Optics and fiber:

State of polarization:
Linear, circular, elliptical

Wave propagation:
Reflection, refraction at an interface
Snell’s Law: \( n_1 \sin \theta_1 = n_2 \sin \theta_2 \)

Fresnel Equations:
Different expressions for parallel and perpendicular polarized components
Amplitude reflectivity and phase shift

Normal incidence reflectivity: \( R = \left( \frac{n_1 - n_2}{n_1 + n_2} \right)^2 \) (power reflectivity)
Critical angle: \( \sin \theta_c = \frac{n_2}{n_1} \) (for total reflection)
Brewster angle: \( \tan \theta_B = \frac{n_2}{n_1} \) (for total transmission, only for parallel component)

Fiber modes:
Numerical aperture \( NA = \sqrt{n_1^2 - n_2^2} \) (what is the physical meaning of \( NA \)?)

\( V \)-number of fiber: \( V = \frac{2 \pi a}{\lambda} NA \) (Note: this wavelength-dependent)

Fiber modes: \( M = V^2 / 2 \) (only valid when \( M >> 1 \))
Single mode condition: \( V < 2.405 \)
Geometries of standard single-mode fiber and standard multi-mode fiber

Birefringence: Beat length \( L_{Beat} = \frac{1}{(\beta_o - \beta_e)} \) where \( \beta_o = \frac{2 \pi}{\lambda} n_o \) and \( \beta_e = \frac{2 \pi}{\lambda} n_e \)

What is the physical meaning of the beat-length?

Fiber loss:
Power attenuation: causes of attenuation, wavelength-dependent nature of attenuation
Power attenuation coefficients:
Typical values: \( \alpha_{dB} = 0.2 \text{dB/km (at 1550nm), } \alpha_{dB} = 0.5 \text{dB/km (at 1320nm).} \)

\( \alpha_{Neper} = \alpha_{dB}/4.343 \)

\( P(z) = P_0 \cdot \left( 10^{\alpha_{dB} z / 10} \right) = P_0 \exp(-\alpha_{Neper}z) = P_0 \exp(-\frac{\alpha_{dB}}{4.343}z) \)
Fiber dispersion:
Modal dispersion (difference modes travelling in different speed, independent of the signal bandwidth). Understand mechanism and ray-trace estimation.

PMD (different polarization modes travelling in different speed, independent of the signal bandwidth). Unit of PMD for short fiber is [ps/km], and for long fiber is [ps/√km]

Mechanisms of phase velocity, group velocity and group velocity dispersion (GVD).

Chromatic dispersion (different frequency (or wavelength) components travelling in different speed)

\[
D \text{ [ps/nm/km]}, \quad \Delta T = L\Delta \lambda. \quad (L: \text{fiber length, } \Delta \lambda: \text{signal optical bandwidth in wavelength})
\]

\[
\beta_2 \text{ [ps}^2/\text{km]}, \quad \Delta T = L\beta_2 \Delta \omega. \quad (L: \text{fiber length, } \Delta \omega: \text{signal optical bandwidth in frequency})
\]

The effect of chromatic dispersion is linearly proportional to the signal bandwidth \(\Delta \lambda\) (or \(\Delta \omega\)).

\[
\Delta \omega = -\frac{2\pi c}{\lambda^2} \Delta \lambda
\]

With chromatic dispersion, the propagation constant can be expressed as:

\[
\beta(\omega) = \beta(\omega_0) + \frac{d\beta}{d\omega} \bigg|_{\omega = \omega_0} (\omega - \omega_0) + \frac{1}{2} \frac{d^2\beta}{d\omega^2} \bigg|_{\omega = \omega_0} (\omega - \omega_0)^2 + \ldots
\]

Know the physical meaning of each term and the relationship between dispersion parameter \(D\) and \(\beta_2 = \frac{d^2\beta}{d\omega^2} \bigg|_{\omega = \omega_0}\) and their units.

Understand the impact of dispersion on the waveform of the optical signal.

If the light source is single frequency, spectral bandwidth of the modulated optical signal depends on the modulation speed. On the other hand, if the light source has wide spectral width (such as an LED), modulation does not significantly change the overall spectral width.

Sources of chromatic dispersion: material dispersion and waveguide dispersion

Standard single mode fiber: \(D(\lambda) = \frac{S_0}{4} \left( \lambda - \frac{\lambda_0^4}{\lambda^3} \right)\)

Where \(S_0\) is dispersion slope and \(\lambda_0\) is zero-dispersion wavelength.

Fiber nonlinearity:
Understand mechanisms of SBS, SRS, and Kerr effect nonlinearities.
Definitions of and calculation of:

Nonlinear phase shift, \(\Phi_{NL}(t) = \gamma P(0,t) \int_0^L e^{-\alpha z}dz = \gamma P(0,t)L_{\text{eff}}\)
Effective length $L_{\text{eff}} = \frac{1 - e^{-\alpha L}}{\alpha} \approx \frac{1}{\alpha}$

Self-phase modulation (SPM) and its relationship with optical signal waveform. Frequency/wavelength deviation caused by SPM

$$\delta f(t) = \frac{1}{2\pi} \gamma L_{\text{eff}} \frac{\partial}{\partial t} [P(0,t)]; \quad \delta \lambda(t) = -\frac{\lambda^2}{2\pi c} \gamma L_{\text{eff}} \frac{\partial}{\partial t} [P(0,t)]$$

General concepts of XPM and FWM, understand the mechanisms

**Semiconductor light emitting diodes and laser diodes: (LED and LD)**

Forward biased PN-junction. Energy band $\Delta E = h\nu$.

*Spontaneous* emission versus *stimulated* emission

Quantum efficiency $\eta_q$ and external efficiency $\eta_{\text{ext}}$

Radiative recombination rate versus non-radiative recombination rate

Why an LED has much lower external efficiency than a laser diode? (due to random direction of the spontaneous emission)

Slope of $P_{\text{opt}}/I$ curve: $dP_{\text{opt}} / dI = \eta_q \eta_{\text{ext}} \frac{hc}{\lambda q}$.

How to drive an LED? (Use current source or voltage source?)

Carrier lifetime and modulation bandwidth, why electric bandwidth is different from optical bandwidth?

**Laser oscillation condition:**

Understand how the gain condition and the phase condition are derived

*Gain condition:* $\sqrt{R_1 R_2 \exp[2(\Gamma g - \alpha)l]} = 1$ (*roundtrip gain is equal to unity*)

Here $R_1$ and $R_2$ are *power* reflectivities of facets, $g$ and $\alpha$ are *field* gain and loss of the material inside the laser cavity with unit $[\text{cm}^{-1}]$, $\Gamma$ is field confinement factor, and $l$ is the cavity length in $[\text{cm}]$.

At lasing threshold: $\Gamma g_{\text{th}} = \alpha + \frac{1}{2l} \ln \left( \frac{1}{R_1 R_2} \right) = \alpha + \alpha_m$

The first term is material loss and the second term is mirror loss

*Phase condition:* $2\beta l = 2m\pi$, or, $2\frac{\pi n}{\lambda} l = 2m\pi$ (n is material refractive index)

(A roundtrip phase delay is multiple-integers of $2\pi$)

What happens if the laser has multiple sections?
This determines the wavelengths or oscillation modes and mode spacing: \( \Delta \lambda = \frac{\lambda^2}{2nl} \), which is also referred to as free-spectral range (FSR).

Material gain \( g \) is proportional to the carrier density \( N \): \( g(N) = a(N - N_0) \)

Material gain curve: parabolic approximation

\[
g(\lambda) = g(\lambda_0) \left[ 1 - \frac{(\lambda - \lambda_0)^2}{(\Delta \lambda_g)^2} \right] \quad \text{(valid only for } |\lambda - \lambda_0| \leq \Delta \lambda_g)\]

**Rate equations** for photon density and carrier density (understand physical meaning of each term)

**Steady state characteristics:**
Threshold carrier density and threshold current

\[
\eta_{ext} = \frac{\Gamma g_{th} - \alpha}{\Gamma g_{th}} = \frac{\alpha_m}{\alpha + \alpha_m}
\]

\[
\alpha_m = \frac{-\ln(R_1R_2)}{4L}
\]

\[
\tau_{ph} = \frac{1}{2v_g(\alpha + \alpha_m)}
\]

\( P_{opt}/I \) curve (above threshold): \( P_{opt} = \eta_{int}\eta_{ext} \frac{hv}{q} (I - I_{th}) \)

Understand the relationship between photon density and output optical power from a laser cavity: \( P_{opt} = P \cdot (hv) \cdot 2\alpha_m v_g \)

Understand definitions and physical meanings of threshold current density and threshold carrier density.

What is the major difference between a laser working below and above threshold?