Part 4: fiber components
Fiber optic system components

- Connectors
- Directional couplers
- Lens couplers
- Attenuators
- Delays
- Polarization controllers
- Isolators
- Filters
- Modulators
- Amplifiers
- Detectors
Connectors

- Cores must be aligned to sub-micron accuracy
  - Sub-micron concentricity between core, cladding, ferrule, sleeve
  - Cores in contact avoid loss at interface (PC)
  - Loss through is ~0.2dB average, though variable and non-repeatable
  - Ends are polished convex, to ensure core contact
  - Still some back reflection at discontinuity (see RWV p. 292, esp. 294)

- Some back reflection still exists, minimized by 8 degree angle (APC)
  - Back reflection loss >60dB

- Screw-on and push-on styles (FC, SC, LC)

- Mechanical splices
  - Push flat cleaved fibers together in a tube or groove
    - Fibers are cleaved flat using a good quality “cleaver”
    - High loss (~2 dB), but quick and cheap

- Fusion splices
  - Melt fibers together with hot arc or filament
  - Lowest loss (<0.02dB), negligible back reflection
  - Align cladding, assume concentricity, or align cores by passing light through
  - Some skill, expensive machine needed ($5-100k, depending on complexity)
Directional couplers

- Evanescent field in cladding couples to nearby core
- High directivity, low loss, easily manufacturable in any coupling ratio
- Tree for multiple splits

![Diagram of directional couplers](image)
Lens coupler

- To break out of fiber for a short distance, to insert some optical element
- Use lenses to make collimated beam between fibers
- Typical gradient index (GRIN) lens (RWV page 754)
- Less than 1dB loss
Attenuators

- Pulling connectors apart (see RWV p. 783)
  - Adjustable
  - Fixed ring
- Blocking free space beam
  - Digitally controlled versions
- Bend loss
  - Loops or s-curves
- Short sections of lossy fiber
  - Packaged like RF attenuators
Variable phase/time delays

- Optical trombone
- Piezo fiber stretcher
- Heated fiber spool
- AO fiber frequency shifter
- Optical IQ modulator
- RF IQ modulator
Trombone, stretcher, heater

- **Optical trombone**
  - A moving mirror or prism on a rail with motor
  - Slow, long range, few dB loss, stable with power removed

- **Piezo fiber stretcher**
  - Pulls on fiber to change delay
    - Equation, note stress and lengthening both
    - Acoustic frequency, low loss, short range (~10^-4 to 10^-5 of total length, 12ps for 40m spool)

- **Heated fiber spool**
  - ~10^-5/C thermal delay coefficient
  - Very slow, low loss, cheap
Piezo stretcher

\[
\Delta t/t = \varepsilon \left\{ 1 + \frac{n_0^2}{2} \left[ P_{12} - v(P_{11} + P_{12}) \right] \right\}
\]

= (0.78 to 0.81)\varepsilon \text{ (depending on ref.)}

**MODULATOR**

<table>
<thead>
<tr>
<th>Operational Wavelengths</th>
<th>1260 to 1625 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulation Constant [low frequency]</td>
<td>27 radians/V @ 1.3 (\mu)m</td>
</tr>
<tr>
<td></td>
<td>23 radians/V @ 1.55 (\mu)m</td>
</tr>
<tr>
<td>Fiber Stretch / Optical Delay</td>
<td>3.8 (\mu)m/V, 0.028 ps/V</td>
</tr>
<tr>
<td>Linearity</td>
<td>3% at full scale drive</td>
</tr>
<tr>
<td>Frequency Range</td>
<td>See chart page 2</td>
</tr>
<tr>
<td>Optical Loss</td>
<td>(\leq 0.5) dB, typical 0.2 dB</td>
</tr>
<tr>
<td>Extinction Ratio</td>
<td>n/a</td>
</tr>
<tr>
<td>Maximum Voltage Range [low frequency]</td>
<td>(\pm 400)V [800V P-P]</td>
</tr>
<tr>
<td>Impedance [off resonance]</td>
<td>Capacitance 0.1 (\mu)F, floating</td>
</tr>
<tr>
<td>Wire Lead</td>
<td>18 inches, flying leads, #30</td>
</tr>
<tr>
<td>Operational Temperature Range</td>
<td>0(^\circ) to 70(^\circ) C</td>
</tr>
<tr>
<td>Fiber Type</td>
<td>SMF-28e, 250 um acrylate jacket</td>
</tr>
<tr>
<td>Fiber Length</td>
<td>40 meters [includes 1 m bare fiber leads]</td>
</tr>
</tbody>
</table>
RF in-phase and quadrature (I&Q) modulator

- Input wave separated into two components, one shifted $\pi/2$ in phase
- Both components can be multiplied by [-1 to 1]
- They are added at the output to produce a phase shifted wave
  - If the control input is a continuous frequency, the modulator becomes a frequency shifter
Optical I and Q modulator

- Input signal is split equally in two arms
- Amplitude and phase can be controlled in both arms
  - Note that if both arms of a Mach-Zehnder modulator are driven together, the device becomes a pure phase modulator
- When recombined, the resultant output wave has controllable phase
- Used in Differential Phase Shift Keying (DPSK) telecommunications
  - Populate the complex plane with a ring of bit values (4 or 8)
Stress birefringence polarization controller

- Variable stress causes variable relative retardation parallel and perpendicular
- Rotation of the retarder with respect to the input polarization
  - Free space optic embodiment is Babinet compensator
Loop polarization controller

- Looping of fibers induces stress birefringence
- Loops ("paddles") are rotated with respect to the input and each other
- Arrangement allows access to any part of the Poincare sphere from any other part
Amplitude modulation

- $M$ is modulation depth
- Note that spectrum analyzer will detect sideband power, so squaring carrier/sideband ratios

$$V(t) = \sqrt{2C} \left[ 1 + M \cos \omega_m t \right] \sin \omega_0 t$$

$$= \sqrt{2C} \left[ \sin \omega_0 t + \frac{M}{2} \sin(\omega_0 + \omega_m) t + \frac{M}{2} \sin(\omega_0 - \omega_m) t \right]$$
Phase modulation

\[ V(t) = \sqrt{2C} \sin \left[ \omega_0 t + \theta \sin \omega_m t \right], \]

- Theta is the modulation depth, which is the peak phase deviation in radians
- If the “pi phase shift” voltage is \( V_p \), the modulation depth is \( \pi \cdot V / V_p \)

\[ V(t) = \sqrt{2C} J_0(\theta) \sin \omega_0 t + \sqrt{2C} \sum_{n=1}^{\infty} J_n(\theta) \sin(\omega_0 + n\omega_m) t \]

\[ + \sqrt{2C} \sum_{n=1}^{\infty} (-1)^n J_n(\theta) \sin(\omega_0 - n\omega_m) t. \]
High-index phase modulation

- Sideband amplitudes are the Bessel functions
- One can observe the sideband power, the square of the amplitudes, with a tunable filter
- Mod index is easily determined by noting the relative sideband heights

\[ e(t) = A_c[J_0(\beta) \cos \omega_c t] - J_1(\beta)[\cos(\omega_c - \omega_m)t - \cos(\omega_c + \omega_m)t] + J_2(\beta)[\cos(\omega_c - 2\omega_m)t + \cos(\omega_c + 2\omega_m)t] - J_3(\beta)[\cos(\omega_c - 3\omega_m)t - \cos(\omega_c + 3\omega_m)t] + \cdots \]

\[ = A_c \sum_{n=-\infty}^{\infty} J_n(\beta) \cos(\omega_c + n\omega_m)t \]
Modulators, electro-optic

- Waveguide on electro-optic substrate (RWV p. 768)
  - Phase
    - Waveguide sort of like a fiber
    - Waveguide material changes index as a function of external field
    - Field applied over a few microns, so low voltage
    - Phase match RF and light for high speed (~100GHz)
  - Amplitude
    - Turns phase modulation into amplitude modulation, by putting phase modulator in an interferometer
    - When phase difference is $\pi$, light is extinguished because field at output looks like higher order mode, doesn’t propagate
    - Note: not an amplitude modulator but a power modulator, thus AM sidebands are different
- RWV page 709, 710
EO amplitude (power) modulator

- Phase

\[ P(t) = P_0 \sin^2 \left( \frac{1}{2} \left( \pi \frac{V(t)}{V_\Pi} + \phi_B \right) \right) \]

\[ = P_0 \frac{1}{2} \left( 1 - \cos \left( \pi \frac{V(t)}{V_\Pi} + \phi_B \right) \right) \]

\[ \sin^2 \theta = \frac{1}{2} \left( 1 - \cos 2\theta \right) \]
Modulators, acousto-optic

- **Bragg diffraction** interacts acoustic wave with optical wave
- Periodic index modulation can be created by acoustic wave (stress-optic effect), launched by RF (piezoelectric effect)
- Index modulation is moving at acoustic velocity, Doppler shifting the optical wave up or down depending on geometry
  - The frequency shift is the RF frequency
  - The added phase shift is the RF phase
- Diffraction efficiency depends on index wave amplitude and interaction length
  - Diffraction efficiency can be modulated by changing RF amplitude, resulting in amplitude modulator
- Other functions such as tunable filters and scanners can be realized using swept RF sources

\[ n(z, t) = n + \Delta n \cos(\omega t - kz), \]

\[ \Delta n = -\frac{1}{3} n^3 p_{ij} a_j, \]
AO frequency shifter

- Constant amplitude RF applied to modulator
- Frequency shift is RF frequency
- Efficiency of diffraction into first order $\sim 60\%$
- Couple light out of fiber and back in after diffraction

\[ K_d = K_i + /- K \]

- $K_i = 2\pi n_i/\lambda_0$ - wave vector of the incident beam.
- $K_d = 2\pi n_i/\lambda_d$ - wave vector of the diffracted beam.
- $K = 2\pi F/v$ - wave vector of the acoustic wave.
Direct modulation of laser diode

- Common in telecom, cable TV
- Capable of very low noise

- Low noise RF source: modelocked laser pulse train on photodiode, bandpass filter at 2GHz
- Source jitter of 11 fsec RMS from 1kHz to 40MHz limited by photodiode shot noise at -155dBc
- Noise after link is 15fsec RMS, 1kHz to 40MHz
- No phase noise added by the link from 10Hz to 10kHz
Isolator

- Based on Faraday effect (RWV page 721)
- Non-reciprocal polarization rotation makes optical “diode” function
- Can be extended to make circulator
- Input polarization-independent versions created by splitting input into two arms, isolating each and then recombining
Filters

- **Dielectric bandpass or notch filter**
  - Stack of transparent layers with alternating indices of refraction (RWV p. 295)
  - Direct analogy with periodic microwave filter designs
- **Fiber Bragg grating**
  - Periodic index modulation in fiber itself, very narrow band notch filter
- **Birefringent filter (Lyot and Solc filters)**
  - Based on wavelength dependence of polarization state after birefringent element
- **Fabry-Perot resonator**
  - Two-mirror resonator, tunable by varying spacing
  - Essentially one-dimensional fiber implementation has near ideal characteristics
Bragg gratings in fiber

- William Morey

Filter Isolation: fraction of a dB to >100dB
Filter Bandwidth: picometers to hundreds nm
Detectors

- PIN junction photodiode is most common fast detector (~100GHz)
  - Bandwidth ~ 0.35/risetime for simple RC
  - Bandwidth ~0.44/pulse width for Gaussian
- Bandgap determines spectral sensitivity
Measuring AM-to-PM characteristic

- Saturation occurs when photocarrier density is high enough to diminish intrinsic electric field
  - Efficiency decreases, ultimately limiting signal amplitude
  - Junction capacitance is modulated, changing phase transfer function
    - “AM-to-PM”
    - Bandwidth decreases
- Time domain response shows “tail”
- Most diodes saturate at around 100-200mV into 50 Ohms, though higher sat power models are available

- “Kink” in AM/PM curve provides zero-slope operating point
  - +/- 10% in power produces <10fs timing shift
  - Power is easily regulated to 1%
Detection in frequency domain

- Note that photocurrent is proportional to optical power
  - Diode output is proportional to the square of the optical field ("square law detector"), thus can be used as a mixer to derive difference frequency (if it’s within detector bandwidth)
  - Observe beats between two optical signals
  - Detect envelope modulation of optical wave
Noise sources in detection

\[
\frac{v_o^2}{2} = \left[ \frac{2q_i d R_d^2}{(R_s + R_d)^2} + \frac{4kT}{R_s + R_d} + \frac{i_n^2}{R_f} + \frac{4kT}{R_f} \right] R_f^2
\]

\[+ \bar{c}_n^2 \left( 1 + \frac{R_f}{R_s + R_d} \right)^2 \text{ V}^2/\text{Hz} \tag{28}\]

where

- \( i_d \): dark current;
- \( i_n \): op-amp input noise current spectral density;
- \( c_n \): op-amp input noise voltage spectral density;
- \( R_d \): photodiode dynamic resistance;
- \( R_s \): photodiode series resistance.