mode Dispersion</td>
<td>ps</td>
<td>0.20</td>
<td>0.05</td>
</tr>
<tr>
<td>Max. Optical Power (Continuous Wave)</td>
<td>mW</td>
<td>300</td>
<td></td>
</tr>
<tr>
<td>Max. Tensile Load</td>
<td>N</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Fiber Type</td>
<td></td>
<td>SMF-28 fiber</td>
<td></td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>°C</td>
<td>-5 to +70</td>
<td></td>
</tr>
<tr>
<td>Storage Temperature</td>
<td>°C</td>
<td>-40 to +85</td>
<td></td>
</tr>
</tbody>
</table>

*IL is 0.3 dB higher, RL is 5 dB lower for each connector added.*
Questions for Thoughts

What is the new fiber component that you think may be useful to have?

Can we replace all traditional optics with fiber-based components?

How can you turn your experimental setup into fiber-based?

Where are fiber-based components made?

How can you start a successful company providing fiber components and devices?