OPTI510R: Photonics

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Announcement

- Final exam May 1, room 307, starting at 11 AM
Review

- Introduction to optical fibers
- Attenuation and dispersion
- Fiber fabrication
- Dispersion compensation
- Nonlinear optical effects
- Optical amplifiers
- Passive fiber components
- Introduction to lasers
- Semiconductor lasers
- Detectors
- Semiconductor detectors
- Optical network
Goals

- Understand the most important concepts in Photonics
- Learn the working principles of photonics devices
- Identify the remaining challenges in the field
- Think about possible solutions
Introduction to optical fibers

The Nobel Prize in Physics 2009

"for groundbreaking achievements concerning the transmission of light in fibers for optical communication"

"for the invention of an imaging semiconductor circuit – the CCD sensor"

Charles K. Kao
1/2 of the prize

Willard S. Boyle
1/4 of the prize

George E. Smith
1/4 of the prize
Optical fibers

The working principle of standard optical fiber can be explained using TIR

Photonics crystal fibers

The refractive index of the core is smaller than the refractive index of the cladding

Guided-wave analysis

- core for $\rho < a$
- cladding for $\rho > a$

$n_2$

$n_1$
Guided-wave analysis

Maxwell’s equations in the Fourier domain lead to

$$\nabla^2 \tilde{E} + n^2(\omega)k_0^2 \tilde{E} = 0.\n$$

$n = n_1$ inside the core but changes to $n_2$ in the cladding.

Useful to work in cylindrical coordinates $\rho, \phi, z$.

Common to choose $E_z$ and $H_z$ as independent components.

Equation for $E_z$ in cylindrical coordinates:

$$\frac{\partial^2 E_z}{\partial \rho^2} + \frac{1}{\rho} \frac{\partial E_z}{\partial \rho} + \frac{1}{\rho^2} \frac{\partial^2 E_z}{\partial \phi^2} + \frac{\partial^2 E_z}{\partial z^2} + n^2 k_0^2 E_z = 0.$$

$H_z$ satisfies the same equation.
Guided-wave analysis

- Use the method of separation of variables:
  \[ E_z(\rho, \phi, z) = F(\rho)\Phi(\phi)Z(z). \]

- We then obtain three ODEs:
  \[ \frac{d^2Z}{dz^2} + \beta^2 Z = 0, \]
  \[ \frac{d^2\Phi}{d\phi^2} + m^2\Phi = 0, \]
  \[ \frac{d^2F}{d\rho^2} + \frac{1}{\rho} \frac{dF}{d\rho} + \left( n^2k_0^2 - \beta^2 - \frac{m^2}{\rho^2} \right) F = 0. \]

- \( \beta \) and \( m \) are two constants (\( m \) must be an integer).

  First two equations can be solved easily to obtain
  \[ Z(z) = \exp(i\beta z), \quad \Phi(\phi) = \exp(im\phi). \]

- \( F(\rho) \) satisfies the Bessel equation.
Guided-wave analysis

- General solution for \( E_z \) and \( H_z \):

\[
E_z = \begin{cases} 
A J_m(p \rho) \exp(i m \phi) \exp(i \beta z) & ; \rho \leq a, \\
C K_m(q \rho) \exp(i m \phi) \exp(i \beta z) & ; \rho > a.
\end{cases}
\]

\[
H_z = \begin{cases} 
B J_m(p \rho) \exp(i m \phi) \exp(i \beta z) & ; \rho \leq a, \\
D K_m(q \rho) \exp(i m \phi) \exp(i \beta z) & ; \rho > a.
\end{cases}
\]

\[ p^2 = n_1^2 k_0^2 - \beta^2, \quad q^2 = \beta^2 - n_2^2 k_0^2. \]

- Other components can be written in terms of \( E_z \) and \( H_z \):

\[
E_\rho = \frac{i}{p^2} \left( \beta \frac{\partial E_z}{\partial \rho} + \frac{\mu_0}{\rho} \frac{\partial H_z}{\partial \phi} \right), \quad E_\phi = \frac{i}{p^2} \left( \frac{\beta}{\rho} \frac{\partial E_z}{\partial \phi} - \mu_0 \omega \frac{\partial H_z}{\partial \rho} \right),
\]

\[
H_\rho = \frac{i}{p^2} \left( \beta \frac{\partial H_z}{\partial \rho} - \varepsilon_0 n^2 \frac{\omega}{\rho} \frac{\partial E_z}{\partial \phi} \right), \quad H_\phi = \frac{i}{p^2} \left( \frac{\beta}{\rho} \frac{\partial H_z}{\partial \phi} + \varepsilon_0 n^2 \frac{\omega}{\rho} \frac{\partial E_z}{\partial \rho} \right).
\]

(credit: G. Agrawal)
Bessel function basics

Bessel functions of the first kind

\[ u(r) \propto J_l(k_T r) \]
(core)

Modified Bessel functions of the second kind

\[ u(r) = K_l(r) \]
(cladding)
Boundary conditions: \( E_z, H_z, E_\phi, \) and \( H_\phi \) should be continuous across the core–cladding interface.

Continuity of \( E_z \) and \( H_z \) at \( \rho = a \) leads to
\[
AJ_m(pa) = CK_m(qa), \quad BJ_m(pa) = DK_m(qa).
\]
Continuity of \( E_\phi \) and \( H_\phi \) provides two more equations.

Four equations lead to the eigenvalue equation
\[
\left[ \frac{J'_m(pa)}{pJ_m(pa)} + \frac{K'_m(qa)}{qK_m(qa)} \right] \left[ \frac{J'_m(pa)}{pJ_m(pa)} + \frac{n_2^2}{n_1^2} \frac{K'_m(qa)}{qK_m(qa)} \right]
= \frac{m^2}{a^2} \left( \frac{1}{p^2} + \frac{1}{q^2} \right) \left( \frac{1}{p^2} + \frac{n_2^2}{n_1^2} \frac{1}{q^2} \right)
\]
\[
p^2 = n_1^2 k_0^2 - \beta^2, \quad q^2 = \beta^2 - n_2^2 k_0^2.
\]

(credit: G. Agrawal)
Eigen-value equation

- Eigenvalue equation involves Bessel functions and their derivatives. It needs to be solved numerically.

- Noting that \( p^2 + q^2 = (n_1^2 - n_2^2)k_0^2 \), we introduce the dimensionless \( V \) parameter as

\[
V = k_0 a \sqrt{n_1^2 - n_2^2}.
\]

- Multiple solutions for \( \beta \) for a given value of \( V \).

- Each solution represents an optical mode.

- Number of modes increases rapidly with \( V \) parameter.

- Effective mode index \( \tilde{n} = \beta / k_0 \) lies between \( n_1 \) and \( n_2 \) for all bound modes.

(credit: G. Agrawal)
Eigen-value equation

- Useful to introduce a normalized quantity
  \[ b = \frac{\bar{n} - n_2}{n_1 - n_2}, \quad (0 < b < 1) \]

- Modes quantified through \( \beta(\omega) \) or \( b(V) \).
Attenuation in optical fiber

- Attenuation coefficient (dB/km)

\[
\alpha = \frac{1}{L} \log_{10} \frac{1}{T} \quad \text{with} \quad T = \frac{P(L)}{P(0)}
\]

- Power transmission ratio as a function of distance \( z \)

\[
\frac{P(z)}{P(0)} = e^{-\alpha z} \quad \text{for} \quad \alpha \quad \text{in} \, \text{km}^{-1}
\]

- Calculate \( \alpha \) (dB) through \( \alpha \) (km\(^{-1}\))

\[
\alpha \text{ (dB)} = 4.343 \times \alpha \text{ (km}^{-1}\text{)}
\]
Sources of attenuation in silica fiber

- **Absorption**
  - Vibrational transitions in the IR
  - Electronic and molecular transitions in the UV
  - Extrinsic absorption from adsorbed water and other impurities

- **Scattering**
  - Rayleigh scattering
  - Extrinsic scattering from defects due to manufacturing errors
  - Raman, Brillouin scattering
Propagation loss in optical fiber

Current loss is < 0.2dB/km for single mode fiber working around 1550nm
Communication window

<1dB/mile of loss over >10 THz of bandwidth!

Loss performance in fused silica fiber
Dispersion in optical fiber

- **Modal dispersion**
  - Occurs in multimode fibers coming from differences in group velocity for different modes

- **Material dispersion**
  - Results from the wavelength dependence of the bulk refractive index

- **Waveguide dispersion**
  - Results from the wavelength dependence of the effective index in a waveguide
  - Material + waveguide dispersion is termed **chromatic dispersion**

- **Polarization mode dispersion**
  - Results from the fact that different polarizations travel at different speeds due to small birefringence that is present

- **Nonlinear dispersion** – example is self-phase modulation
Modal dispersion occurs in multimode fibers as a result of differences in the group velocities of the various modes.

A single pulse of light entering an M-mode fiber spreads into M pulses.

Estimate of pulse spread

\[
\sigma_\tau = \frac{1}{2} \left( \frac{L}{v_{\min}} - \frac{L}{v_{\max}} \right),
\]

- Where \( v_{\min} \) and \( v_{\max} \) are the smallest and largest group velocity of the modes.

For step index fiber,

\[
v_{\min} \approx c_1 (1 - \Delta), \quad v_{\max} \approx c_1, \quad \Delta = (n_1^2 - n_2^2) / 2n_1^2
\]

\[
\sigma_\tau \approx \frac{L\Delta}{2c_1}
\]
Material dispersion

- Spread of wave packet after traveling a distance $L$ through a dispersive material

$$\Delta \tau = \frac{L}{c} \left( N_g(\lambda_1) - N_g(\lambda_2) \right) = \frac{L}{c} \frac{dN_g}{d\lambda} \Delta \lambda = \frac{L}{c} \frac{dN_g}{d\lambda} \Delta \lambda$$

Since

$$\frac{dN_g}{d\lambda} = \frac{d}{d\lambda} \left( n - \lambda \frac{dn}{d\lambda} \right) = -\lambda \frac{d^2 n}{d\lambda^2}$$

We get

$$\Delta \tau = -\lambda \frac{d^2 n}{d\lambda^2} \frac{L}{c} \Delta \lambda \quad \text{where}$$

$$D_M = -\lambda \frac{\partial^2 n}{c \partial \lambda^2}$$

is the material dispersion parameter
In single-mode fibers the group delay, \( \tau_g \), determines the transit time of a pulse traveling through a unit length of fiber. To get the waveguide dispersion we want to express the group delay in terms of normalized parameters, \( b \) and \( V \):

**Normalized propagation constant:**

\[
b = \frac{\frac{\beta}{k_0} - n_{\text{clad}}}{n_{\text{core}} - n_{\text{clad}}}.
\]

**Normalized frequency:**

\[
V = \frac{2\pi a}{\lambda_0} \sqrt{n_{\text{core}}^2 - n_{\text{clad}}^2}
\]

\[
\tau_g = \frac{d\beta}{d\omega} = \frac{d\beta}{dk_0} \frac{dk_0}{d\omega} = \frac{1}{c} \frac{d\beta}{dk_0}.
\]

Using normalized parameters:

\[
\frac{d\beta}{dk_0} = \frac{d\beta}{dV} \frac{dV}{dk_0} = \frac{d\beta}{dV} \frac{V}{k_0}.
\]

We get:

\[
\tau_g = \frac{1}{c} \frac{d\beta}{dk_0} = \frac{1}{c} \frac{V}{k_0} \frac{d\beta}{dV}.
\]
Waveguide dispersion

Defining $\Delta = \frac{n_{\text{core}} - n_{\text{clad}}}{n_{\text{core}}}$ and with $\beta = [b(n_{\text{core}} - n_{\text{clad}}) + n_{\text{clad}}]k_0 \approx k_0 n_{\text{clad}}(1 + b\Delta)$ (when $\Delta$ is small),

$$\tau_g = \frac{1}{c} \frac{V}{k_0} \frac{d}{dV} \left[k_0 n_{\text{clad}}(1 + b\Delta)\right]$$

$$= \frac{1}{c} \frac{V}{k_0} \frac{d(k_0 n_{\text{clad}})}{dV} + \frac{1}{c} \frac{V}{k_0} \frac{d(b\Delta k_0 n_{\text{clad}})}{dV}$$

$\tau_w$ : waveguide delay

$\tau_m$ : material delay

$$\tau_w = \frac{1}{c} \frac{V}{k_0} \frac{d(b\Delta k_0 n_{\text{clad}})}{dV}.$$ Noting that $V = \sqrt{2\Delta n_{\text{clad}} k_0 a}$, we get:

$$\tau_w = \frac{1}{c} n_{\text{clad}} \Delta \frac{d(bV)}{dV},$$ from which we get the waveguide dispersion

$$\frac{d\tau_w}{dV} = \frac{1}{c} n_{\text{clad}} \Delta \frac{d^2(bV)}{dV^2}.$$ With $dV = a\sqrt{n_{\text{core}}^2 - n_{\text{clad}}^2} dk_0$ and $d\lambda = -\frac{\lambda}{k_0} \frac{dk_0}{k_0}$,

we finally get:

$$\frac{d\tau_w}{d\lambda} = -\frac{n_{\text{clad}} \Delta}{c \lambda} \frac{d^2(bV)}{dV^2}.$$ Waveguide dispersion!

Note: Here we have neglected the dependence of $\Delta$ on $k_0$, which is negligibly small.
Waveguide dispersion

\[ b, \frac{d(Vb)}{dV} \text{ and } V \frac{d^2(Vb)}{dV^2} \] as a function of the V number:

Chromatic dispersion of SMF

- Chromatic dispersion is the combination of material and waveguide dispersion in single-mode fiber

\[ D = -\frac{\lambda}{c} \frac{d^2 n_{\text{core}}}{d\lambda^2} - \frac{n_{\text{core}}}{c\lambda} \frac{\Delta V}{dV^2} \left( \frac{d^2 (Vb)}{dV^2} \right) \]

\( (D_{\text{Material}}) \quad (D_{\text{Waveguide}}) \)

- At 1.55 \( \mu \)m, \( D = +17 \text{ps/km-nm} \)
- At 1.312 \( \mu \)m, dispersion is zero

Fabrication techniques

- Fiber preform fabrication
- Fiber pulling
Rod-in-tube technique

Rod-in-tube method: UA

High precision ultrasonic drilling and grinding machines for glass rod processing

UA fiber drawing tower
Modified Chemical deposition

Modified chemical vapor deposition method
Active fiber fabrication

MCVD process

Nano-particle vapor deposition (Liekki)

http://www.youtube.com/watch?v=6CqT4DuAVxs
There are a lot of specialty optical fibers!

- Photonics crystal fibers
- Doped (active) optical fibers
- Liquid core optical fibers (*if have time*)
- Large mode area optical fibers
- Chiral core coupled optical fibers
- Polarizing fibers
- ...
Photonics crystal fibers

Dispersion compensation

- Pre-chirp technique
- Dispersion compensating fibers
- Chirped fiber Bragg grating
Dispersion compensating fibers

Total Dispersion in Several Fiber Types

- Standard Single Mode: Zero at 1.3 μm
- Nonzero Dispersion-Shifted: Zero at 1.5 μm
- Dispersion-Compensating
Dispersion compensating fibers

<table>
<thead>
<tr>
<th>Standard fiber</th>
<th>Dispersion compensating fiber</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Standard fiber diagram" /></td>
<td><img src="image2.png" alt="Dispersion compensating fiber diagram" /></td>
</tr>
</tbody>
</table>

\[
\beta_{21}L_1 + \beta_{22}L_2 = 0, \text{ or }
\]

\[
D_1L_1 + D_2L_2 = 0.
\]

Advantage:

- Fiber format
- Low cost
- Broadband

Disadvantage:

- Small mode field diameter
- Higher loss

DCF modules
Nonlinear effects in optical fibers

- Introduction to nonlinear optics
- Stimulated Brillouin scattering
- Stimulated Raman scattering
- Self-phase modulation
- Cross phase modulation
- Soliton propagation
- Four-Wave-Mixing (FWM)
Nonlinear optics

\[ P = \chi^{(1)} E + \chi^{(2)} E^2 + \chi^{(3)} E^3 + \ldots \]

\( \chi^{(2)}, \chi^{(3)} \ldots \) are very small

**Table 4.1.1 Typical values of the nonlinear refractive index**

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>( n_2 ) (cm(^2)/W)</th>
<th>( \chi_{1111}^{(3)} ) (m(^2)/V(^2))</th>
<th>Response Time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electronic polarization</td>
<td>( 10^{-16} )</td>
<td>( 10^{-22} )</td>
<td>( 10^{-15} )</td>
</tr>
<tr>
<td>Molecular orientation</td>
<td>( 10^{-14} )</td>
<td>( 10^{-20} )</td>
<td>( 10^{-12} )</td>
</tr>
<tr>
<td>Electrostriction</td>
<td>( 10^{-14} )</td>
<td>( 10^{-20} )</td>
<td>( 10^{-9} )</td>
</tr>
<tr>
<td>Saturated atomic absorption</td>
<td>( 10^{-10} )</td>
<td>( 10^{-16} )</td>
<td>( 10^{-8} )</td>
</tr>
<tr>
<td>Thermal effects</td>
<td>( 10^{-6} )</td>
<td>( 10^{-12} )</td>
<td>( 10^{-3} )</td>
</tr>
<tr>
<td>Photorefractive effect ( b )</td>
<td>(large)</td>
<td>(large)</td>
<td>(intensity-dependent)</td>
</tr>
</tbody>
</table>

Nonlinear optical effects

- Second harmonic generation (SHG)
- Third harmonic generation (THG)
- High harmonic generation (HHG)
- Sum/Difference frequency generation (SFG/DFG)
- Optical parametric processes (OPA, OPO, OPG)
- Kerr effect
- Self-focusing
- Self-phase modulation (SPM)
- Cross-phase modulation (XPM)
- Four-wave mixing (FWM)
- Multiphoton absorption
- Photo-ionization
- Raman/Brillouin scattering
- and more…
Stimulated Brillouin scattering

- Predicted by Leon Brillouin in 1922
- Scattering of light from acoustic waves
- Becomes a stimulated process when input power exceeds a threshold level
- Low threshold power for long fibers (5 mW)

Most of the power reflected backward after SBS threshold is reached!
Stimulated Brillouin scattering

- Pump produces density variations through electrostriction, resulting in an index grating which generates Stokes wave through Bragg diffraction.

- Energy and momentum conservation require:

\[ \Omega_B = \omega_p - \omega_s; \quad \mathbf{k}_A = \mathbf{k}_p - \mathbf{k}_s \]

- Acoustic waves satisfy the dispersion relation:

\[ \Omega_B = v_A^*|\mathbf{k}_A| = v_A^*|(\mathbf{k}_p - \mathbf{k}_s)| \sim 2^* v_A^*|\mathbf{k}_p| = 2^* v_A^* 2\pi^* n_p / \lambda_p \]

\[ f_A = \frac{\Omega_B}{2\pi} = 2^* v_A^* 2\pi^* n_p / \lambda_p \sim 11\text{GHz} \quad \text{(Brillouin frequency shift)} \]

if we use \( v_A = 5.96 \text{ km/s} \), \( n_p = 1.45 \), and \( \lambda_p = 1550\text{nm} \)
Brillouin gain spectrum in optical fibers

- Measured spectra for (a) silica-core (b) depressed-cladding, and (c) dispersion-shifted fibers

- Brillouin gain spectrum is quite narrow (50 MHz)

- Brillouin shift depends on GeO$_2$ doping within the core

- Multiple peaks are due to the excitation of different acoustic modes

Brillouin threshold in optical fibers

\[
\begin{align*}
\frac{dI_p}{dz} &= -g_B I_p I_s - \alpha I_p, \\
\frac{dI_s}{dz} &= -g_B I_p I_s + \alpha I_s,
\end{align*}
\]

\( \alpha \) is the fiber loss

\( g_B \) is the Brillouin gain coefficient

\[
P_{th} g_B L_e \frac{A_{eff}}{L_e} = 21
\]

\( P_{th} \) is the Brillouin threshold

Stimulated Raman scattering

• Discovered by C. V. Raman in 1928
• Scattering of light from vibrating silica molecules
• Amorphous nature of silica turns vibrational state into a band
• Raman gain is maximum near 13 THz
• Scattered light red-shifted by 100 nm in the 1.5 mm region

SRS threshold

\[
\begin{align*}
\frac{dI_s}{dz} &= g_R I_p I_s - \alpha_s I_s, \\
\frac{dI_p}{dz} &= -\frac{\omega_p}{\omega_s} g_R I_p I_s - \alpha_p I_p,
\end{align*}
\]

\[\frac{g_R P_{\text{cr}} L_{\text{eff}}}{A_{\text{eff}}} \approx 16.\]

For telecom fibers, \(A_{\text{eff}} = 50 - 75 \ \mu \text{m}^2\)

\[g_R = 10^{-13} \text{ m/W}\]

- Threshold power \(P_{th} \sim 100\text{mW} \) is too large to be of concern
- Inter-channel crosstalk in WDM systems because of Raman gain
Self-phase modulation (SPM)

\[ \gamma = \frac{n_2 \omega_0}{c A_{\text{eff}}} \]

\[ \varphi_{NL} = \gamma P_0 L \]

- First observed inside optical fiber by Stolen and Lin (1978)
- 90-ps pulses transmitted through a 100-m-long fiber
- Output spectrum depends on shape and chirp of input pulses.
- Even spectral compression can occur for suitably chirped pulses.
Optical Amplifiers

- Erbium Doped Fiber Amplifiers (EDFAs)
- Semiconductor Optical Amplifiers
- Raman Amplifiers
- Optical Parametric Amplifiers
Types of Optical Amplifiers

**Erbium Doped Fiber Amplifiers (EDFA’s)**
- Best performance
- Low cost, robust
- Wide spread use

**Semiconductor Optical Amplifiers**
- Small package
- Potential use for low-cost applications
- Potential use for optical switching

**Raman Amplifiers**
- Better noise performance compared to EDFA

**Optical parametric amplifier**
- High gain, broader bandwidth
Erbium-doped fiber amplifier

- Working around 1550nm
- Wide operating bandwidth
- Amplification of multiple channels
- Diode pumping
- Low cost, robust

First demonstration
Prof. David Payne and team
Published the research paper in the year 1987
at the University of Southampton, UK
Erbium-doped fiber amplifier

Main pump wavelengths: 980nm and 1480nm
Main optical characteristics

- Amplifier gain: \[ G = 10 \log \left( \frac{P_{\text{out}}}{P_{\text{in}}} \right) \]
- Gain non-uniformity
- Gain bandwidth
- ASE
- Gain saturation
- Noise figure: \[ NF = \frac{(S/N)_{\text{in}}}{(S/N)_{\text{out}}} \]
Gain saturation

(a) Signal Output Power (dBm)

(b) Gain (dB)

(c) ASE Power (dBm)

(d) Total Output Power (dBm)
Typical amplifier performance:

- High gain (30 - 50 dB)
- Low noise figure (3 - 6 dB)
- High output power (10 - 20 dBm)
- Flat gain (3 dB in 20 nm)
- High efficiency (40 - 80 %)
- Polarization insensitive

\[ \lambda_e = 1550 \text{ nm}, \ L = 10 \text{ m}, \ P_e = -20 \text{ dBm}, \ P_p = 50 \text{ mW} \]
EDFA: Disadvantages

- Can only work at a narrow wavelength range (C and L band)
- Requires specially doped fiber as gain medium
- Three-level system, so gain medium is opaque at signal wavelengths until pumped
- Requires long path length of gain medium (tens of meters in glass)
- Gain very wavelength-dependent and must be flattened
- Gain limited by cooperative quenching
- Relatively high noise figure due to ASE
Semiconductor optical amplifiers

- Small package
- Potential use for low-cost applications
- Potential use for optical switching
Semiconductor optical amplifiers

Performance of a typical SOA

Compared to EDFA: Lower gain, high noise figure, and lower output power
Semiconductor optical amplifiers

Historically, SOA problems:

- **SOA fast (≈ 1 ns) ⇒ bit-timescale signal distortions**
  
  NRZ signal through SOA

- **Nonlinearities, four-wave mixing ⇒ problem with WDM**

⇒ **EDFA preferred, except:**
  
  - Niche: transmissions outside C-band
  - Niche: integrated amplifiers (e.g. with photodiode)
  - Active MZI gates
  - Signal processing: λ conversion, regeneration...
Raman Fiber Amplifiers

Working principle of EDFA

Schematic of the quantum mechanical process taking place during Raman scattering

Raman Fiber Amplifiers

Raman gain profiles for a 1510-nm pump in three different fiber types. SMF, standard single mode fiber; DSF, dispersion shifted fiber; DCF, dispersion compensating fiber.
Schematic diagram of a Raman amplifier
Raman Fiber Amplifiers

Evolution of signal power in a bidirectionally pumped, 100-km-long Raman amplifier as the contribution of forward pumping is varied from 0 to 100%.

Which one is better? Co-pumping or Counter-pumping?
Degenerate and non-degenerate FWM process depicted on an energy level diagram.

Require optical fiber with zero dispersion near the pump wavelength for phase matching.
Optical Parametric Amplifier

Parametric gains are on both sides of the pump laser.

Graph showing parametric gain as a function of $\lambda_s - \lambda_p$, nm, with the equation $G = \frac{1}{4} \exp(2\gamma P_p L)$ and $G = (\gamma P_p L)^2$.
Optical Parametric Amplifier

FOPO with 70dB gain!
Optical Parametric Amplifier

Advantages:

• Gain bandwidth increasing with pump power
• Arbitrary center wavelength
• Very large gain (70dB)
• Unidirectional gain (no need for isolator)
• Compatibility with all-fiber devices
• High power capability
• Distributed amplification (low noise figure)
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
- …
Passive fiber components

- Directional couplers
- WDM couplers
- Isolators
- Fiber spicing and connectorization
Point-to-point WDM Transmission System - Building Blocks -
Lasers

- Brief history
- Laser characteristics
- Laser types
- Laser modes of operation
- Laser market
- Fiber lasers
Longitudinal modes

Allowed modes of the cavity are those where mirror separation is equal to multiple of half wavelength.

\[ L = q\frac{\lambda}{2} \]

, q is an integer

Frequency separation:

\[ \Delta \nu = \frac{c}{2L} \]

for \( L >> \lambda \)
Laser types

- Solid state lasers (crystal based)
- Gas lasers
- Semiconductor lasers
- Fiber lasers
Modes of operation

- Continuous wave
  - Single-frequency lasers
- Q-switched lasers
- Mode-locked lasers
Semiconductor lasers

- Brief history
- p-n junction
- Semiconductor laser based on p-n junction
- Double heterostructure
- Fabrication tools
- Bandgap engineering
- Examples of semiconductor lasers
Lasers based on p-n junction

The energy band diagram of a degenerately doped p-n with no bias. (b) Band diagram with a sufficiently large forward bias to cause population inversion and hence stimulated emission.

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Lasers based on p-n junction

- January 1962: observations of super-luminescences in GaAs p-n junctions (Ioffe Institute)
- Sept.-Dec. 1962: laser action in GaAs and GaAsP p-n junctions (General Electric, IBM, Lebedev Institute)

A schematic illustration of a GaAs homojunction laser diode. The cleaved surfaces act as reflecting mirrors.

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Lasers based on heterostructure

• p-n junction design requires cryogenic temperature to lase
• Large current density needed to create population inversion

Solution: Double Heterostructure! (DHS)

(a) A double heterostructure diode has two junctions which are between two different bandgap semiconductors (GaAs and AlGaAs).

(b) Simplified energy band diagram under a large forward bias. Lasing recombination takes place in the p-GaAs layer, the active layer.

(c) Higher bandgap materials have a lower refractive index.

(d) AlGaAs layers provide lateral optical confinement.

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Lasers based on heterostructure

Two important advantages:

1. Due to the thin p-GaAs layer a minimal amount of current is required to increase the concentration of injected carriers at a fast rate. This is how threshold current is reduced for the purpose of population inversion and optical gain.

2. A semiconductor with a wider bandgap (AlGaAs) will also have a lower refractive index than GaAs. This difference in refractive index is what establishes an optical dielectric waveguide that ultimately confines photons to the active region.

Room temperature operation possible!
Lasers based on heterostructure

Schematic representation of the DHS injection laser in the first CW-operation at room temperature
Superluminescent diodes (SLDs) are semiconductor laser diodes with strong current injection so that stimulated emission outweighs spontaneous emission.

Output of SLD is generally greater than LED and lower than LD. Spectrum is narrower than LED and broader than LD.

Application in sources with low coherent time, such as optical coherence tomography, fiber optic gyroscopes and fiber optic sensors
The Nobel Prize in Physics 2000

"for basic work on information and communication technology"

“for developing semiconductor heterostructures used in high-speed- and opto-electronics”

“for his part in the invention of the integrated circuit”

Zhores I. Alferov
b. 1930

Herbert Kroemer
b. 1928

Jack S. Kilby
1923–2005
Progress

Main problem: heat management
Impact of dimensionality on density of states

- **3D**
- **2D**
- **1D**
- **0D**
Quantum dot: artificial atom

- Atom
- Semiconductor
- Quantum dot

- photon
- forbidden gaps
- valence band
- conduction band
- phonon
- electron levels
- hole levels

- kT
Distributed feed-back laser

- Single frequency operation
- Low noise performance
- Suitable for WDM networks
Vertical cavity surface emitting laser

- Low threshold currents (<1mA)
- Narrow emission lines (often single frequency operation). This is caused by the very short cavity length, which results in large longitudinal mode spacing
- Circular beam, efficient coupling into single mode optical fiber
- The possibility of fabricating 2 dimensional arrays of lasers (e.g. $10^3 \times 10^3$ diodes) on the same chip, with each laser individually addressable
Photodetectors

- Introduction
- Most important characteristics
- Photodetector types
  - Thermal photodetectors
  - Photoelectric effect
  - Semiconductor photodetectors
Introduction

- Photodetector converts photon energy to a signal, mostly electric signal such as current (sort of a reverse LED)

- Photoelectric detector
  - Carrier generation by incident light
  - Carrier transport and/or multiplication by current gain mechanism
  - Interaction of current with external circuit

- Thermal detector
  - Conversion of photon to phonon
  - Propagation of phonon
  - Detection of phonon
Important characteristics

- Wavelength coverage
- Sensitivity
- Bandwidth (response time)
- Noise
- Area
- Reliability
- Cost
Absorption of photons creates carriers (electrons)

- External photoeffect: electron escape from materials as free electrons
- Internal photoeffect (photoconductivity): excited carriers remain within the material to increase conductivity

Useful formula:

\[ \lambda (\mu m) = \frac{1.24}{E_g (eV)} \]
• Electrons were emitted immediately, no time lag.
• Increasing intensity of light increased number of photoelectrons but not their maximum kinetic energy.
• Red light will not cause ejection of electrons, no matter what the intensity (linear regime).
• A weak violet light will eject only a few electron, but their maximum kinetic energies are greater than those for intense light of longer wavelength.

$h \nu = W + K.E.$
Vacuum photodiode operates when a photon creates a free electron at the photocathode, which travels to the anode, creating a photocurrent.

Photocathode can be opaque (reflection mode) or semitransparent (transmission mode).

Original electron can create secondary electrons using dynodes, with successive higher potentials, such as a photomultiplier tube, PMT.
Photomultiplier tubes typically require 1000 to 2000 volts for proper operation. The most negative voltage is connected to the cathode, and the most positive voltage is connected to the anode. Voltages are distributed to the dynodes by a resistive voltage divider, though variations such as active designs (with transistors or diodes) are possible.
Semiconductor photodetectors

- p-n photodiode
- Response time
- p-i-n photodiode
- APD photodiode
- Noise
- Wiring
- Arrayed detector (Home Reading)
p-n photodetector

Photons are absorbed and e-h are generated everywhere, but only e-h in presence of E field is transported. A p-n junction supports an E field in the depletion layer.

Region 1: e-h generated in depletion region quickly move in opposite directions under E. External current is in reverse direction from n to p direction. Each carrier pair generates a pulse of area e.

Region 2: e-h generated outside the depletion layer have a finite probability in moving into the layer by random diffusion. An electron in the p side and a hole in the n side will be transported to the external circuit. Diffusion is usually slow.

Region 3: e-h generated cannot be transported, wandered randomly, are annihilated by recombination. No signal to external circuit.
Response time

1) Finite diffusion time: carriers take nanosecond or longer to diffuse a distance of ~ 1 μm.
2) Junction capacitance puts a limit on the intensity modulation frequency
   \[ \omega = \frac{1}{RC} \]
3) Finite transit time of carriers across depletion layer

Illustration of the response of a p-n photodiode to an optical pulse when both drift and diffusion contribute to the detector current:
**i-V characteristics**

\[ i = i_s \left[ \exp \left( \frac{eV}{kT} \right) - 1 \right] - i_p \]

- \( i_p \), photocurrent is proportional to photon flux
Modes of photodiode operations: (1) open circuit (photovoltaic), (2) short circuit and (3) reverse biased (photoconductive)

Light generated e-h pair. E field and voltage increase with carrier. Responsivity of photovoltaic cell is measured in V/W.

Short circuit operation. Responsivity is typically measured in A/W.
Reversed bias mode

Photodiodes are operated in strongly reversed bias mode because
1) Strong $E$ fields give large drift velocity, reducing transit time
2) Strong bias increases depletion width, reducing capacitance
3) Increase depletion layer leads to more light collection

Reversed biased operation of a photodiode without a load resistor.  
Reversed biased operation of a photodiode with a series load resistor.
Example-silicon photodiode

Planar diffused silicon photodiode

Equivalent circuit
- $C_j$: junction capacitance
- $R_{sh}$: shunt resistance
- $R_s$: series resistance
- $R_L$: load resistance
The $pn$ junction photodiode has two drawbacks:

- Depletion layer (DL) capacitance is not sufficiently small to allow photodetection at high modulation frequencies (RC time constant limitation).
- Narrow DL (at most a few microns) → long wavelengths incident photons are absorbed outside DL → low QE

The $pin$ photodiode can significantly reduce these problems.

Intrinsic layer has less doping and wider region (5 – 50 μm).
A table below lists operating characteristics of common \textit{p-i-n photodiodes}. In the parameters the dark current is the current generated in a photodiode in the absence of any optical signal. The parameter rise time is defined as the time over which the current builds up from 10 to 90\% of its final value when the incident optical power is abruptly changed.

For Si and Ge, $W$ typically has to be in the range of 20 – 50 \textmu m to ensure a reasonable quantum efficiency. The bandwidth is thus limited by a relatively long collection time. In contrast, $W$ can be as small as 3 – 50 \textmu m for InGaAs photodiodes resulting in higher bandwidths.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>Si</th>
<th>Ge</th>
<th>InGaAs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>$\lambda$</td>
<td>\textmu m</td>
<td>0.4–1.1</td>
<td>0.8–1.8</td>
<td>1.0–1.7</td>
</tr>
<tr>
<td>Responsivity</td>
<td>$R$</td>
<td>A/W</td>
<td>0.4–0.6</td>
<td>0.5–0.7</td>
<td>0.6–0.9</td>
</tr>
<tr>
<td>Quantum efficiency</td>
<td>$\eta$</td>
<td>%</td>
<td>75–90</td>
<td>50–55</td>
<td>60–70</td>
</tr>
<tr>
<td>Dark current</td>
<td>$I_d$</td>
<td>nA</td>
<td>1–10</td>
<td>50–500</td>
<td>1–20</td>
</tr>
<tr>
<td>Rise time</td>
<td>$T_r$</td>
<td>ns</td>
<td>0.5–1</td>
<td>0.1–0.5</td>
<td>0.02–0.5</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>$\Delta f$</td>
<td>GHz</td>
<td>0.3–0.6</td>
<td>0.5–3</td>
<td>1–10</td>
</tr>
<tr>
<td>Bias voltage</td>
<td>$V_b$</td>
<td>V</td>
<td>50–100</td>
<td>6–10</td>
<td>5–6</td>
</tr>
</tbody>
</table>
Photodiode based on graphene
Avalanche photodiodes (APDs) are preferred when the amount of optical power that can be spared for the receiver is limited. Their responsivity can significantly exceed 1 due to built-in gain. The physical phenomenon behind the gain is known as *impact ionization*. Under certain conditions an accelerating electron can acquire sufficient energy to generate a new electron-hole pair. The net result is that a single primary electron creates many secondary electrons and holes, all of which contribute to the current.

The generation rate is governed by two parameters, $\alpha_e$ and $\alpha_h$, the *impact-ionization coefficients* for electrons and holes, respectively. Their numerical values depend on the semiconductor material and on the electric field that accelerates electrons and holes. Figure below shows the coefficients for several semiconductors.

The values for $\alpha_e$ and $\alpha_h \sim 1 \times 10^{-4}$ cm$^{-1}$ are obtained for electric fields in the range of $2 - 4 \times 10^5$ V/m. Such high fields are obtained by applying a high voltage of (~ 100 V) to the APD. These values decreases with increasing temperature.
Avalanche Photodiodes

- Impact ionization processes resulting in avalanche multiplication

- Impact of an energetic electron's kinetic energy excites VB electron to the CV.
Photodetector Noise

**Shot noise**: Shot noise is related to the statistical fluctuation in both the photocurrent and the dark current. The magnitude of the shot noise is expressed as the root mean square (rms) noise current:

\[ I_{sn} = \sqrt{2q(I_p + I_D)\Delta f} \]

q is charge of electron, \(1.6 \times 10^{-19}\) C

**Thermal or Johnson noise**: The shunt resistance in a photodetector has a Johnson noise associated with it. This is due to the thermal generation of carriers. The magnitude of this generated current noise is:

\[ I_{jn} = \sqrt{\frac{4k_B T\Delta f}{R_{SH}}} \]

\(k_B\) is Boltzmann Constant
\(k_B = 1.38 \times 10^{-23}\) J/K
Photodetector Noise

Total Noise
The total noise current generated in a photodetector is determined by:

\[ I_{tn} = \sqrt{I_{sn}^2 + I_{jn}^2} \]

Noise Equivalent Power (NEP)
Noise Equivalent Power is the amount of incident light power on a photodetector, which generates a photocurrent equal to the noise current. NEP is defined as:

\[ NEP = \frac{I_{tn}}{R_\lambda} \]
# APD example

<table>
<thead>
<tr>
<th>Item #</th>
<th>APD110C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector Type</td>
<td>InGaAs APD</td>
</tr>
<tr>
<td>Wavelength Range</td>
<td>900 - 1700 nm</td>
</tr>
<tr>
<td>Typical Max Responsivity</td>
<td>9 A/W  @ 1500 nm M = 10</td>
</tr>
<tr>
<td>Transimpedance Gain</td>
<td>100 kV/A 50 kV/A with 50 Ω Termination</td>
</tr>
<tr>
<td>Maximum Conversion Gain</td>
<td>0.9 x 10⁸ V/W</td>
</tr>
<tr>
<td>Active Detector Diameter</td>
<td>0.2 mm</td>
</tr>
<tr>
<td>CW Saturation Power</td>
<td>4.2 μW</td>
</tr>
<tr>
<td>Max Input Power²</td>
<td>1 mW</td>
</tr>
<tr>
<td>Output Bandwidth (3dB)</td>
<td>DC - 50 MHz</td>
</tr>
<tr>
<td>Minimum NEP</td>
<td>0.46 pW/(Hz¹/₂)</td>
</tr>
<tr>
<td>Electrical Output</td>
<td>BNC, 50 Ω</td>
</tr>
<tr>
<td>Max Output Voltage Threshold</td>
<td>3.6 V</td>
</tr>
<tr>
<td>DC Offset Electrical Output</td>
<td>≤±15 mV</td>
</tr>
<tr>
<td>Device Dimensions</td>
<td>2.0&quot; x 3.0&quot; x 1.1&quot; (50.8 mm x 76.2 mm x 27.9 mm)</td>
</tr>
<tr>
<td>Power Supply</td>
<td>±12 V @ 200 mA (110/230 VA switchable)</td>
</tr>
</tbody>
</table>
Electrical wiring

Reverse biased photodetector
Electrical wiring

Amplified photodetector
Introduction to Network

- Modulation formats
- Signal multiplexing
  - Time
  - Code
  - Wavelength
- System performance
  - Bit Error Rate
  - Optical signal to noise ratio
  - Eye diagram
- Network architecture, limitation
- CIAN
System Performance

- Important parameters of a digital communication system
  - Bit error rate: BER
  - Optical signal to noise: OSNR
  - Q factor

- All parameters are monitored regularly to track the health of the network

- Parameters are related to each other
Bit error rate (BER): One of the most important ways to determine the quality of a digital transmission system is to measure its Bit Error Rate (BER). BER is calculated by comparing the transmitted sequence of bits to the received bits and counting the number of errors. The ratio of how many bits received in error over the number of total bits received is the BER. This measured ratio is affected by many factors including: signal to noise ratio, distortion, and jitter.

\[
\text{BER} = \frac{N_{\text{err}}}{N_{\text{bits}}}
\]

For a good system performance BER < 10^{-12}
An eye diagram is a common indicator of the quality of signals in high-speed digital transmissions. An oscilloscope generates an eye diagram by overlaying sweeps of different segments of a long data stream driven by a master clock.

In practical terms this may be achieved by displaying the data waveform on a sampling oscilloscope triggered from the system clock.
The performance of digital fiber-optic transmission systems can be specified using the Q-factor. The Q-factor is the electrical signal-to-noise ratio (SNR) at the input of the decision circuit in the receiver terminal Rx. For the purpose of calculation, the signal level is interpreted as the difference in the mean values $v_0$ and $v_1$, and the noise level is the sum of the standard deviations $\sigma_0$ and $\sigma_1$ at the sampling time:

$$Q = \frac{v_1 - v_0}{\sigma_1 + \sigma_0}$$
BER is a conditional probability of receiving signal $y$ while the transmitted signal is $x$, $P(y/x)$, where $x$ and $y$ can each be digital 0 or 1. Since the transmitted signal digital states can be either 0 or 1, we can define $P(y/0)$ and $P(y/1)$ as the PDFs (probability density function) of the received signal at state $y$ while the transmitted signals are 0 and 1, respectively. Suppose that the probability of sending digital 0 and 1 are $P(0)$ and $P(1)$ and the decision threshold is $v_{th}$; the BER of the receiver should be:

$$BER = P(0)P(v > v_{th}/0) + P(1)P(v < v_{th}/1)$$

$$P_{Gaussian}(y) = \frac{1}{\sigma \sqrt{2\pi}} \exp\left(-\frac{(v - v_m)^2}{2\sigma^2}\right)$$

If Gaussian noise is assumed
The probability for the receiver to declare 1 while the transmitter actually sends a 0 is:

\[
P(v > v_{th}/0) = \frac{1}{\sigma_0 \sqrt{2\pi}} \int_{v_{th}}^{\infty} \exp\left(-\frac{(v - v_0)^2}{2\sigma_0^2}\right) dy = \frac{1}{\sqrt{2\pi}} \int_{Q_0}^{\infty} \exp\left(-\frac{\xi^2}{2}\right) d\xi
\]

Where \( \xi = (v - v_0)/\sigma_0 \), \( Q_0 = \frac{v_{th} - v_0}{\sigma_0} \), Q-value or quality factor.

Similarly, the probability for the receiver to declare 0 while the transmitter actually sends a 1 is:

\[
P(v < v_{th}/1) = \frac{1}{\sigma_1 \sqrt{2\pi}} \int_{-\infty}^{v_{th}} \exp\left(-\frac{(v_1 - v)^2}{2\sigma_1^2}\right) dy = \frac{1}{\sqrt{2\pi}} \int_{Q_1}^{\infty} \exp\left(-\frac{\xi^2}{2}\right) d\xi
\]

\[
\text{BER} = \frac{1}{2} P(v > v_{th}/0) + \frac{1}{2} P(v < v_{th}/1)
\]

\[
= \frac{1}{2 \sqrt{2\pi}} \left\{ \int_{Q_0}^{\infty} \exp\left(-\frac{\xi^2}{2}\right) d\xi + \int_{Q_1}^{\infty} \exp\left(-\frac{\xi^2}{2}\right) d\xi \right\}
\]

, \( P(0) = P(1) = 0.5 \) is assumed.
A widely used mathematical function, the error function, is defined as:

$$erf(x) = \frac{2}{\sqrt{\pi}} \int_{0}^{x} \exp(-y^2)dy$$

And the complementary error function is defined as:

$$erfc(x) = 1 - erf(x) = \frac{2}{\sqrt{\pi}} \int_{x}^{\infty} \exp(-y^2)dy$$

$$BER = \frac{1}{4} \left\{ \text{erfc} \left( \frac{Q_0}{\sqrt{2}} \right) + \text{erfc} \left( \frac{Q_1}{\sqrt{2}} \right) \right\}$$
Bit Error Testing - Eye diagram

By symmetry, we can assume $Q_1 = Q_0 = Q$, or

$$\frac{v_{th} - v_0}{\sigma_0} = \frac{v_1 - v_{th}}{\sigma_1}$$

\[\Rightarrow BER = \frac{1}{2} \text{erfc} \left( \frac{Q}{\sqrt{2}} \right) \quad \text{where} \quad Q = \frac{v_1 - v_0}{\sigma_1 + \sigma_0}\]