Back to Basics in Optical Communications Technology

Agilent Technologies

Back to Basics in Optical Communications Technology

Today . . .

The innovations that enable 2.5 $\rightarrow$ 10 $\rightarrow$ 40 $\rightarrow$ 1000 Gb/s

The science that drives the technology

Recipe:

(1) Review the physical foundation of the technology
(2) Derive the technology from the science
(3) The major issues in development of the technology
(4) Characterization and test of the technology

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The Science: Four Easy Pieces

1. Geometric Optics
   - How fibers work

2. Physical Optics
   - Properties of electromagnetic waves
   - Optical filters and spectrum analyzers

3. Atomic Physics
   - How transmitters, receivers, and amplifiers work

4. Electrodynamics of continuous media
   - How the index of refraction affects the system
   - Dispersion

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But first, a word from our sponsors. . .

s Agilent Technologies' Lightwave Training

- Optical Spectrum Analysis/OSA User's Course
- Characterizing Polarization Effects
- Eye Diagram Analysis
- TDR in High-Speed Digital Design
- Bit Error Rate Analysis
- Digital Communications Analyzer User's Course

Today's Presentation
A pre-requisite for other courses

- Understanding Lightwave Technology
- Understanding Optical Passive Device Characterization
- Understanding Optical Transmitters and Receivers and Their Characterization
- Understanding DWDM
- Back to Basics in Optical Communications Technology
- Understanding Optical Networking
- The Elements of Lightwave Technology

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Today's Presentations

- Geometric Optics: The optic fiber as a waveguide
- Physical Optics and Passive Component Characterization
- Light Transmission, Reception and Modulation: Active Component Characterization
- Optical Signal Amplification and DWDM
- Dispersion: The evolution of the index of refraction with wavelength and polarization
- Characterizing the Optical Network

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High Speed Networking

Why we're all here. . .

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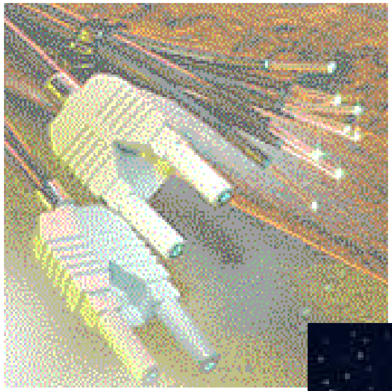
Networking at High Speed

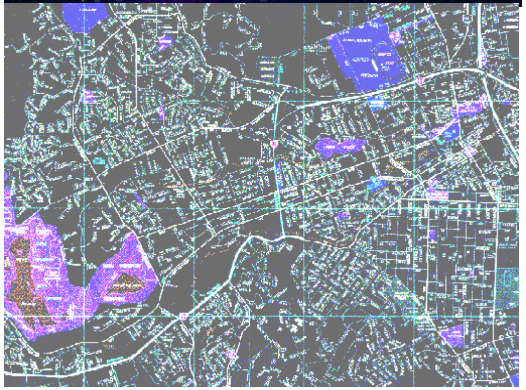
Pulses of infrared light

guided through glass fibers

move huge blocks of data

long or short distances





- *insensitive to electrical interference*
- *cheap and light weight*

Telephone Data Cable TV

Long distances	WAN - Wide Area Net's
Short Distances	LAN - Local Area Net's
In between	MAN - Metro Area Net's

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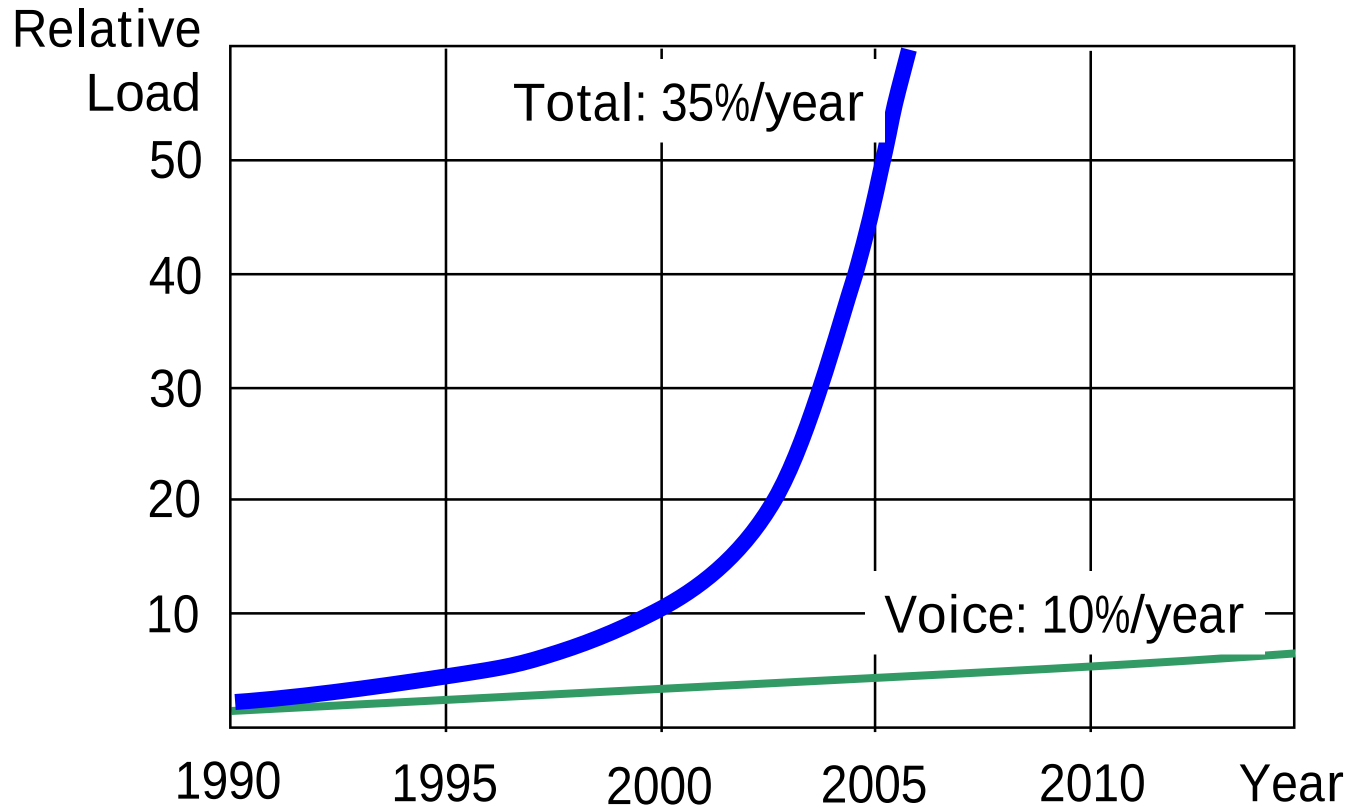
High Speed Networking is *Accelerating*



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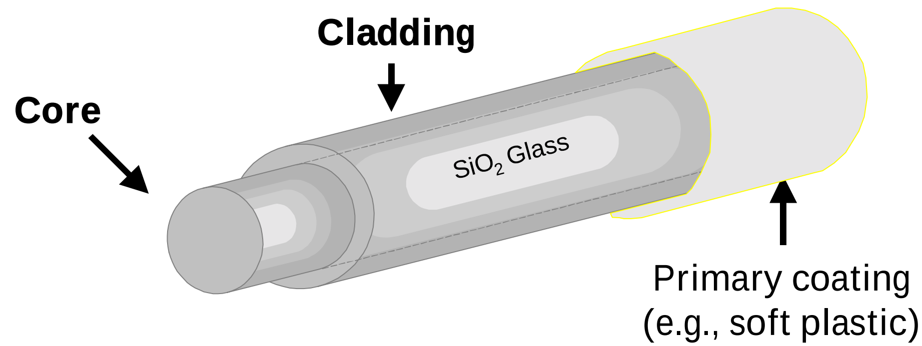
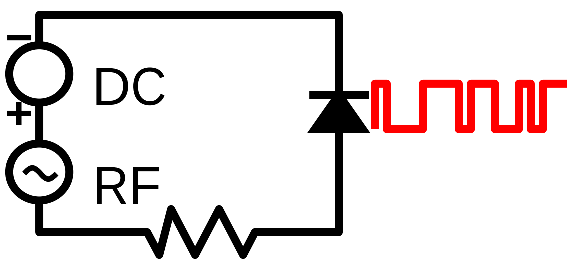
Optic Fiber based Networking

- Information is carried by light confined in glass fibers:



- Light is modulated by pulsing the source:



$$P_{"1"} >> P_{"0"} > 0$$

$$\frac{P_{"1"}}{P_{"0"}} \approx 10\,\mathrm{dB}$$

- SONET/SDH are Timed Division Multiplex (TDM) protocols:

OC-3 51.84 Mb/s OC-12 622 Mb/s OC-48 2.488 Gb/s OC-192 9.953 Gb/s

OC-768 40 Gb/s

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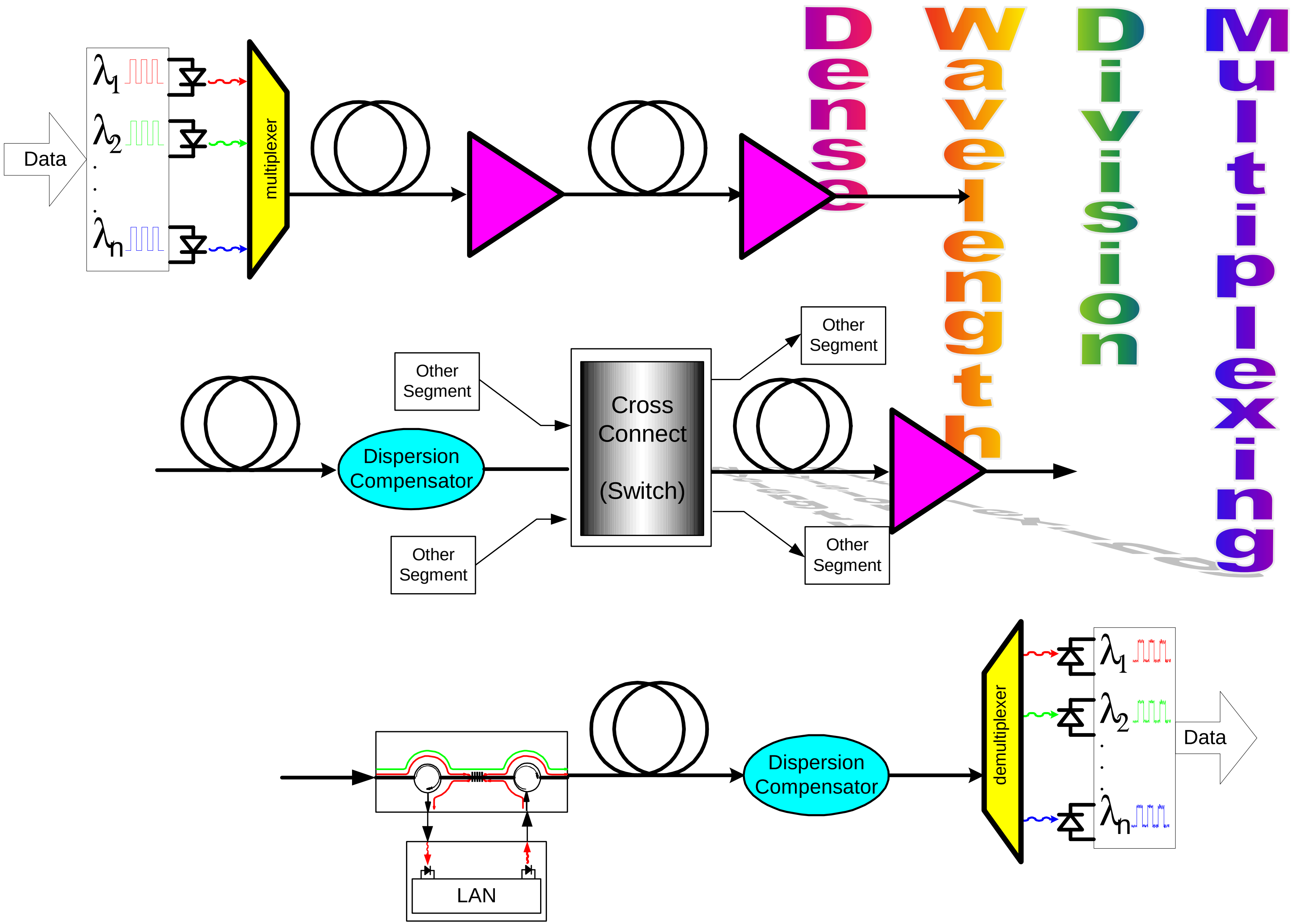
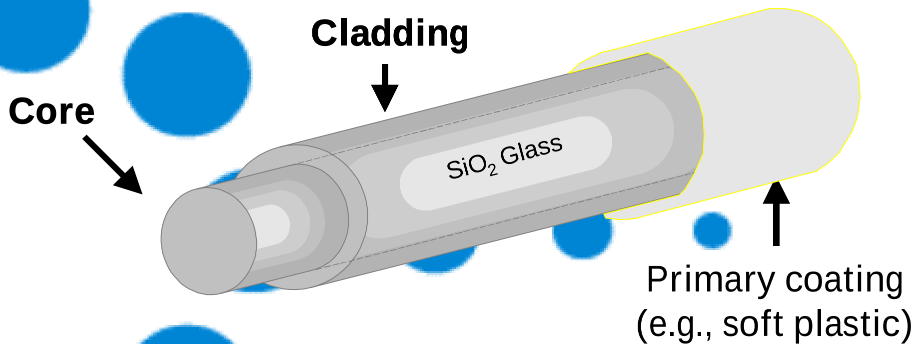
Optical Networking - The DWDM Forest



Geometric Optics

- The index of refraction
- Total internal reflection
- The optic fiber as a waveguide
- Single and multi mode fibers



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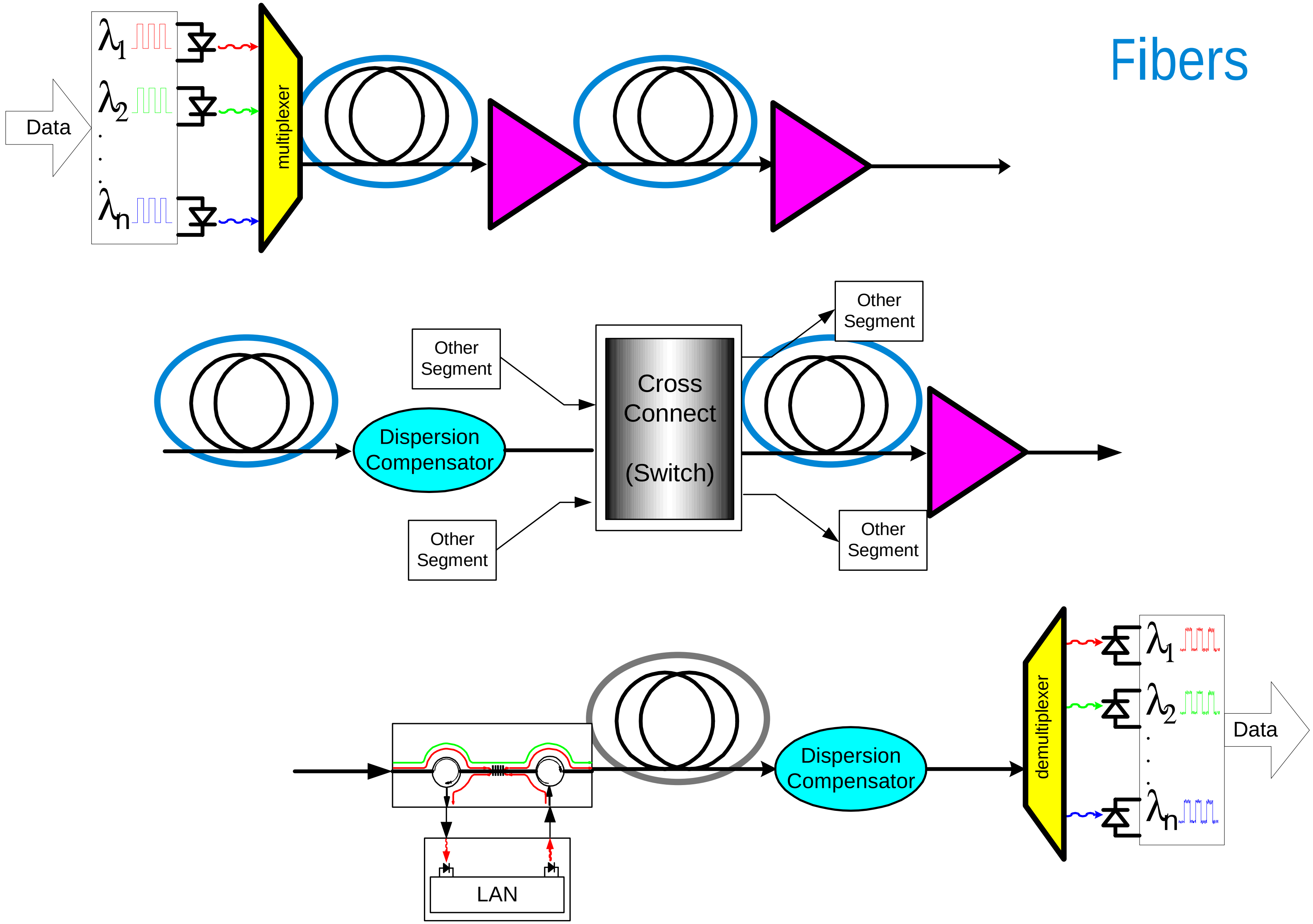
Optical Networking - The DWDM Forest



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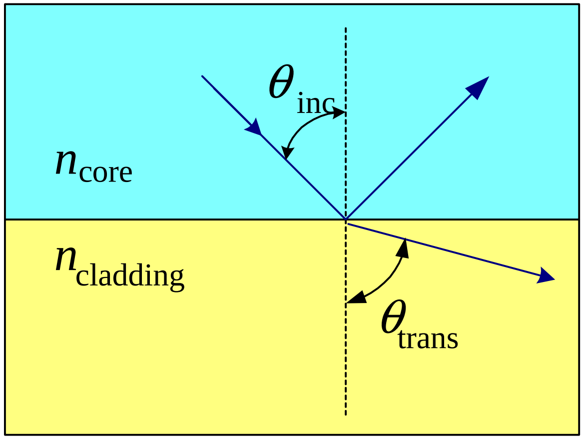
Optic Fibers and the Index of Refraction, *n*(λ)

The index of refraction of a dielectric is given by

$$n(\lambda) \equiv \frac{c_{vacuum}}{c_{medium}}$$

- At the boundary of two media, incident light is reflected or transmitted (a.k.a., 'refracted'),
- The relationship between the angles of incidence and transmission is given by
  Snell's Law:

$$n_{\text{core}} \sin(\theta_{\text{inc}}) = n_{\text{cladding}} \sin(\theta_{\text{trans}})$$



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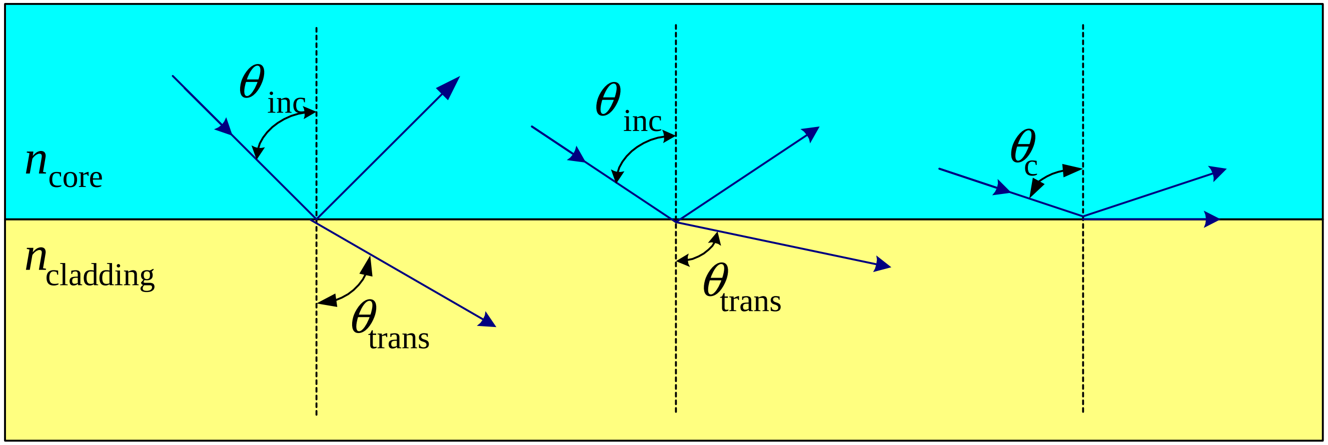
Optic Fibers Contain Light by
Total Internal Reflection

At incident angles larger than a critical angle, all light is reflected - contained:

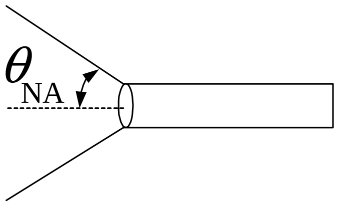
$$n_{\text{core}} \sin(\theta_{\text{inc}}) = n_{\text{cladding}} \sin(\theta_{\text{trans}}) \qquad \theta_{trans} = 90^\circ \Rightarrow \text{Total Internal Reflection}$$

$$n_{\text{core}} > n_{\text{cladding}}$$

$$\Rightarrow \theta_{\text{inc}} < \theta_{\text{trans}}$$



- Typical values: $\Rightarrow \theta_{TIR} \sim 80° - 85°$
- Bending cables $\Rightarrow$ losses
- Only light injected in a cone of some angle smaller than θ_{NA} will be contained by the fiber



- The spec' for this is numerical aperture, *NA*: $NA \equiv \sin\theta_{NA} = \sqrt{n_{core}^2 - n_{clad}^2}$

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Conducting Waveguide Analogy

Optic Fibers are *dielectric* waveguides

First, consider *conducting* waveguides:

Boundary Conditions:

$$\mathbf{E}_{T\ cond} = 0 \text{ and } \mathbf{B}_{\perp\ cond} = 0$$

give . . .

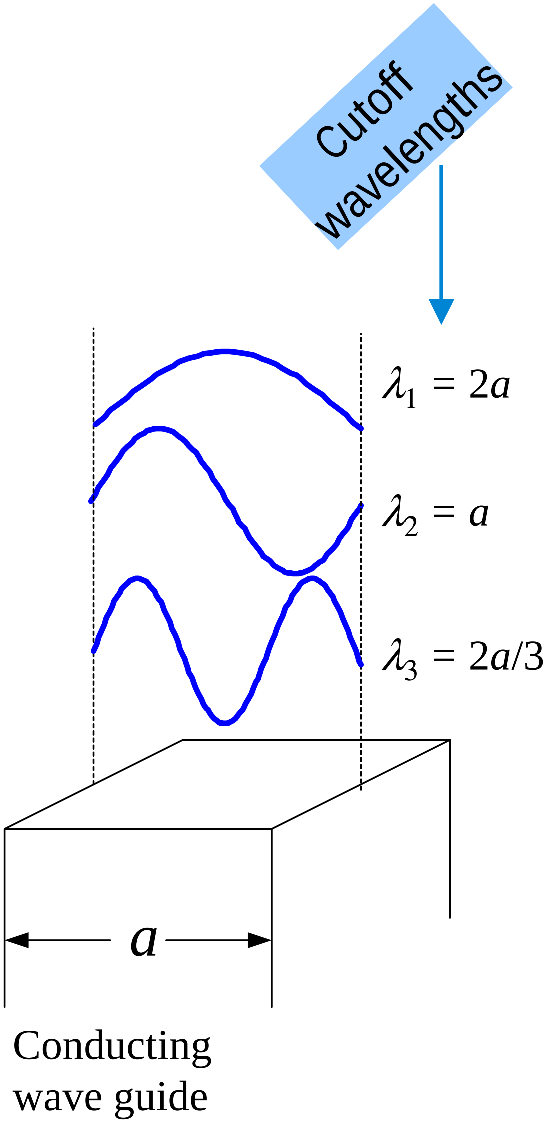
The cutoff wavelengths, or frequencies, determine the modes of propagation

Single Mode (SM) $\Rightarrow$ $a < \lambda < 2a$

Multi Mode (MM) $\Rightarrow$ $\lambda < a$

For a given range of wavelengths there are Single and Multi Mode waveguides

- single mode doesn't mean single wavelength



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Modal Dispersion:

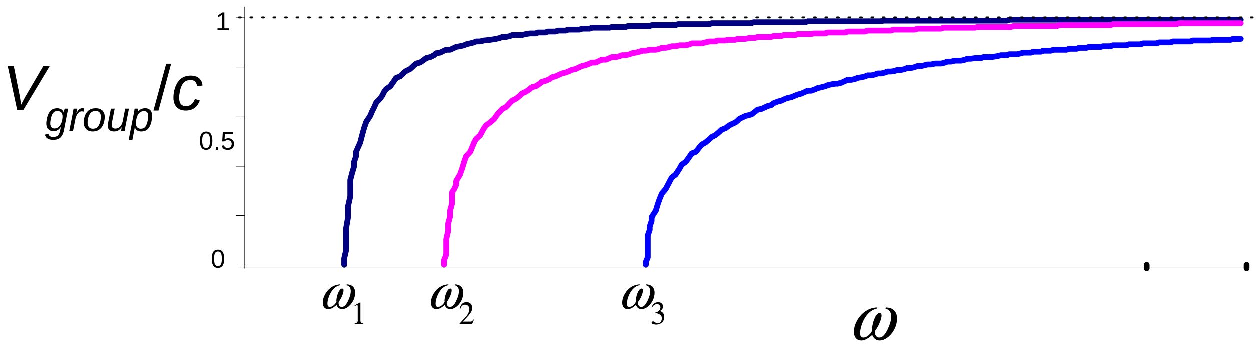
Waveguide dispersion arises from the dependence of the group velocity on the frequency, ω, and the mode-cutoff frequency $\omega_{cutoff} = 2\pi c/\lambda_{cutoff}$.

$$v_{group} = c\sqrt{1 - \frac{\omega^2_{\text{cutoff}}}{\omega^2}}$$

Conducting waveguide

Modal dispersion occurs when a pulse is composed of waves of more than one mode.

The different modes travel at very different, speeds $\Rightarrow$ Modal Dispersion



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Optic Fibers are Dielectric Waveguides

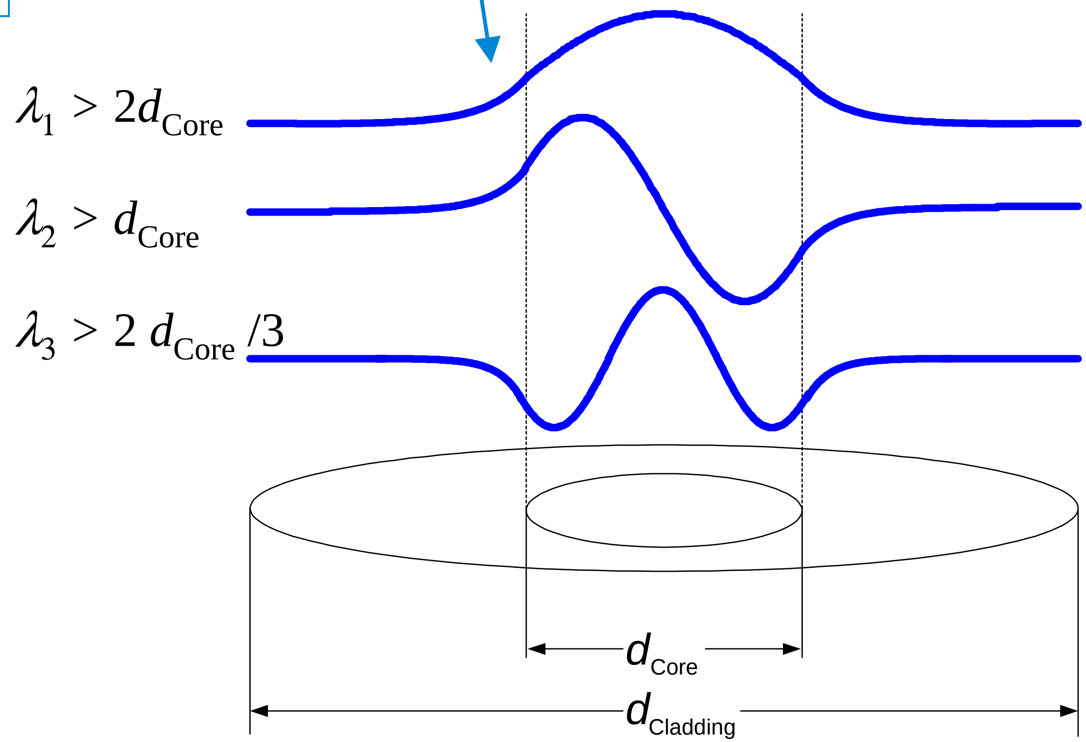
$$\nabla^2 \mathbf{E} = n^2 \varepsilon_0 \mu_0 \frac{\partial^2 \mathbf{E}}{\partial t^2}$$

$$E = E(r) e^{j(\omega t - \beta z)}$$

Transverse standing wave

Longitudinal traveling wave

Boundary conditions:
Smooth decay of the electric field at the core/cladding boundary



Single mode cutoff wavelength is larger than the fiber core diameter

Single Mode: $\lambda_1 < \lambda < \lambda_2$

e.g., for $\lambda \cong 1.5$ µm,

$d_{Core} \cong 10$ µm.

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Multi Mode Fibers

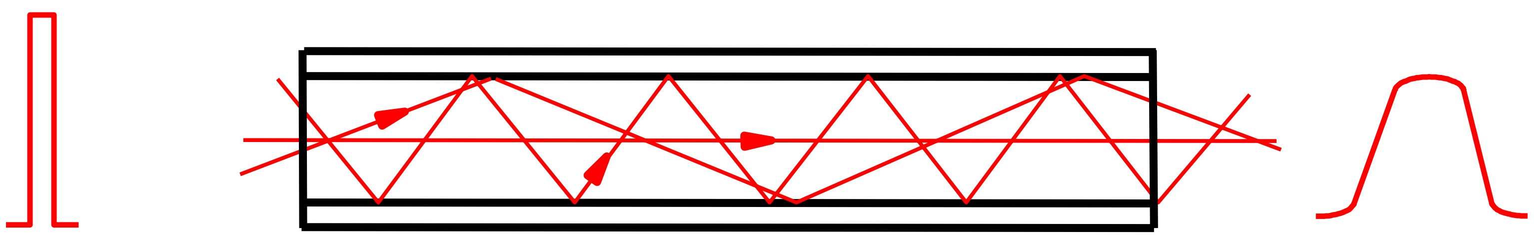
Modal Dispersion

- In Multi Mode fibers suffer Modal Dispersion from

$$v_{group} \sim c\sqrt{1-\frac{\omega_{\text{mode}}^2}{\omega^2}}$$

- Bitrate x Distance product is severely limited!

100/140 μm Silica Fiber:	~ 20 Mb/s • km
0.8/1.0 mm Plastic Optical Fiber:	~ 5 Mb/s • km



Single mode fibers do not suffer modal dispersion!

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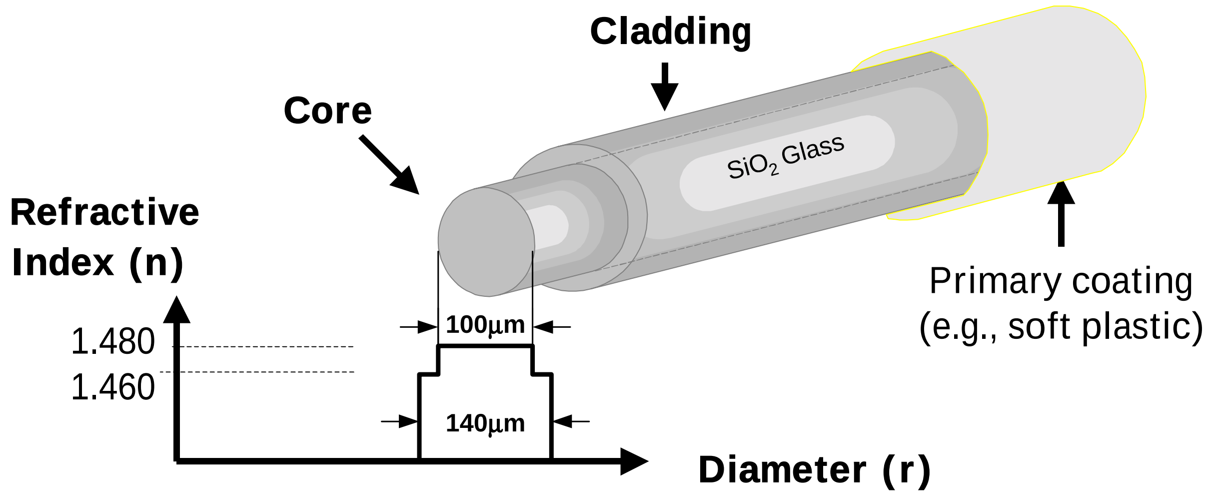
Fiber Structure

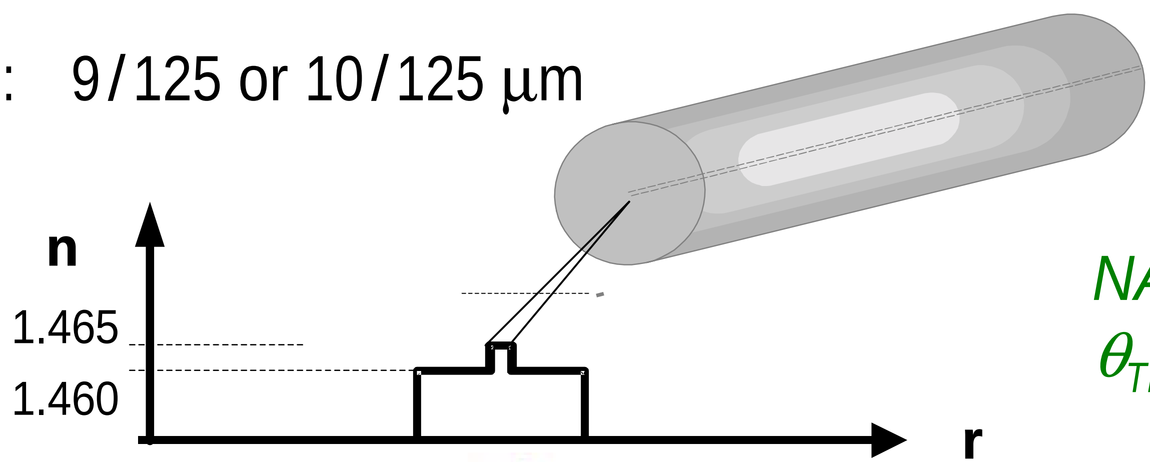
Multi-mode: 100/140 or 200/280 µm



$NA = 0.24$

$\theta_{TIR} = 80^o$

Single Mode: 9/125 or 10/125 µm



$NA = 0.12$

$\theta_{TIR} = 85^o$

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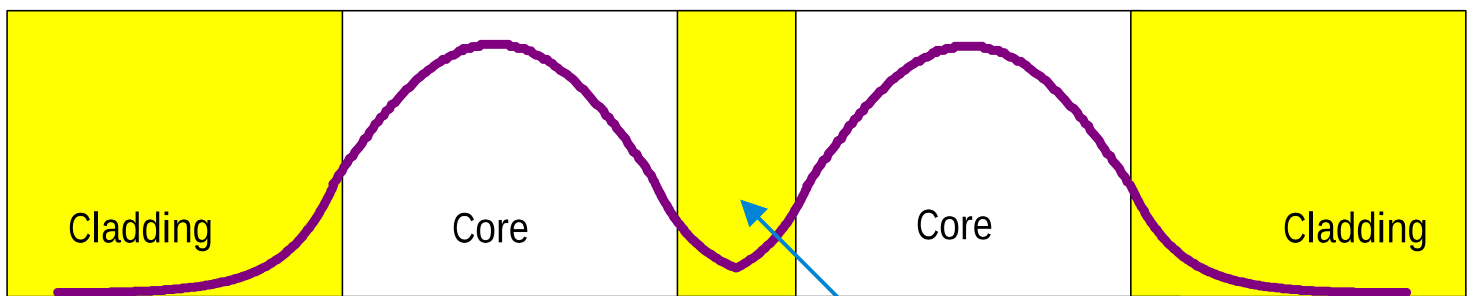
Couplers

The solution includes the smooth decay of $\mathbf{E}$ in the cladding

- This “evanescent wave” travels along with the guided wave
- Energy travels along the cladding and it’s easy to get it out

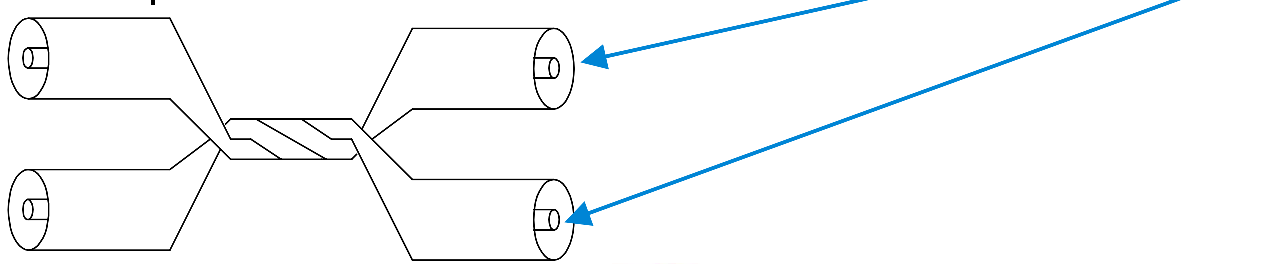
Join two fibers together - a double wave guide

- Light can tunnel from one core to the other - a coupler



Waves tunnel from one core to the next

This is how couplers work



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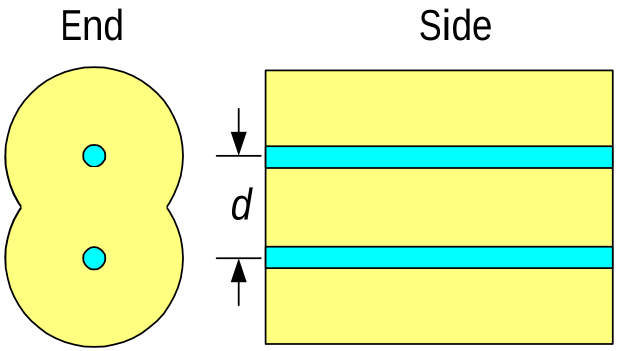
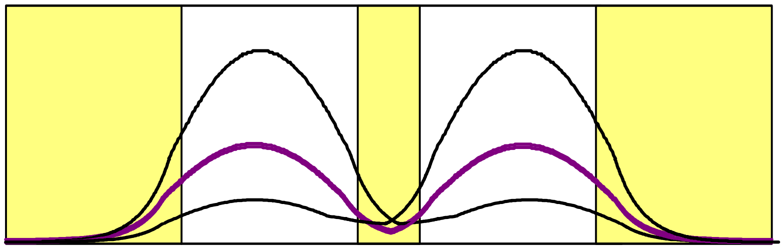
The Directional Coupler
Single Waveguide with Two Cores



Solving the wave equation with two *single mode* cores gives . . .

A transverse wave that oscillates between cores



- Incident signal power oscillates back and forth between the two cores as the light propagates the length of the coupler

The distance along the fiber where the signal is in a given core depends on . . .

- Wavelength
- The distance between the cores
- The geometry of the two original single mode fibers

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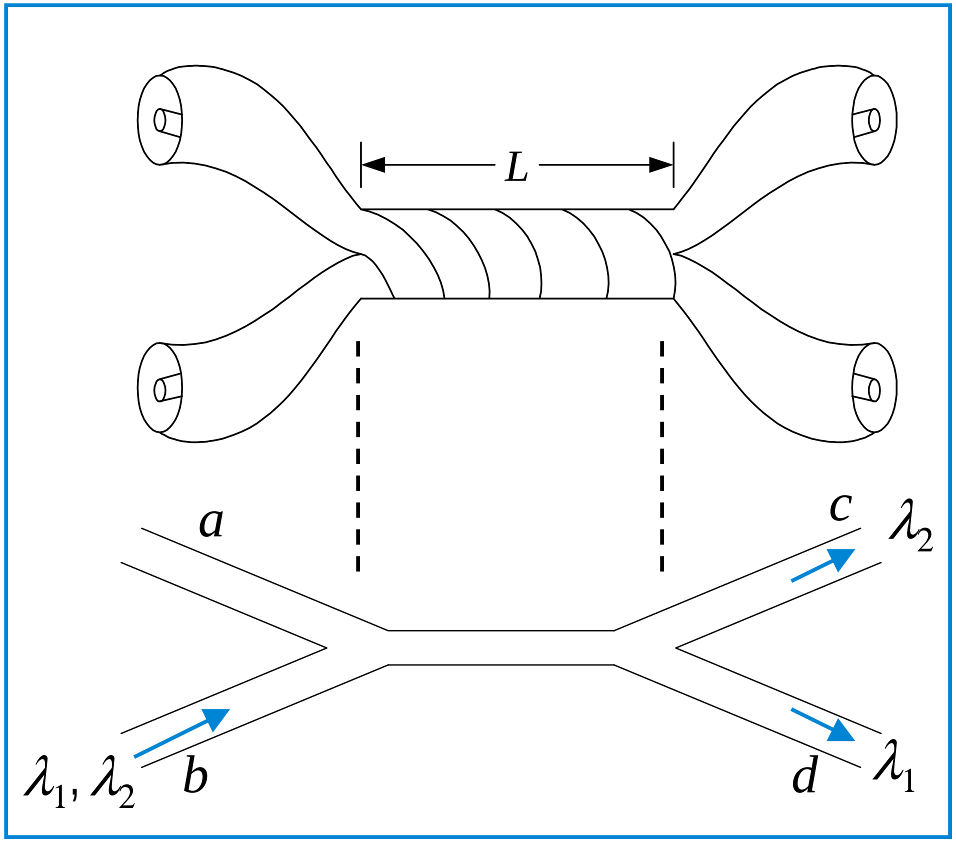
Wave Coupling Splitters

The length of a directional coupler can be tuned so that incident light of a given wavelength will exit the coupler in a specific core

- Couplers can be designed to demultiplex incoming signals
- In reverse the demultiplexer is a multiplexer
- With different single mode fibers and geometry couplers can be very selective with narrow channel spacing.
- The wavelength dependence can also be reduced over ~ 100 nm to give a wavelength independent 3 dB coupler.



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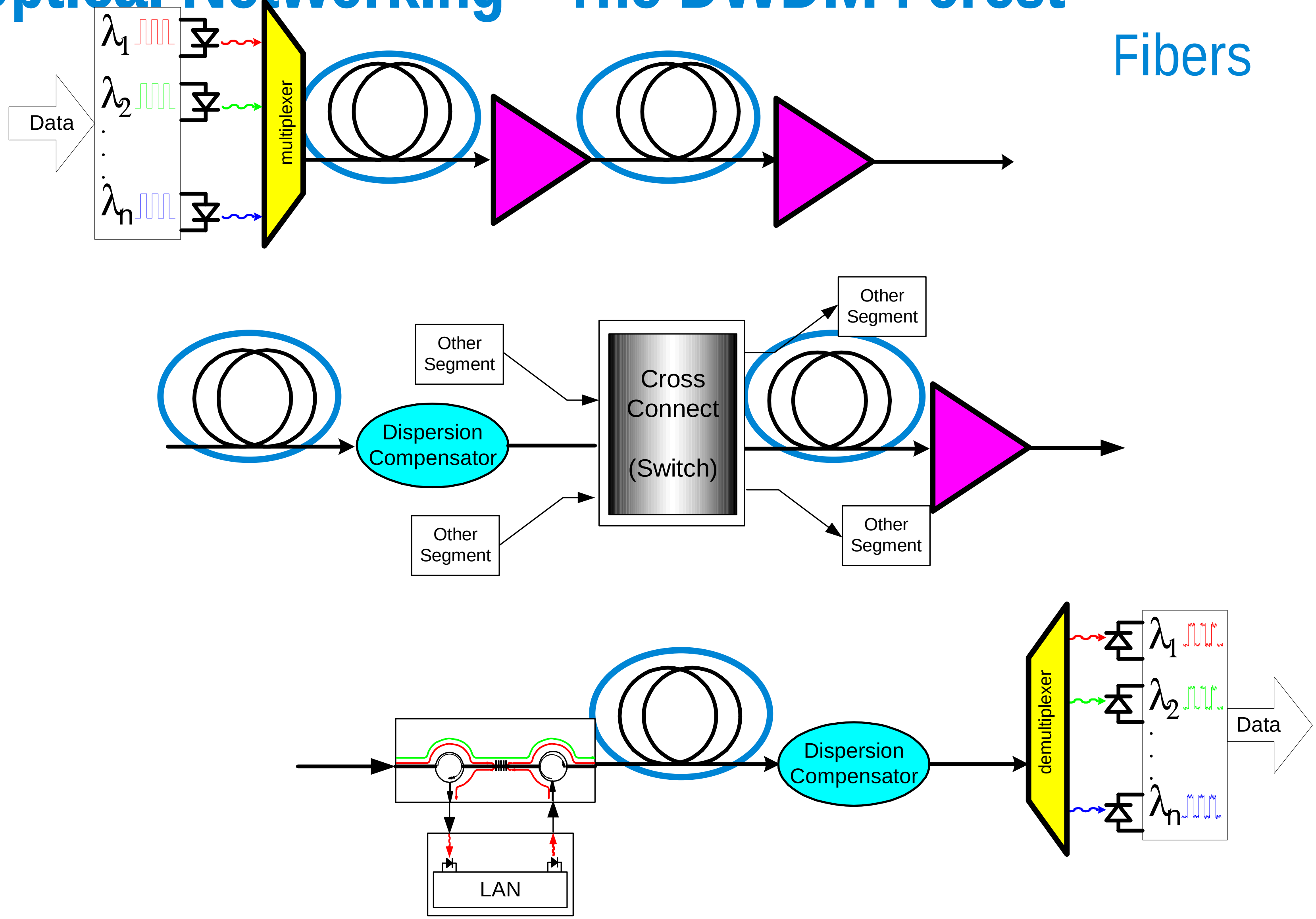
Optical Networking - The DWDM Forest



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Physical Optics

and

Passive Component Characterization

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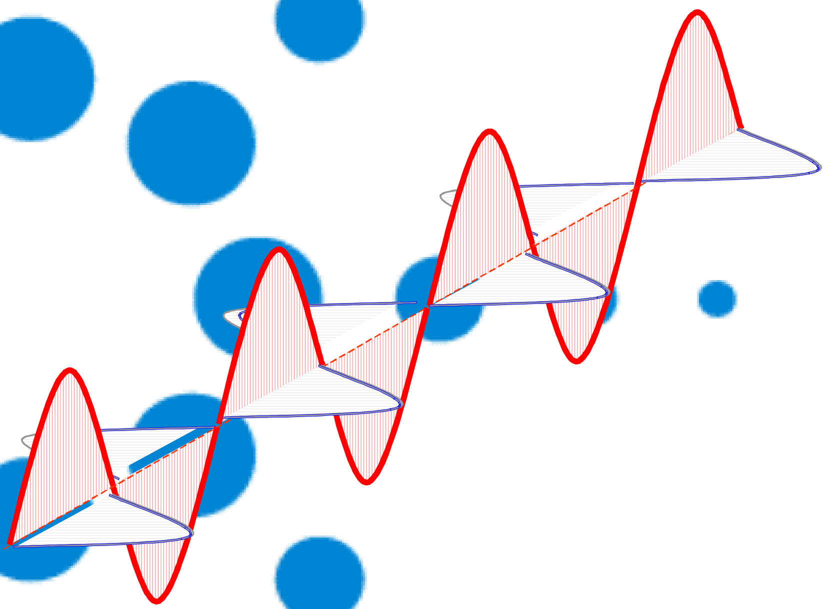
Physical Optics

Electromagnetic waves



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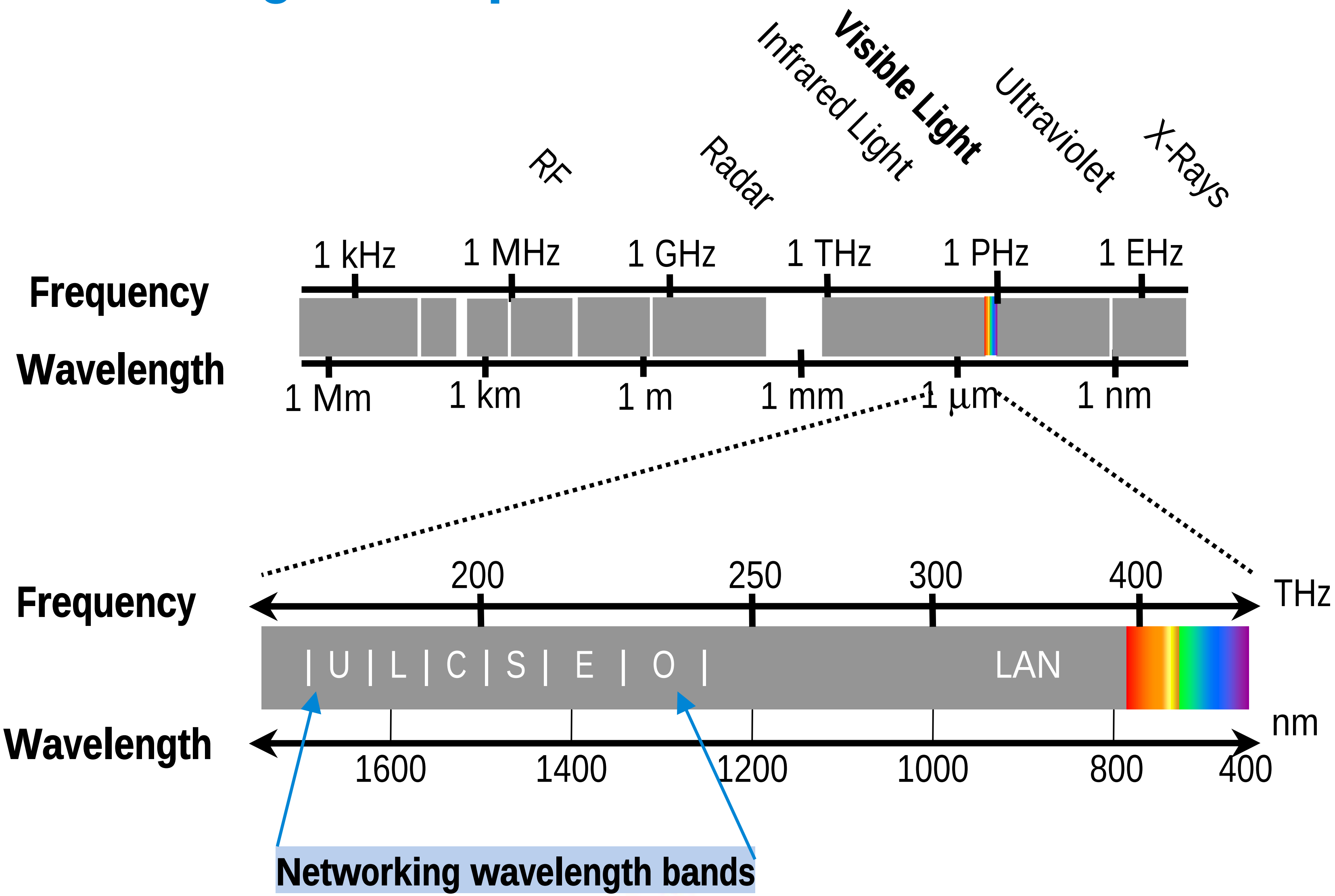
Electromagnetic Spectrum



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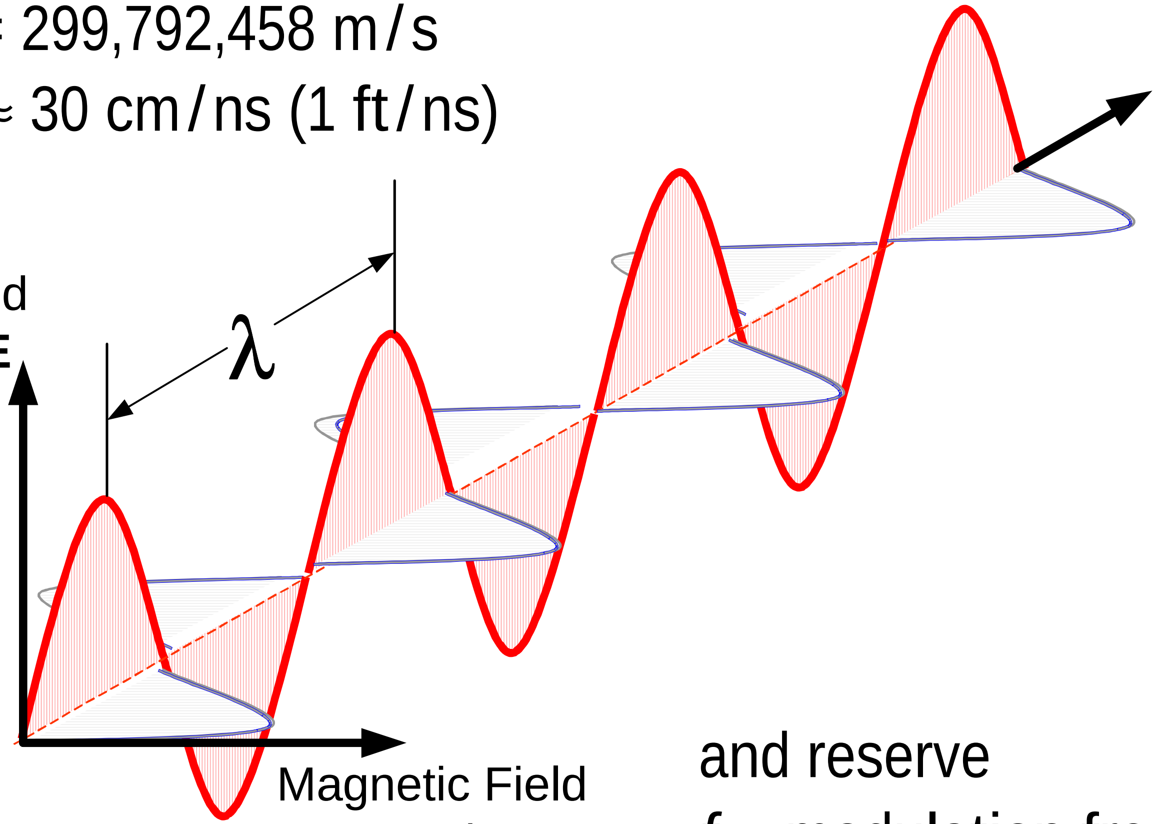
Waves

Describe light with

λ = wavelength, ν = frequency
≈ 1500 nm ≈ 200 THz

$\lambda\nu$ = c = 299,792,458 m/s
≈ 30 cm/ns (1 ft/ns)

Electric Field
Strength, **E**



Magnetic Field
Strength, **B**

and reserve
f = modulation frequency

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The relationship between optical frequency bandwidth, $\Delta\nu$ and wavelength linewidth, $\Delta\lambda$

Let frequency bandwidth be $\Delta \nu$

and wavelength linewidth be $\Delta \lambda$

Then since $\lambda \nu = c$

or $\nu = \frac{c}{\lambda}$

The relationship between bandwidth and linewidth is $\Delta \nu = -\frac{c}{\lambda^2} \Delta \lambda$

or, equivalently $\Delta \lambda = -\frac{c}{\nu^2} \Delta \nu$

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Electromagnetic Waves

Recipe for creating electromagnetic waves:

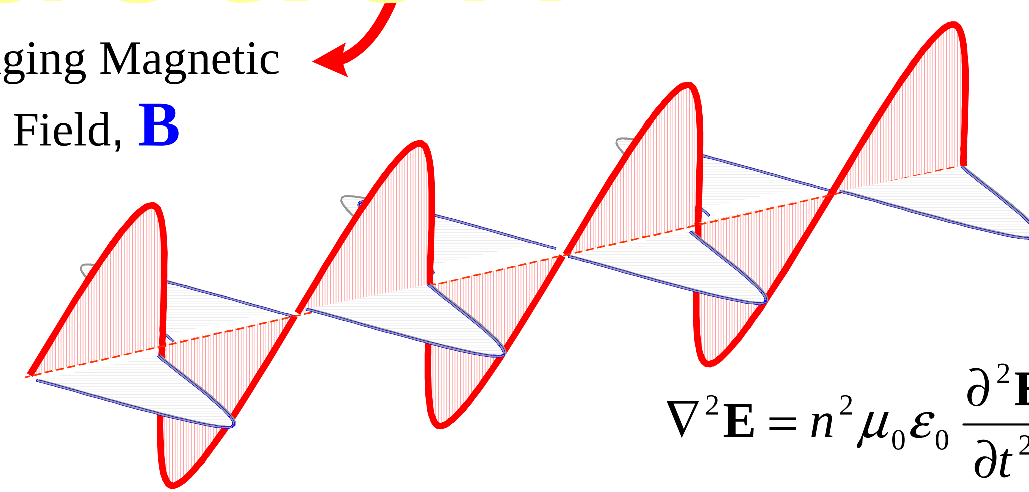
Changing Electric Field, **E**

$$n^2\mu_0\varepsilon_0\int_A \frac{d\mathbf{E}}{dt}\cdot d\mathbf{S} = \oint_C \mathbf{B}\cdot d\mathbf{l}$$

Induction

Changing Magnetic Field, **B**

$$-\int_A \frac{d\mathbf{B}}{dt}\cdot d\mathbf{S} = \oint_C \mathbf{E}\cdot d\mathbf{l}$$



$$\nabla^2\mathbf{E} = n^2\mu_0\varepsilon_0\frac{\partial^2\mathbf{E}}{\partial t^2}$$

$$\nabla^2\mathbf{B} = n^2\mu_0\varepsilon_0\frac{\partial^2\mathbf{B}}{\partial t^2}$$

The strength of the magnetic field is small so we only consider the electric field.

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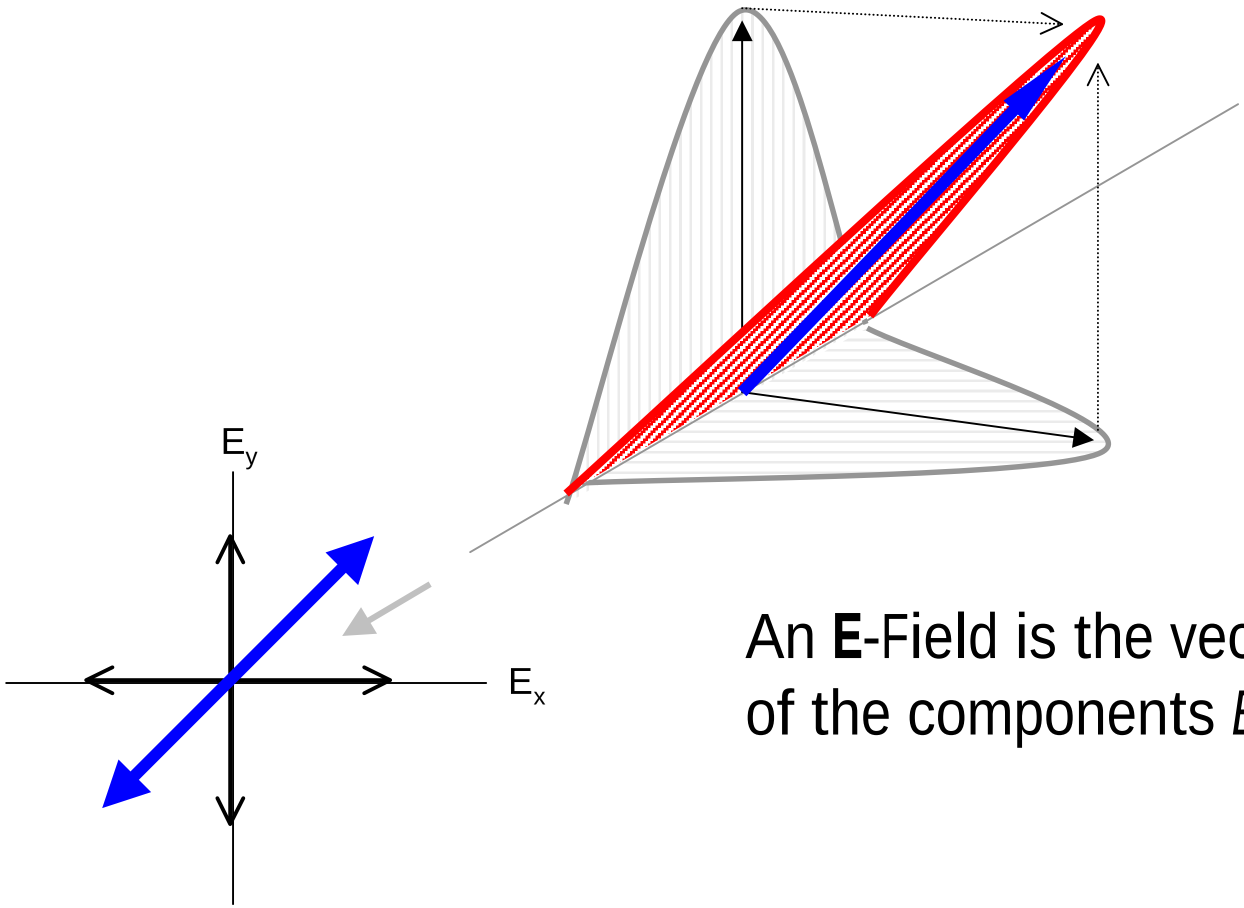
Electric Field Components



An **E**-Field is the vector sum of the components E_x and E_y

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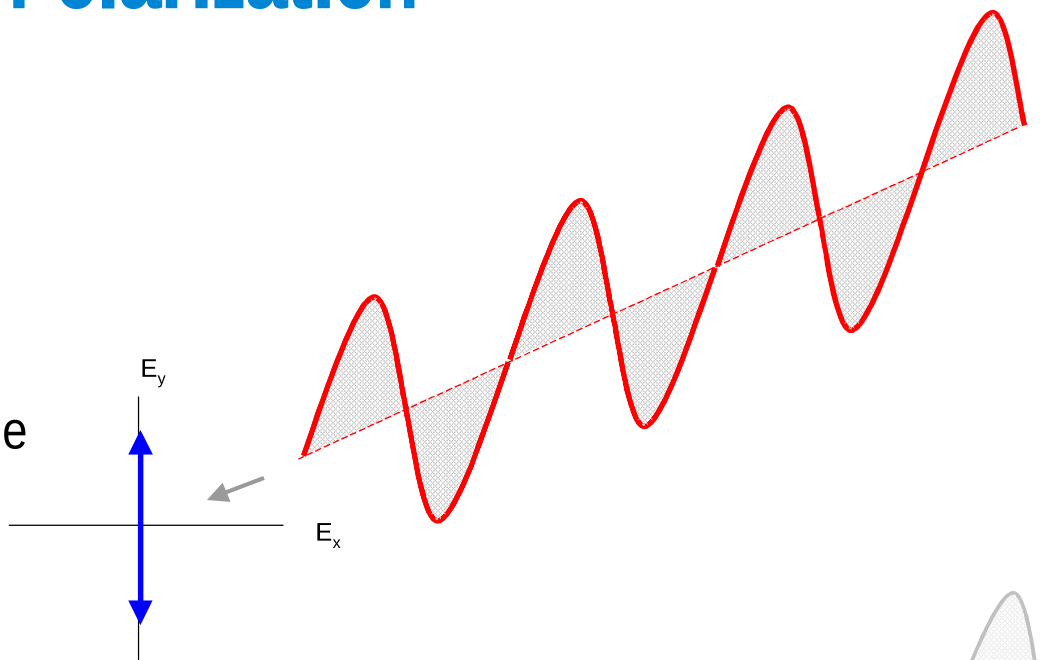
Introduction to Polarization

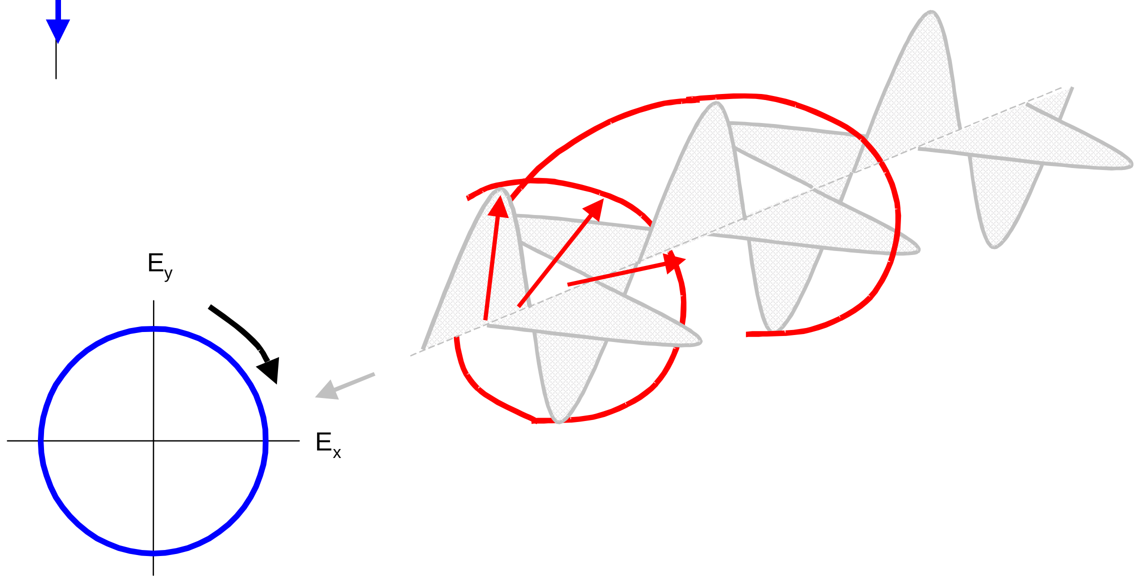
Linear Polarization

Projection of **E** is a line



Circular Polarization

Projection of **E** is a circle



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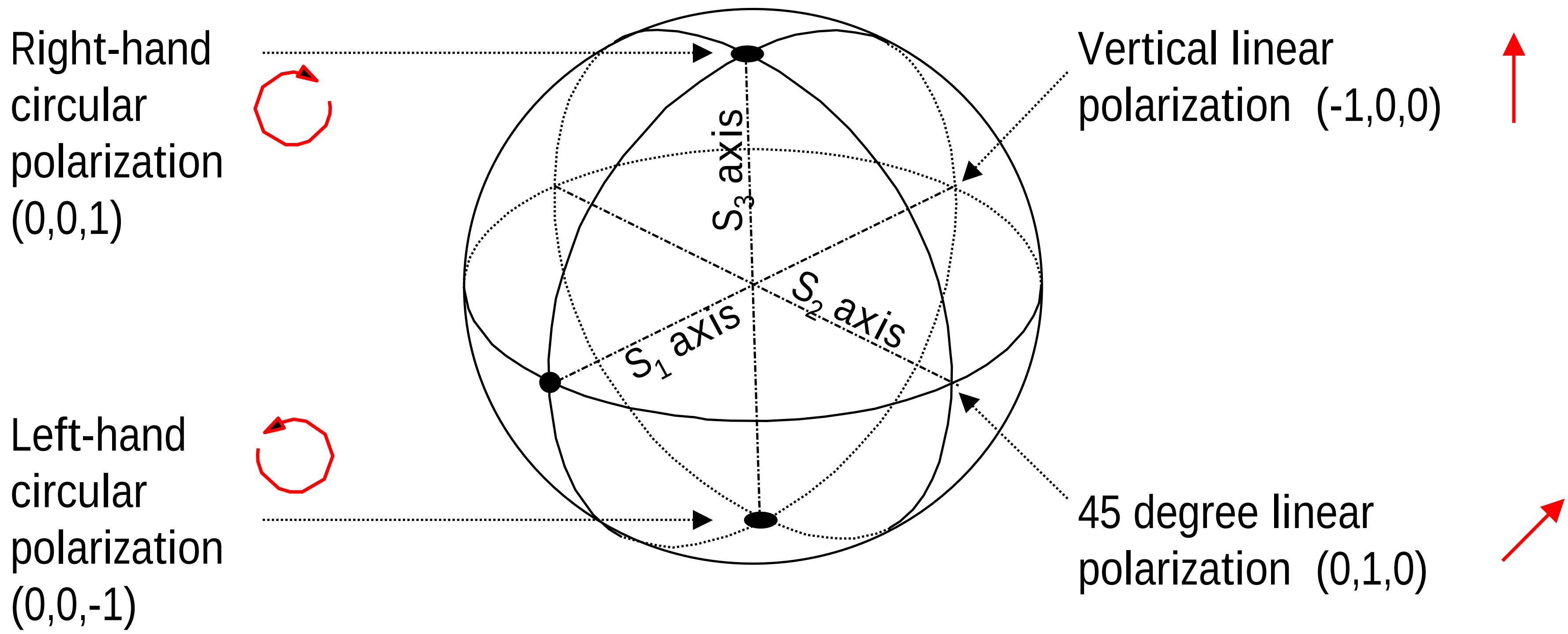
Poincaré Sphere
Representation of Polarization

Graphical representation of ***state*** of polarization using Stokes parameters (S_1, S_2, S_3)



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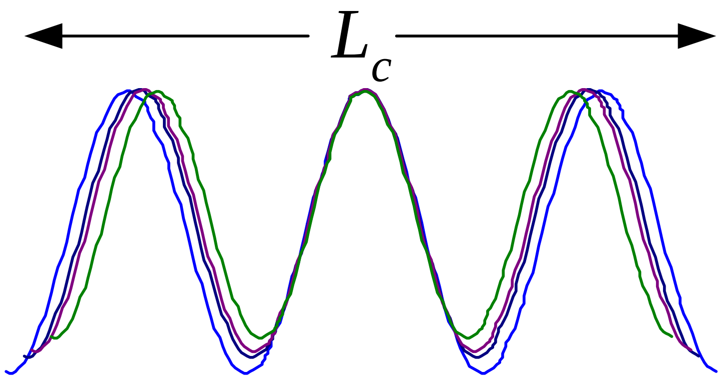
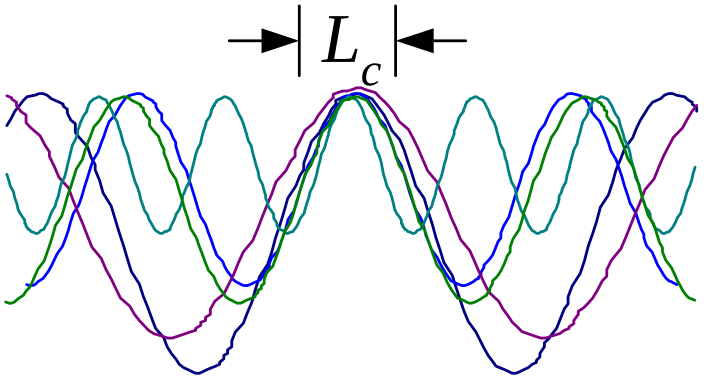
Coherence

Coherence ⇒ the phase relationship of waves



Coherent waves

components of coherent waves have well defined phase relationships.



Incoherent waves

components of incoherent waves have *random indeterminate* phase relationships.

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Coherence Time and Coherence Length

Coherence time (T_C)

Average time for the wave train to lose its phase relationships

Coherence length (L_C) $L_C = c \times T_C$

Average distance over which superposed waves lose their phase relationships

There is a Fundamental Relationship between Coherence and Bandwidth

$$\Delta\nu \times T_C \approx 1/4\pi$$

1. The bandwidth determines the coherence length and time,

$$T_c \approx 1/(4\pi\Delta\nu),\ \ L_c \approx c/(4\pi\Delta\nu)$$

2. A minimum optical bandwidth is required for a pulse of duration ΔT, $\Delta\nu \approx 1/(4\pi\Delta T)$

Restricts the spacing of DWDM signals for given rates

Short coherence length ⇔ broadband source

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Coherence and Optical Bandwidth

Examples

Light Bulb:

$$\left.\begin{array}{l}\text{Spectral Line Width} > 500\ \text{nm} \\ BW_{Optical} > 50\ \text{THz}\end{array}\right\} \Leftrightarrow \left\{\begin{array}{l} T_C < 0.02\ \text{ps} \\ L_C < 5\ \mu\text{m}\end{array}\right.$$

LED:

$$\left.\begin{array}{l}\text{Spectral Line Width} \approx 50\ \text{nm} \\ BW_{Optical} \approx 5\ \text{THz}\end{array}\right\} \Leftrightarrow \left\{\begin{array}{l} T_C \approx 0.2\ \text{ps} \\ L_C \approx 50\ \mu\text{m}\end{array}\right.$$

DFB Laser:

$$\left.\begin{array}{l}\text{Spectral Line Width} \approx 0.1\ \text{pm} \\ BW_{Optical} \approx 10\ \text{MHz}\end{array}\right\} \Leftrightarrow \left\{\begin{array}{l} T_C \approx 100\ \text{ns} \\ L_C \approx 30\ \text{m}\end{array}\right.$$

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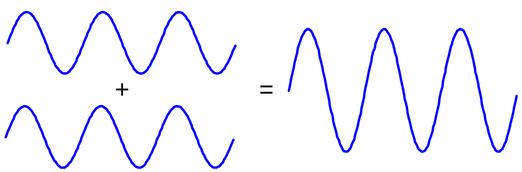
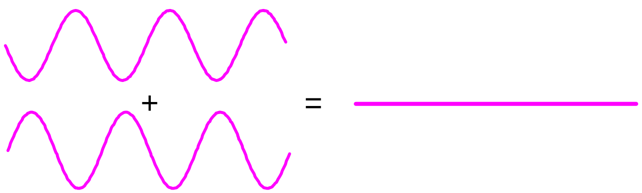
Interference

Interference = effect of adding waves from different sources

Constructive Interference



Destructive Interference



Conditions for interference:

- waves must be coherent and have the same polarization
- coherent sources add in phase

$$P_{\text{Total}}(t) = \left(\sum_k E_k \sin(\omega t + \varphi_k) \right)^2$$

Incoherent sources
add in power:

$$P_{\text{Total}}(t) = \sum_k P_k(t) = \sum_k \left[E_k \sin(\omega t + \varphi_k) \right]^2$$

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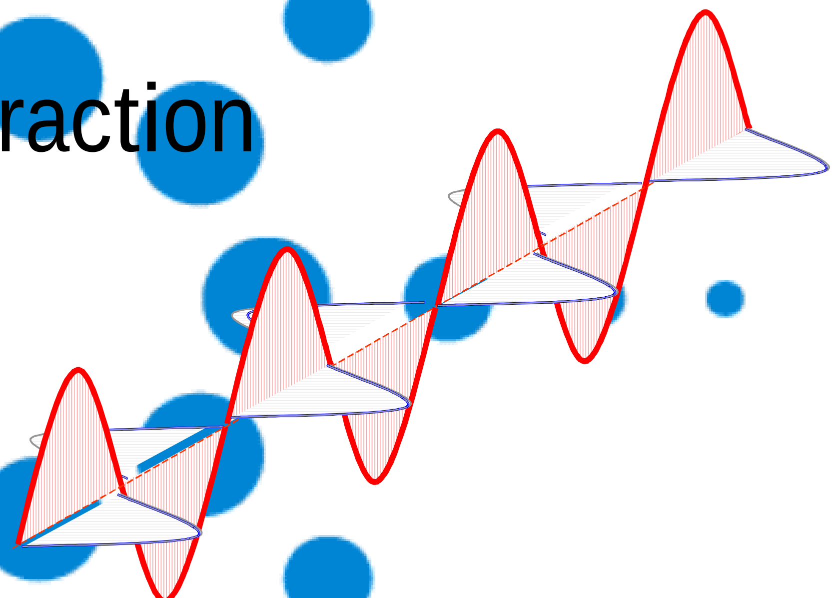
Physical Optics

Interference and Diffraction



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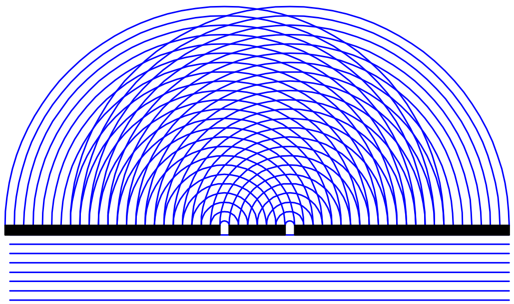
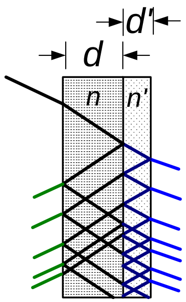
Interference Based Technologies

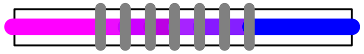
Interference



Thin Film filters

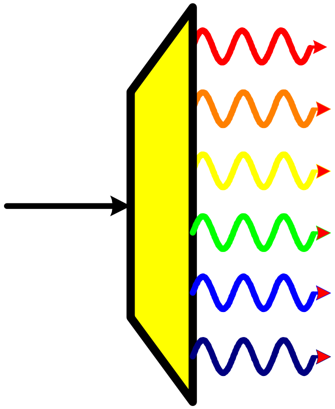


Fiber Bragg Grating



Wavelength Meter

Optical Mux/Demux



Optical Spectrum Analyzer

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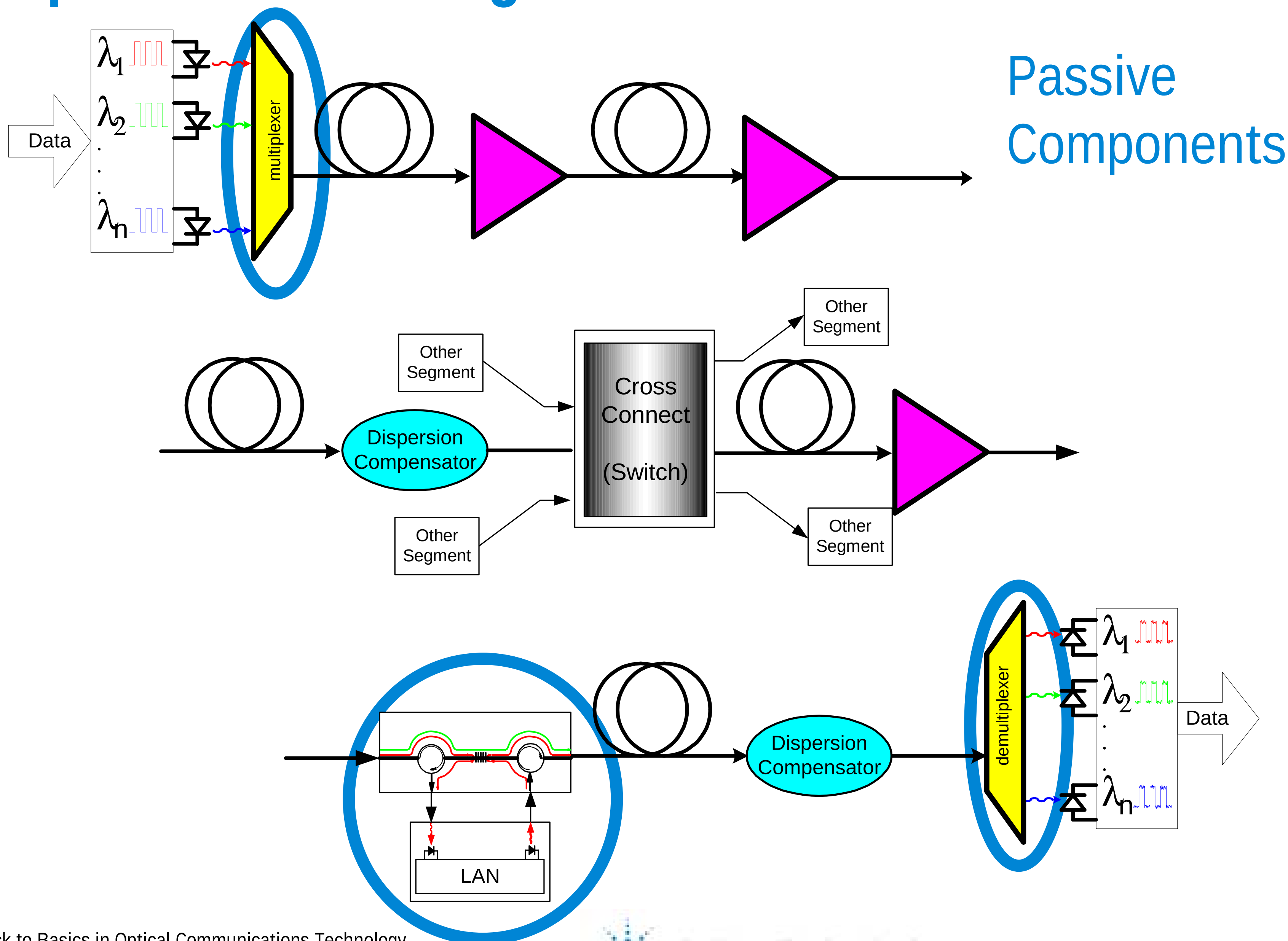
Optical Networking - The DWDM Forest



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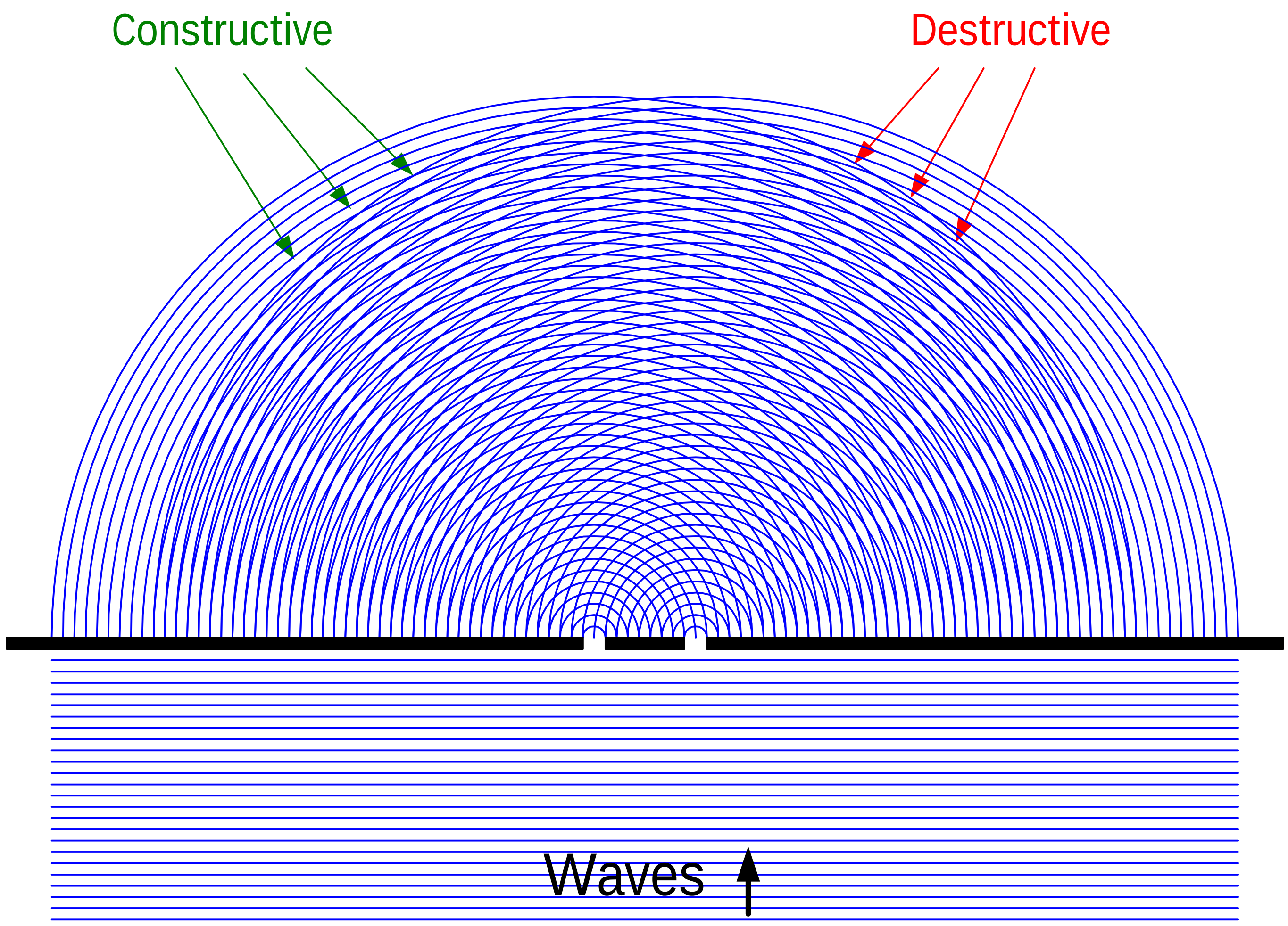
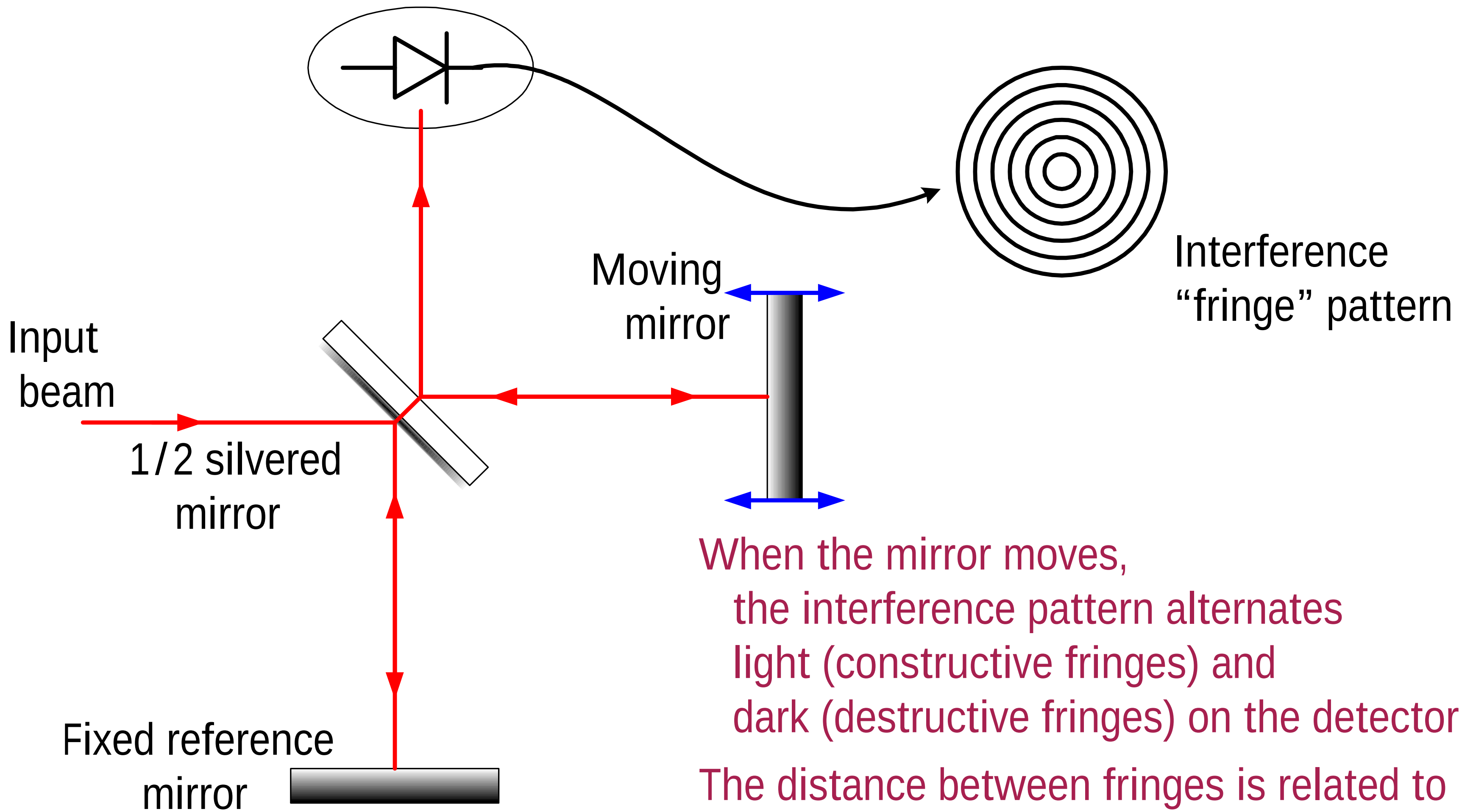
Interference Between Two Sources



Interference in One Dimension
The Michelson Interferometer



When the mirror moves,
the interference pattern alternates
light (constructive fringes) and
dark (destructive fringes) on the detector.

The distance between fringes is related to
the wavelength of light

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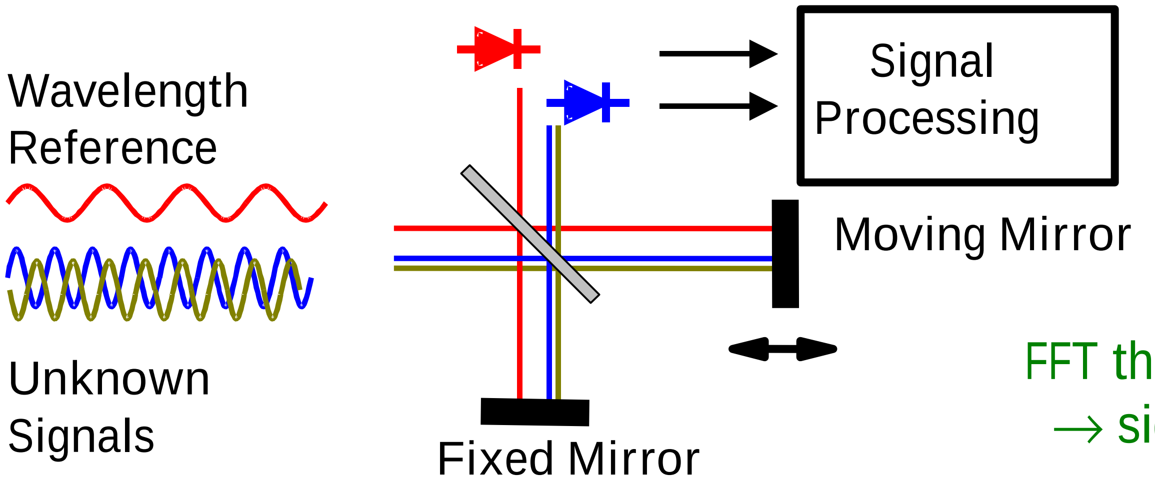
The Wavelength Meter

With a reference beam the Michelson interferometer can measure *absolute* wavelengths



FFT the fringe pattern
$\rightarrow$ signal spectrum

with an accuracy of 300 fm and resolution bandwidth of 30 pm

e.g., Agilent 86122

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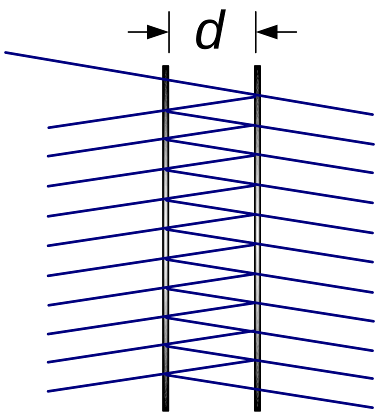
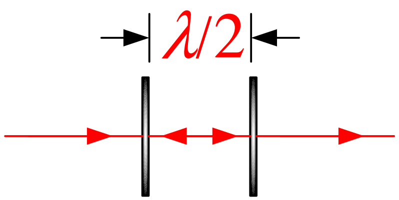
The Fabry Perot Etalon

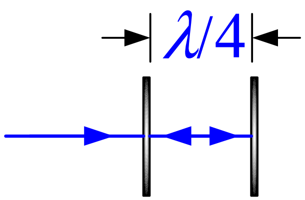
A resonant cavity containing
multiple reflections / transmissions



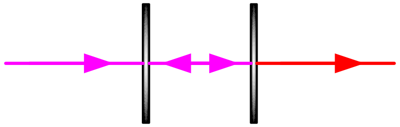
If $d = \lambda/2$ then
reflections and transmissions
interfere constructively



If $d = \lambda/4$ then
interference is destructive



Which makes a filter



It’s also the foundation for a LASER, as we’ll see soon.

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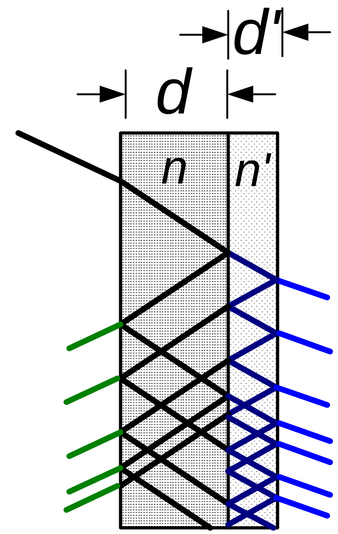
Thin Films

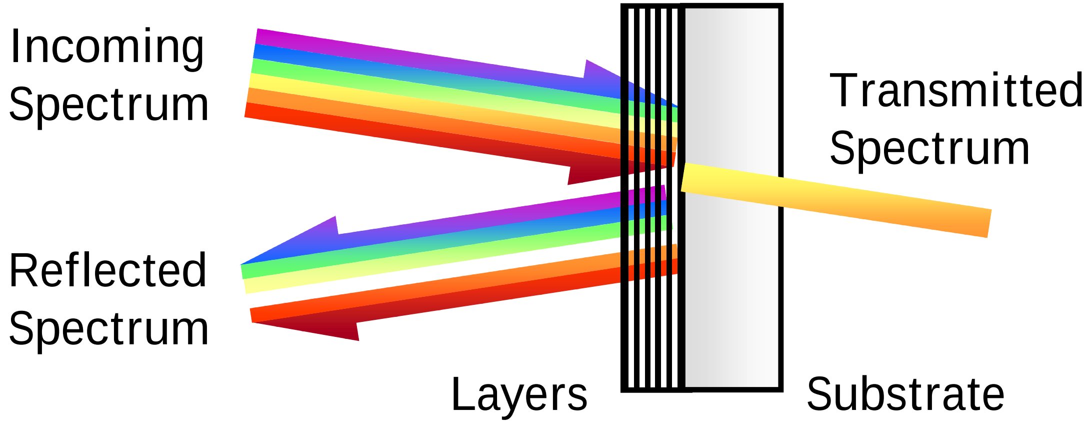


Series of Fabry-Perot Etalons with different properties

Anti-reflective coatings
 - must be centered at some wavelength

Selective transmission / reflective coatings

Many possibilities:



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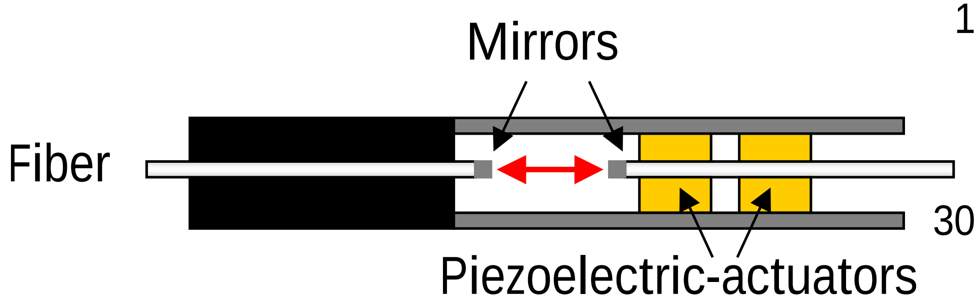
Tunable Fabry-Perot Filters

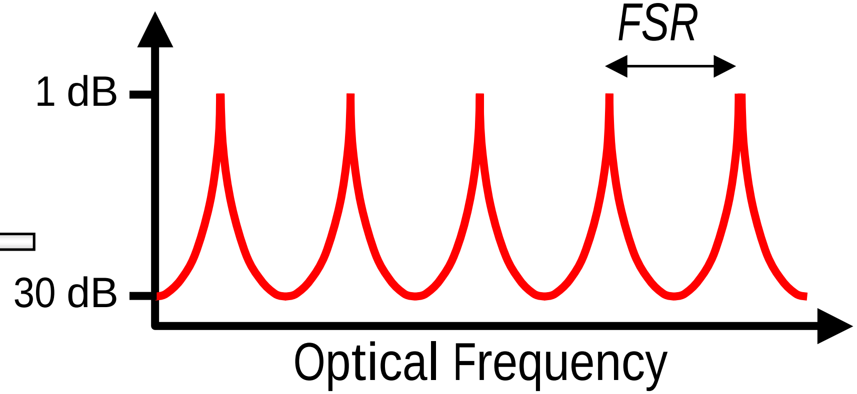
- Filter shape

  Repetitive passband with Lorentzian shape
  Free Spectral Range $FSR = c / 2 \cdot n \cdot L$ (L: cavity length)
  Finesss $F = FSR / BW$ (BW: 3 dB bandwidth)

- Typical specifications for 1550 nm applications

  FSR: 4 THz to 10 THz, *F*: 100 to 200, *BW*: 20 to 100 GHz
  Insertion loss: 0.5 to 35 dB





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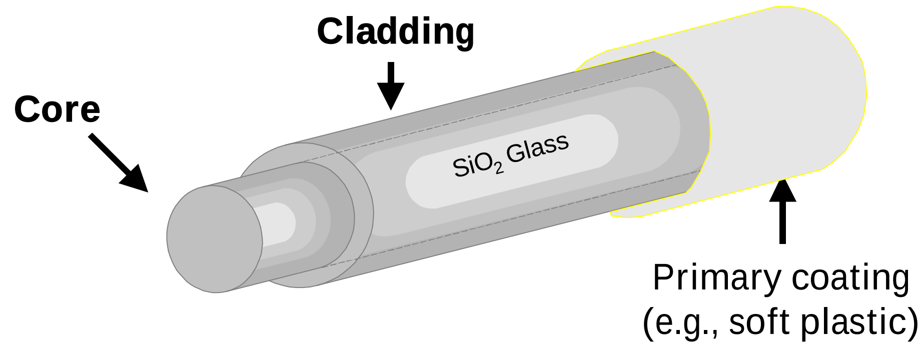
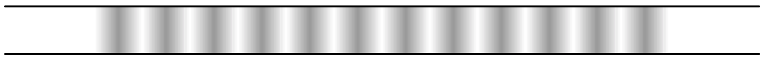
The In-Fiber Bragg Grating (FBG)

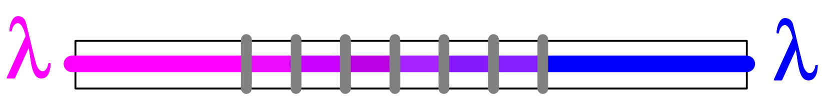
A simple filter and a cornerstone of the Optical Revolution



- To make a stretch of fiber into a grating:
  'scratch' the fiber with ultra-violet light



- Waves are transmitted and reflected at each 'scratch'
- Regular intervals between gratings $\rightarrow$ reflect one wavelength
  - a notch filter



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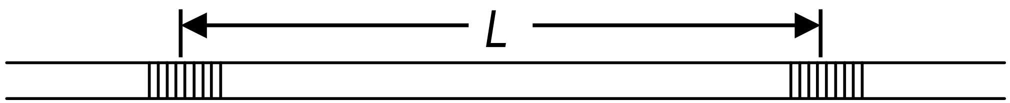
In Fiber Bandpass and Chirped Filters

Band Pass Filters

- Combine simple Fiber Bragg Gratings (FBG) to form Etalons tuned to different wavelengths and make in fiber Fabry-Perot bandpass filter

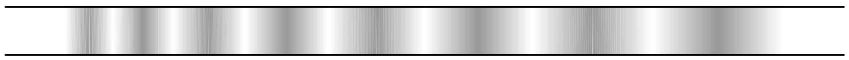


- Overlap gratings tuned to different wavelengths - Moire filter

Chirped Filters

- Uneven grating spacing can be used in different applications

  - e.g., compensation of Chromatic Dispersion (more later)



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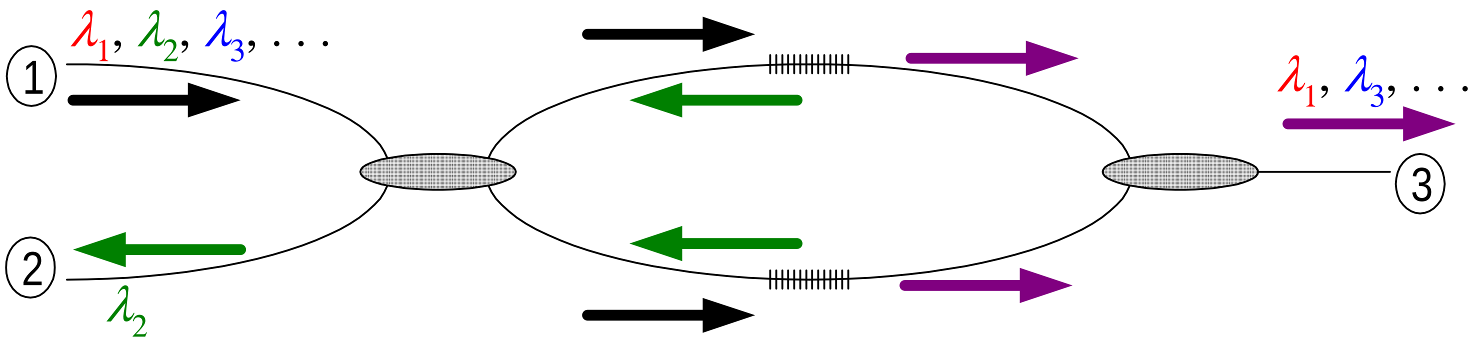
Interferometric Filters

Combined Technology: Coupler + Interferometer + FBG



- λ_2 is reflected by the gratings
- The Coupler is chosen so that the λ_2 couples to 2 on reflection

  Only λ_2 emerges from 2
- The second coupler is wavelength-independent to form a "Mach-Zehnder" band pass filter.

  Make mux/demux, add-drop node, etc

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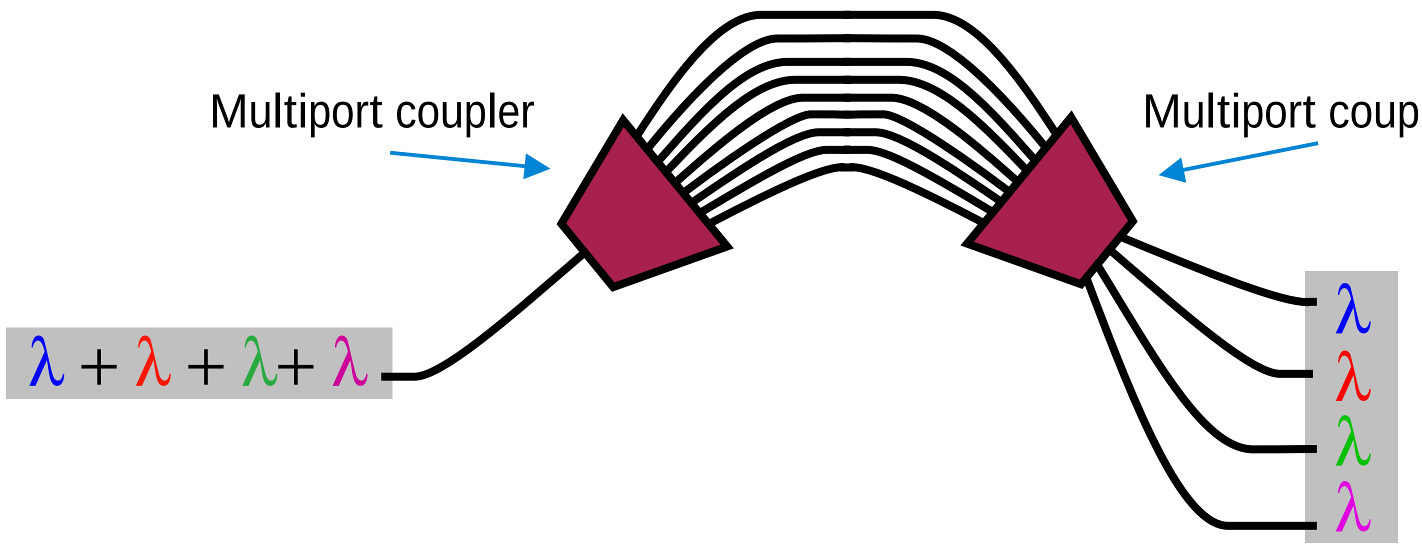
Arrayed Waveguide Grating
Generalized Mach-Zehnder Interferometric Filter

An MZI filter with wavelength dependent coupling

- 1 x n mux/demux
- Lower loss, flatter passband

Array of waveguides shifts the relative phases of each wavelength resulting in constructive and destructive interference of different wavelengths at different outputs



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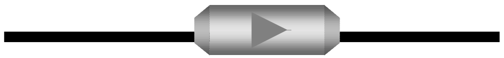
Polarization Based Technology

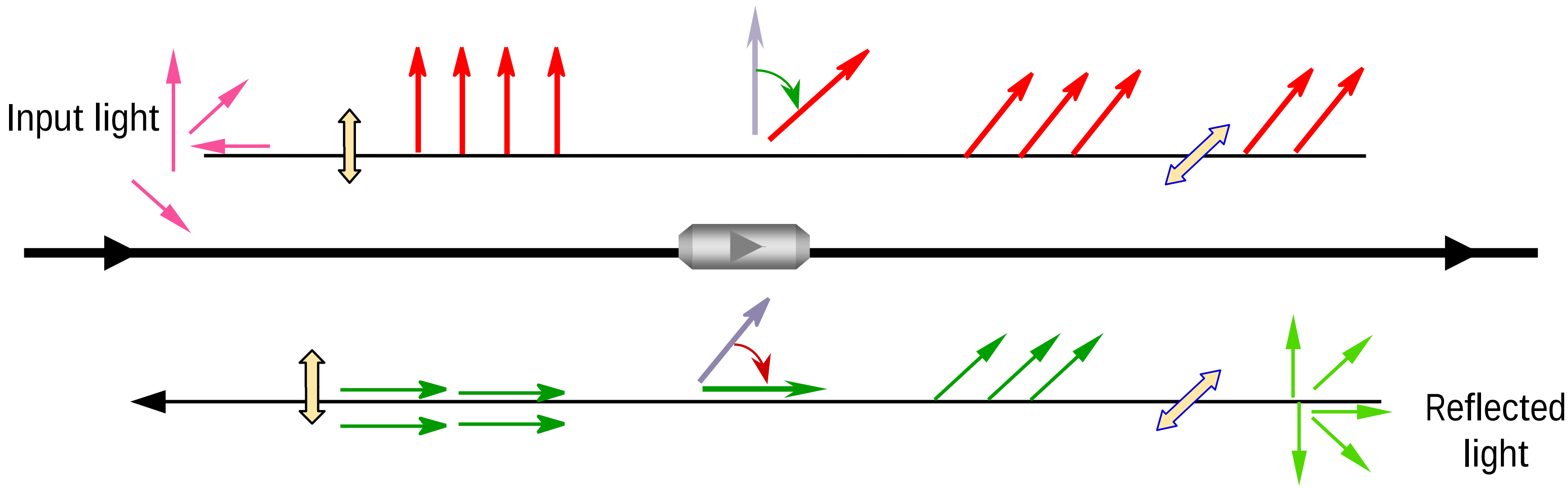
The Isolator



Main application:

To protect lasers and optical amplifiers from reflections that can cause instabilities

- Input light is polarized and transmitted through a series of polarizors
- Series of polarizors reject light of *all polarizations* in the back direction



Low loss in forward direction - 0.2 to 2 dB

High loss in reverse direction - 20 to 80 dB

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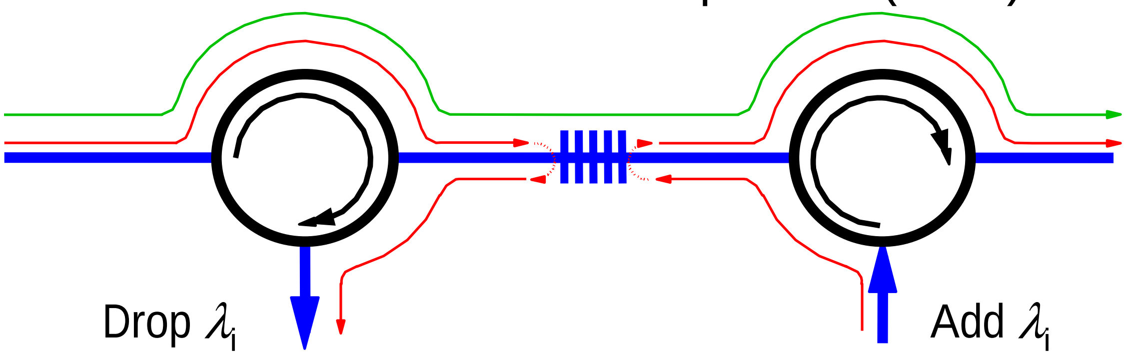
Add Drop Nodes and Circulators
Combined Technology: Coupler + Isolator + FBG

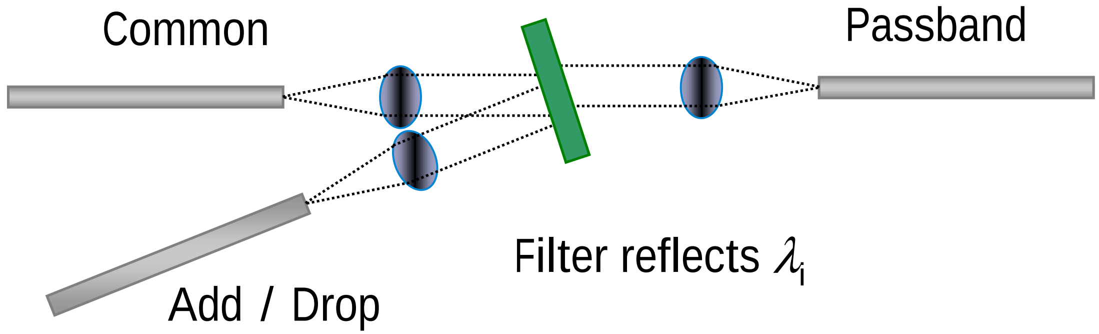
Three isolated ports:

- Port 1 $\rightarrow$ port 2
- Port 2 $\rightarrow$ port 3
- Port 3 $\rightarrow$ port 1

Circulator based Add Drop Node (ADN)



Thin film based ADN



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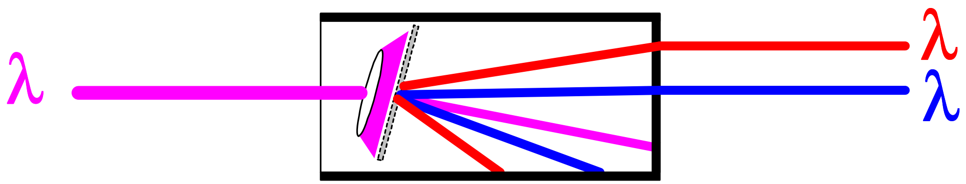
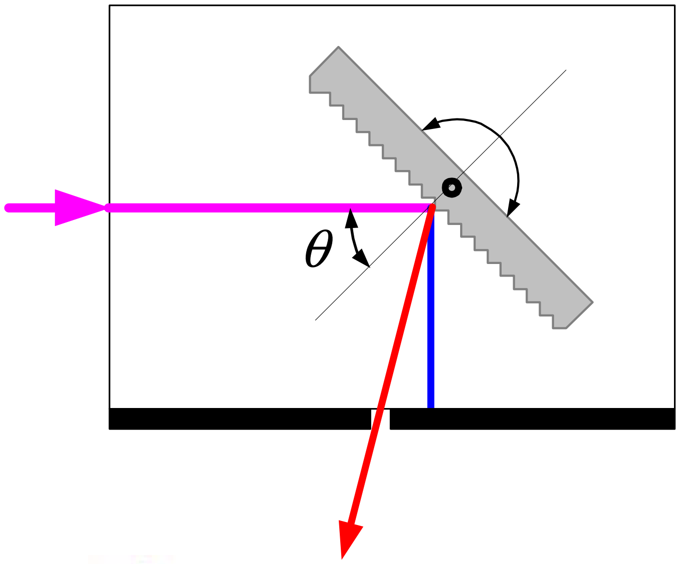
Monochromators and Optical Spectrum Analyzers
Two Dimensional Gratings

Transmission grating



Reflection grating



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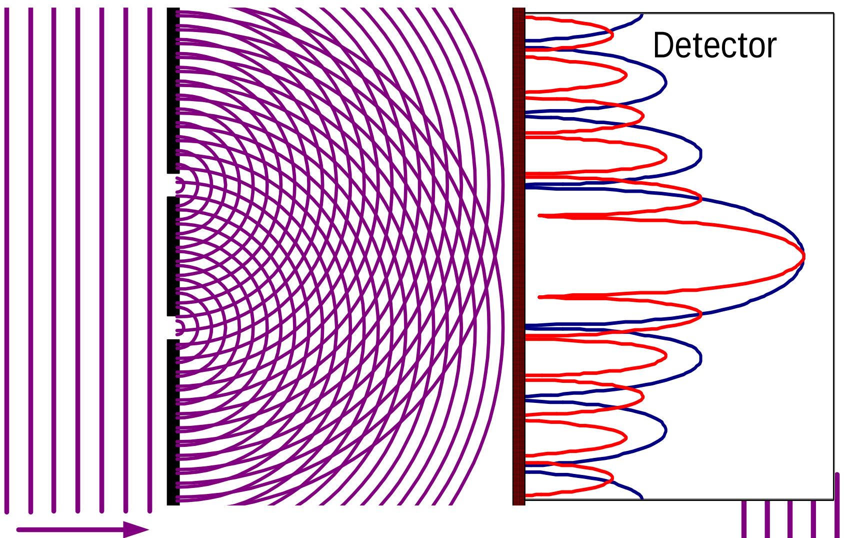
Interference From Gratings

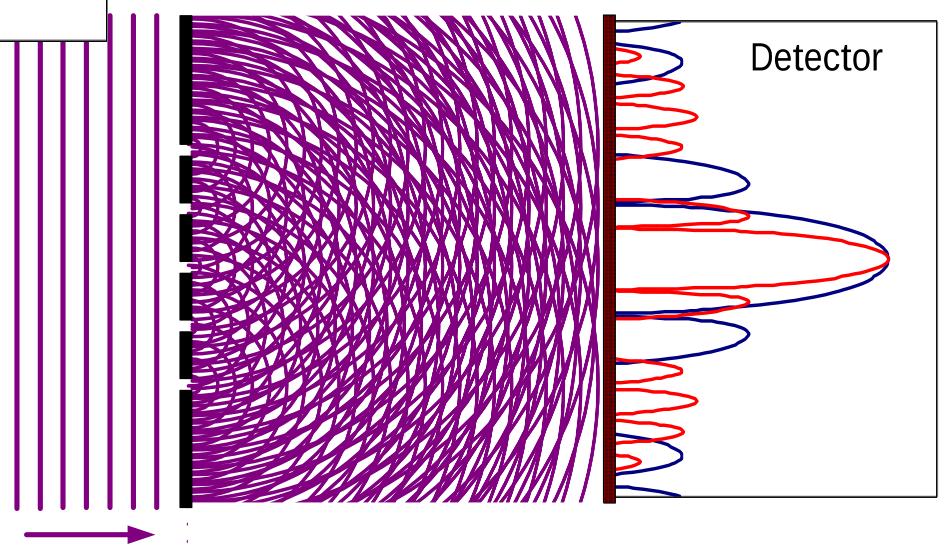
Two Slits



More slits

→ more interference

Five Slits



With more interference

purple → red and blue

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Spectrum is Resolved

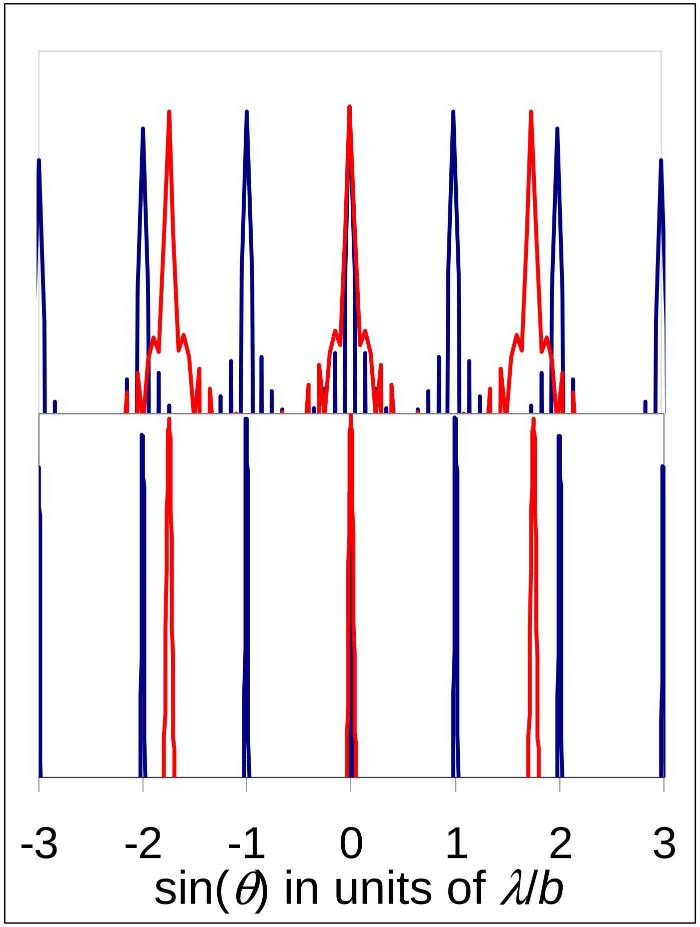
Increasing the number of slits

50 slits

1000 slits

Increases the spectral resolution

Wavelengths can be resolved with amazing accuracy: $\delta\lambda \approx 60 \text{ pm}$



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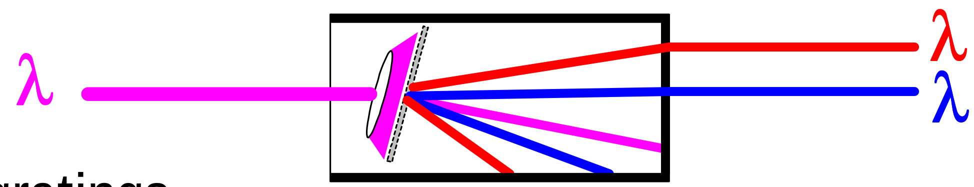
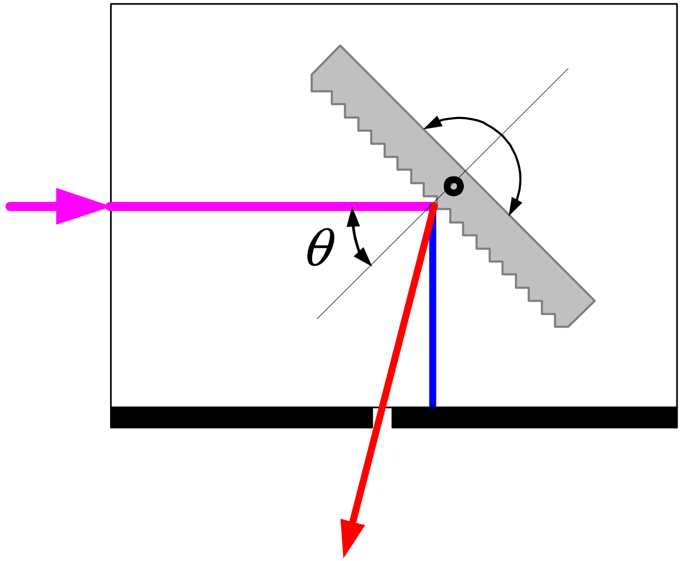
Grating Based Technologies

Gratings are the basis for many tools and components:

- Monochromators



Transmitting gratings
and
reflecting gratings



- Notch/passband filters,
- Multiplexers/demultiplexers
- Optical Spectrum Analyzers

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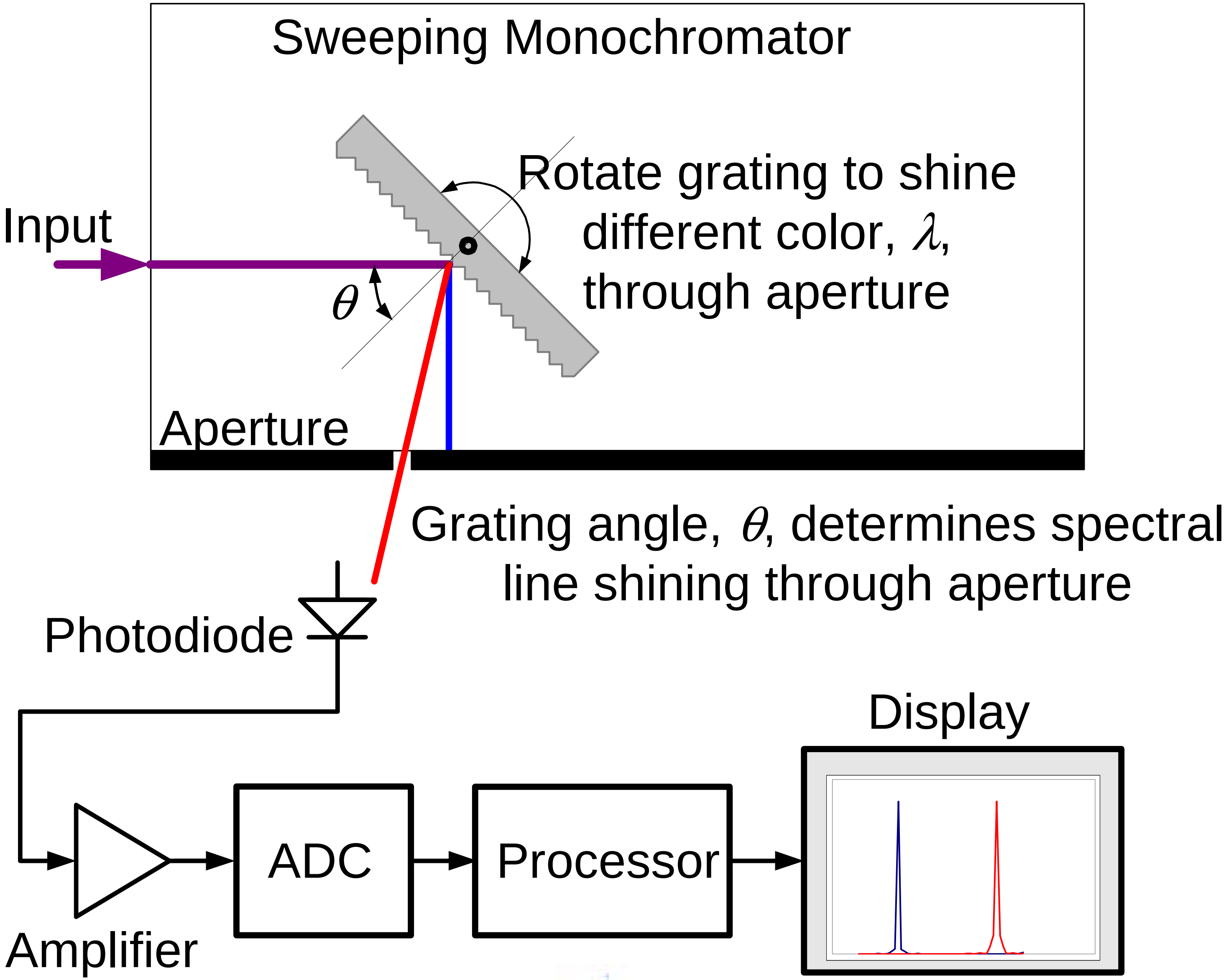
Grating Based Optical Spectrum Analyzer



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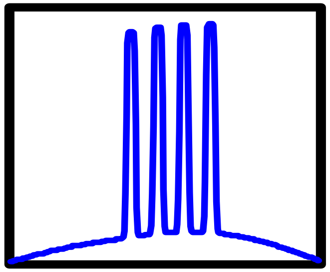
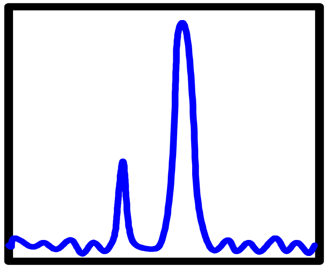
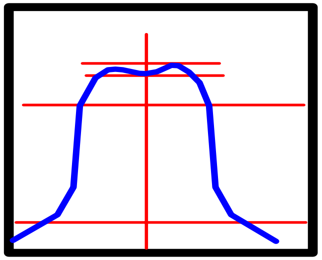
Optical Spectrum Analysis
Examples



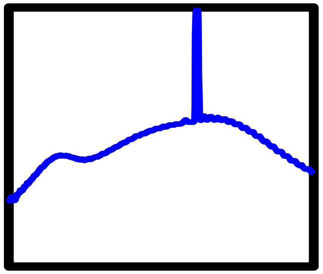
WDM Signals
Signal to noise for
channel spacings
as low as 50 GHz



Source Testing
FP, DFB lasers
Amplitude, SMSR



WDM Components
50 GHz Mux, Filters,
Add/Drop Components



Optical Amplifier Testing
Gain, Noise Figure, tilt
et cetera

Performance
Accuracy, $\lambda = \lambda_0 \pm 10$ pm
Resolution, $\delta\lambda \sim 40$ pm
Dynamic range ~ 70 dB

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Physical Optics

Component Characterization

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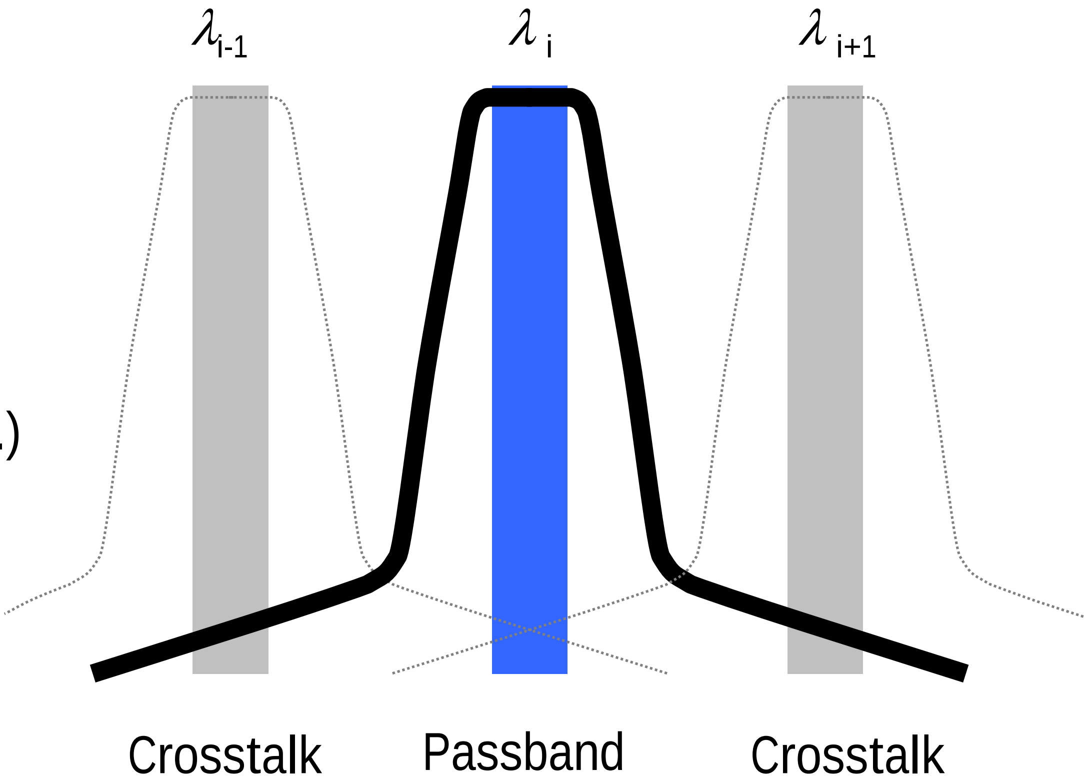
Filter Characteristics

Passband

- Insertion loss
- Ripple
- Wavelengths
  (peak, center, edges)
- Bandwidths (0.5 db, 3 db, ..)
- Polarization dependence

Stopband

- Crosstalk rejection
- Bandwidths (20 db, 40 db, ..)



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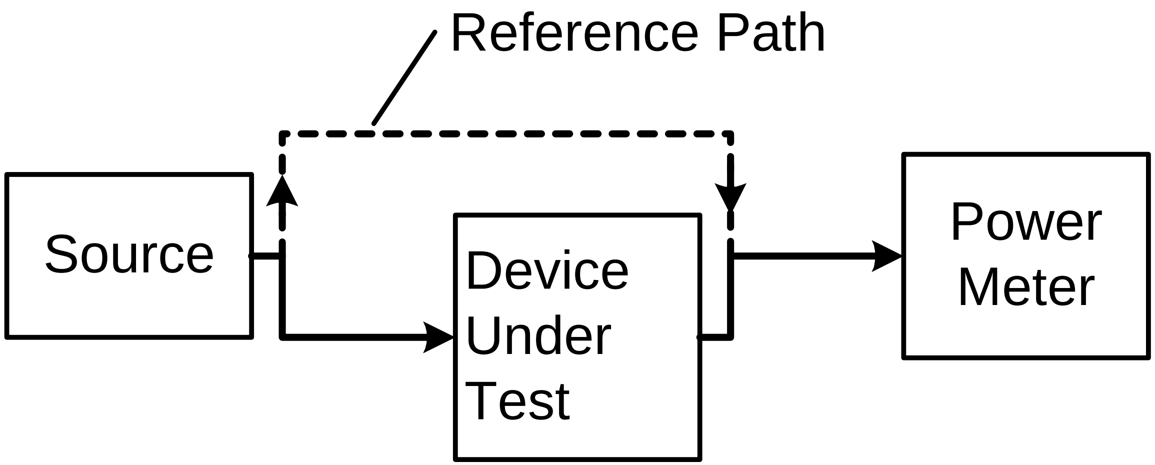
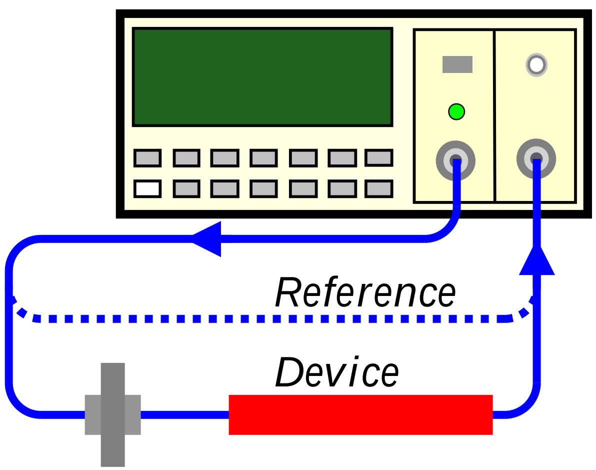
Total Insertion Loss

A measure of the loss of light within an optical component.





$$IL(\mathrm{dB}) = 10\log_{10}\frac{P_{With\,DUT}}{P_{Without\,DUT}}$$

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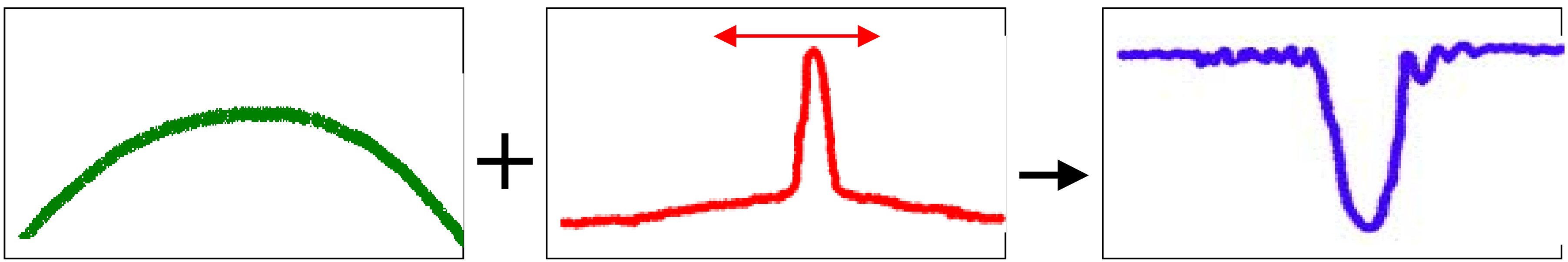
Filter Transmission Spectrum (Insertion Loss)
OSA Method:

Broadband Source + λ-Selective Detector

Notch Filter



Source spectrum

Detector sensitivity and resolution

Transmitted spectrum

- Fast Sweep
- High Dynamic Range
- Good Sensitivity
- Incoherent Light

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Test Solution

8614x Optical Spectrum Analyzer series

- Built in applications to characterize

  Sources, DWDM signals,
  Passive Components,
  Amplifiers

- Built in Broadband Sources
- ± 10 pm λ absolute accuracy
- ± 2 pm repeatability
- 60 pm λ resolution bandwidth
- 70+ dB dynamic range
- 600 nm → 1700 nm

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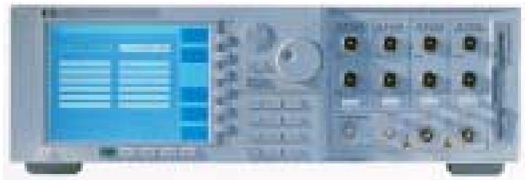
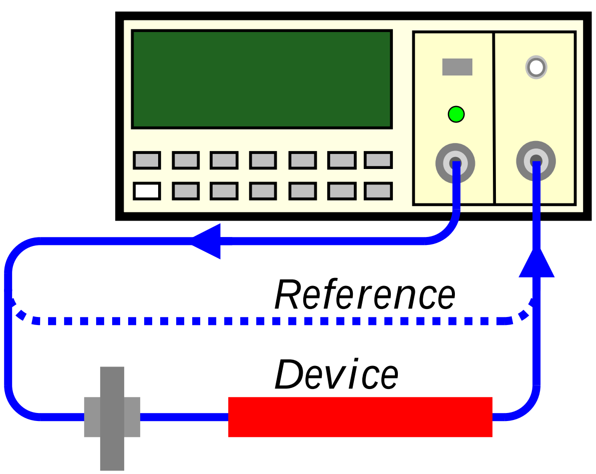
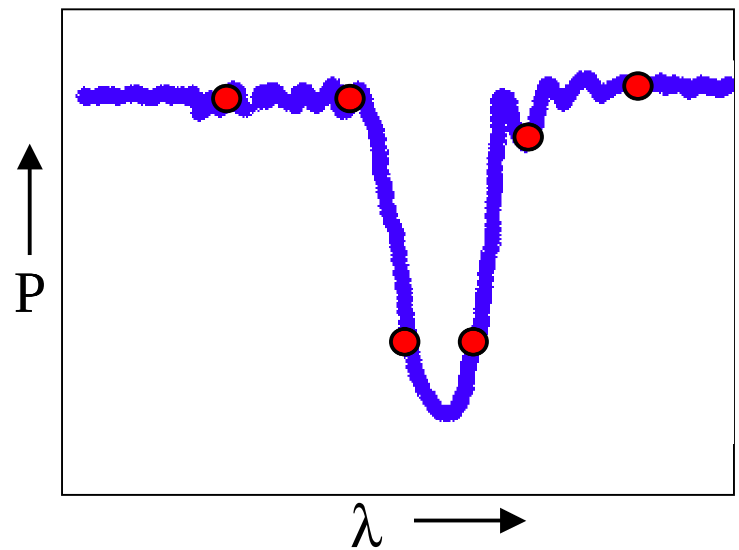
Filter Transmission Spectrum (Insertion Loss)
TLS Method: λ-Selective Source + Broadband Detector



$$IL = 10\log_{10}\frac{P_{With\,DUT}(\lambda)}{P_{Without\,DUT}(\lambda)}$$



Notch Filter



Parameters to Test

- Center λ
- 3 dB Bandwidth
- Ripple
- Isolation

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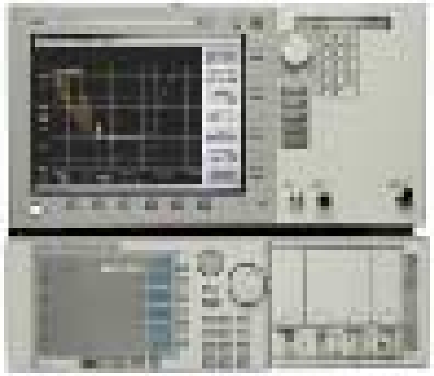
Test Solutions

Tunable Laser System / Power Meter + Photonic Foundation Library

- Configurable to perform all parameter tests
- Scaleable to multi-channels
- λ resolution 0.1 pm
- Low SSE

86082 Wavelength Domain Component Analyzer



- Fast filter characterization
- λ resolution: < 1 pm
- Speed: > 2 sweeps/s
- Range: 1260 $\rightarrow$ 1640 nm
- Vertical accuracy ± 0.06 dB

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Insertion Loss as a Function of Wavelength
Swept Insertion Loss

Two standard approaches:

1. Use a Tunable Laser Source (TLS)
   - Worry about back scattering interference issues
2. Use a Broadband source and an OSA
   - Short coherence length of source $\Rightarrow$ no interference issues
   - Must calibrate and subtract baseline spectrum
   - Need high spectral density (energy at each wavelength)

Reference p/n 5980-1454E:
State of the art characterization of optical components for DWDM applications

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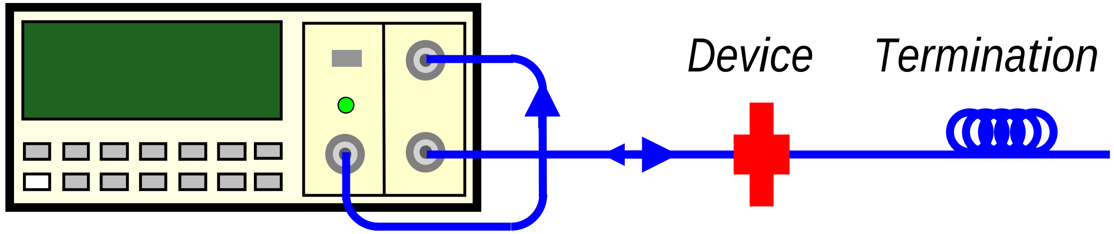
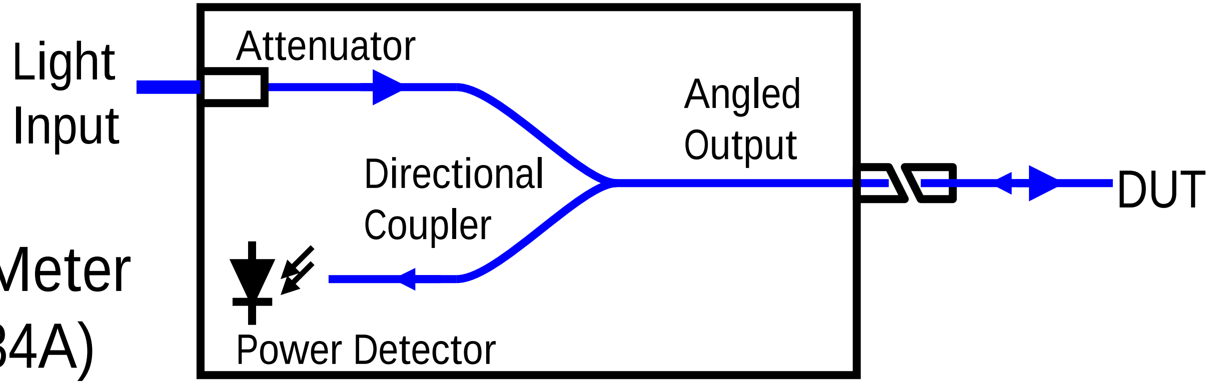
Return Loss

Total Return loss

$$RL = -10\log_{10}\frac{P_{reflected}}{P_{reference}}$$

- A measure of the light reflected by a component





Return Loss Meter Module (81534A)

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Insertion / Return Loss Measurement Subtleties

Beware of multiple reflections!!

- If multiple reflections occur within a distance less than L_C
  then there will be interference fringes on the detector
  $\Rightarrow$ uncertainty in RL up to 100%
- Avoid using coherent beams
  LED or Tungsten lamp ideal, but too low spectral energy density
  for most cases
- But RL(λ) may be desired and may depend on λ and
  a narrow source has a large L_C
- Common to use a Fabry-Perot laser
  high power, with sidebands to mitigate interference,
  still . . . L_C ~ meters

Understand the device and the source

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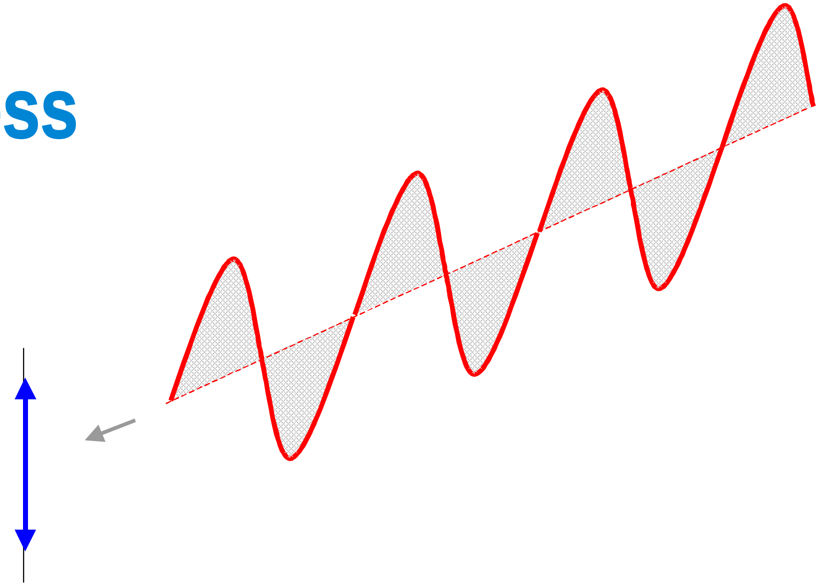
Polarization Dependent Loss

Recall Polarization describes the orientation of the electric field



The attenuation of light in fibers and network elements varies according to polarization.

Polarization Dependent Loss
the variation of attenuation with polarization.

Monitor output power of DUT while varying polarization to get

$$PDL(\mathrm{dB}) = 10\log_{10}\frac{P_{\max}}{P_{\min}}$$

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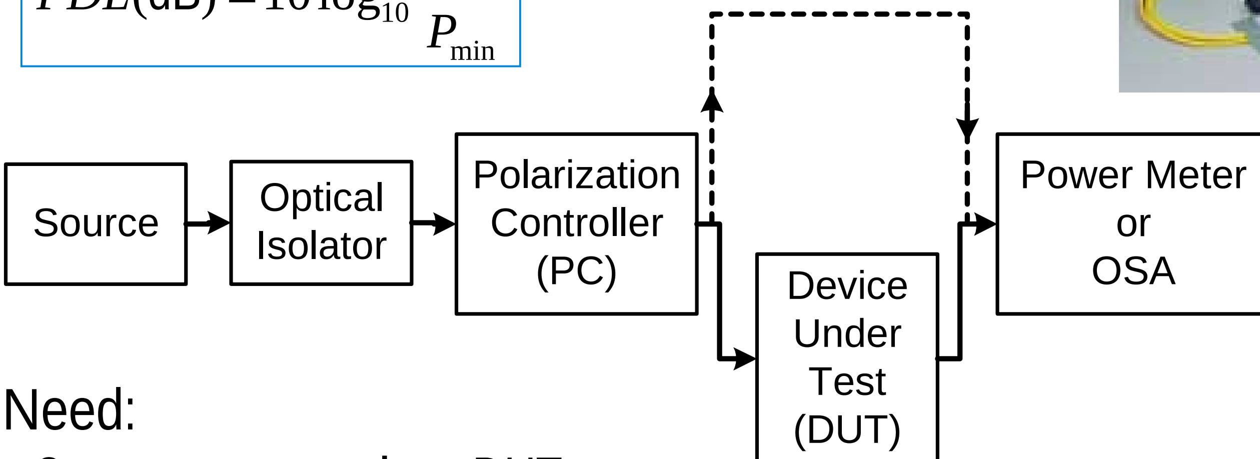
Polarization Dependent Loss

Insertion loss with polarization control:

$$PDL(\text{dB}) = 10\log_{10}\frac{P_{max}}{P_{min}}$$



Need:

- Constant power into DUT
- Polarization Controller (PC)
  either provide all states,
  or use a Müller matrix technique
- Polarization independent power meter / OSA

Look for PDL < 0.1 dB

8169 Polarization Controller

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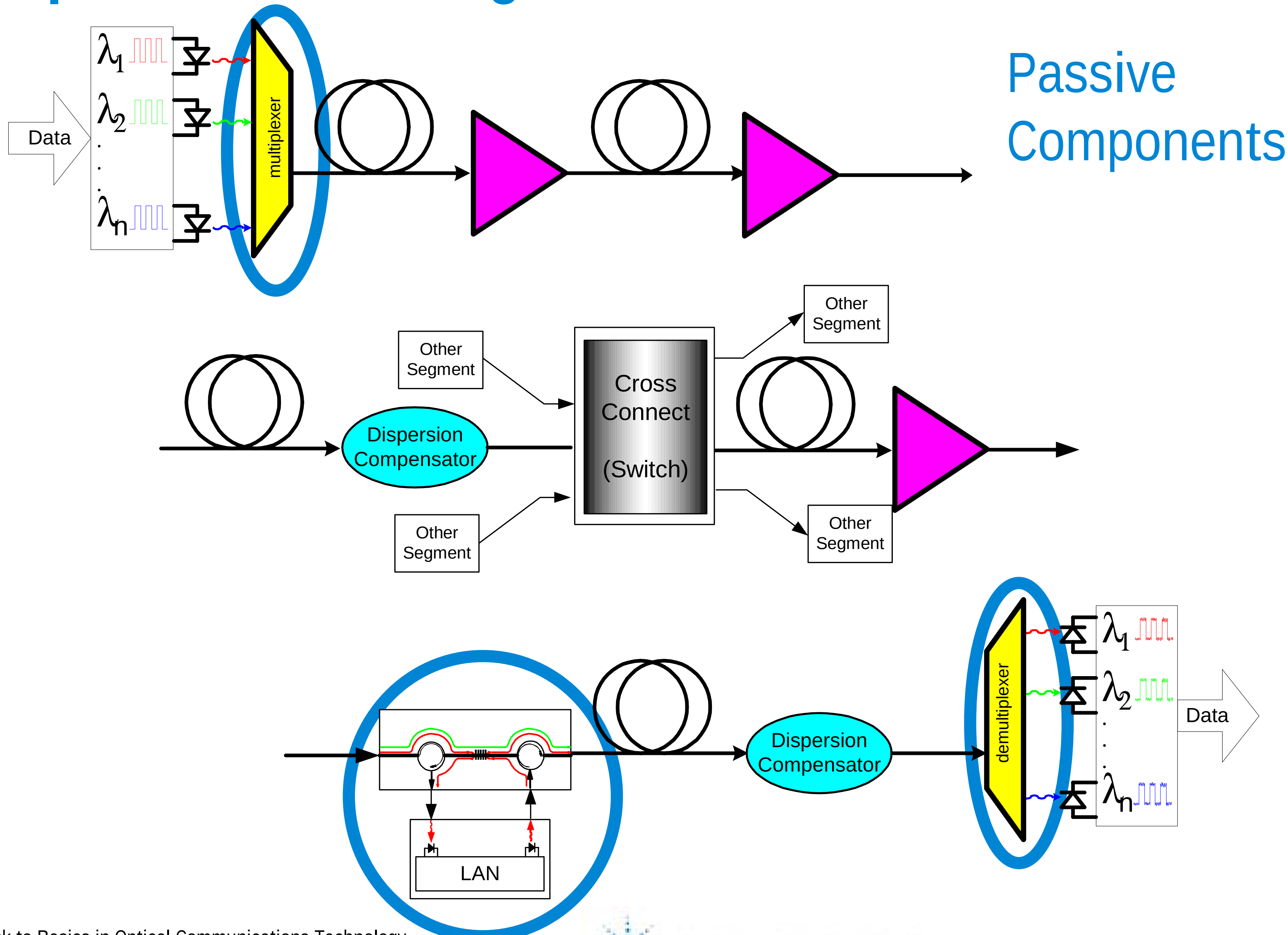
Optical Networking - The DWDM Forest



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Light Transmission, Reception, and Modulation:

Active Component Characterization

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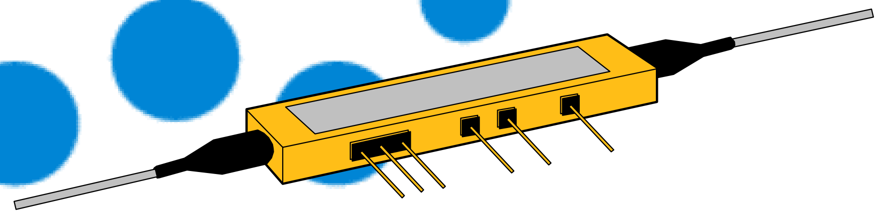
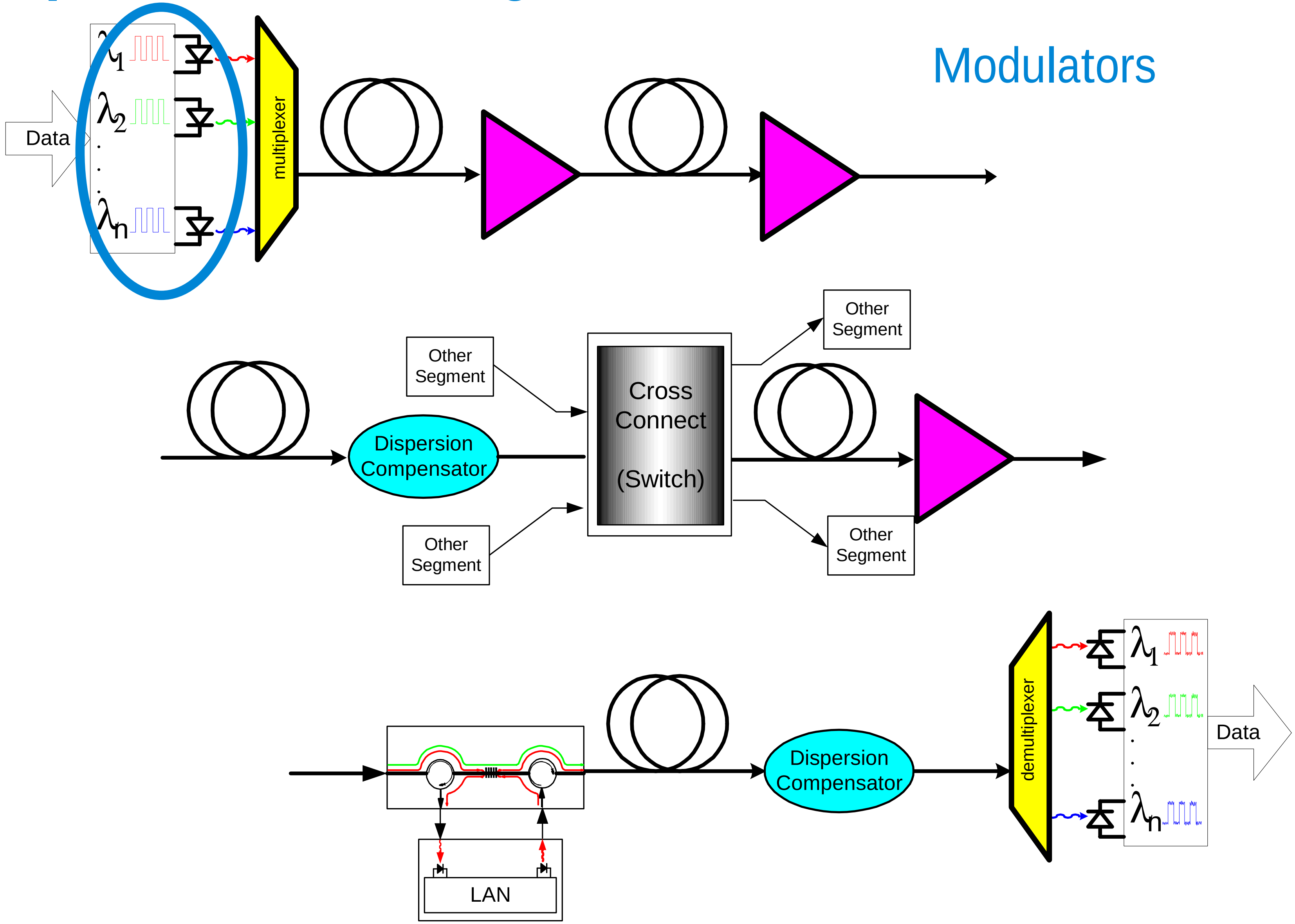
Modulation



Putting information into pulses of light

Internal and external modulators

Optical Networking - The DWDM Forest



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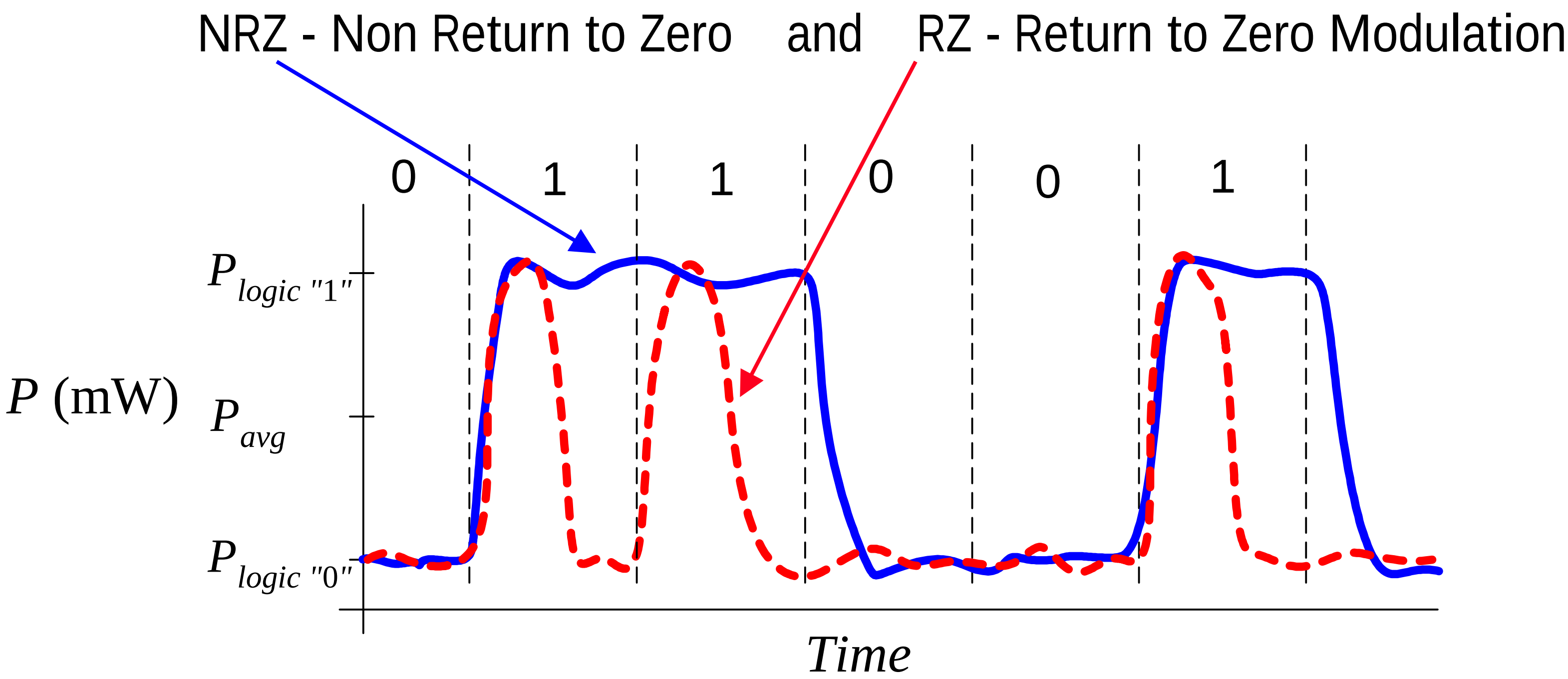
Modulation
Encoding Data into Light Pulses



Extinction ratio: $E = \frac{P_{Logic\ "1"}}{P_{Logic\ "0"}}, \quad E(\text{dB}) = 10\log_{10}\frac{P_{Logic\ "1"}}{P_{Logic\ "0"}}$ typically, about 10 dB.

Average power: $P_{Avg} = \frac{1}{2}\left(P_{Logic\ "1"} + P_{Logic\ "0"}\right)$

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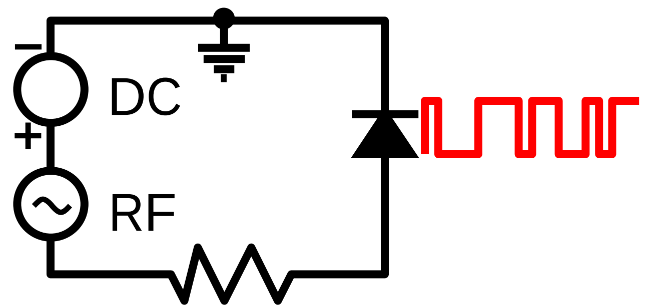
Modulation Techniques

Encoding data into binary pulses

Direct modulation:

modulate LASER input power

- LASER chirp
- 1.5 Mb/s - 2.5 Gb/s

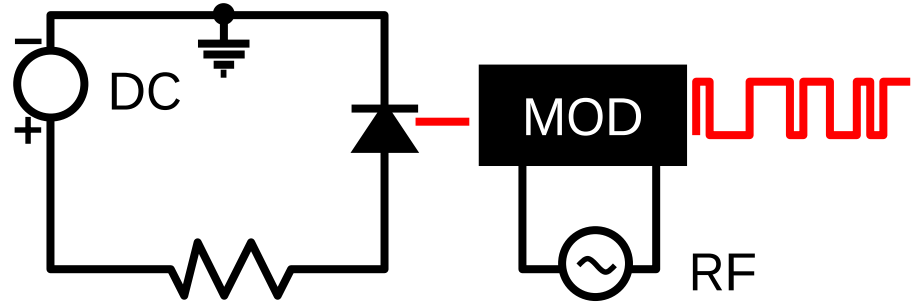


Indirect modulation:

Indirect or phase modulation

- Modulation with absorption or
- Modulate with interference

  Constructive $\Rightarrow$ 1, destructive $\Rightarrow$ 0
- AM sidebands dominate line width
- Can approach $\Delta\nu = 1/(4\pi\Delta T_{bit})$
- 10 Gb/s - 40 Gb/s $\rightarrow$ 200 Eb/s



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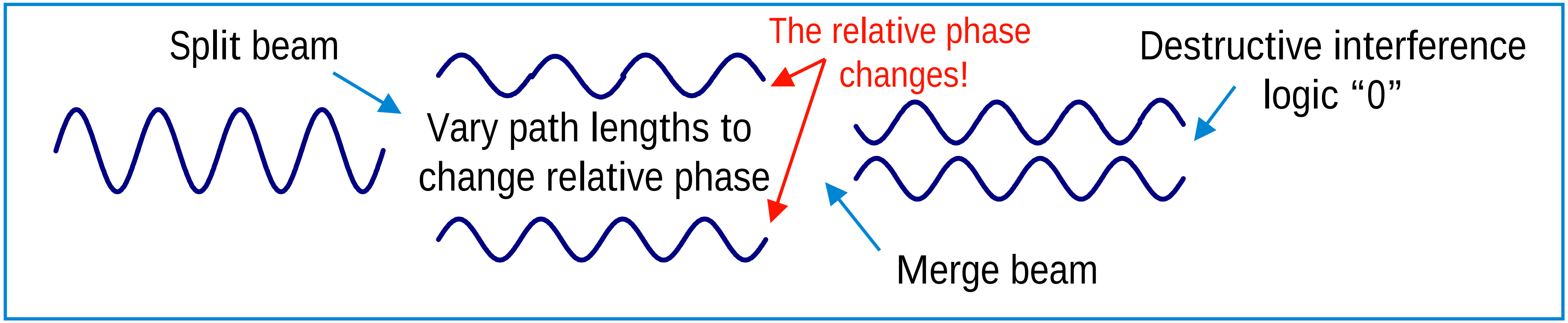
Indirect Modulation
Mach-Zehnder Principle

Split the beam and vary the optical path lengths to get:

- Logic "0" - destructive interference - optical path length difference of $(2n\text{-}1)\,\lambda/2$
- Logic "1" - constructive interference - optical path length difference of $n\lambda$



An external electric field applied to some crystals, e.g., $LiNbO_3$, changes the index of refraction, $n = n(\mathbf{E})$

1. Use an RF modulation signal to apply a voltage across the crystal
2. Varies the index of refraction of each path
3. Change the path lengths to get desired interference

$\rightarrow$ Modulate the light signal!

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Indirect Modulation
Electro-Absorptive Modulation

A solid-state based shutter

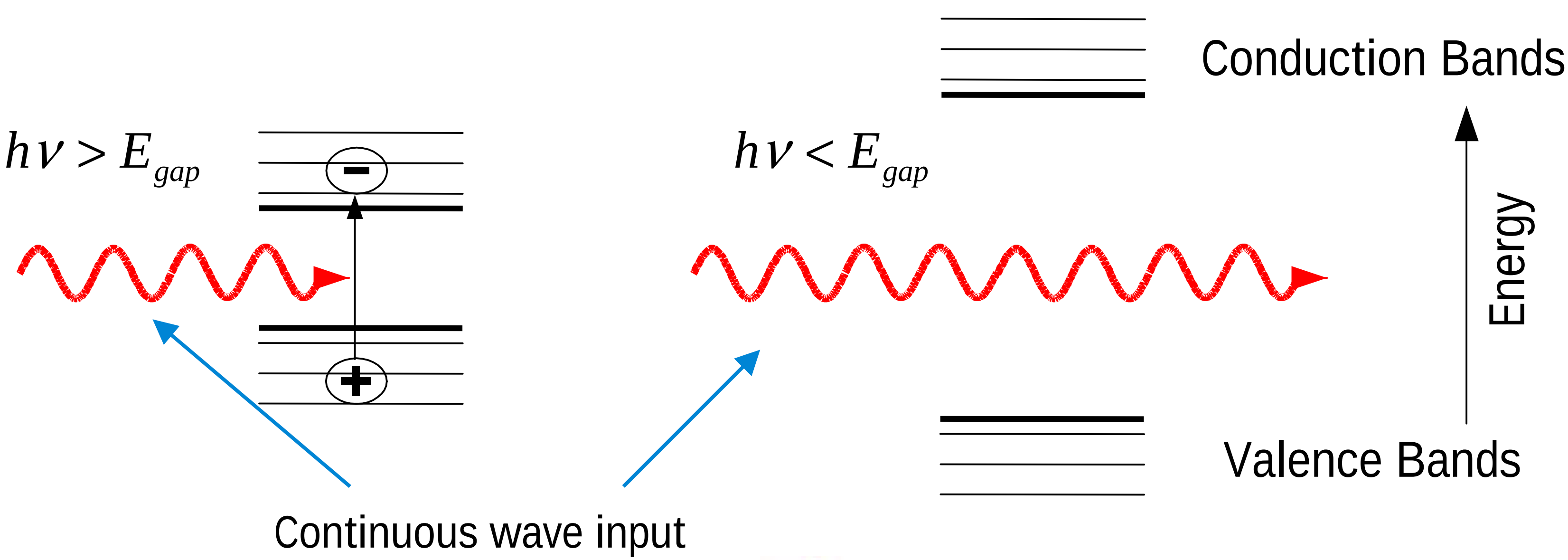
Pass a continuous wave through a diode

Logic “0” - High reverse bias, smaller band gap

⇒ light is mostly absorbed

Logic “1” - No applied bias, larger band gap

⇒ light transmits through



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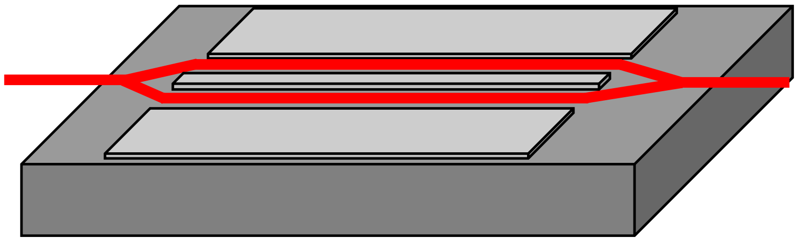
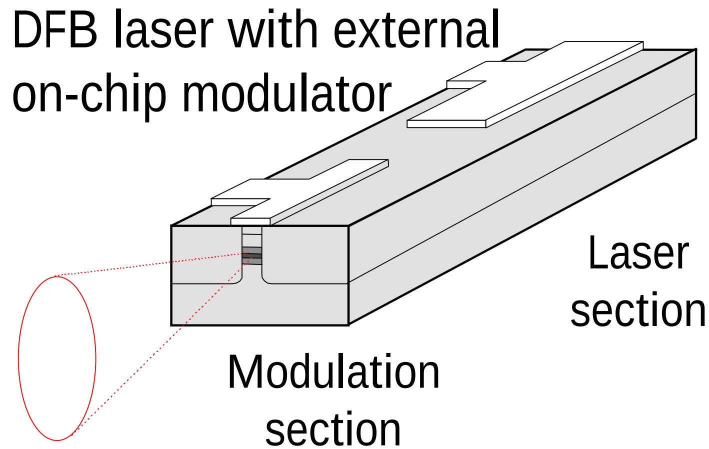
Indirect Modulators

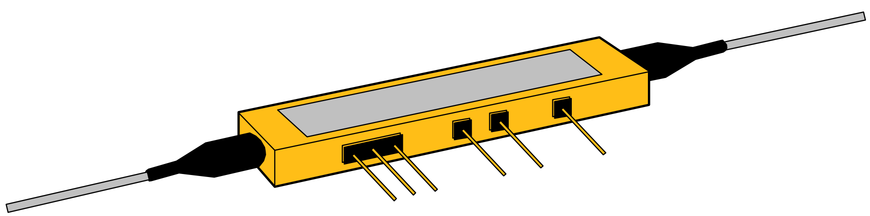
Mach-Zehnder Modulator



Polarization sensitive, need correct launch

Electro-Absorptive Modulator





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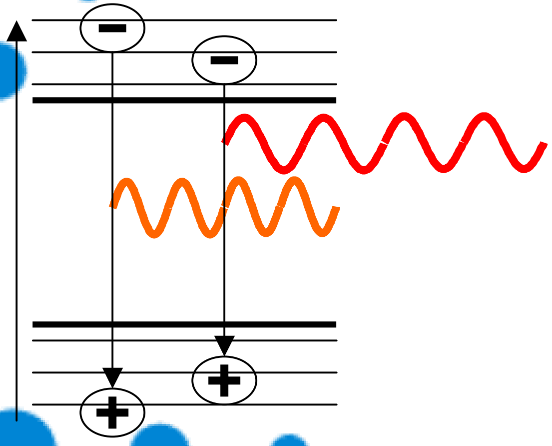
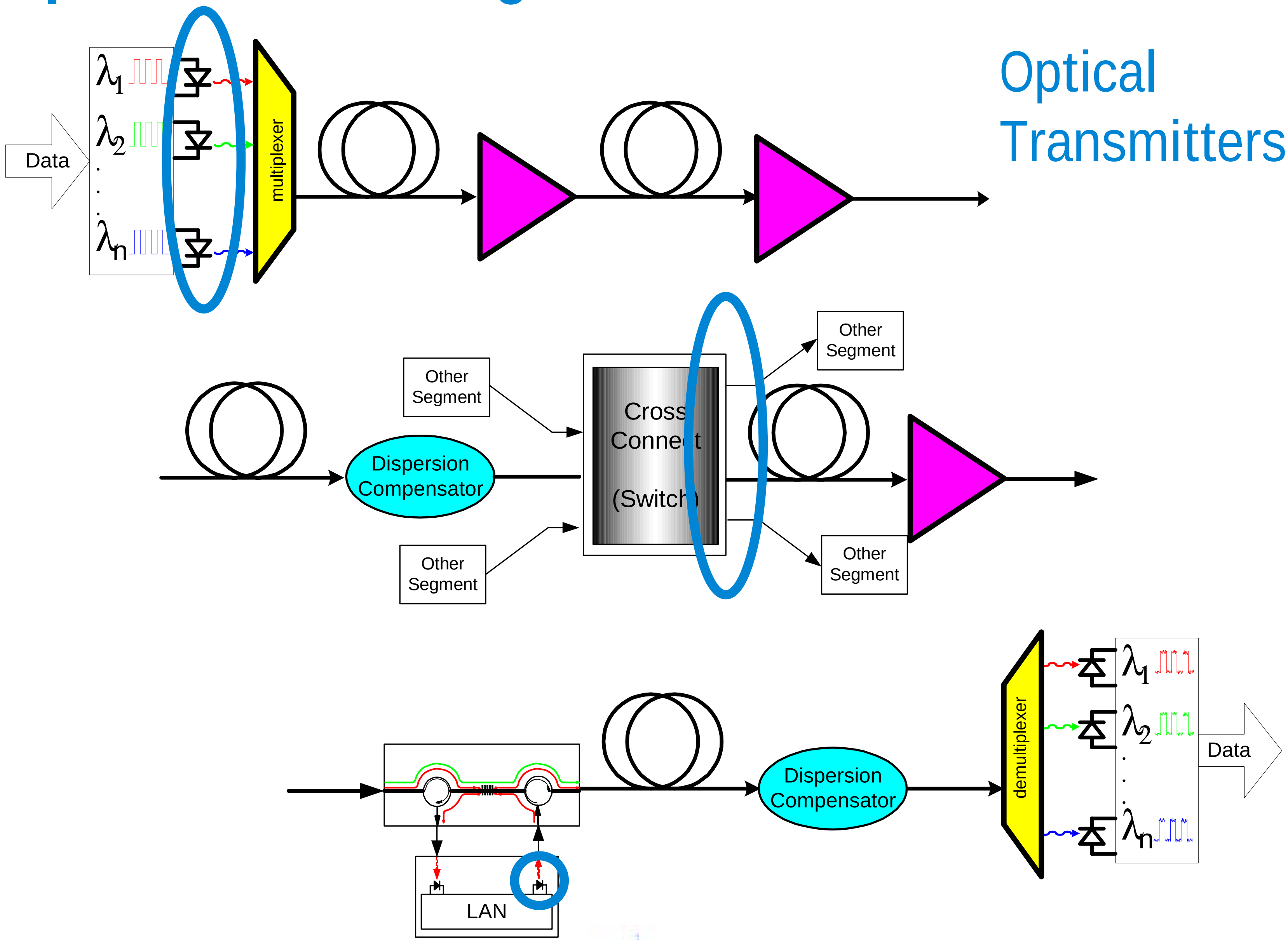
Atomic Physics:
Light Generation



- Electromagnetic radiation
- Light Emitting Diodes (LED)
- Light Amplification by Stimulated Emission of Radiation (LASER)

Optical Networking - The DWDM Forest



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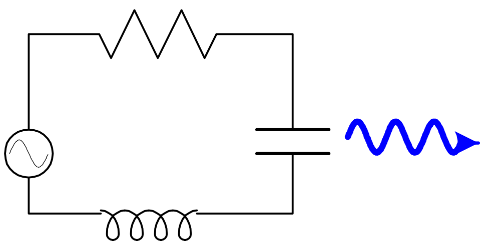
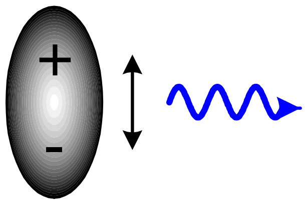
The Premise for Radiation

All radiation results from the acceleration of a charge

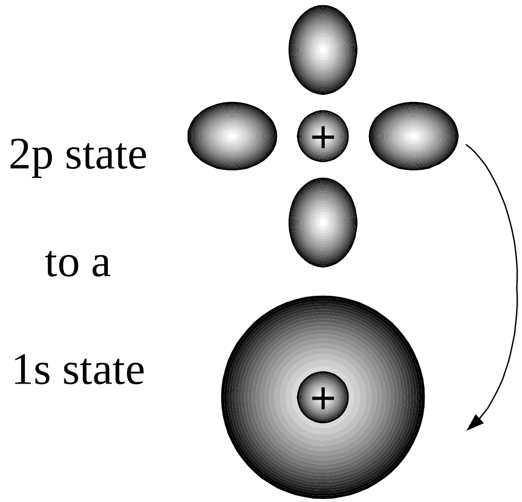
- An LRC circuit

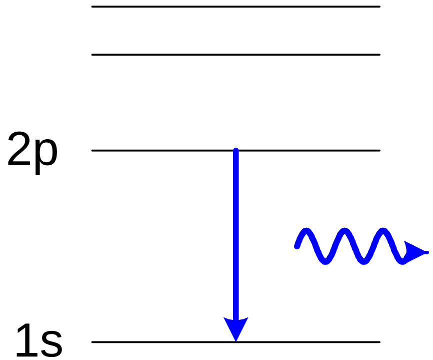


An oscillating dipole:



- An atomic transition





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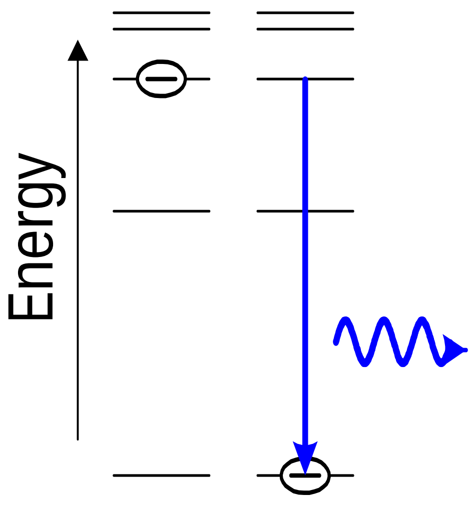
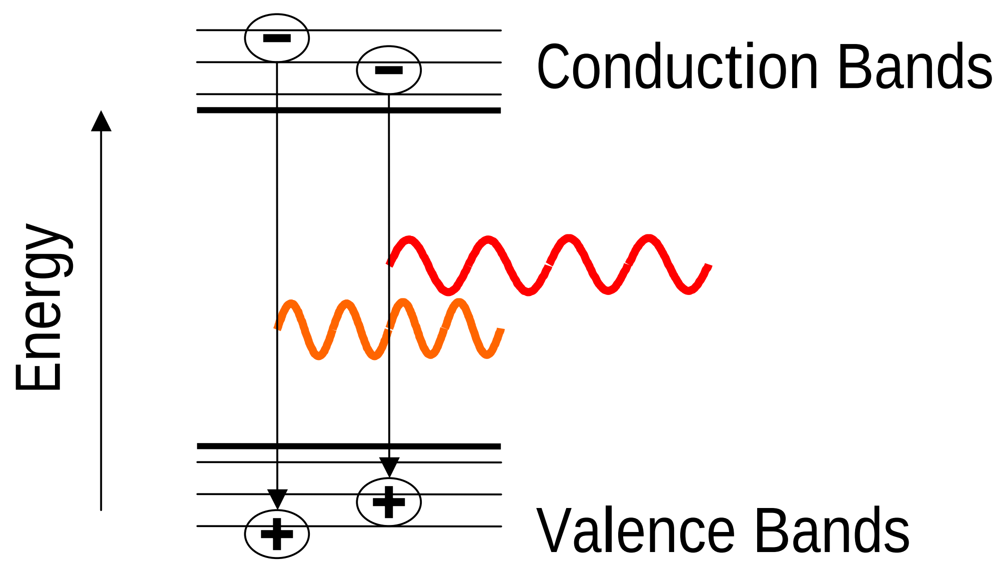
Spontaneous Emission

Light is spontaneously emitted when an electron decays from a higher to a lower energy state.

In an atom



In a semiconductor



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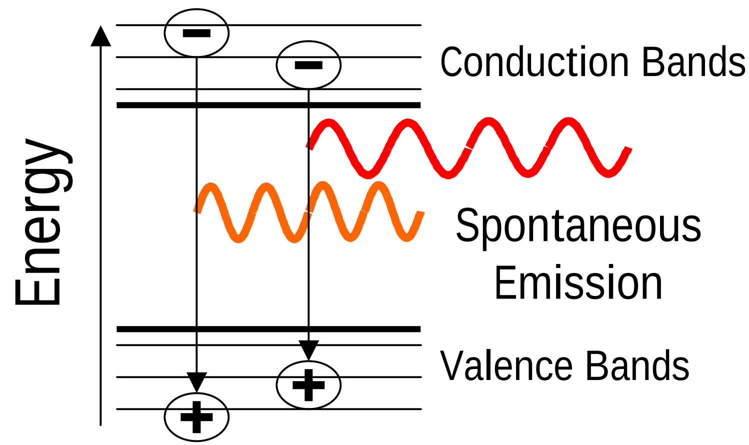
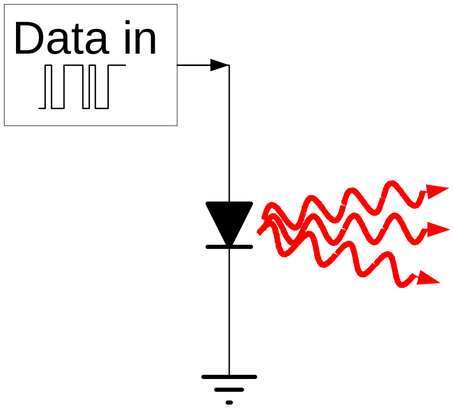
Light Emitting Diode (LED)

Datacom through air & multimode fiber

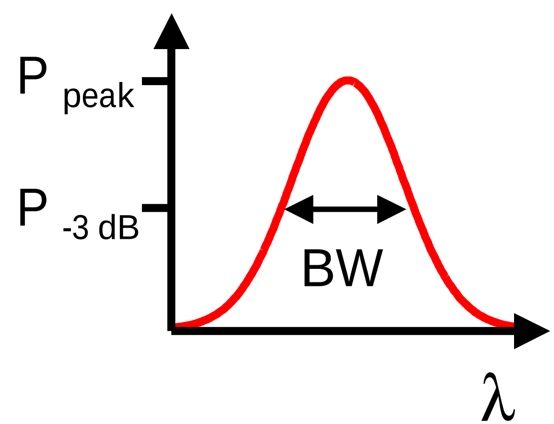
- Inexpensive
    - (laptops, airplanes, LANs)





Key characteristics

- Most common for 780, 850, 1300 nm
- Total power up to a few µW
- Spectral width 30 to 100 nm
- Coherence length 0.01 to 0.1 mm
- No specific polarization



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LASER

Light Amplification by Stimulated Emission of Radiation

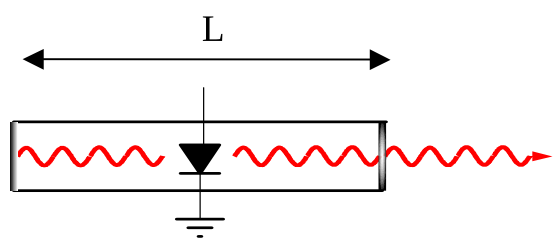
Requirements for LASER:

- Confine light in a resonant cavity to set up standing waves
- Excite more electrons to higher energy levels
- More photons from stimulated emission than from spontaneous emission

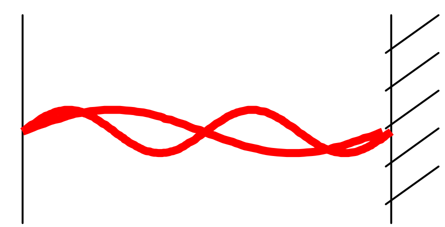
"*population inversion*"

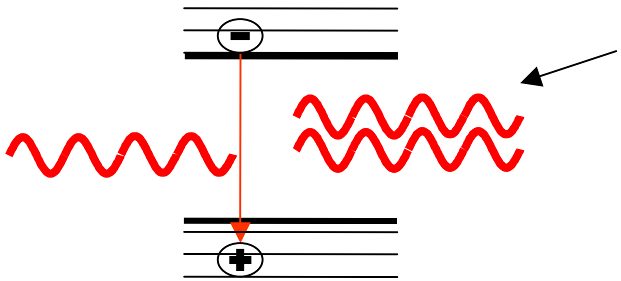
Stimulated Emission will resonate in the cavity

⇒ amplification



Mirrors confine λ's to $2L/n$ & also reject non-perpendicular light





Stimulated Emission ⇒ light that is

monochromatic (same wavelength)
coherent (in phase)
polarized

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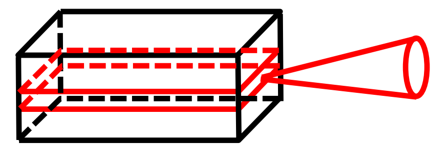
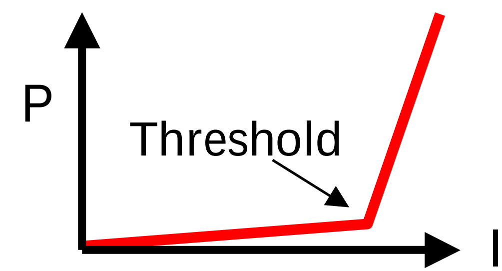
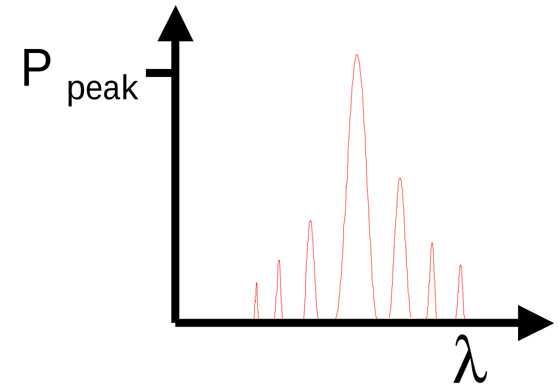
Fabry-Perot (FP) Laser

- Reflective coatings along cavity allow only $n\lambda/2$ wavelengths through
- Multiple longitudinal mode (MLM) spectrum
  - "Classic" semiconductor laser
    - First fiberoptic links (850 or 1300 nm)
    - Today: short & medium range links
- Key characteristics
  - Most common for 850 or 1310 nm
  - Total power up to a few mW
  - Spectral width 3 to 20 nm
  - Mode spacing 0.7 to 2 nm
  - Highly polarized
  - Coherence length 1 to 100 mm
  - Good coupling into fiber







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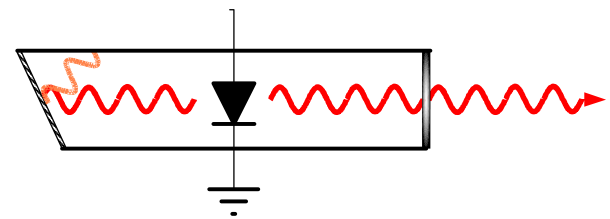
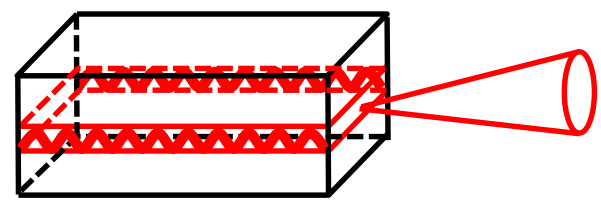
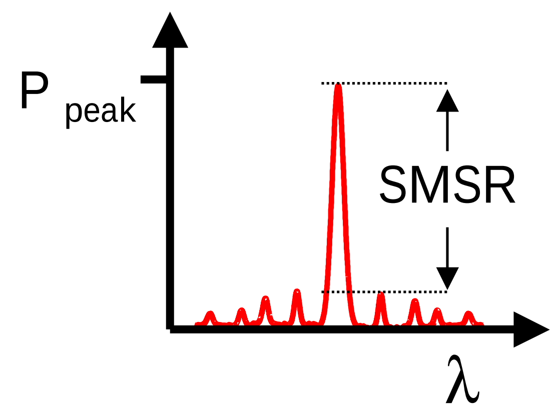
Distributed Feedback (DFB) Laser

- Sidemodes filtered out
- Single longitudinal mode (SLM) spectrum
- High performance telecommunication laser
  - Most expensive (difficult to manufacture)
  - Long-haul links & DWDM systems
- Key characteristics
  - Mostly around 1550 nm
  - Total power 3 to 50 mw
  - Spectral width 10 to 100 MHz
    - (0.08 to 0.8 pm)
  - Sidemode suppression ratio
    - SMSR > 50 dB
  - Coherence length 1 to 100 m
  - Small NA ($\rightarrow$ good coupling into fiber)







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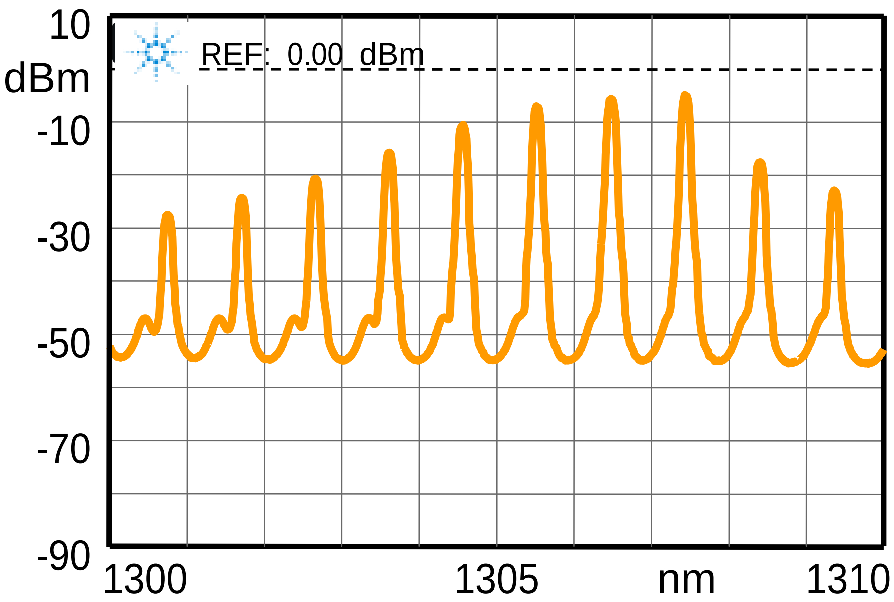
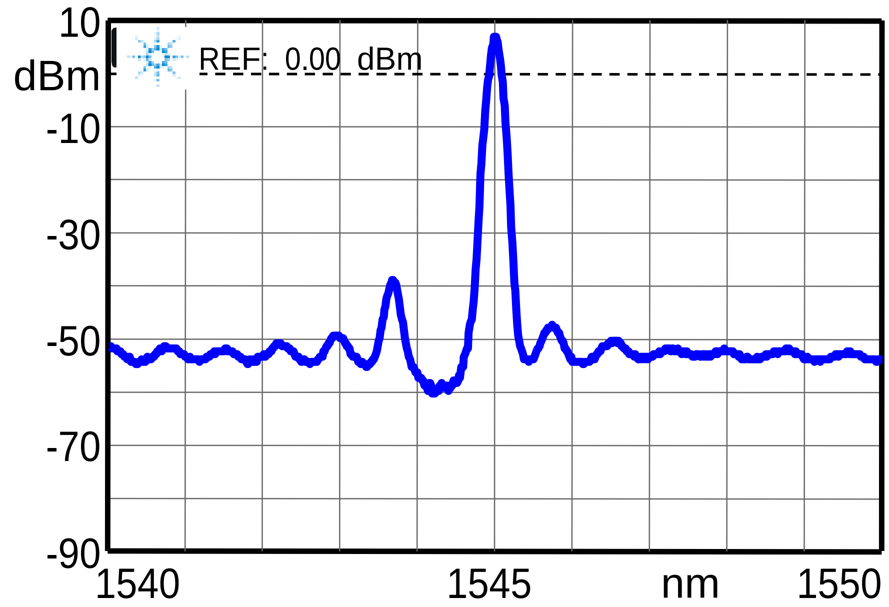
Comparison of FP and DFB Lasers

Fabry-Perot Laser



DFB Laser



Power versus wavelength

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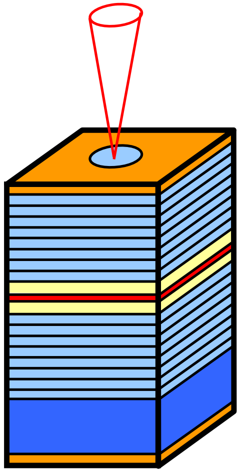
Vertical Cavity Surface Emitting Lasers

Distributed Bragg Reflector (DBR) Mirrors

- Alternating layers of semiconductor material
- 40 to 60 layers, each $\lambda/4$ thick

Key properties

- Wavelength range 780 to 1310 nm
- Gigabit ethernet
- Spectral width < 1 nm
- Total power > -10 dBm
- Coherence length: 10 cm to 10 m
- Numerical aperture: 0.2 to 0.3



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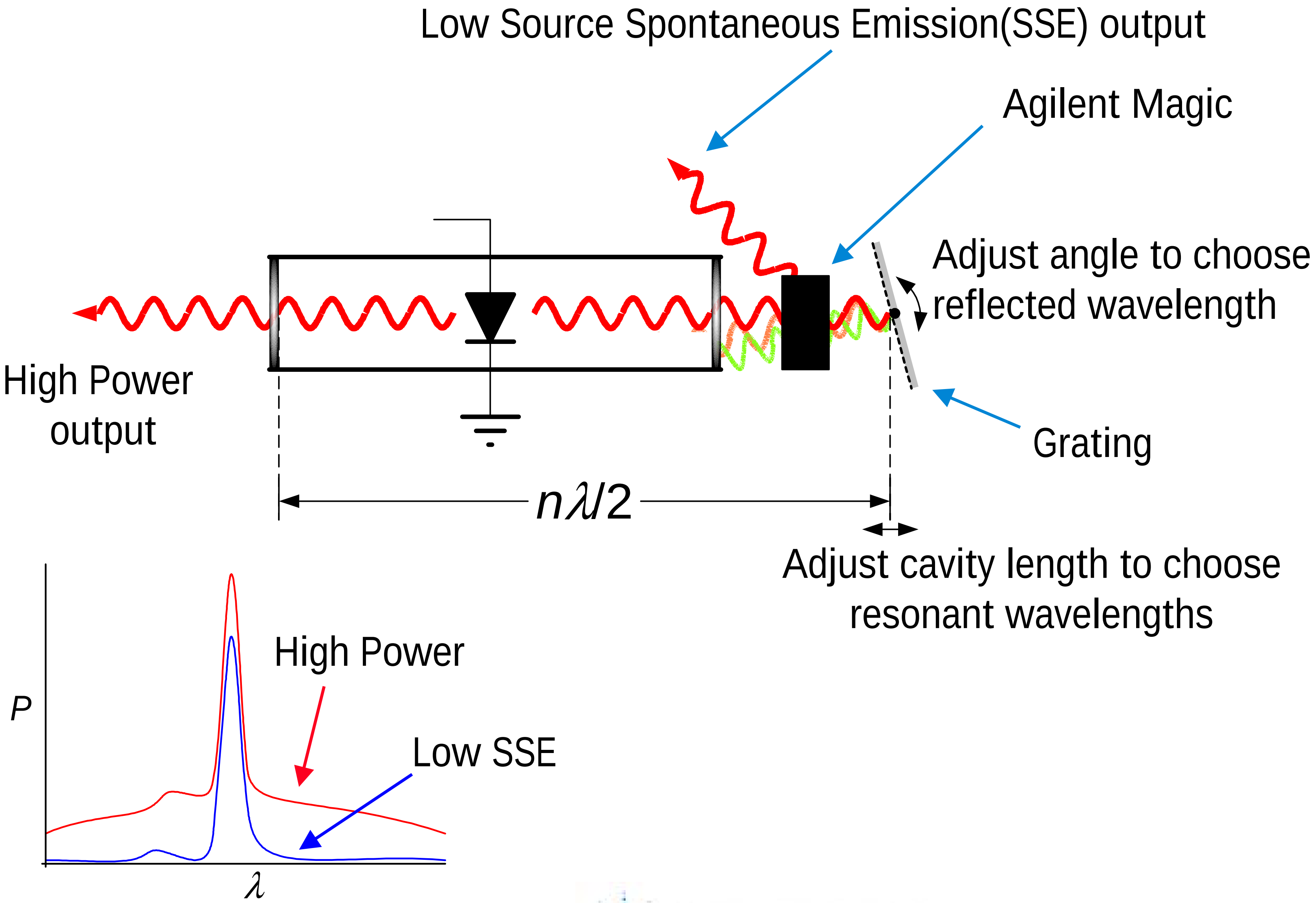
External Cavity / Tunable Lasers



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Tunable Laser System

The Agilent TLS systems for the 8164 mainframe

- 1260 < λ < 1640 nm in three different modules
- Two Power outputs:
  - +5 dBm peak (high power output)
  - - 6 dBm peak (low SSE output)
    - 60 dB signal to SSE ratio
- ±10 pm absolute wavelength accuracy
- ±2-3 pm typical relative wavelength accuracy, mode-hop free
- 0.1 pm wavelength resolution

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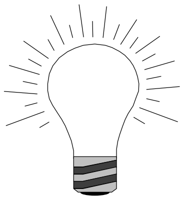
Other Light Sources



Need for small coherence length high power light sources:

White light source

- Specialized tungsten light bulb
- Wavelength range 900 to 1700 nm,
- Power density 0.1 to 0.4 nw/nm (SM), 10 to 25 nw/nm (MM)

Amplified spontaneous emission (ASE) source

- “Noise” of an optical amplifier without input signal
- Wavelength range 1525 to 1570 nm
- Power density 10 to 100 µw/nm

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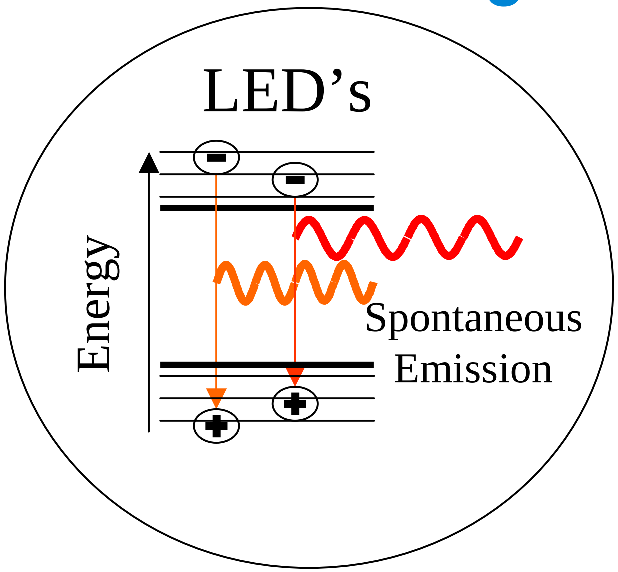
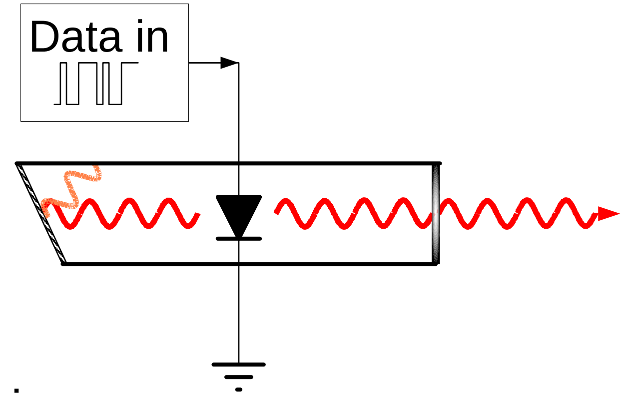
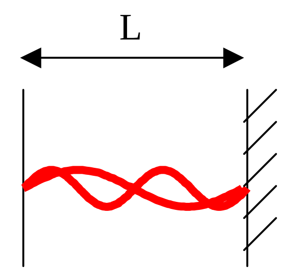
Summary
Semiconductor Light Sources



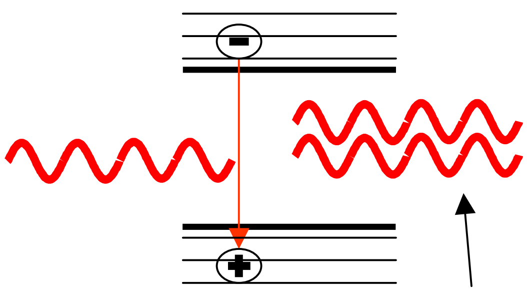


LASER's

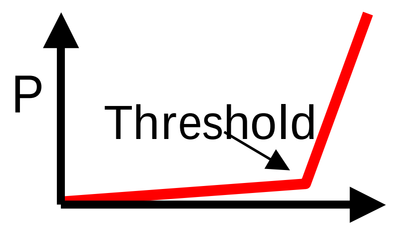
Lasers Require
- Stimulated Emission
- Population Inversion
- Confinement



Mirrors confine λ's to 2L / n & also reject non-perpendicular light



Stimulated Emission
(monochromatic & in-phase)



More electrons in upper energy level than lower
(more photons emitted than absorbed)

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Parameters to Test
Characterization of Transmitters

Output Power

- Power meter

Wavelength

- Optical Spectrum Analyzer, $\lambda_{accuracy} \sim \pm 15$ pm, $\delta\lambda \sim 50$ pm
- Interferometer-based wavelength meter, $\lambda_{accuracy} \sim \pm 5$ pm, $\delta\lambda \sim 0.3$ pm

Linewidth, chirp, modulation effects, ultra DWDM structure

- High Resolution Spectrometer, $\lambda_{accuracy} \sim \pm 15$ pm, $\delta\lambda \sim 8$ fm

Distortion, Relative Intensity Noise (RIN), harmonic noise,
Spontaneous emission / recombination relaxation effects

- Lightwave Signal Analyzer

Electrical-Optical Response, Bandwidth
Recombination time scale affects modulation properties

- Lightwave Component Analyzer

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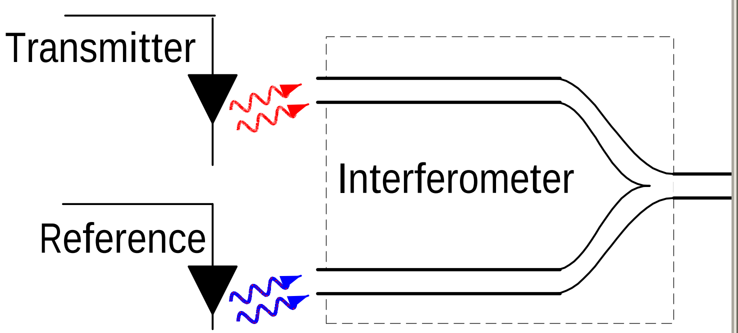
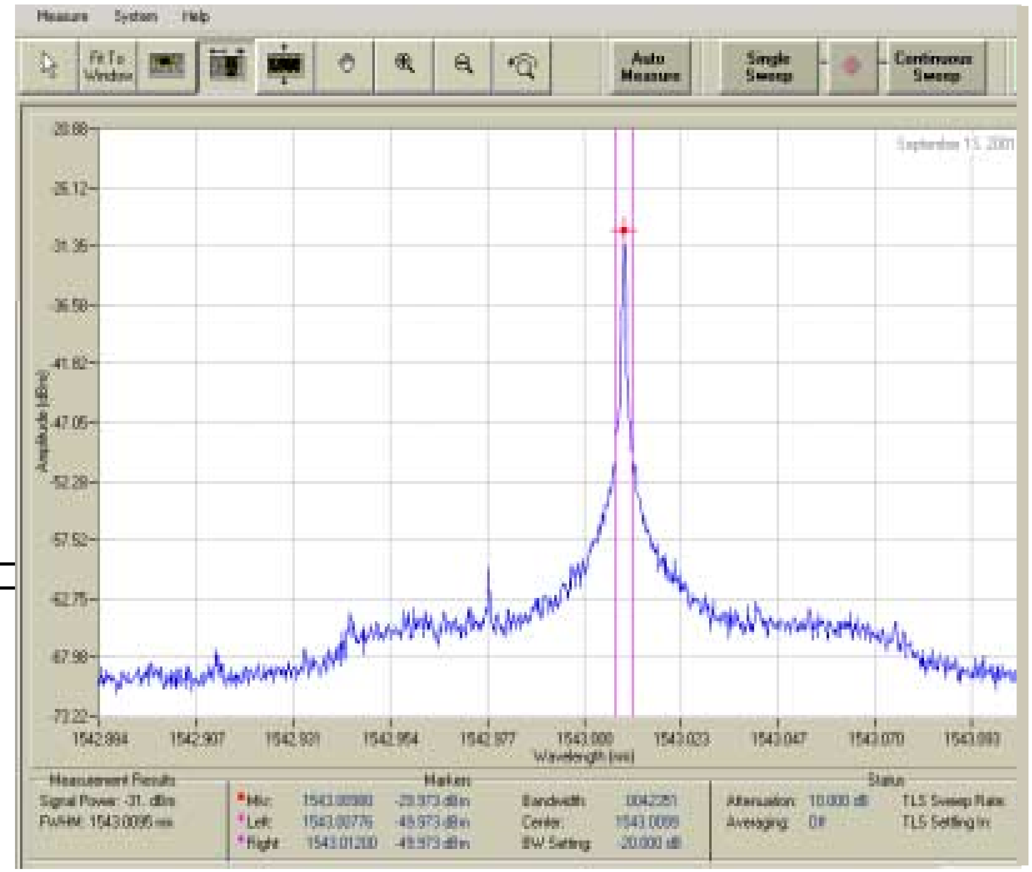
Transmitter Linewidth Measurement
With a High Resolution Spectrometer

Optical Heterodyne

- Measure transmitter line structure with terrific detail

  resolution: 8 fm





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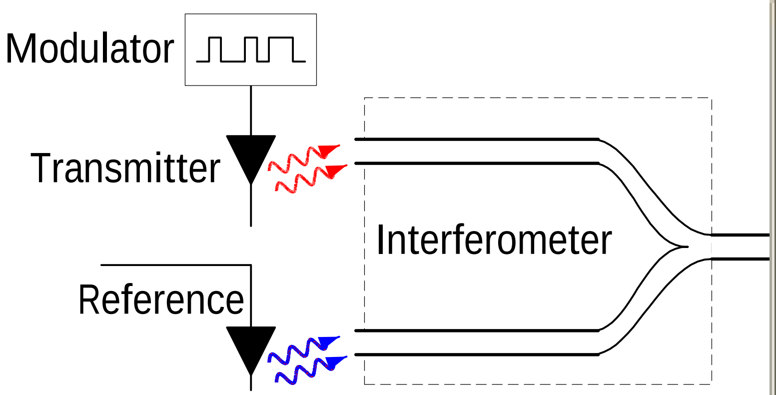
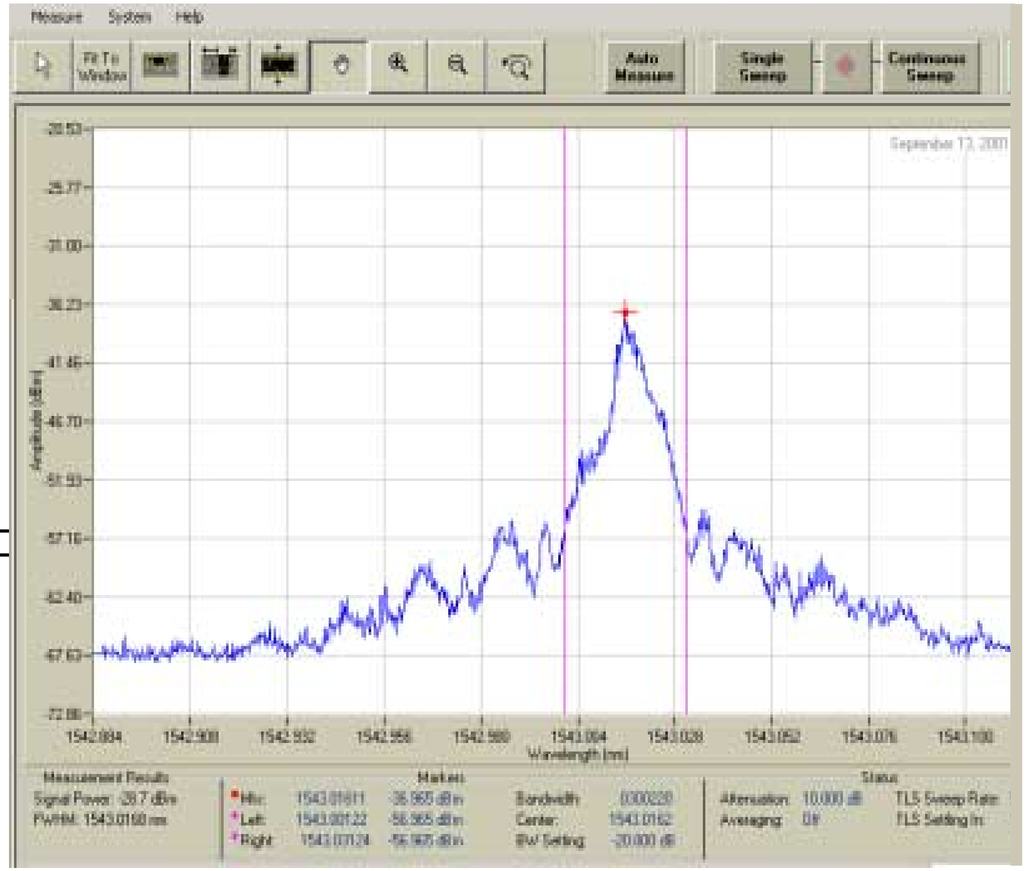
Chirp / FM Measurement
With an HRS

Chirp = A change in the optical frequency caused by direct modulation of the laser

Direct Modulation





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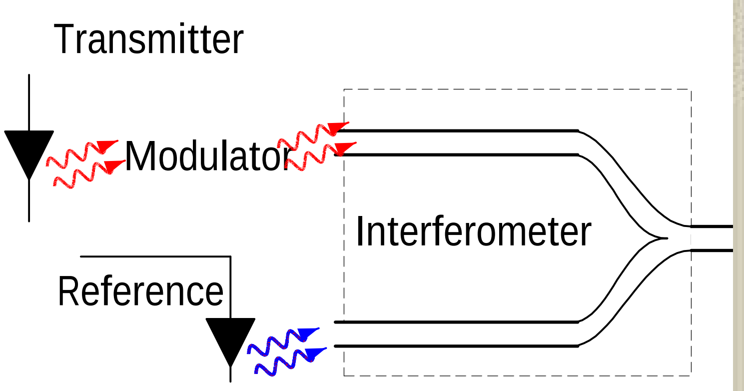
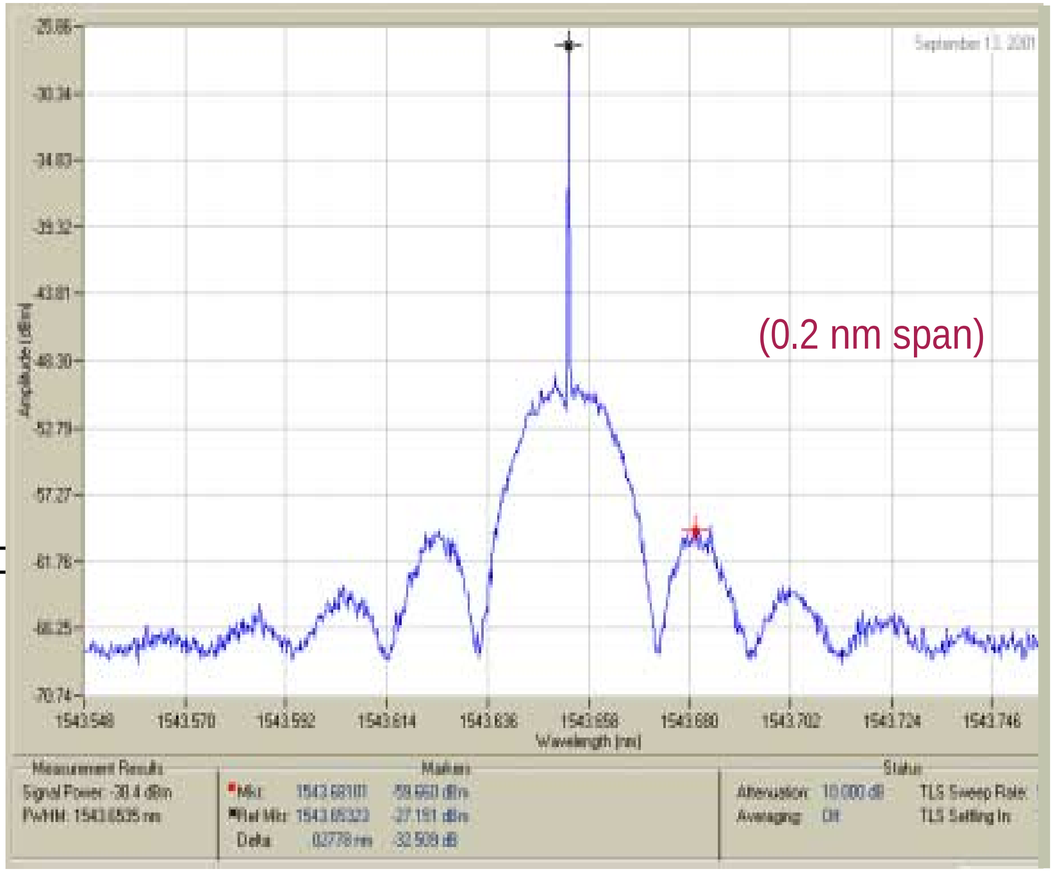
Chirp / FM Measurement
With an HRS

Indirect Modulation with a Mach Zehnder modulator





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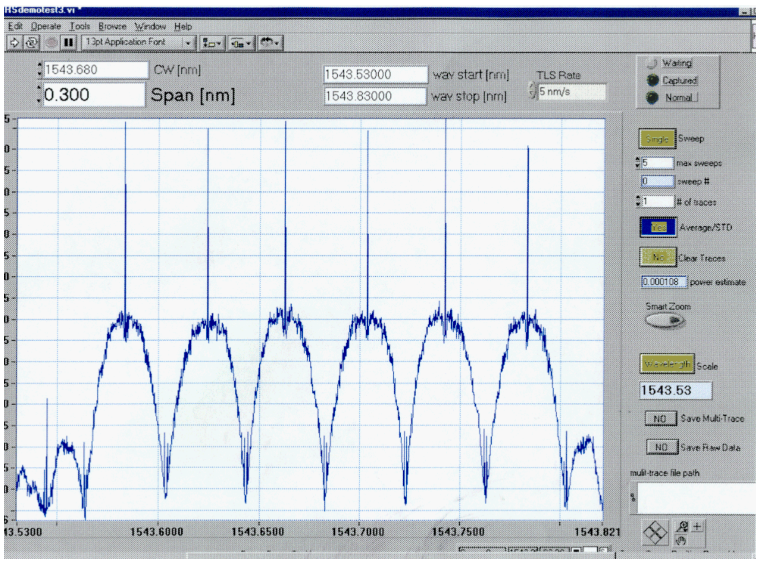
High Resolution Optical Spectrometer
Agilent 83452A

- Optical Heterodyne and high resolution spectrum analysis

  Linewidth, laser spectral symmetry, modulation spectrum, relaxation oscillations, close-in sidebands, UltraDWDM spectra

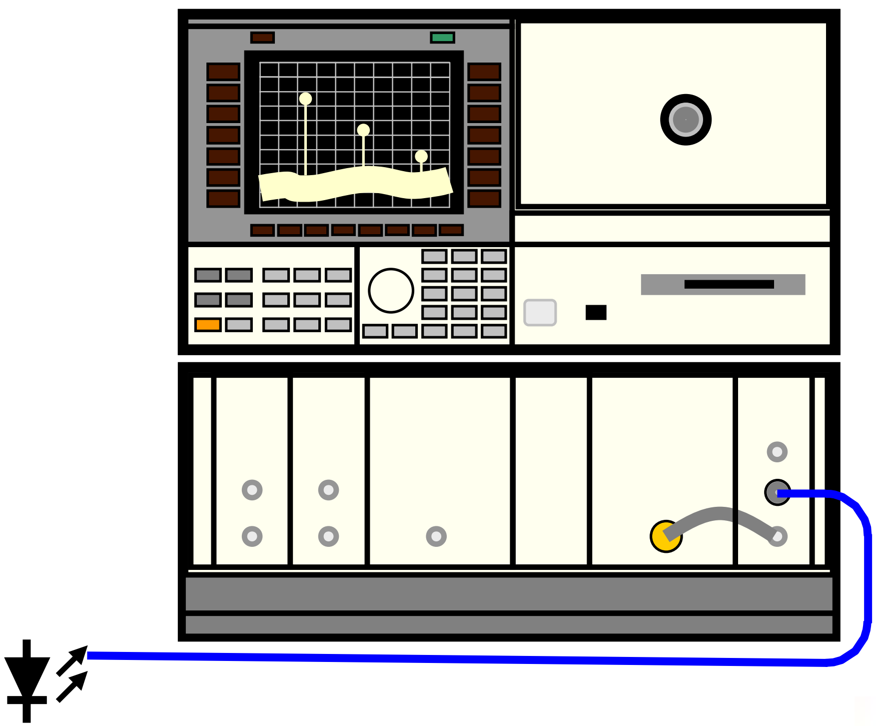
  Resolution: better than 80 fm (10 MHz)
  Dynamic Range: 60 dB

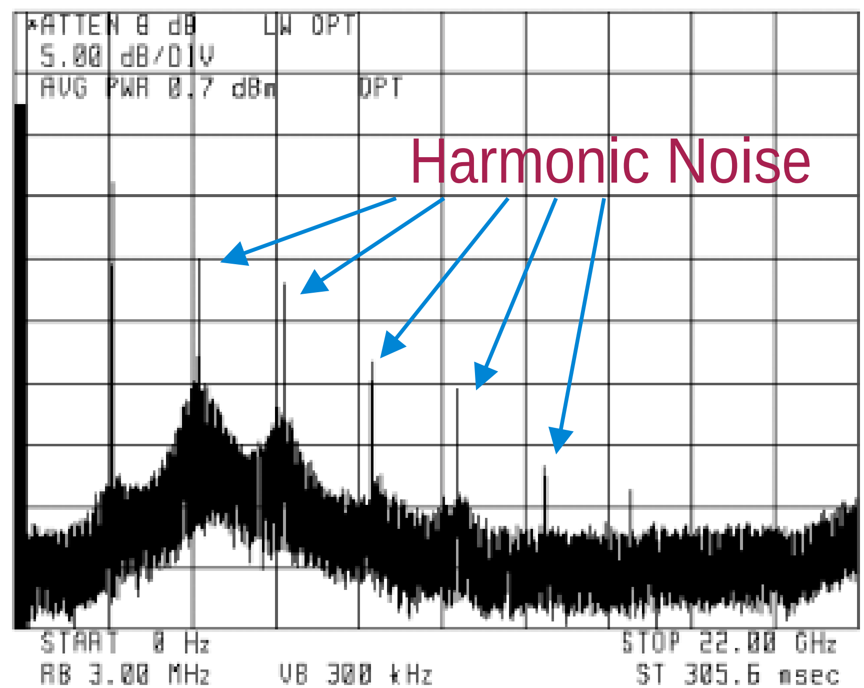


Ultra DWDM spectrum

Lightwave Signal Analyzer

- Essentially a wide-bandwidth, calibrated O→E + Electrical Spectrum Analyzer
- Measures average optical power vs frequency, (over modulation frequency range!)





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Relative Intensity Noise
Noise from the Transmitter

Relative Intensity Noise
(Incidental Amplitude Modulation)

$$\mathrm{RIN} = \frac{1}{BW}\frac{(\Delta P)^2}{P_{avg}^2}\left[\mathrm{Hz}^{-1}\right]$$

Measures laser fluctuations at modulation frequencies

The “power variance spectral density”, $(\Delta P)^2 / BW$, is the fluctuation of power observed in the interval f_{mod} to $f_{mod} + df_{mod}$ per unit modulation bandwidth, df_{mod}.

After electrical conversion (recall (optical power)$^2 \propto$ (electrical power)), measure RIN from the electrical spectrum analyzer:

$$i_{RIN} \approx i_{avg} \times \sqrt{RIN \cdot BW}$$

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Measuring Relative Intensity Noise
With an LSA

$$RIN \equiv 10 \times \log\left(\frac{(\Delta P)^2}{P_{avg}^2}\right)\frac{1}{BW} \quad [\mathrm{dB/Hz}]$$

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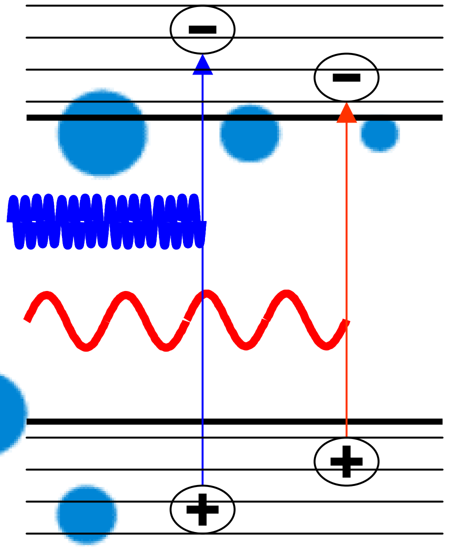
Atomic Physics:
Light Detection

- Solid state photon counters
  responsivity
- Photo Diodes
  efficiency, gain, dark current



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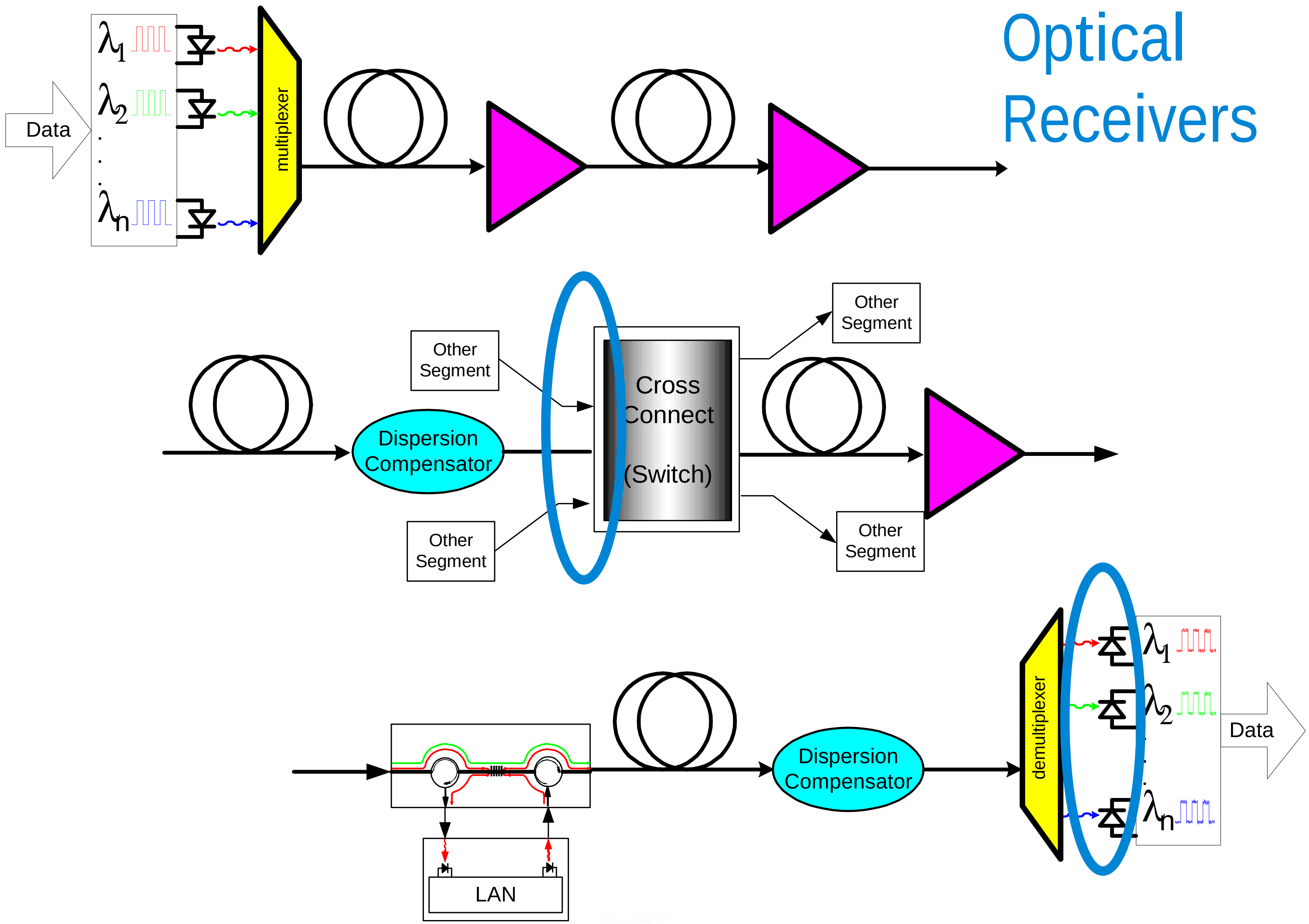
Optical Networking - The DWDM Forest



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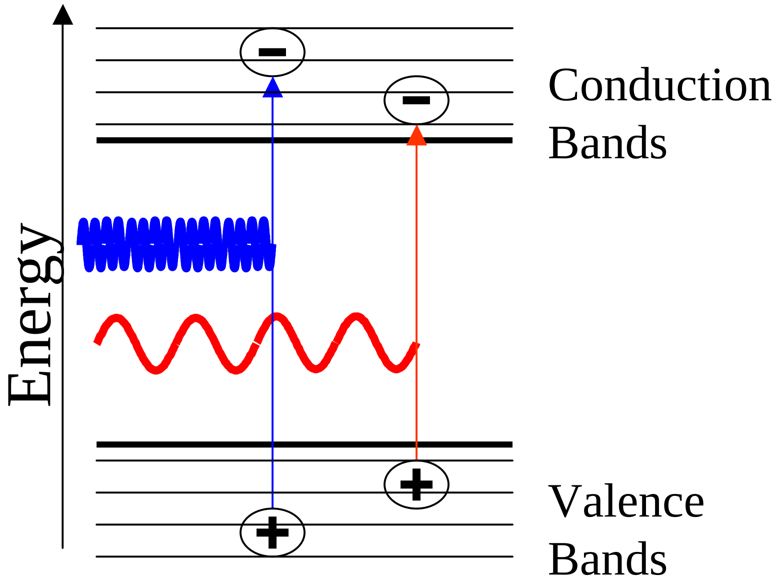
Light Detectors

- Photons are absorbed in an intrinsic layer of semiconductor $\rightarrow$ create e^- - hole pairs

- Apply a reverse-bias potential $\rightarrow$ photocurrent



- Quantum Efficiency = number of electrons created per photon, $\eta(\lambda)$
- Responsivity = photocurrent per unit of optical power (A/W)

$$R(\lambda) = \frac{i_{\mathrm{Photo}}(\lambda)}{P_{\mathrm{Optical}}(\lambda)} = \eta(\lambda)\frac{e\lambda}{hc}$$

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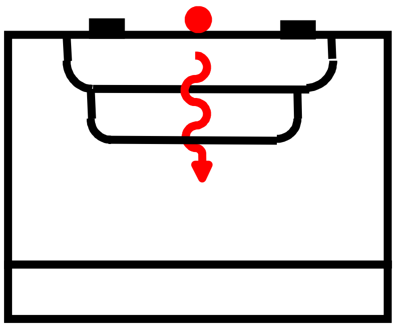
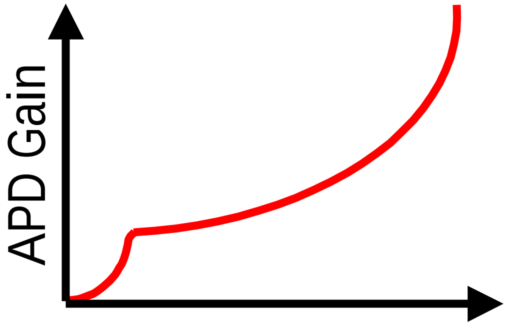
Photo Diodes

PIN (p-layer, intrinsic layer, n-layer)
- Highly linear, low dark current
- Detector is followed by a Transimpedance Amplifier



Avalanche photo diode (APD)
- Intrinsic gain up to x100 lifts the optical signal above electrical noise of receiver
- Strong temperature dependence



Main characteristics
- Quantum efficiency (electrons/photon)
- Dark current
- Wavelength dependence, *responsivity*

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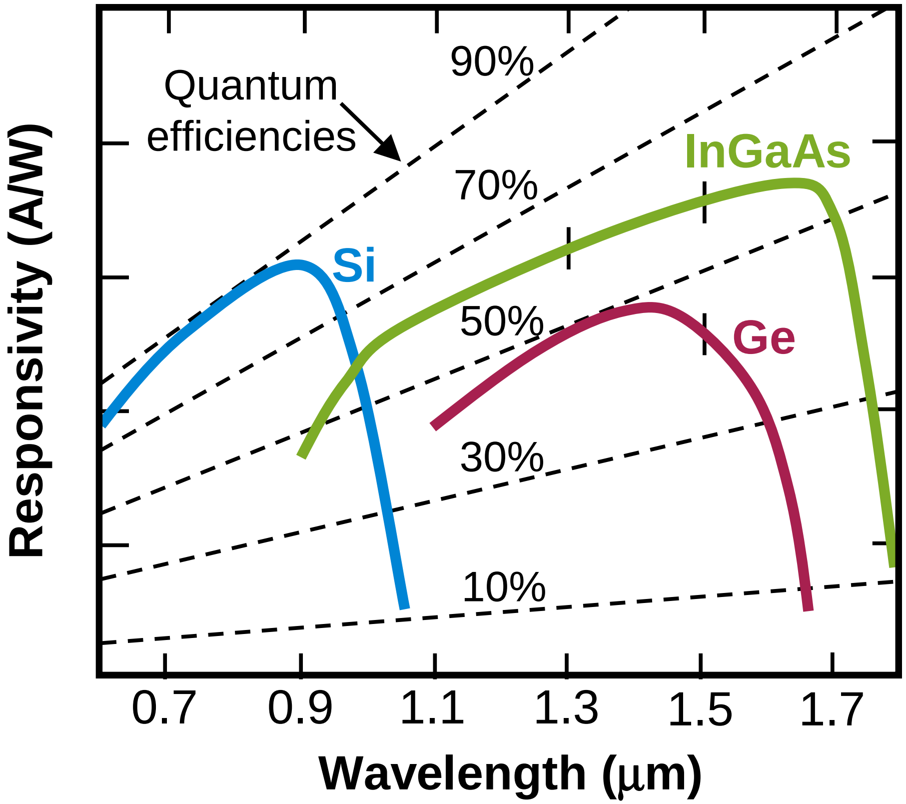
Material Aspects of PIN Diodes

Silicon (Si)
    Least expensive

Germanium (Ge)
    "Classic" detector

Indium gallium arsenide (InGaAs)
    Smooth responsivity
    High speed



- *Notice the sharp wavelength rolloff*
  - due to $E_{band\ gap} > h\nu = hc/\lambda$

$$R(\lambda) = \eta(\lambda)\frac{e\lambda}{hc}$$

Quantum efficiency

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Noise

Thermal (Johnson) Noise is the intrinsic noise from the load resistor in the photodiode circuit

R = Load resistance
k = Boltzmann's constant = 1.38×10^{-23} J/K
T in Absolute, B = modulation bandwidth

$$i_{Therm-rms} = \sqrt{\frac{4kT \cdot B}{R}}$$

Dark current, i_d, is the current generated in the absence of light

- Thermally or spontaneous diffusion generated charge in the photodiode. Typical values at T = 300 K, Si: 1 - 10 nA, Ge: 50 - 500 nA, InGaAs: 1 - 20 nA

Shot Noise, (quantum noise) is from the random arrival time of electrons in the detector- Shot noise causes the photo-current to fluctuate about a mean, i_{avg} and includes the dark current.

$$i_{shot-rms} = \sqrt{2e(i_{avg} + i_d)B}$$

- Trouble with small signals in noisy environments
- "Shot noise limited" means shot noise > thermal noise

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Receivers:
Sensitivity and Modulation Bandwidth

High sensitivity requires a large/deep detector

- Need to detect each photon = increase quantum efficiency
  - create more electron-hole pairs and catch each one

Large Bandwidth requires a small/shallow detector

- Need to finish detection process fast to accommodate a short pulse

Larger the detector the longer the “relaxation time” of the detection process

→ Tradeoff between sensitivity and bandwidth:
Larger bandwidth, lower sensitivity

Example:

		Sensitivity	Modulation rate
Lightwave Clock/Data Receivers:	Agilent 83446A	-28 dBm	2.5 Gb/s
	Agilent 83434A	-16 dBm	10 Gb/s

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Typical Power Levels

Transmitter:

–6 to +17 dBm (0.25 to 50 mW)

Optical Amplifier:

+3 to +20 dB (gain of 2 to 100 times input)

Difference between optical and electrical power:

Optical power is converted to photocurrent,

$$i_{photo} = P_{optical} G, \quad G = \text{conversion gain, typically 0.4 - 0.9 A/W,}$$

so

$$P = i^2 R \quad \Rightarrow \quad P_{electric} = (P_{optical} G)^2 R$$

in dB, a change in P_{optical} means twice that change in P_{electric}

$$\Delta P_{electric}(\text{dB}) = 10 \log \frac{P_{electric\ f}}{P_{electric\ i}} = 20 \log \frac{P_{Optical\ f}}{P_{Optical\ i}}$$

$$\boxed{\Delta P_{electric}(\text{dB}) = 2 \Delta P_{optical}(\text{dB})}$$

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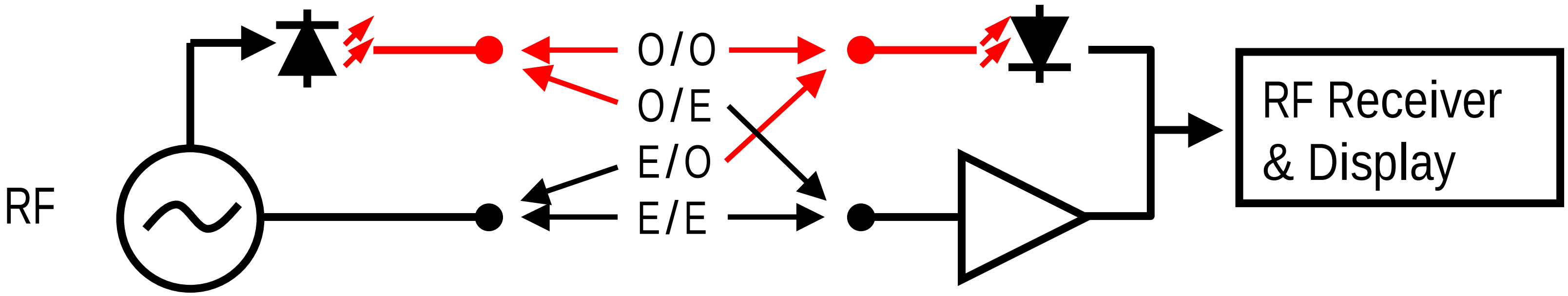
Active Component Characterization
Transmitters, Receivers, Regenerators

Measure Electro-optic response

- Fixed wavelength, measure response vs f_{mod}
- Vector network analyzer with precisely calibrated optical interface
- Measures E/O, O/O, O/E, E/E devices
- Gives 3 dB bandwidth
- Flatness of frequency response



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Lightwave Component Analysis

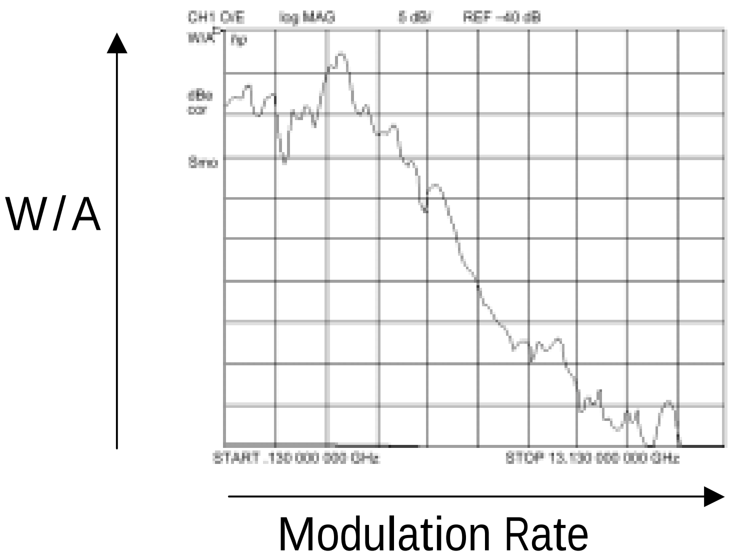
Source Responsivity = Optical power produced (W)/ electrical current supplied (A)

Receiver Responsivity = Electrical current produced (A)/ optical power supplied (W)

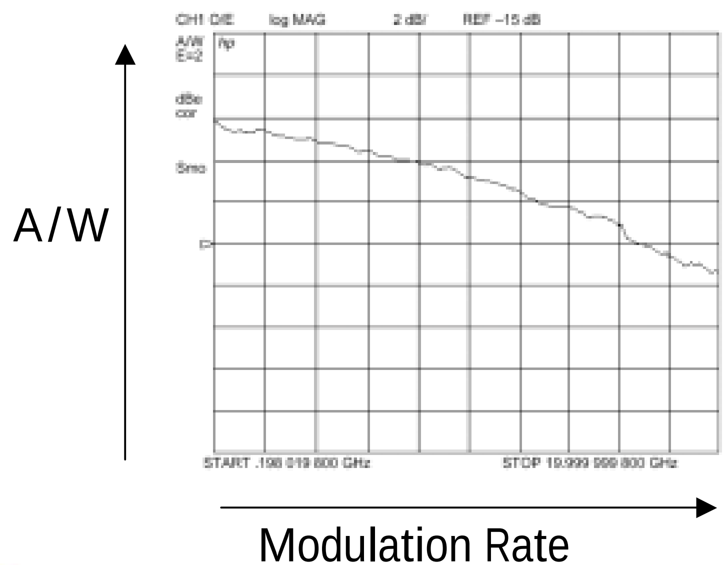
$$R_s\,(\mathrm{dB}) = 20\log_{10}\left(\frac{\Delta P_{out}}{\Delta I_{in}}\right)$$

$$R_r\,(\mathrm{dB}) = 20\log_{10}\left(\frac{\Delta I_{out}}{\Delta P_{in}}\right)$$

Typical Laser Frequency Response



Typical Photodiode Frequency Response



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Frequency Response and Modulation Bandwidth
Lightwave Component Analyzers

8702
300 KHz - 3 or 6 GHz

8703
50 MHz - 20 GHz

86030
45 MHz - 50 GHz

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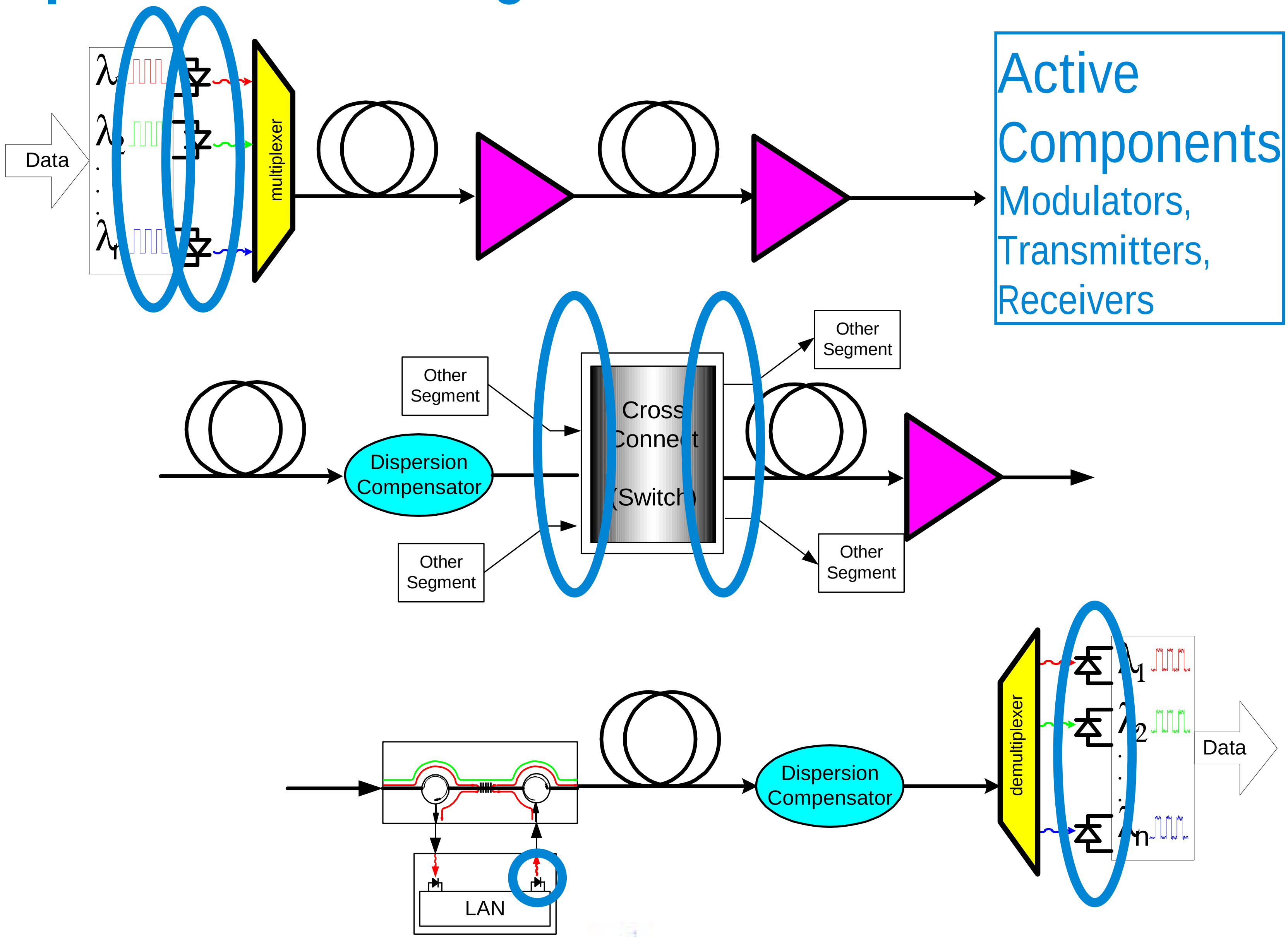
Optical Networking - The DWDM Forest



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Optical Signal Amplification and DWDM

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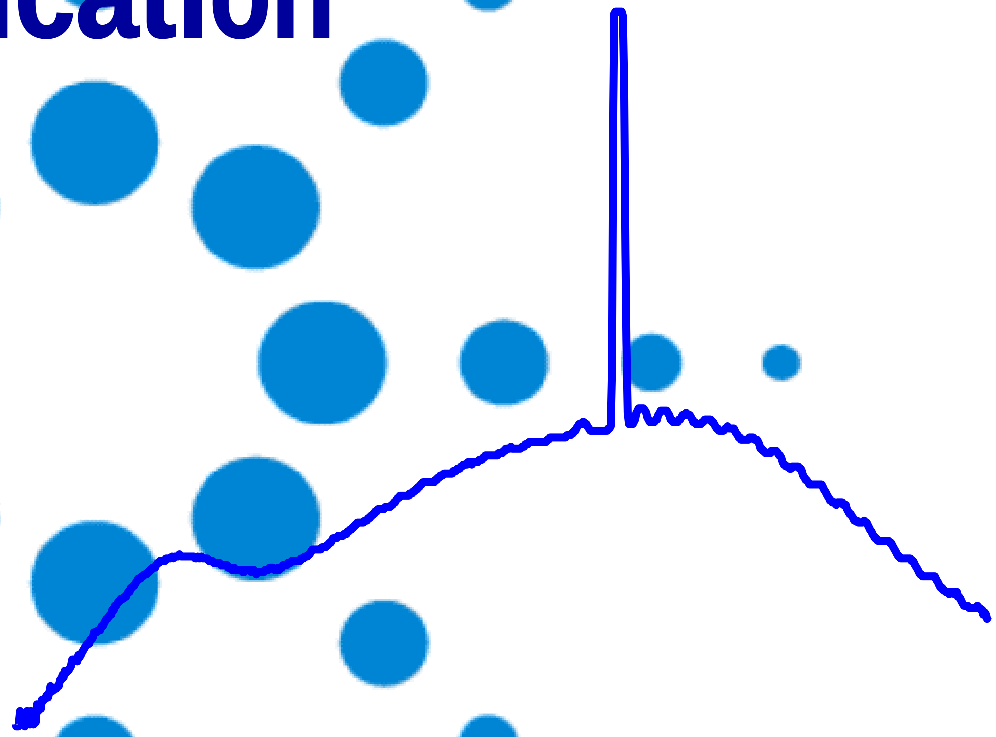
Atomic Physics:
Optical Amplification



Raman scattering

Optical pumping

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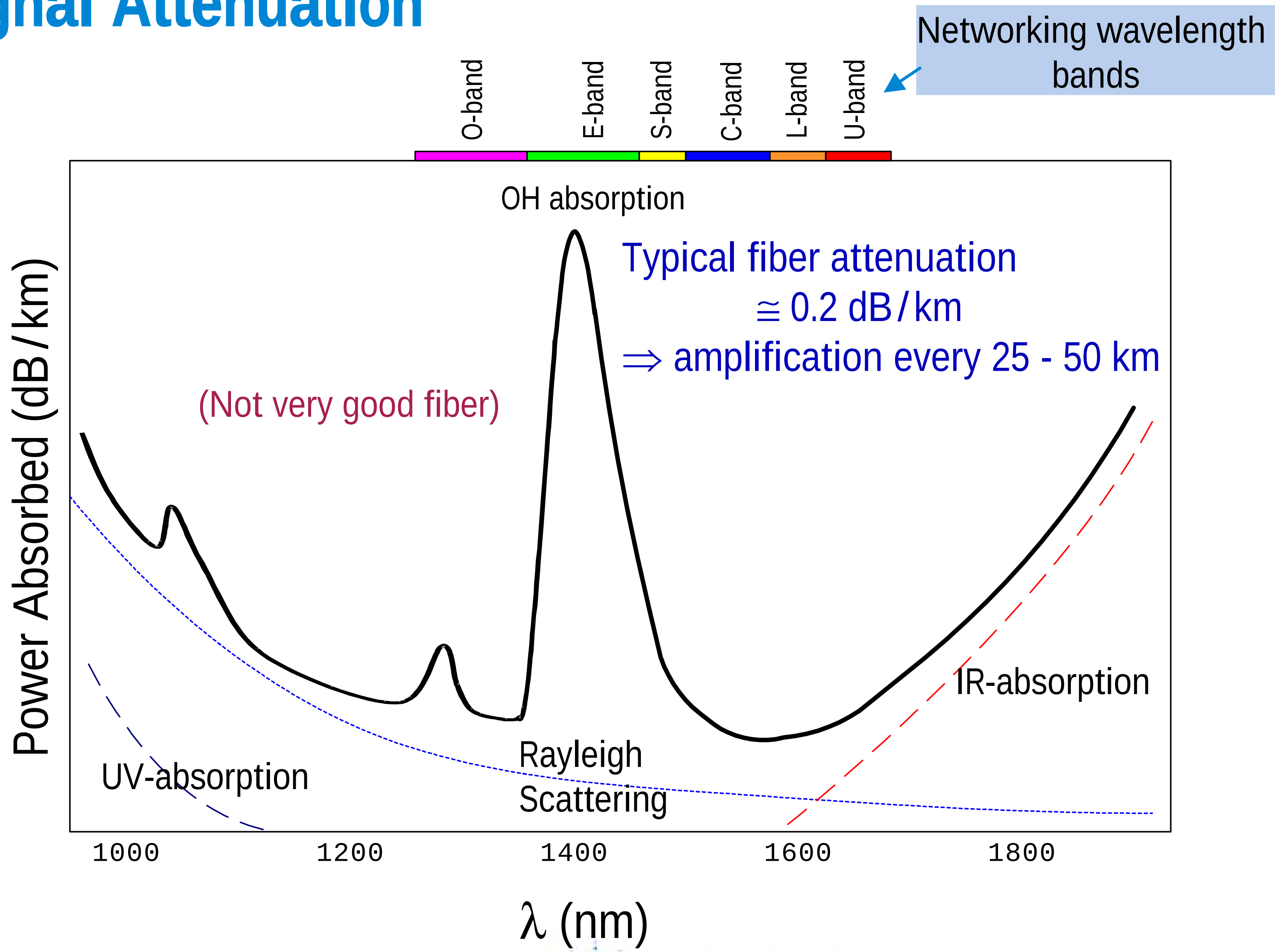
Signal Attenuation



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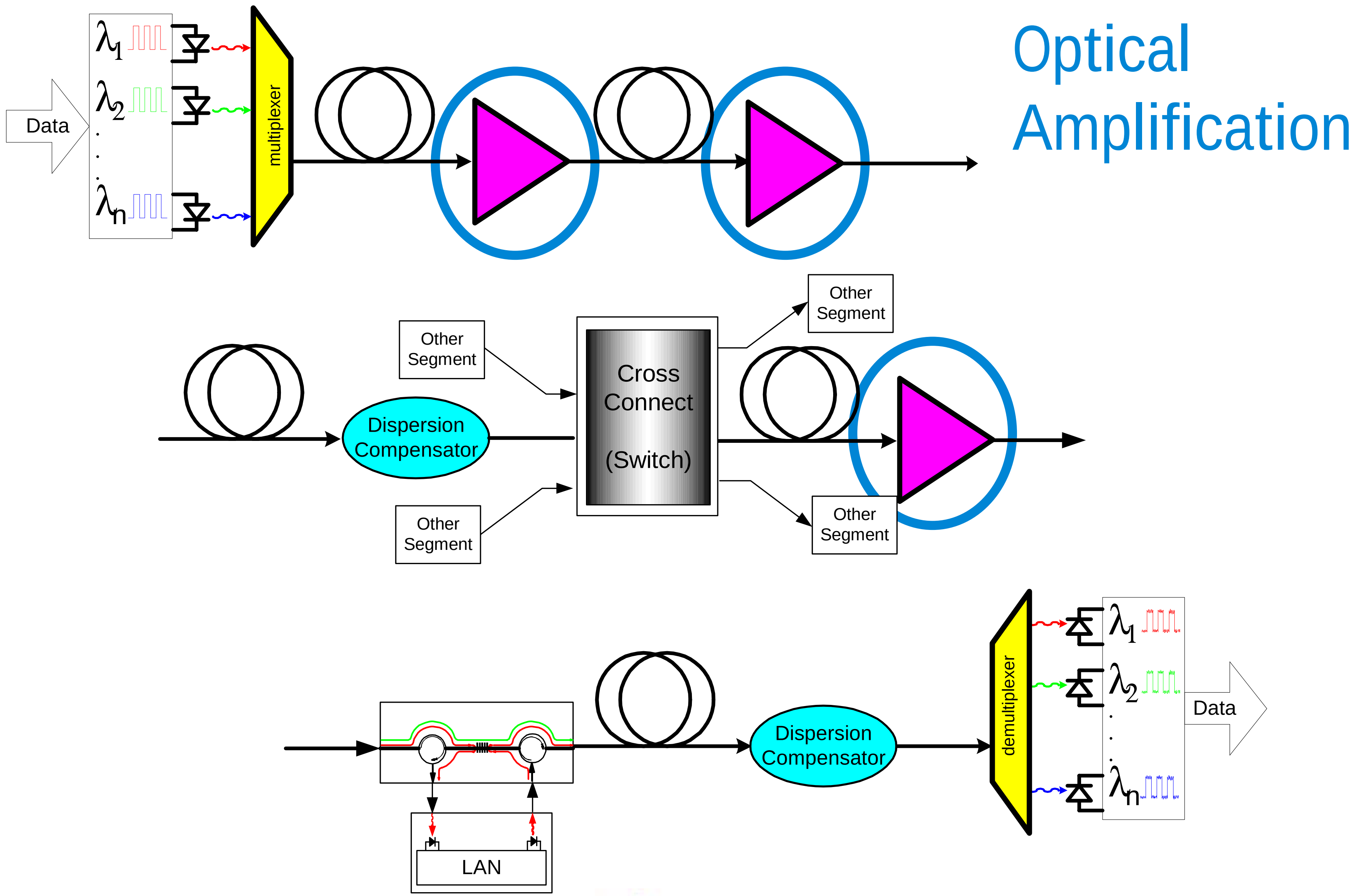
Optical Networking - The DWDM Forest



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Spontaneous and Stimulated Emission

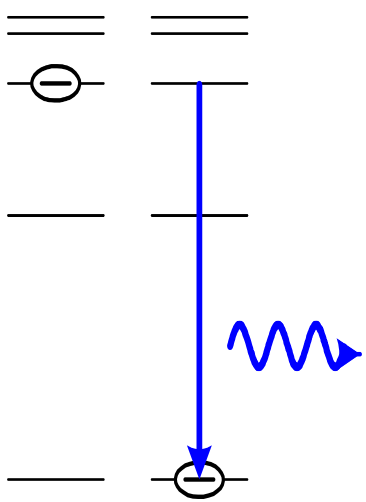
Spontaneous emission

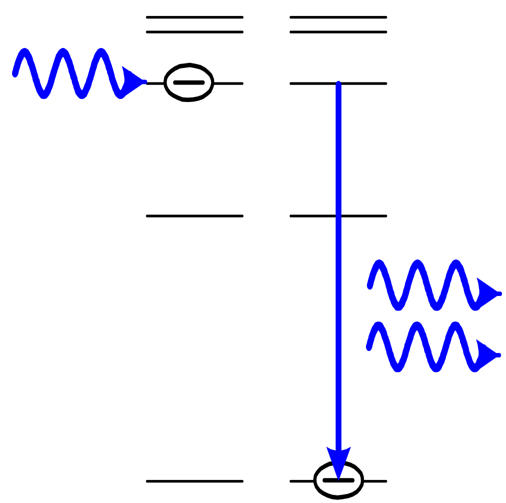
Light is spontaneously emitted when an electron decays to a lower energy state.

Stimulated emission

Incident light stimulates the decay of an electron. Light is emitted that is *identical* to incident light.

- Same wavelength, direction, polarization, and phase





Twice as much light outgoing as incident
→ gain of two

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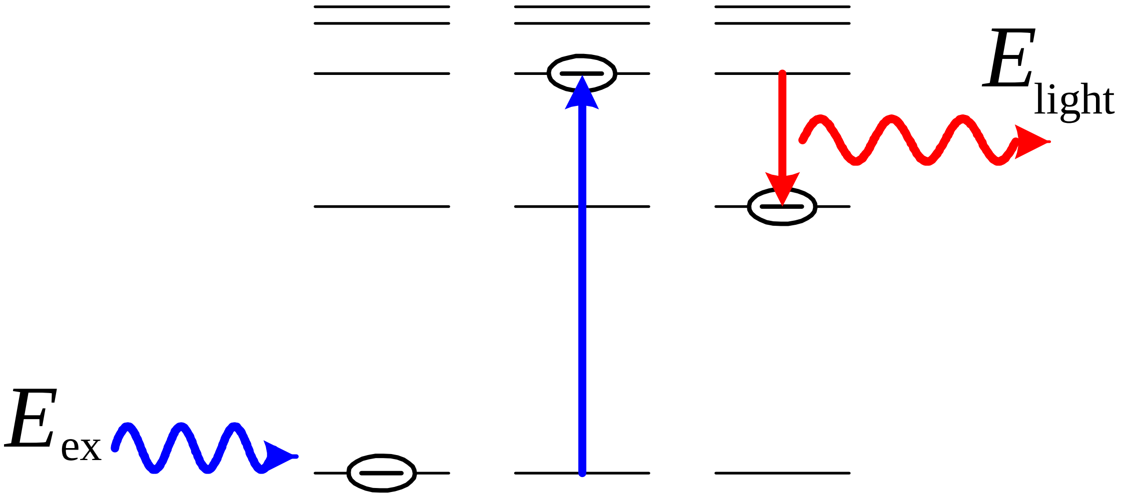
Raman Scattering

When a bound electron is excited to some energy E_{ex} and decays by emitting light of energy E_{light} , with

$E_{light} \neq E_{ex}$ it is called Raman scattering



Lifetime of the excited state is the “relaxation time”

~ 1 ms - metastable (Erbium)

< 1 ns - unstable (SiO_2)

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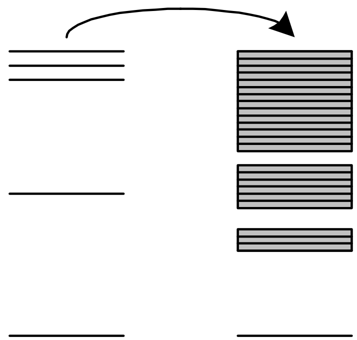
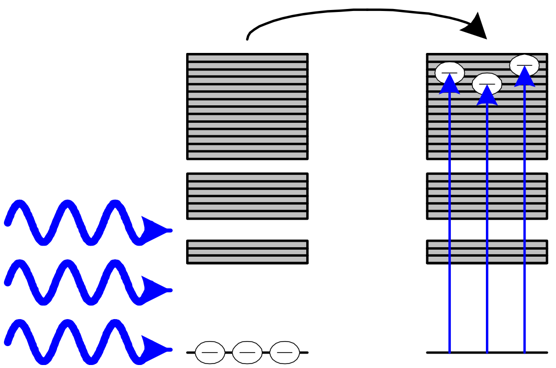
Optical Amplifiers - Erbium Doped Fiber Amplifier

1. Dope a fiber with erbium



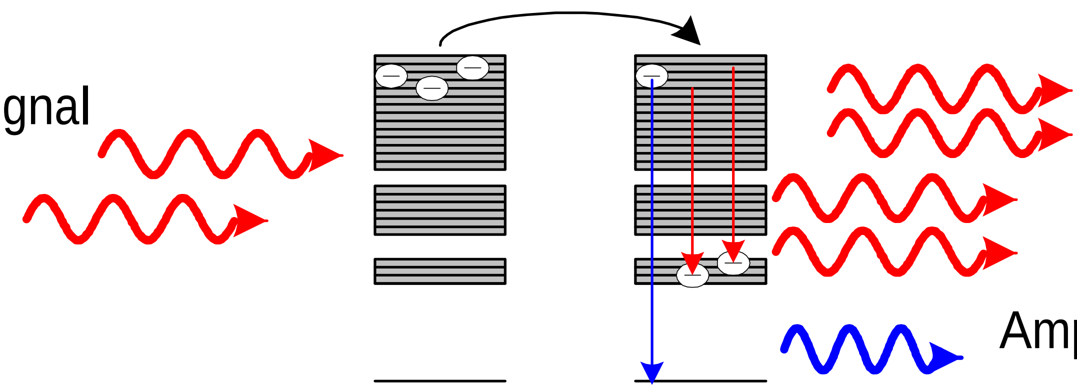
2. Pump energy into the fiber

Pump light



3. Transmit and amplify the signal

Signal



Amplified signal

Amplified Spontaneous Emission (ASE) noise!

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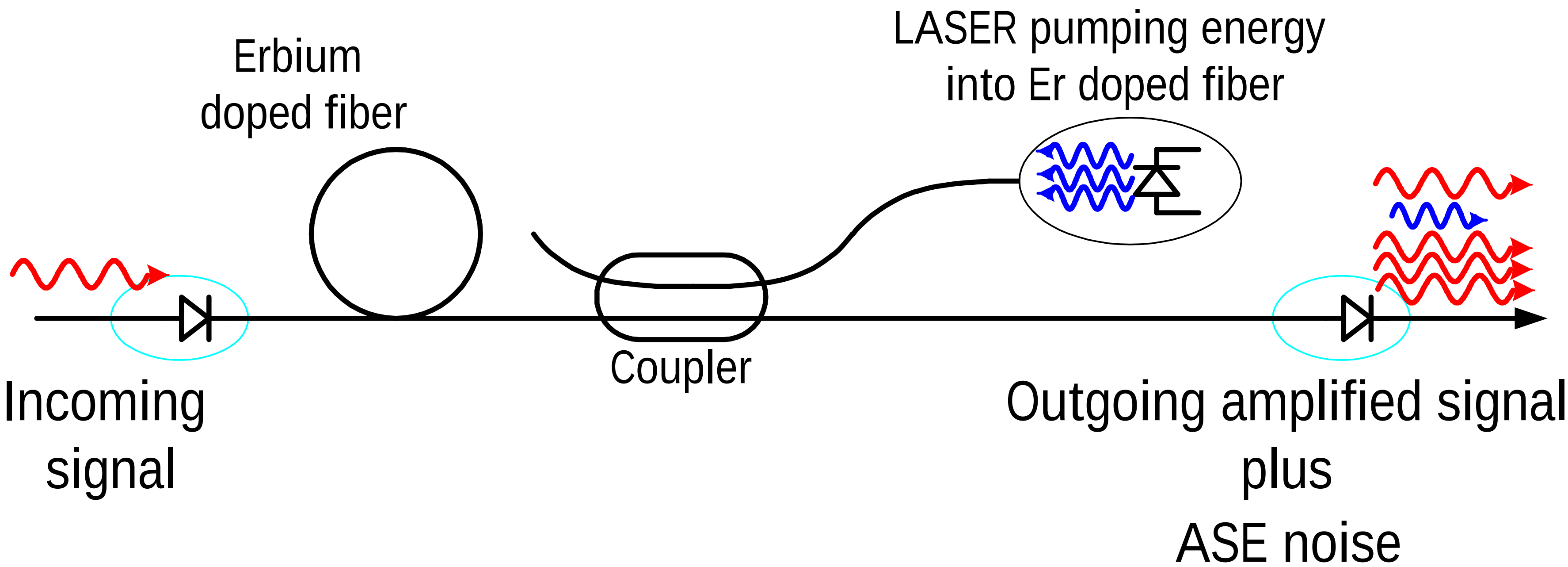
Erbium Doped Fiber Amplifiers



Two major characteristics:
Gain
Noise

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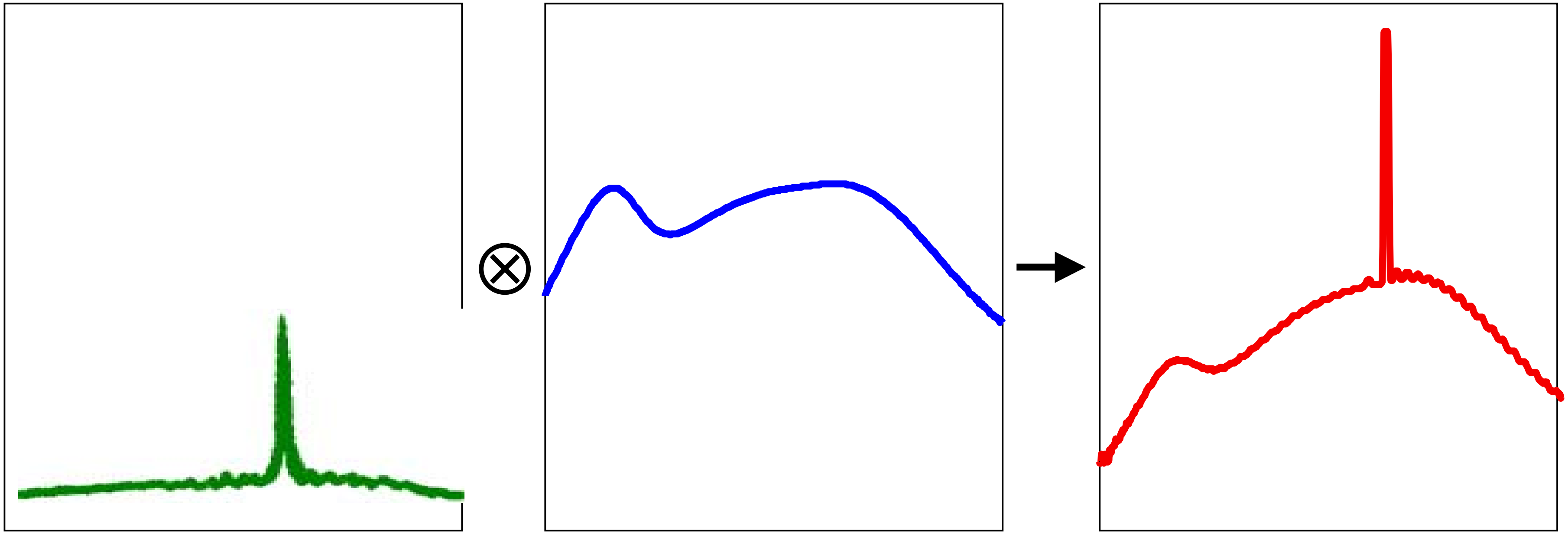
Amplifier Input / Output Spectra

Signal spectrum

Amplifier Spectrum with ***no*** input

Amplified Signal Spectrum (Amplified Signal + Reduced ASE + Amplified Source noise)



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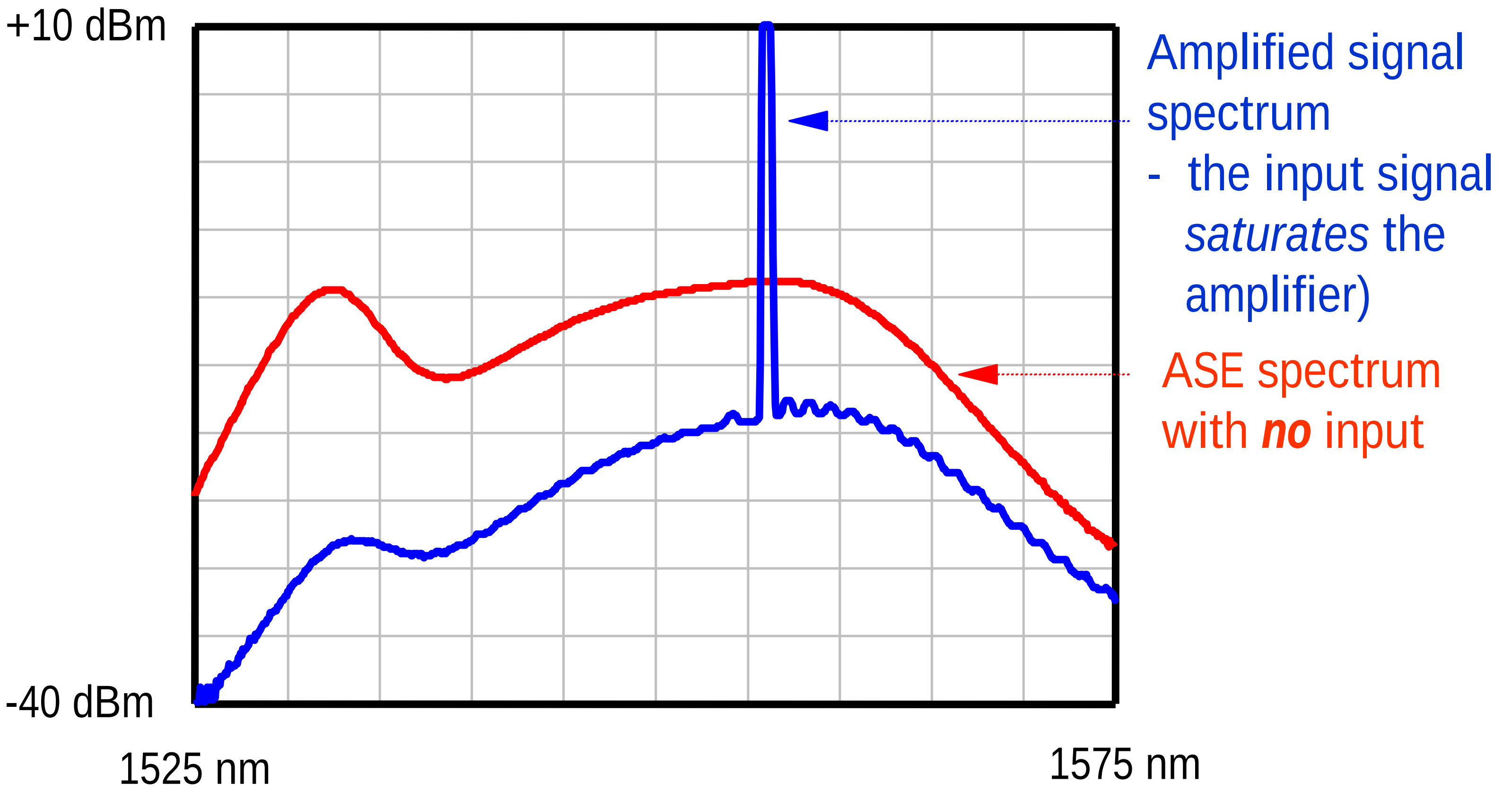
Output Spectrum



The relaxation time of Er causes a ~ 1 ms time scale for the ASE background to shift between levels with and without a signal

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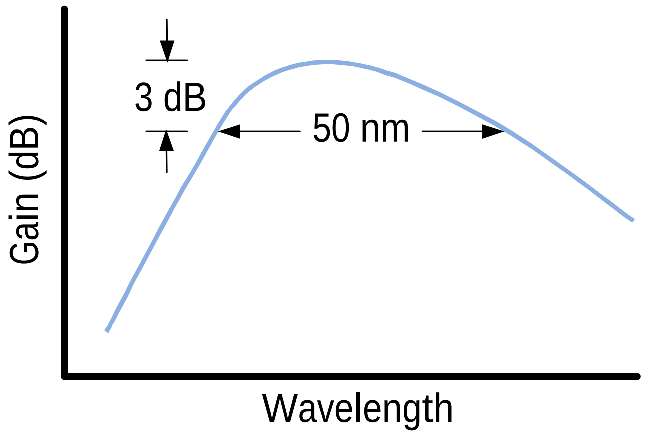
Other Optical Amplifier Technology

Semiconductor and Raman Optical Amp's

Same physical principle but different energy structure

- Other Dopants: xDFA
- Semiconductor Optical Amplifier (SOA)
  - Stimulated emission in of the signal as it traverses an excited semiconductor
  - Pump to high energy states by bias current or external pump laser
  - Tend to be very noisy

  Gain region can be tuned with band gap



- Raman Amplifier

  Use vibrational energy states of SiO_2 instead of atomic states of a dopant

  Raman scattering among vibrational states

  Pump laser through the whole fiber
  - pump energy is very high
  - states are not metastable

  Gain region over ~ 100 nm centered about 13 THz above the pump frequency

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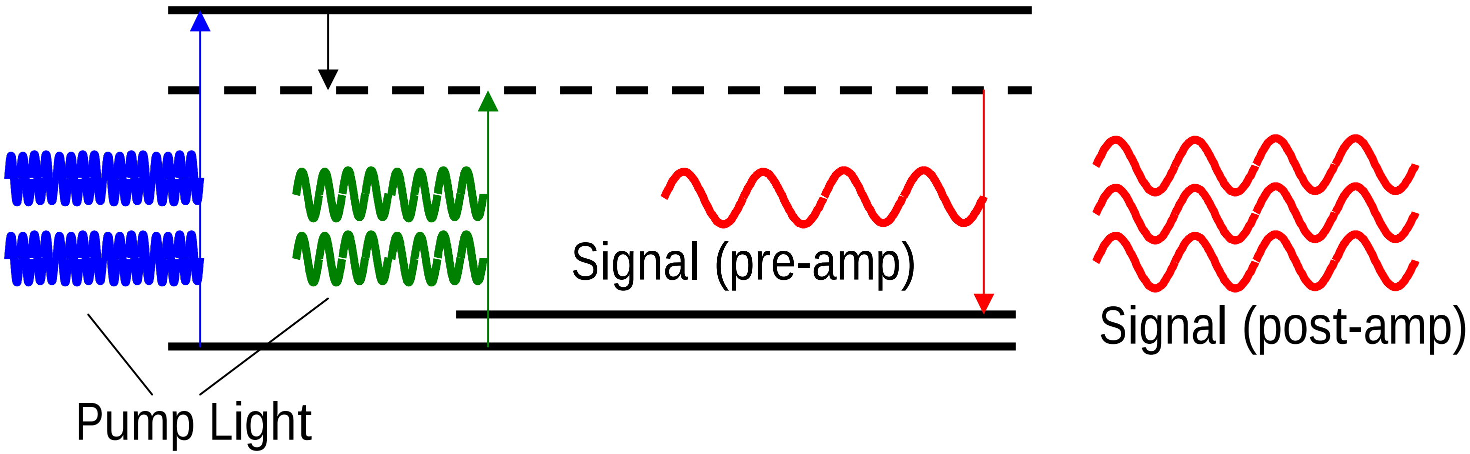
Optical Amplifiers - Summary



EDFA

- Material is doped with Erbium
- Material is pumped with
  1480 or 980nm
- Good for 1550nm signals

Raman Amplifier

- Whole undoped fiber is pumped
- Wide signal λ-range
- Amplification throughout fiber length
- High pump power required

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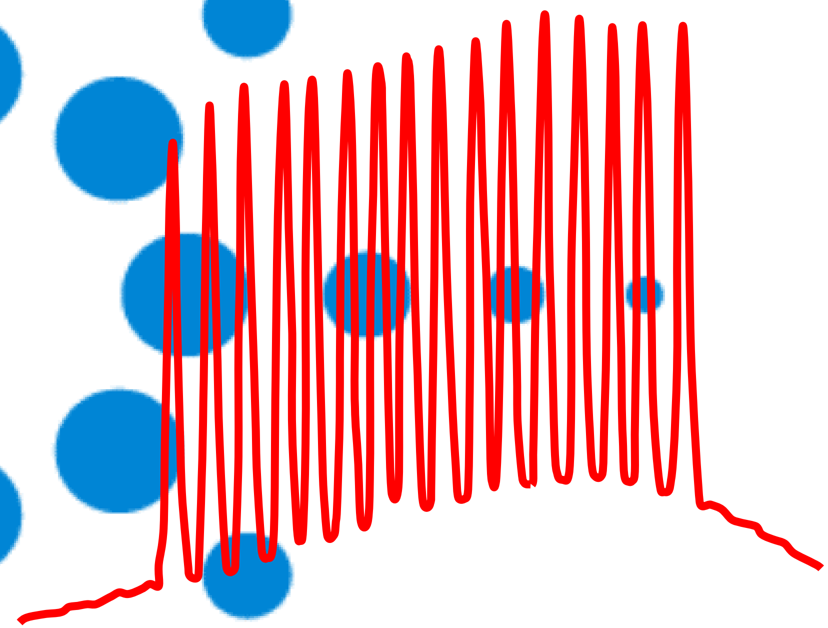
DWDM

Dense

Wavelength

Division

Multiplexing



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Introduction to Dense Wavelength Division Multiplexing

Use many different wavelengths on one fiber

- single mode or multi-mode fibers

Combine different wavelengths to increase data rate

- e.g., 125 λ's at 40 Gb/s each $\rightarrow$ 5 Tb/s (Alcatel, Feb-2002)

New and growing technology requiring

- λ mux/demux and optical switch technologies
- peculiar dispersion properties
- worry about noise at different λ's
- worry about optical crosstalk - four wave mixing

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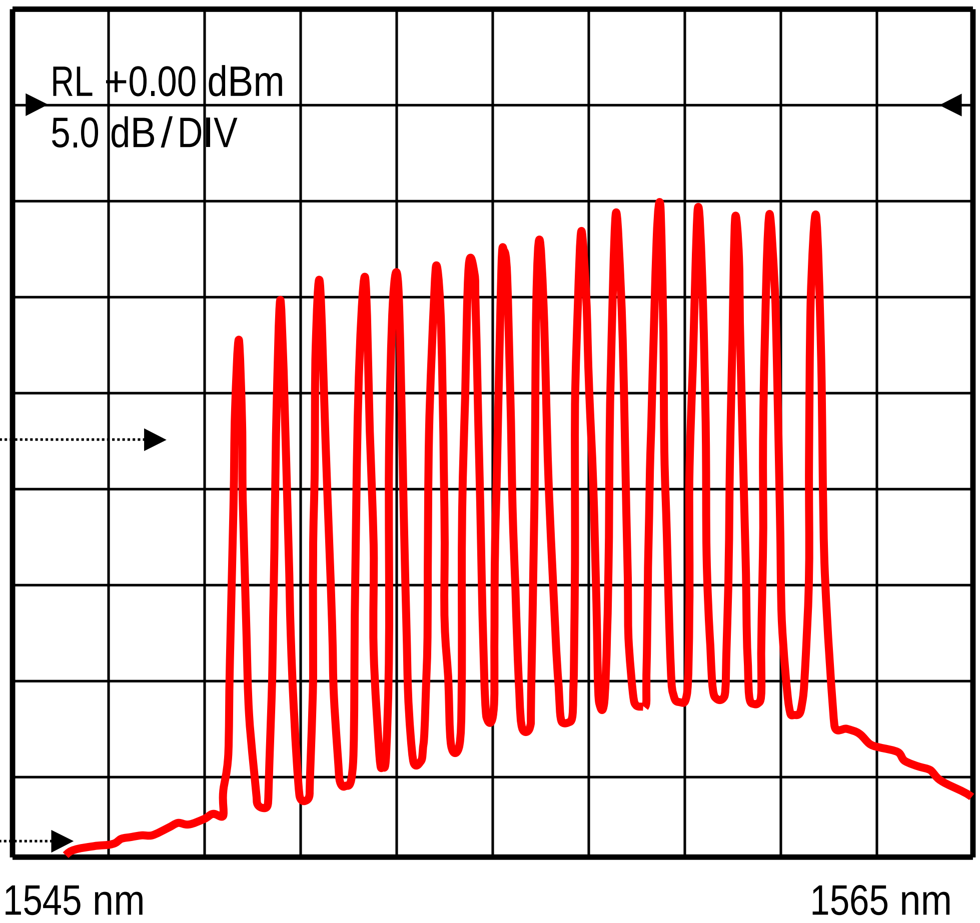
Amplified Dense Wavelength Division Multiplex Spectrum

Channels: 16
Spacing: 100 GHz (~ 0.8 nm)

Amplified
Spontaneous
Emission (ASE)



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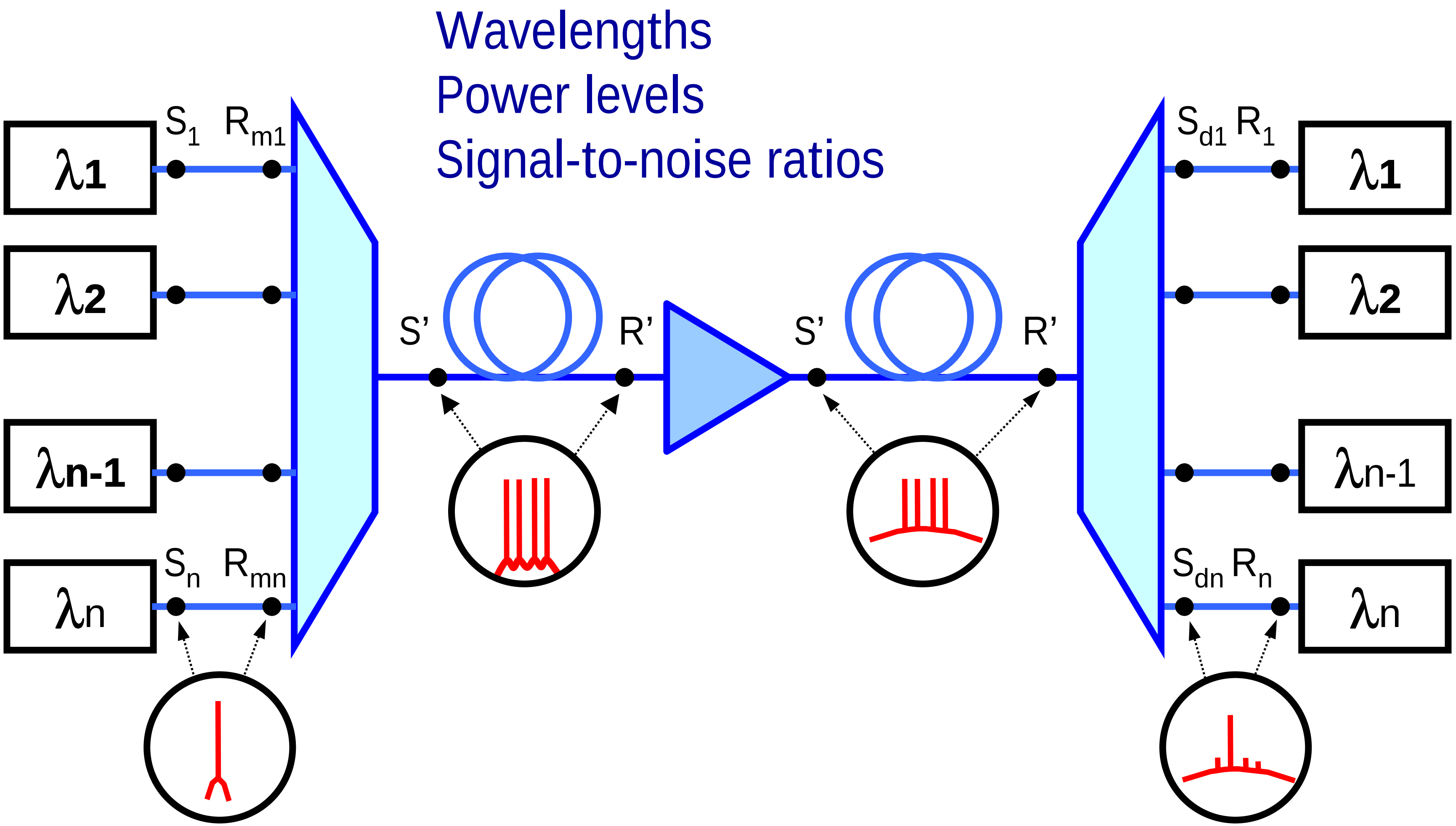
Basic DWDM Design



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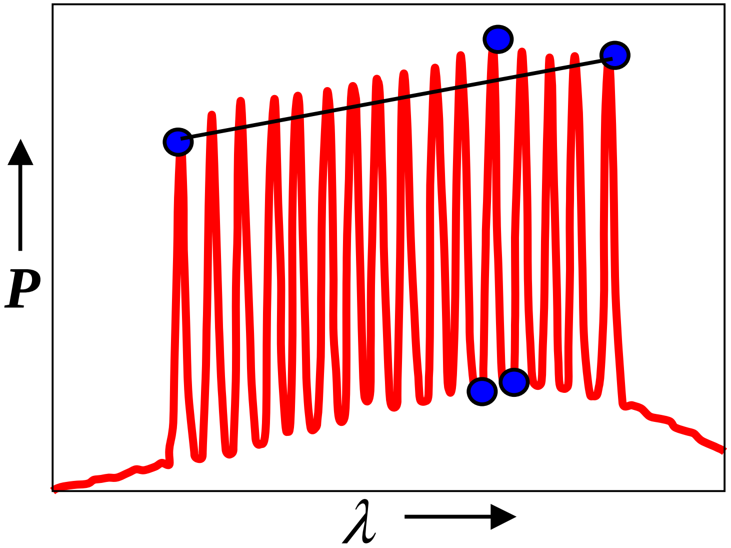
Amplified DWDM Spectrum
Parameters to Test

Parameters to Test
- Channel Gain
- Noise Figure
- Center λ
- Span Tilt
- Gain Flatness
- Channel Spacing



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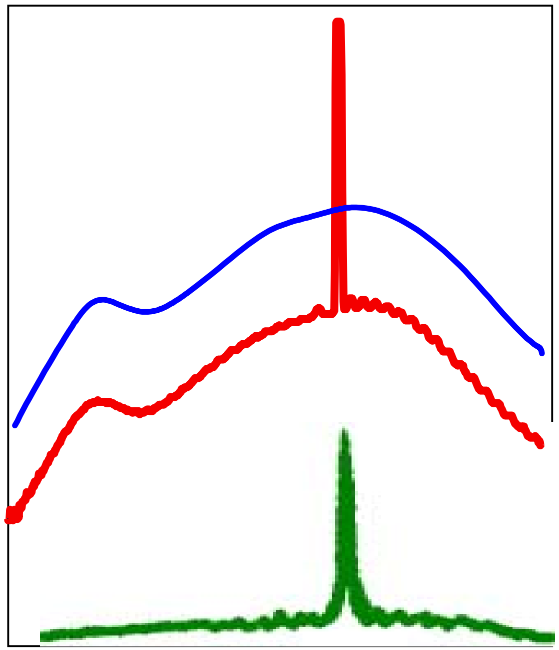
Amplifier Characteristics



$$G = \frac{P_{out}^{Signal}}{P_{in}^{Signal}}$$

Gain = 0 → 50 dB

$$\text{Noise Figure} = \frac{\text{SNR}_{in}}{\text{SNR}_{out}}$$

Noise Figure = 3.5 → 12dB

- ● (blue) = Output Spectrum of Amplifier without input
- ● (green) = Input spectrum to Amplifier
- ● (red) = Output spectrum from Amplifier

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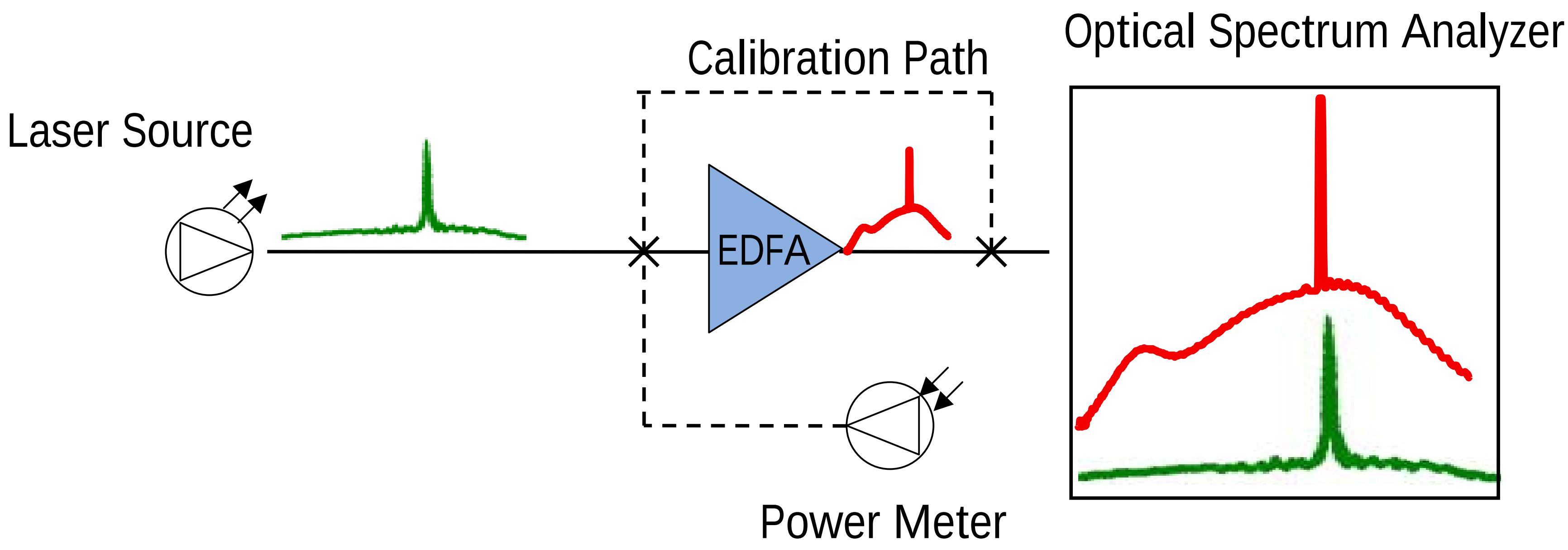
Interpolated Source Subtraction (ISS) Method

<u>Gain & Noise Figure</u>

1. Measure a constant wave input spectrum
2. Measure the amplified constant wave output spectrum
3. Interpolate across the signal to estimate the background at the signal wavelength ⇒ separate signal and noise



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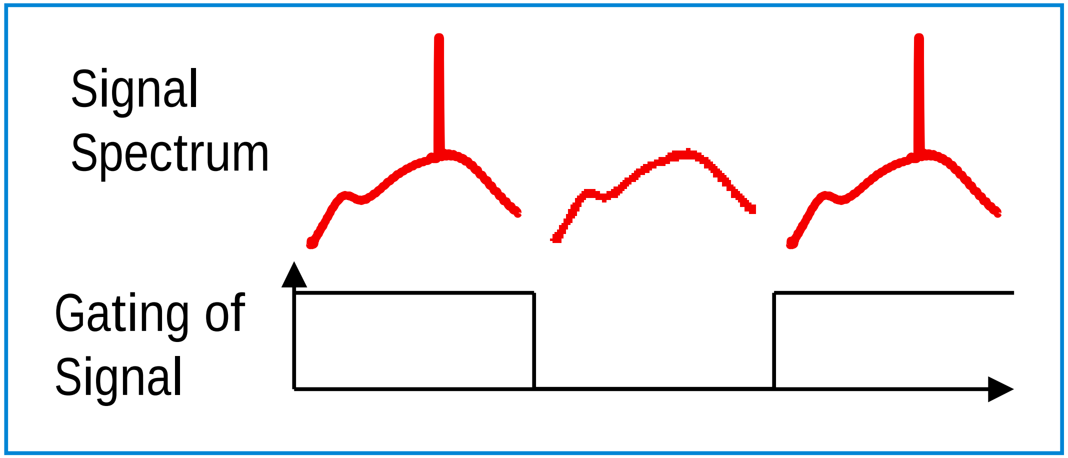
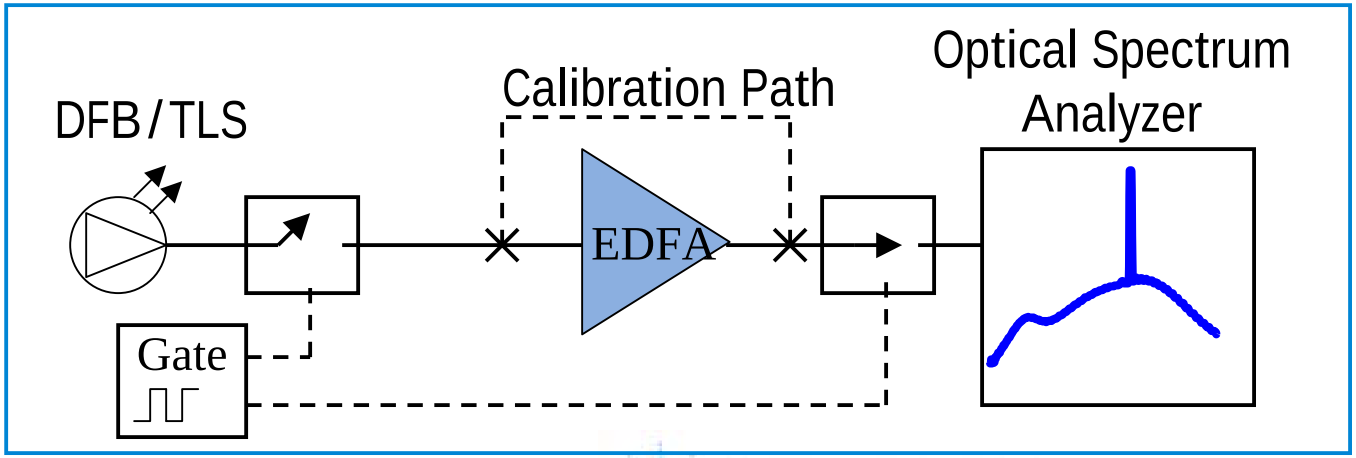
Time Domain Extinction (TDE) Method

<u>Gain & Noise Figure</u>

1. Measure output with signal gated off



2. Long relaxation time (metastability) of the Erbium excited states allow direct measurement of the spontaneous emission curve



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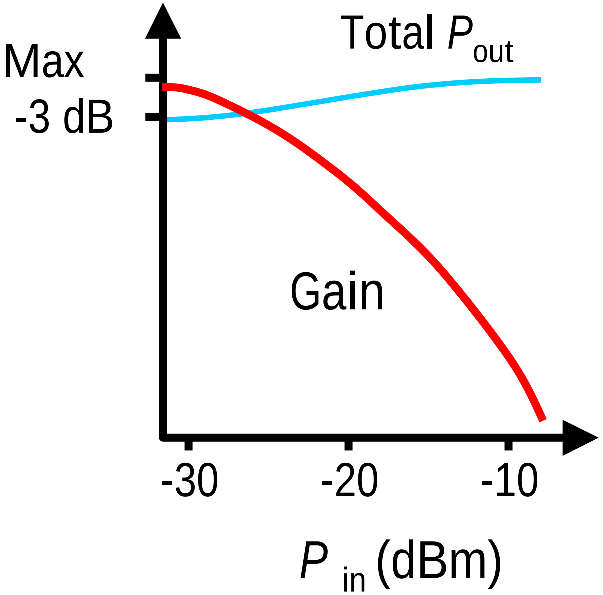
Gain Compression

Total output power: Amplified signal + ASE

- EDFA is in *saturation* if almost all Erbium excited states are consumed by amplification
- Total output power remains almost constant
- Lowest noise figure

Preferred operating point

- Power levels in link stabilize automatically



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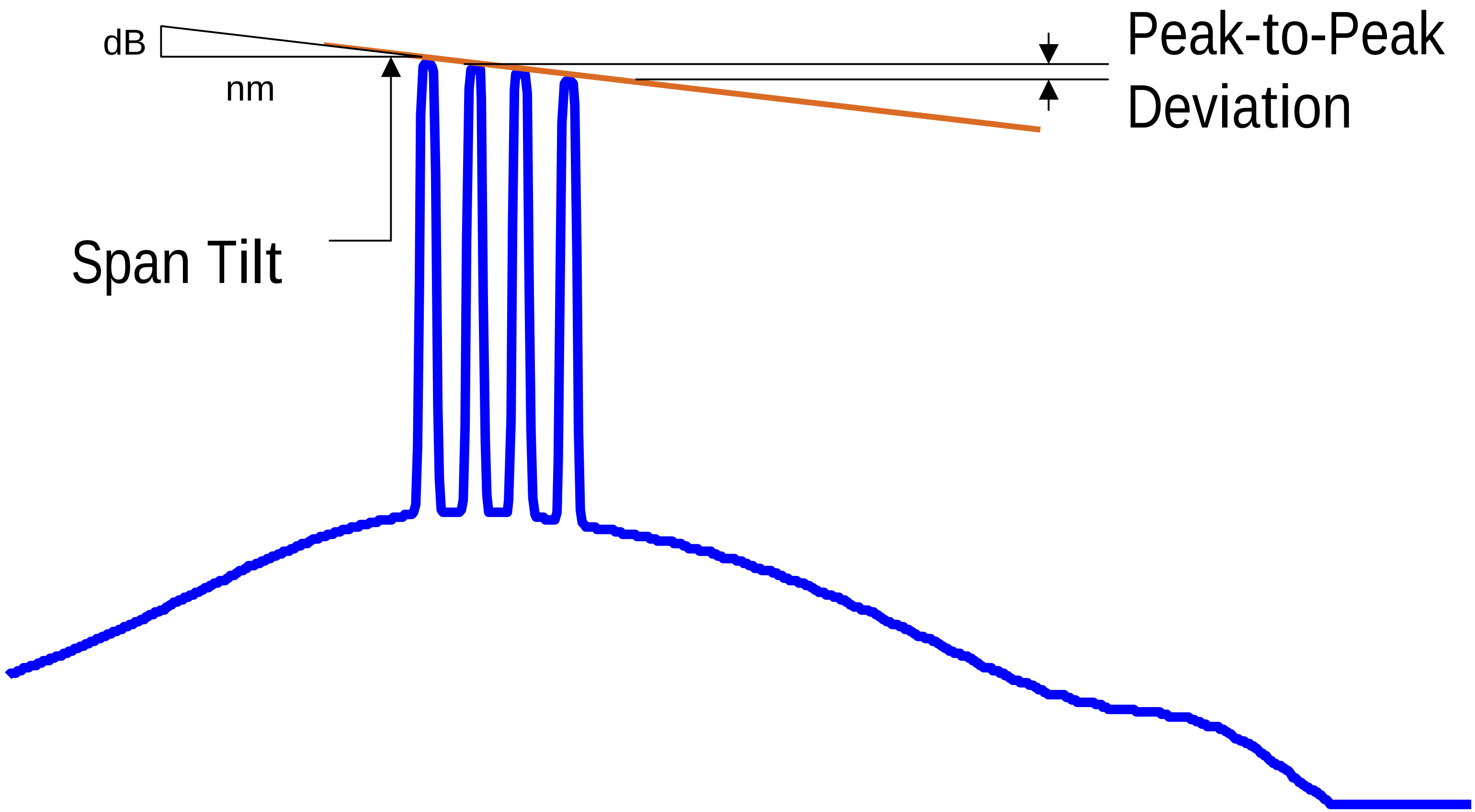
Span Tilt and Peak to Peak Deviation



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Characterizing Semiconductor and Raman Amplifiers

Erbium Doped Fiber Amplifiers (EDFAs) use energy levels that are metastable states, $\Delta T \sim 1$ ms, a long time compared to f_{mod}.

Semiconductor and Raman Amplifiers use unstable states:

$\Delta T_{Raman} \sim 0.005$ ps and $\Delta T_{SOA} \sim 1$ ns

- Time Domain Extinction methods are not useful
- Limited to Interpolated Source Subtraction (ISS) for measuring gain and noise figure

The gain of Raman and semiconductor amplifiers depend strongly on signal polarization, EDFA only weakly.

- Measure gain and noise figure as a function of signal polarization

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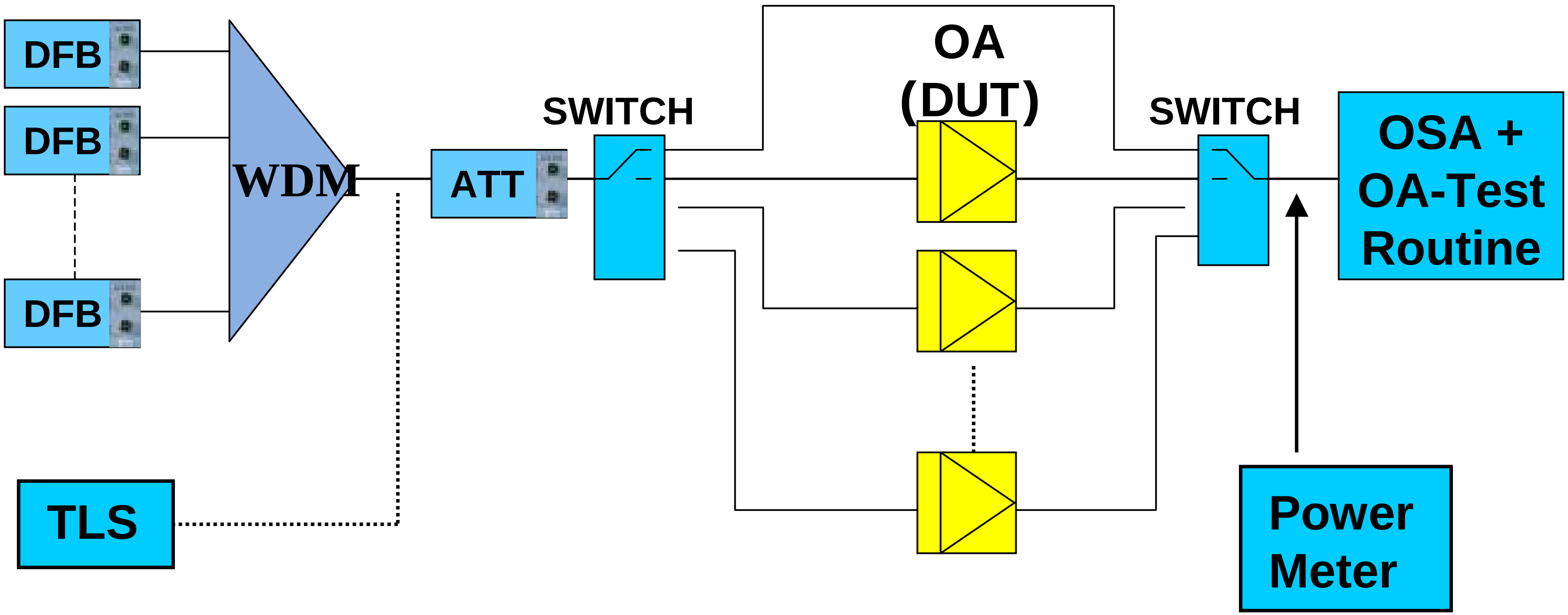
Standard Amplifier Test Setup
EDFA, Semiconductor, and Raman Amplifier



OSA separates signals from broadband spontaneous emission

Amplifier characteristics depend on input power, wavelength, polarization
• Sources simulate operation (multichannel, adjustable power...)

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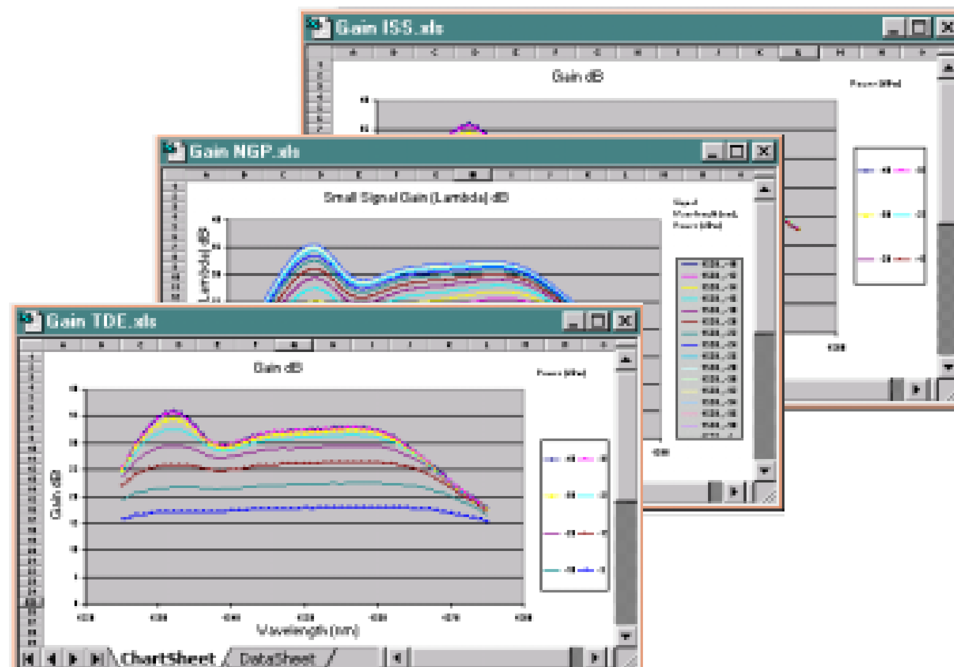
The Complete EDFA Test Solution

- Time Domain Extinction Method
- Interpolated Source Subtraction Method
- Noise Gain Profile Method



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Issues in DWDM

SM fiber can tolerate up to 50 mW (+17 dBm)

- Nonlinear effects start causing trouble around 10 dBm
- About 100 kW/m^2!
- limits available channel power to Power/channel < 50 mW/$N_{channels}$

Optical Amplifiers have limited effective λ range

- e.g., EDFA: $1525 < \lambda < 1565$ (roughly)

High power densities cause nonlinear scattering

- e.g., Kerr effect: $n = n(\mathbf{E})$

$\Rightarrow$ Four Wave Mixing (FWM), self-phase modulation, . . ., *noise*

Trends:

Higher capacity

- 160 wavelengths
- 12.5 GHz spacing

All optical network (the grail)

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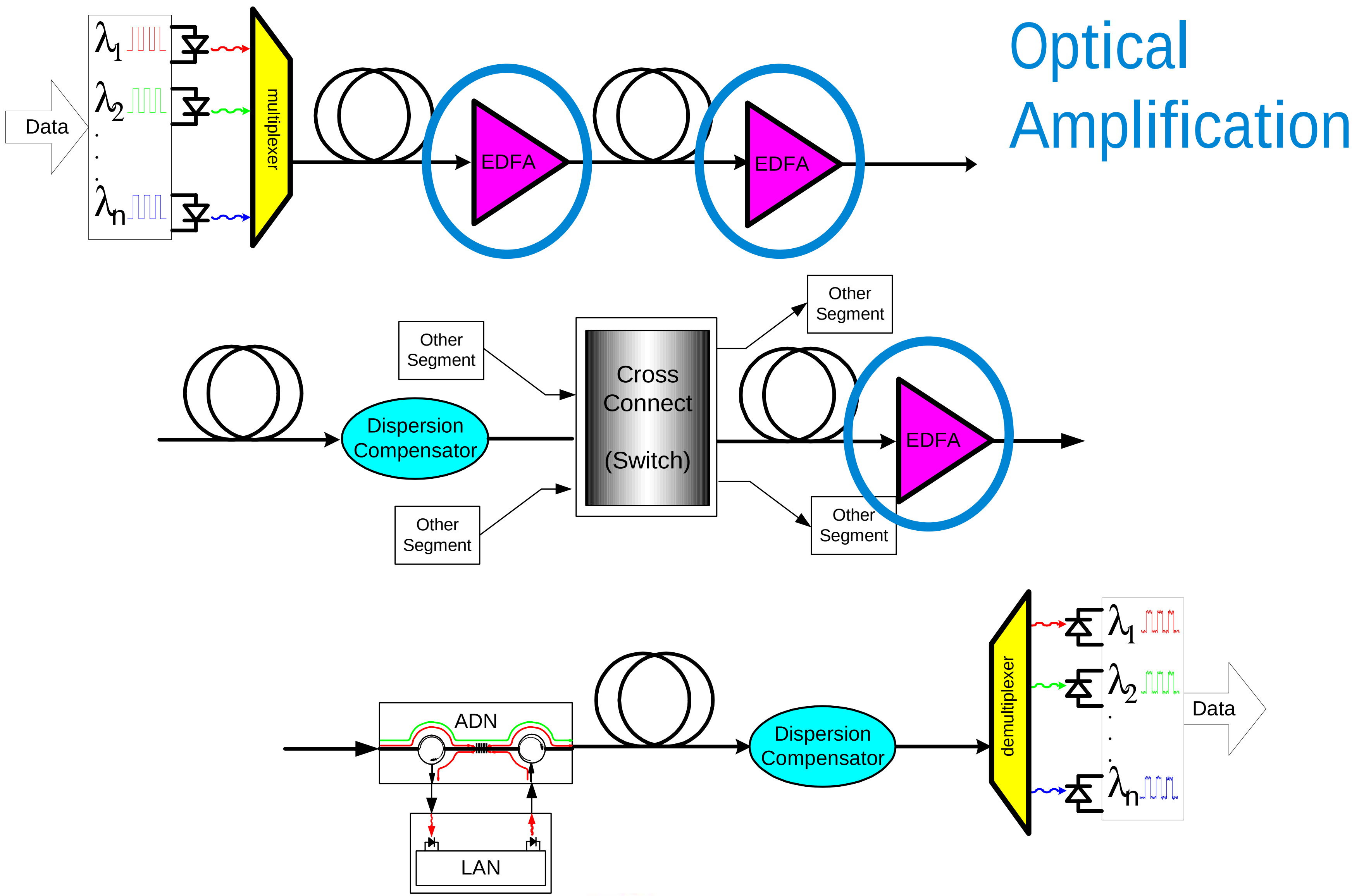
Optical Networking - The DWDM Forest



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Dispersion:

The evolution of the index of refraction with wavelength and polarization

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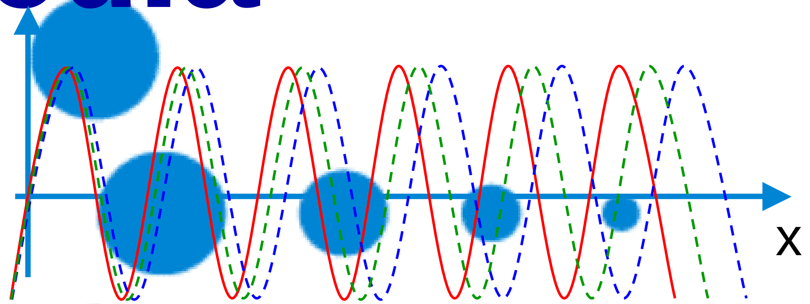
Electrodynamics of Continuous Media

Chromatic dispersion



Polarization mode dispersion

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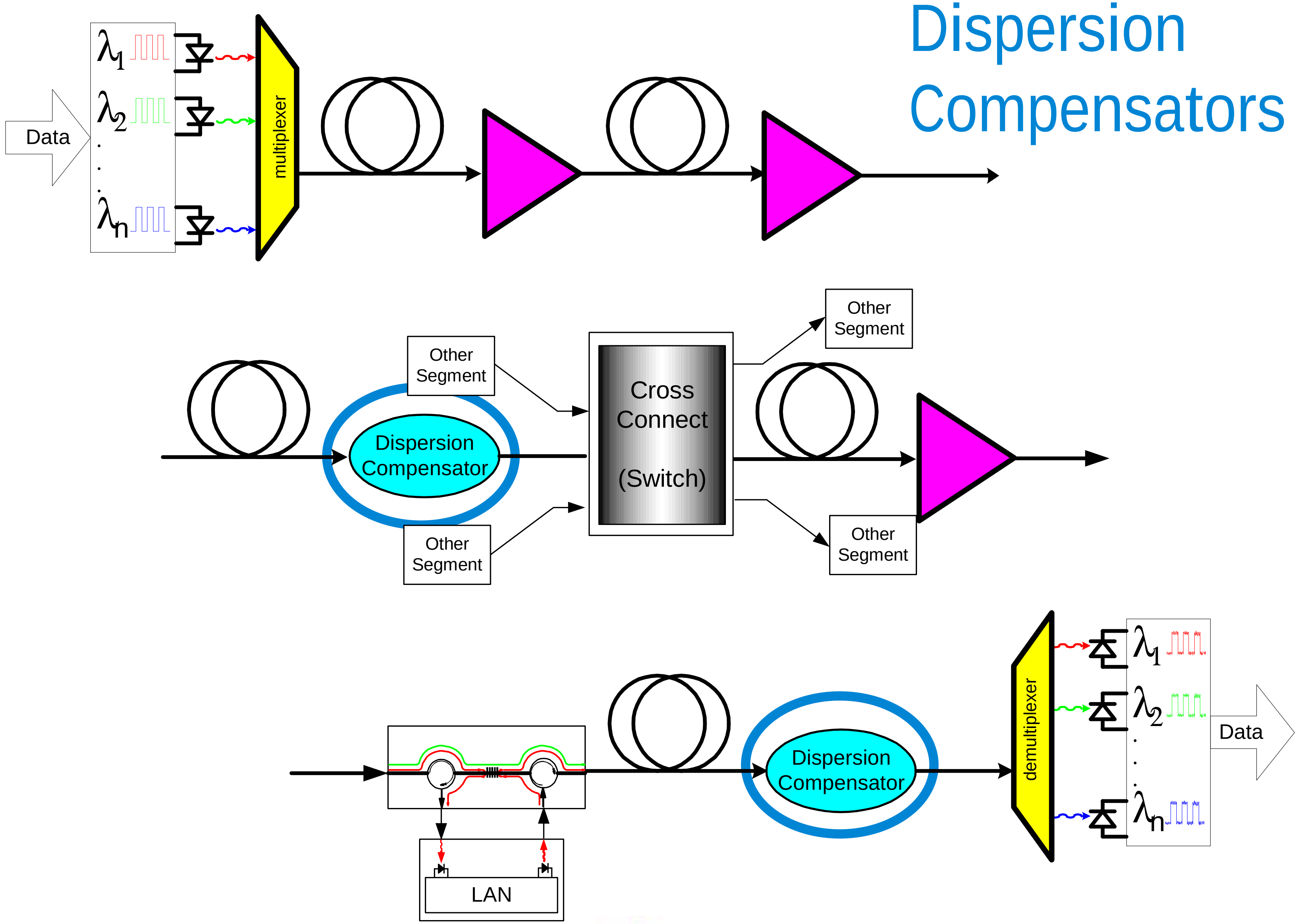
Optical Networking - The DWDM Forest

Dispersion Compensators



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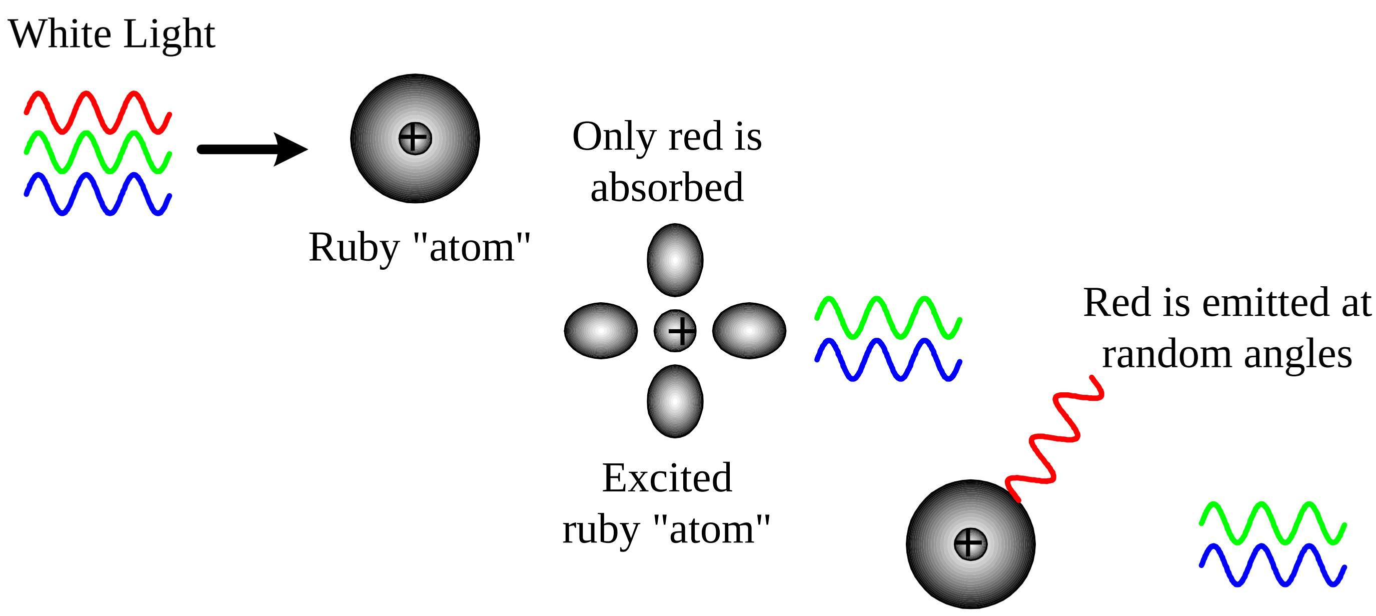
Color: Index of refraction

Why is a ruby red?



Because the $n_{Ruby}(\lambda)$ has a resonance at λ_{red}.

For pigments, e.g., red paint, the other colors are absorbed in the mess of organic molecules that have many available energy states resulting in heat.

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The Index of Refraction

The index of refraction of a dielectric is given by $n(\lambda) = {c_{\text{vacuum}}}/{c_{\text{media}}}$

- The energy carried by light is determined by the frequency, not the wavelength, so the frequency of light in media doesn't change, but the wavelength does.

$$n(\lambda) = \frac{c_{\text{vacuum}}}{c_{\text{media}}} = \frac{\lambda_{\text{vacuum}}\nu}{\lambda_{\text{media}}\nu} = \frac{\lambda_{\text{vacuum}}}{\lambda_{\text{media}}} \qquad c_{\text{media}}(\lambda) = c_{\text{vacuum}} \frac{\lambda_{\text{media}}}{\lambda_{\text{vacuum}}}$$

- The index of refraction varies with wavelength,
  - different colors travel at different speeds $\Rightarrow$ chromatic dispersion.
- The index of refraction can also vary with polarization
  - "birefringence" $\Rightarrow$ polarization mode dispersion

The heart of these phenomena is the response of the media to the electric and magnetic fields that compose the light.

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Chromatic Dispersion Spreads Pulses

⇒ Increases the Bit Error Rate

Recall from coherence:

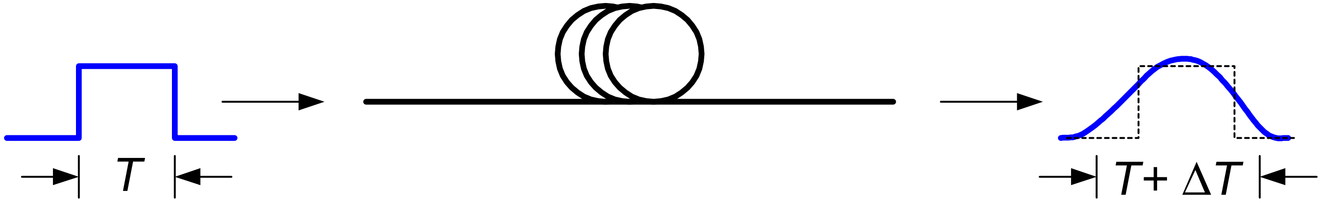
⇒ the minimum frequency/wavelength spread of a pulse of light is

$$\Delta\nu \times T_C \approx 1/4\pi$$

$$\text{thus } \Delta\nu \geq \frac{1}{4\pi T_{Pulse}} \quad \text{or} \quad \Delta\lambda \geq \frac{\lambda^2}{4\pi c T_{Pulse}}$$

⇒ $n = n(\lambda)$ narrower the pulse, the larger the chromatic dispersion

- Modulation sidebands and chirp also increase pulse wavelength content



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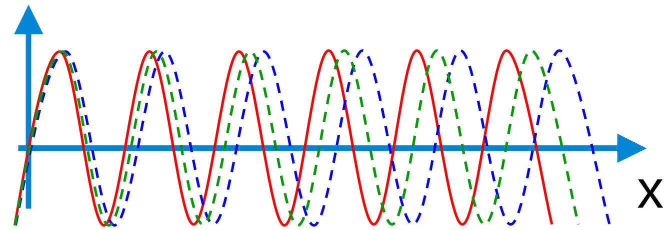
The Cause of Chromatic Dispersion



Two causes:

1. Material Dispersion

- The response, “permittivity”, of the media:

$$n(\lambda) = \frac{c_{\text{vacuum}}}{c_{\text{media}}} = \sqrt{\frac{\varepsilon\mu}{\varepsilon_0\mu_0}} \approx \sqrt{\frac{\varepsilon}{\varepsilon_0}} = \sqrt{\kappa}$$

Dielectric constant

2. Waveguide Dispersion

- $n_{core}(\lambda)$ and $n_{cladding}(\lambda)$ vary differently with λ

  $\Rightarrow$ different boundary conditions for different wavelengths

  $\Rightarrow$ different solutions to the wave equation

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Chromatic Dispersion - Definitions

- Define

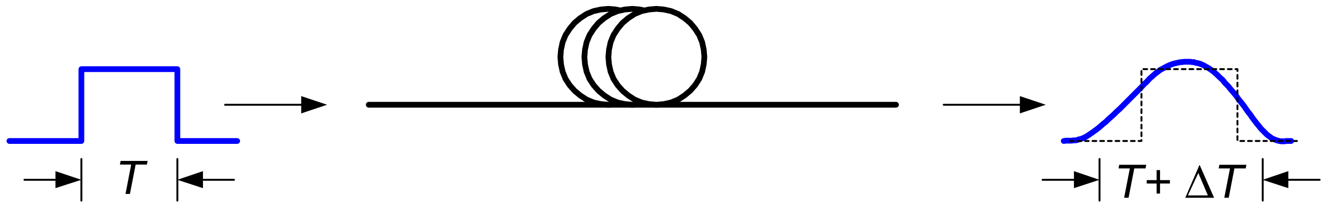
$$\text{chromatic dispersion} \equiv \frac{d\tau_g(\lambda)}{d\lambda}$$

describes how the propagation time varies with wavelength in ps/nm where $\tau_g(\lambda)$ is the propagation time along a fiber of length *L*.

- Factor out the length and get the

$$\text{chromatic dispersion coefficient, } D_\lambda \equiv \frac{1}{L}\frac{d\tau_g(\lambda)}{d\lambda}$$

The pulse spreads by an amount $\Delta T \approx L D_\lambda \Delta\lambda$



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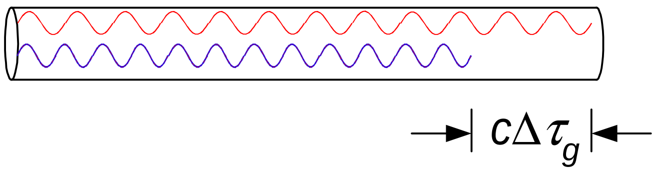
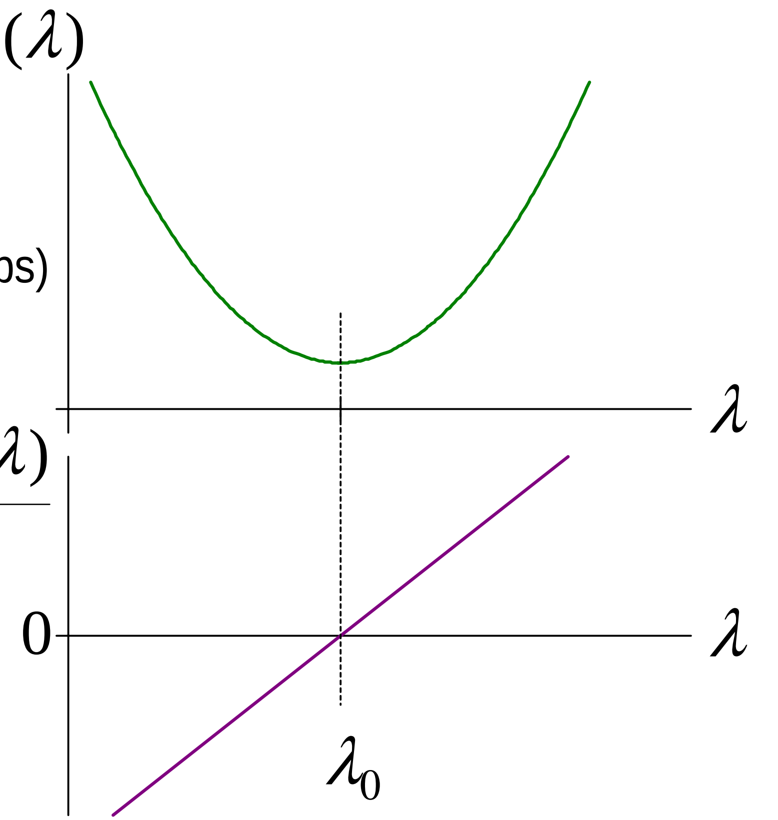
Chromatic Dispersion Observables



Group Delay (ps)



$$D_\lambda \equiv \frac{1}{L}\frac{d\tau_g(\lambda)}{d\lambda}$$

Chromatic dispersion coefficient (ps/nm·km)

Zero dispersion wavelength, typically 1300 nm

Typical CD value: 10 ps/nm·km

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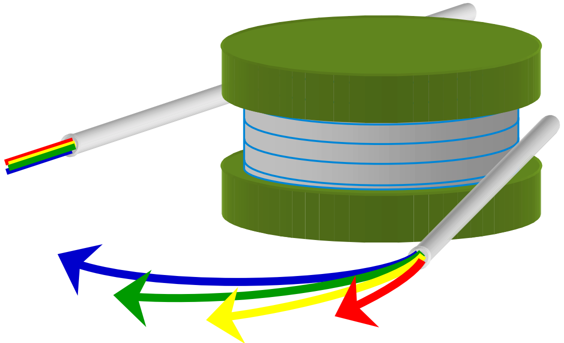
Tolerable Levels of Chromatic Dispersion

Require $\Delta\tau_g \ll \frac{1}{B}$ with B = bit rate in Gb/s



since $d\lambda = -\frac{c}{\nu^2} d\nu$ and $d\nu \approx B$ so $d\lambda \propto B$

From coherence

and $L \times D_\lambda = \frac{d\tau_g}{d\lambda} \propto \frac{1}{B^2}$

For 1 dB penalty: $L \times D_\lambda < 10^5 / B^2$

Bit rate:	2.5 Gb/s	10 Gb/s	40 Gb/s
max dispersion:	16,000 ps/nm	1000 ps/nm	63 ps/nm
max length:	940 km	60 km	4 km

Dispersion can be good! DWDM systems can have very high power density
1 mW/$\lambda \rightarrow$ 1 GW/m^2 Dispersion spreads out the energy, decreasing energy densities.

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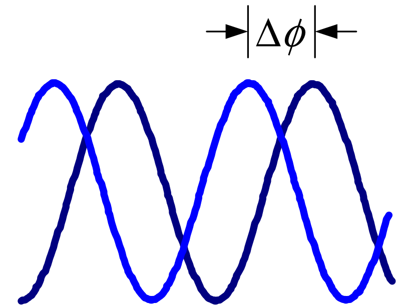
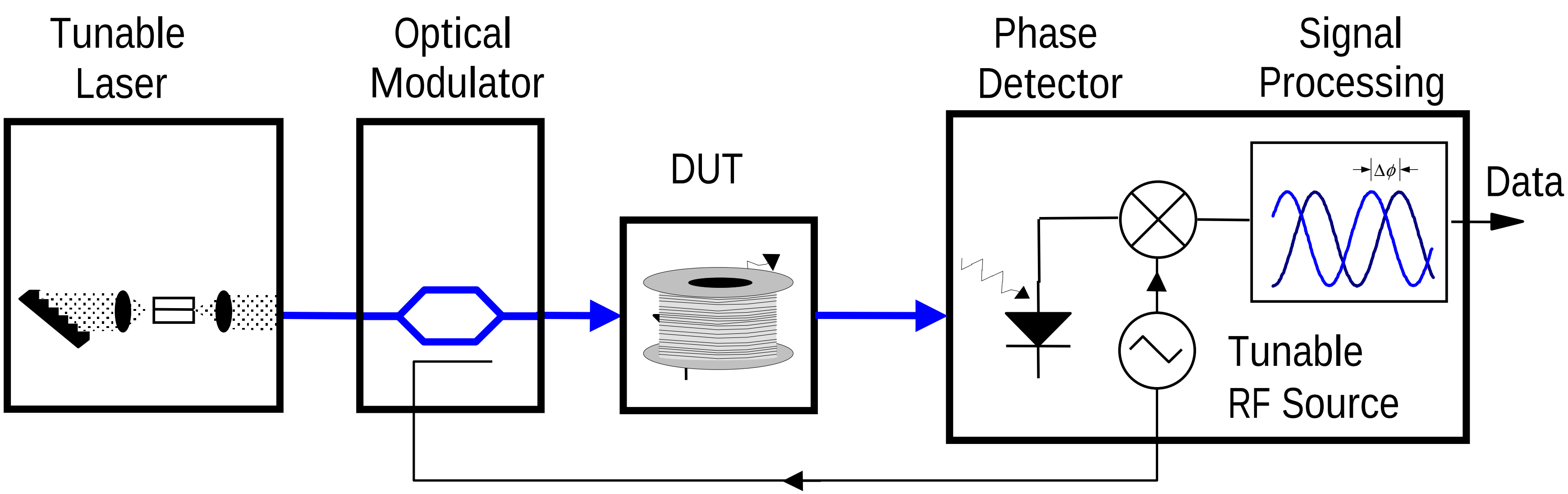
Chromatic Dispersion Measurements
Modulation Phase Shift Method

1. Form sinusoidal pulses of light of wavelength λ, at f ~ 1 GHz
2. Measure phase difference between generated and received pulses, $\Delta\phi$
3. Convert phase difference to differential group delay

$$\Delta\tau_g(\lambda) = \Delta\phi_\lambda / 2\pi f$$

4. Fit curve to $\Delta\tau_g(\lambda)$ and calculate $D_\lambda \equiv \frac{1}{L}\frac{d\tau_g(\lambda)}{d\lambda}$





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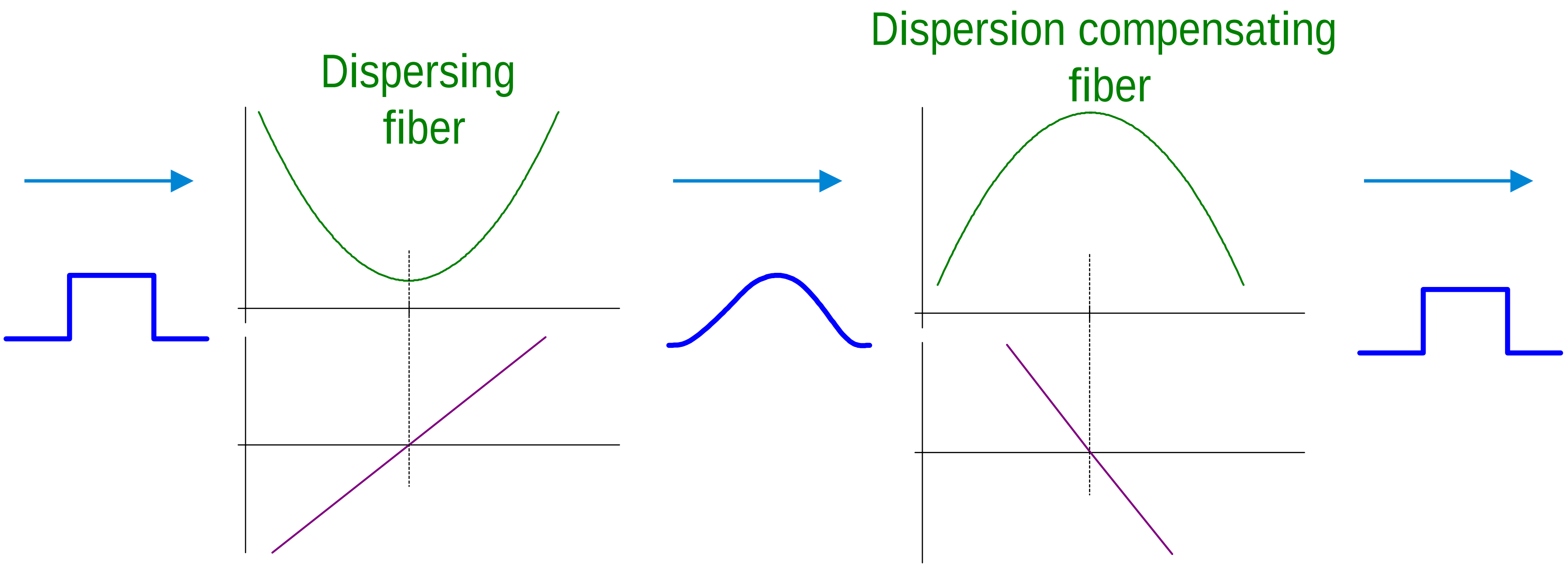
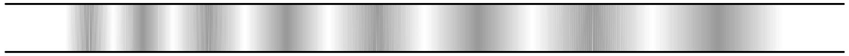
Chromatic Dispersion Compensation

Dispersion compensating fiber:

- Follow a segment of dispersing fiber with a segment of dispersion compensating fiber



There are also compensating components, e.g., the chirped FBG



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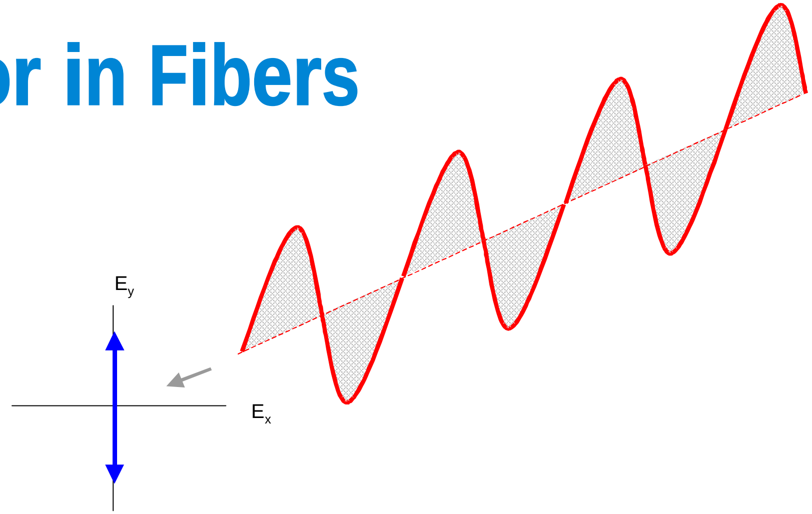
Polarization Behavior in Fibers

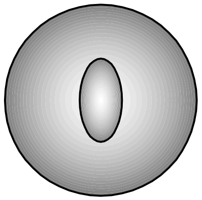
Recall: Light is polarized



- Polarization can change on every reflection
  - bends in the fiber change the polarization
- Index of refraction can vary with polarization
  - Crystal asymmetry and impurities $\longrightarrow n = n(\lambda, \mathbf{r})$
  - Fiber cross section asymmetry $\longrightarrow$

    boundary conditions differ with different orientation

    different polarizations have different boundary conditions



$\longrightarrow$ Polarization Mode Dispersion (PMD)

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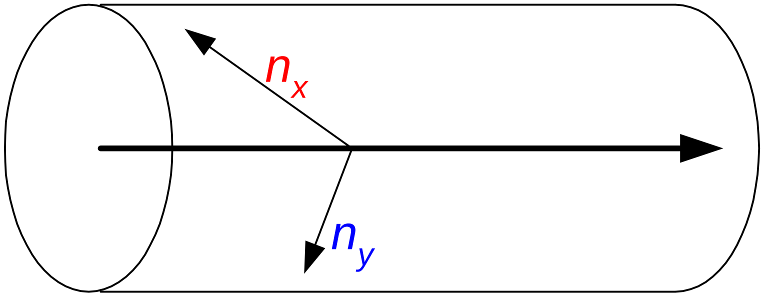
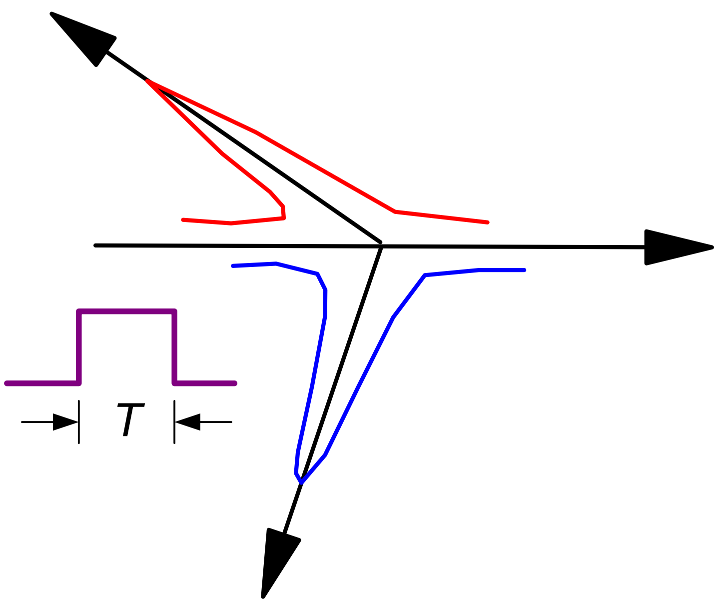
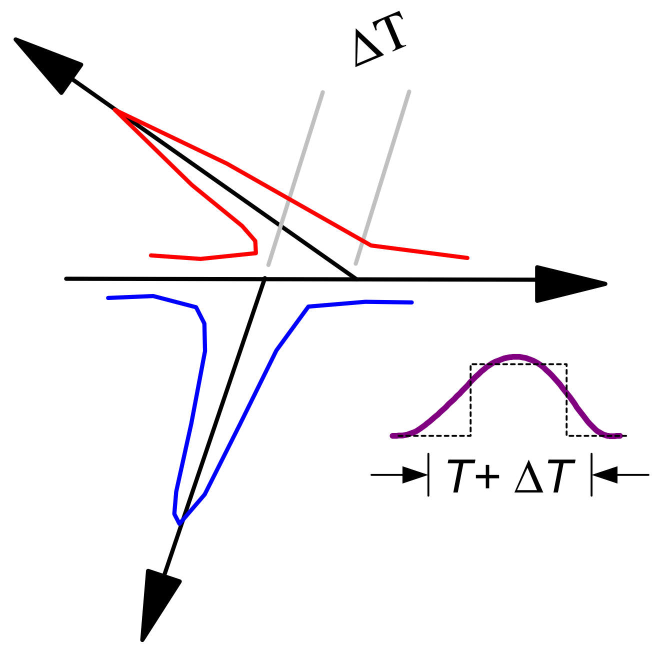
Principle States of Polarization

Fibers and components have distinct slow and fast polarization axis







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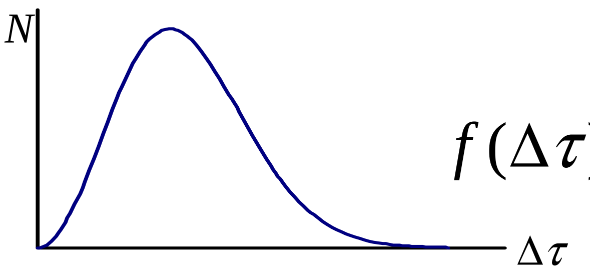
PMD in fibers is a Random Process

Small random variations in fiber geometry and media cause unpredictable changes in polarization states and principal states of polarization

- For fiber length much larger than the correlation length, ($L >> L_C$)

The Differential Group Delay, $\Delta\tau$, follows a Maxwellian distribution



$$f(\Delta\tau) = \sqrt{\frac{2}{\pi}} \cdot \frac{\Delta\tau^2}{\alpha^3} e^{-\frac{\Delta\tau^2}{2\alpha^2}}$$

Since $\Delta\tau$ contributions from different segments are independent, they combine to a total in quadrature (i.e., like the sides of a right triangle):

$\Delta\tau_{total} = \sqrt{\Delta\tau_1^2 + \Delta\tau_2^2 + \cdots + \Delta\tau_N^2}$ $\rightarrow$ The mean DGD, $\langle\Delta\tau\rangle$, increases with $\sqrt{L}$

For *components*, e.g., filters, ($L >> L_C$) PMD is deterministic

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Tolerable Levels of Polarization Mode Dispersion

PMD is a *random process* depending on temperature and geometry

PMD combines like the legs of a right triangle: $\Delta\tau_{Total} = \sqrt{\sum \Delta\tau_i^2}$

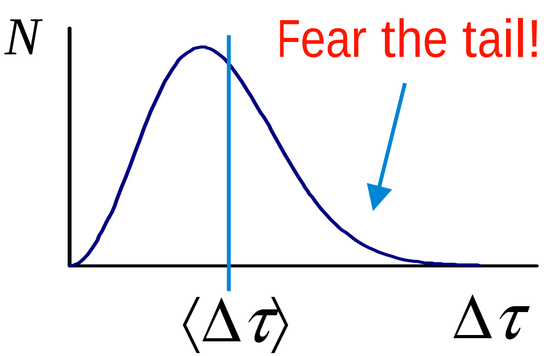
Define the 1st order PMD Coefficient: $P \equiv \frac{\langle \Delta\tau \rangle}{\sqrt{L}}$

- 1st order PMD is wavelength independent
- 2nd order PMDdepends on wavelength, but is very small

Typical good quality fiber: $\approx 0.2\ \text{ps}/\sqrt{\text{km}}$

Older, poor quality fiber: $\approx 1-2\ \text{ps}/\sqrt{\text{km}}$

Tolerate $\langle \Delta\tau_{Total} \rangle << 0.1/B$



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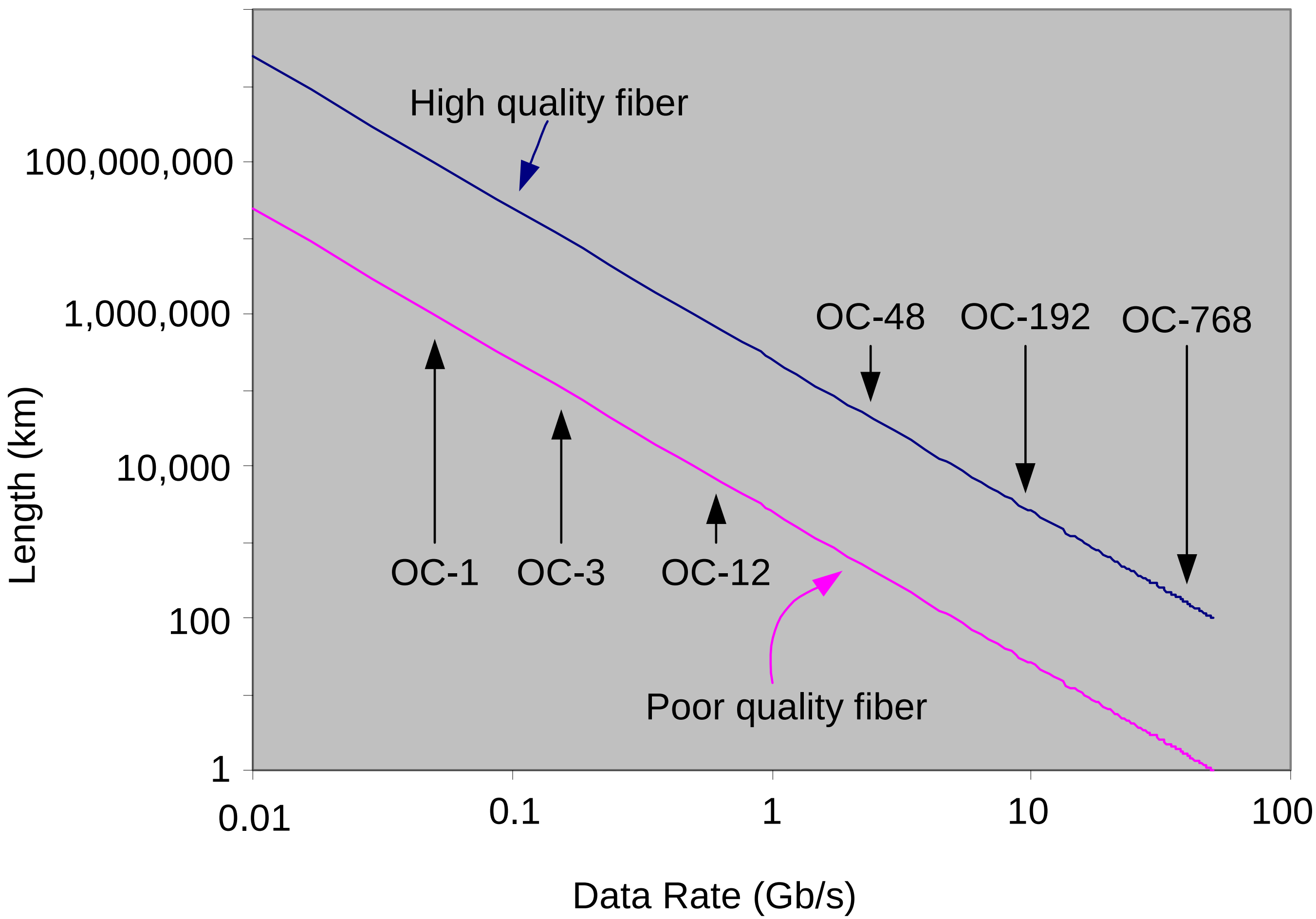
Maximum Fiber Length Tolerable to PMD



Require:
$\langle \Delta\tau \rangle < 0.1 / B$

high quality
$\Rightarrow$ 0.2 ps / √km
low quality
$\Rightarrow$ 2 ps / √km

The graph is for the average, $\langle \Delta\tau \rangle$

Fear the tail!

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Measuring Polarization Mode Dispersion

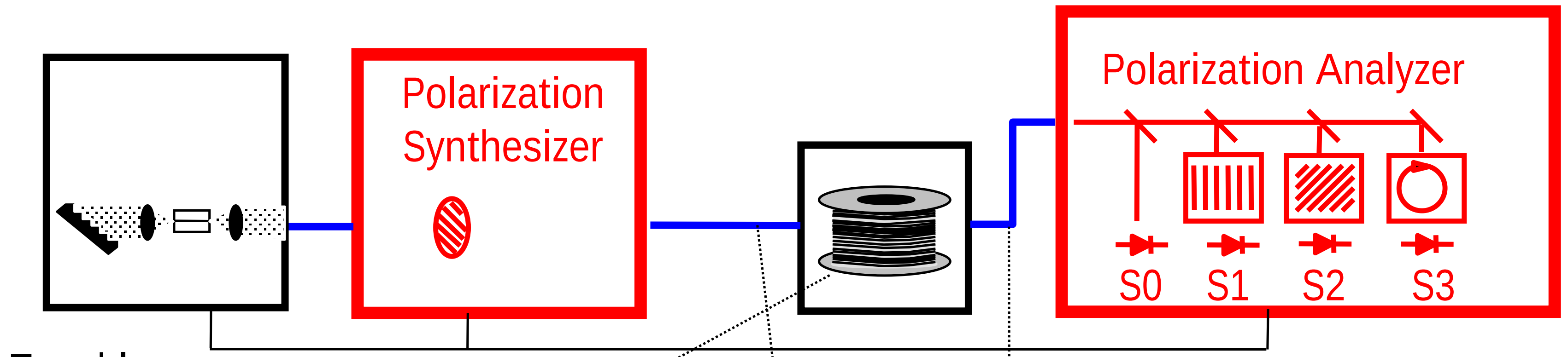
Jones Matrix Eigenanalysis method:

Measure DUT Transfer matrix

at three known polarizations

at a set of wavelengths, $\mathbf{J}(\lambda)$: $\mathbf{J}(\lambda)\ \mathbf{P}_{in} = \mathbf{P}_{out}$

Extract $\Delta T(\lambda)$ by diagonalizing $\mathbf{J}(\lambda)$



Transfer Matrix

$$\begin{bmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} O_1 \\ O_2 \end{bmatrix}$$

$$\mathbf{J}(\lambda) \quad \mathbf{P}_{in} = \mathbf{P}_{out}$$

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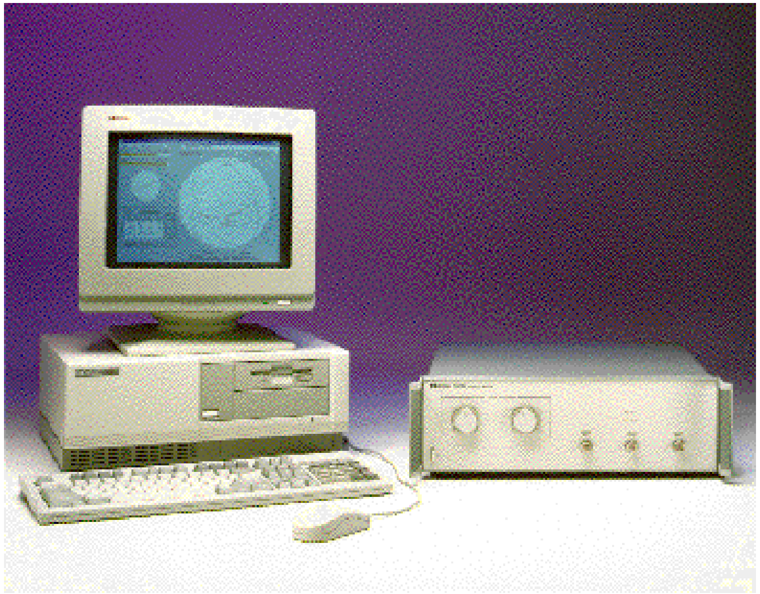
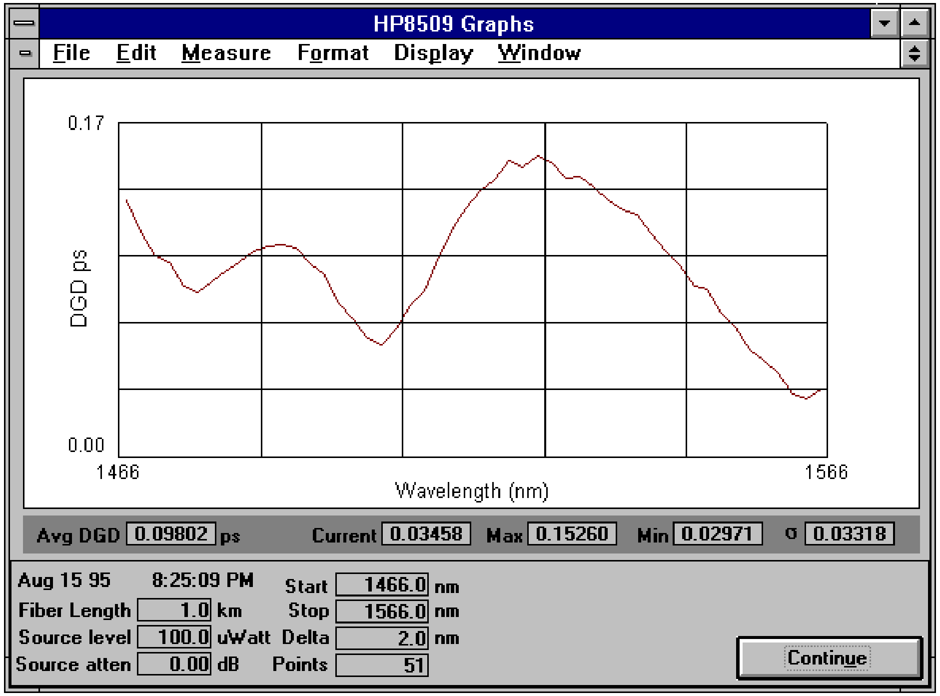
Jones Matrix Eigenanalysis (JME) Result





Cannot compensate PMD with a passive device

- Must have feedback to monitor PMD and actively compensate

Also measure PMD with Modulation phase shift and interferometric techniques

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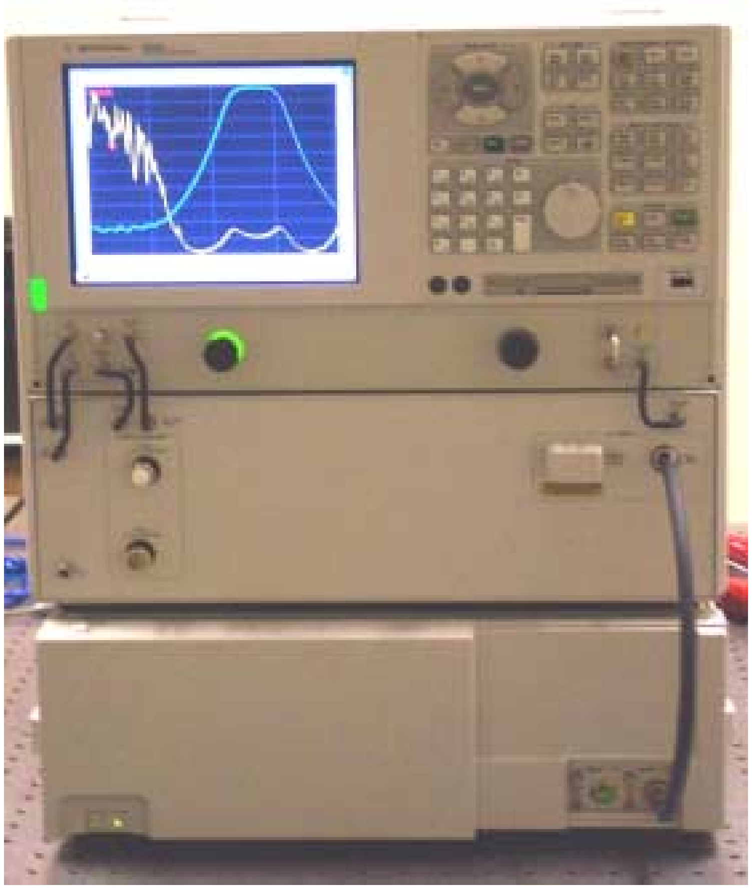
Complete Dispersion Test Set Agilent 86038

Modulation Phase Shift Method

Single connection measurement of Chromatic Dispersion and Polarization Mode Dispersion

Excellent for

- Broadband device characterization
  e.g., spools of fiber
- Narrowband device characterization
  e.g., filters, mux/demux, etc.



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All Parameter Test Set
Agilent 81910

Part of the Agilent Lightwave Measurement System (816x)

- Swept insertion loss, return loss, polarization dependent loss
- Chromatic and Polarization Mode Dispersion - interferometric technique
  both insertion *and* reflection

Optimized for narrow-band components (e.g., filters, mux/demux, isolators, etc.)

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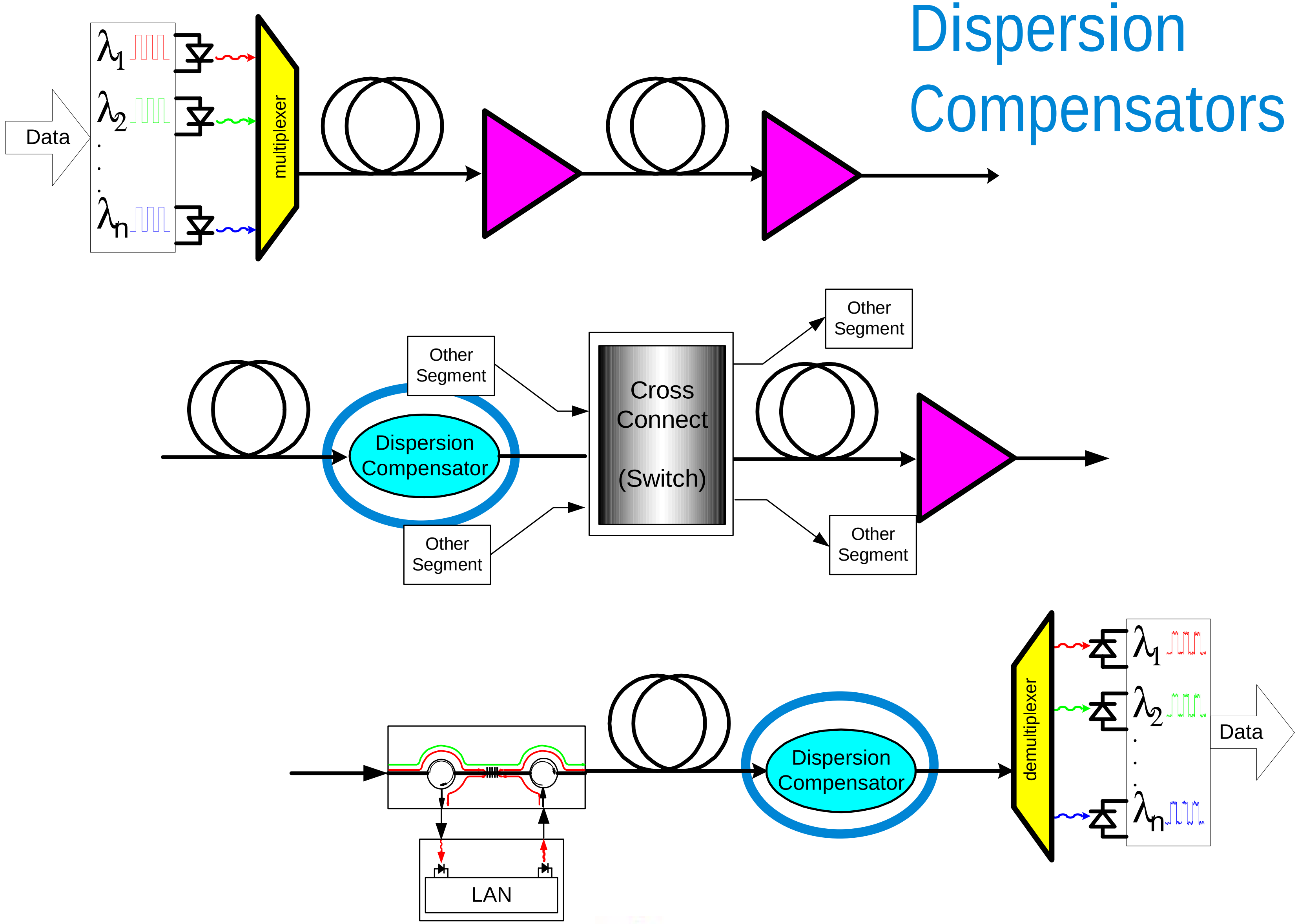
Optical Networking - The DWDM Forest

Dispersion Compensators



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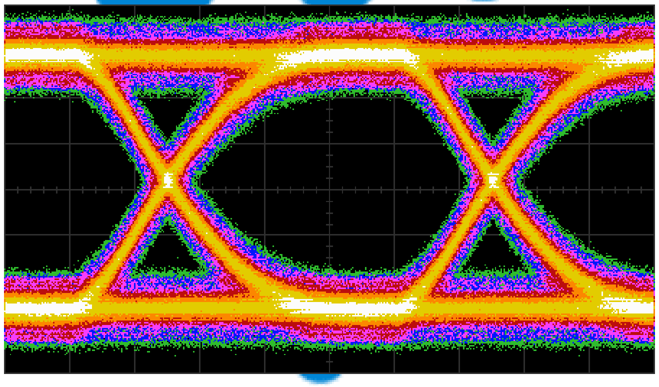
Characterizing the System

Optical Time Domain Reflectometry
Noise
Bit Error Rate Measurments
Eye diagram analysis
  - Extinction ratio
  - Jitter
  - Mask tests



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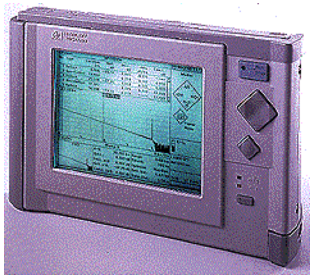
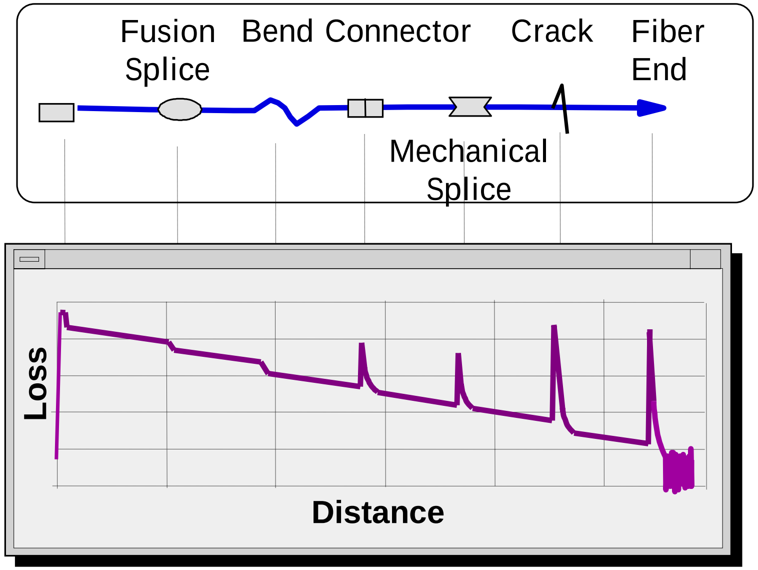
Optical Time Domain Reflectometry:
Link Characterization



Optical Time-Domain Reflectometer (with Power Meter, Visual Fault Finder, and Laser Source)

- "Optical radar"
- Measures loss vs. distance
- 10 m - 200 km range
- Key tool in installation and maintenance
- MM and SM modules



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Bit Error Ratio

Bit error ratio,

BER = # of bits received in error / # of bits received

Gives a good indication of the performance of a component, link or entire network

Typical BER spec: 1.0×10^{-12}

Tradeoff between

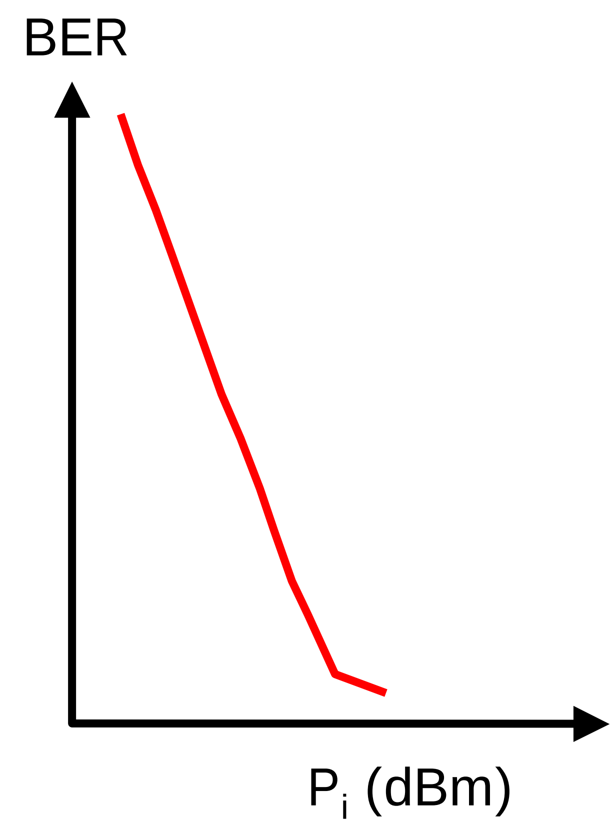
minimum input power and

acceptable bit error rate

Larger the power

less effect of dispersion,

less noise from optical amplifiers, etc.



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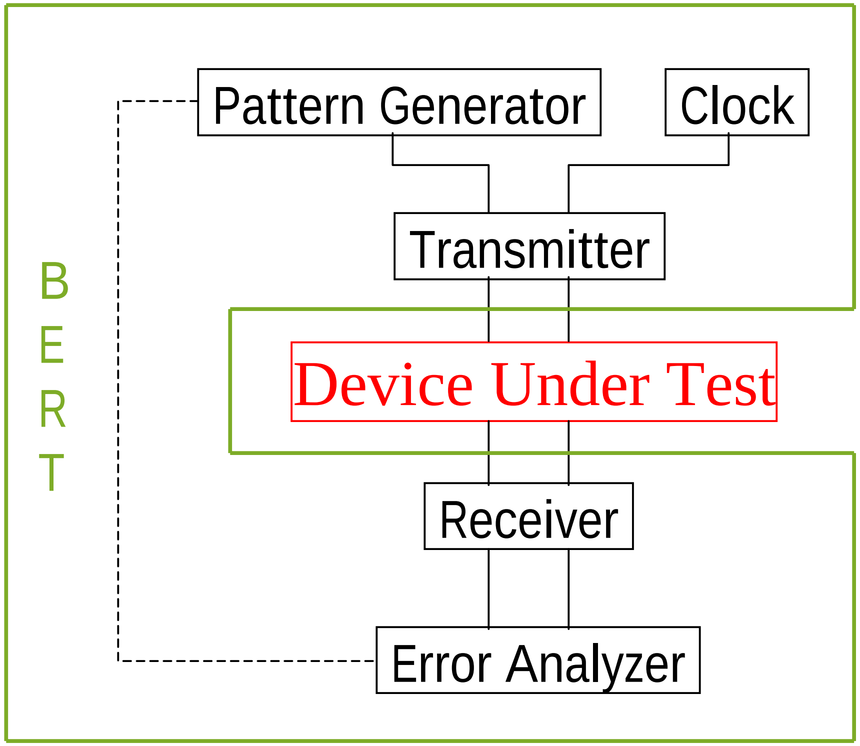
Measurement of Bit Error Rates:
The BERT



- Pseudo Random Binary Sequences provide known patterns that simulate random data
- Devices can be tested for BER under various stressful conditions such as clock-data delays, long runs of 1's or 0's, low power levels etc.

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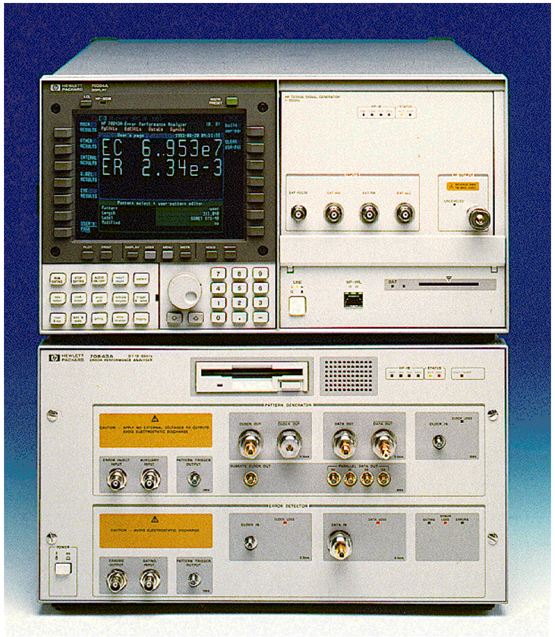
BERTs



71612 HSBERT (up to 12.5 Gb/s)

81250 ParBERT (up to 43 Gb/s)

86130 Bitalyzer (up to 3.6 Gb/s)

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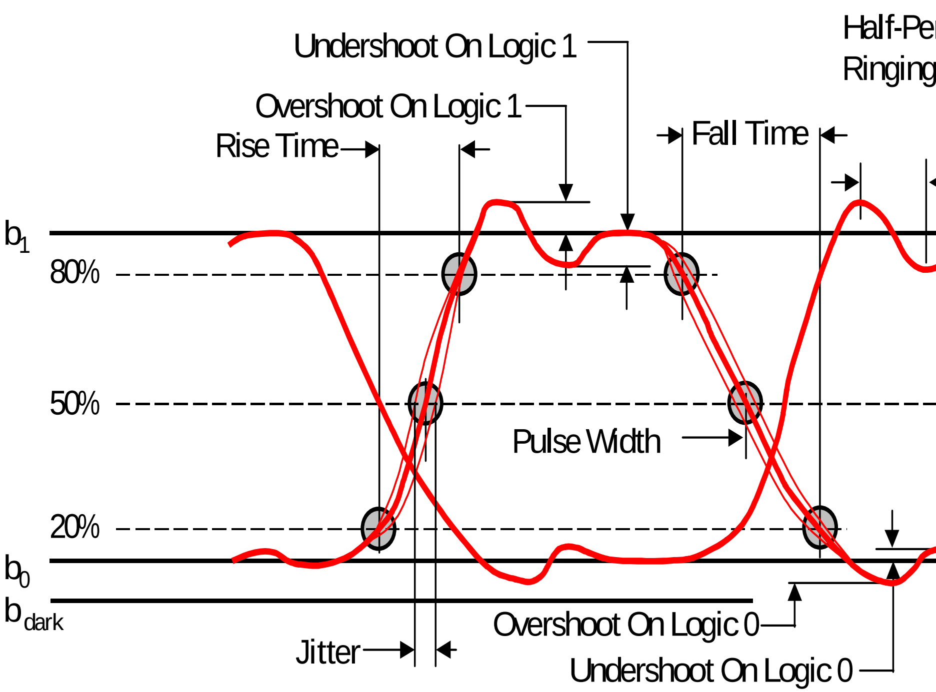
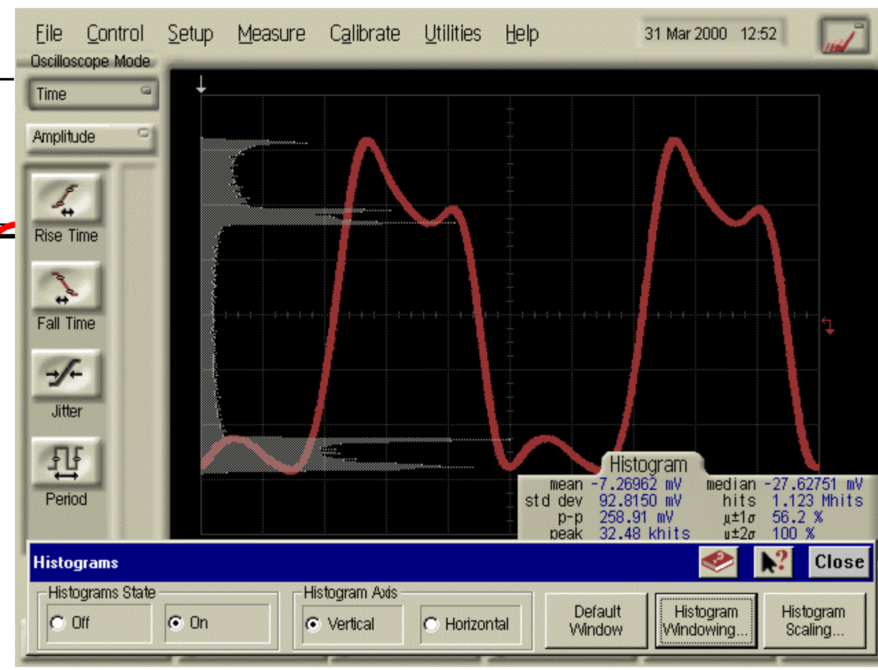
Pulse Parameters





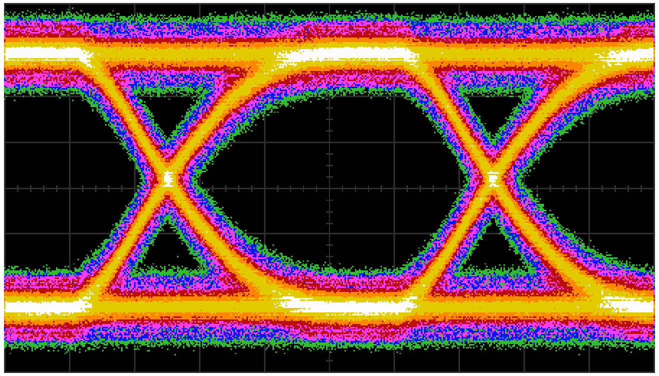
Eye Diagram Analysis

Standard compliance verification
(SONET / SDH, G-Ethernet, Fibre Channel, ..)

- Mask
- Pulse Parameters
- Extinction Ratio

Signal capture of patterns causing bit errors

- Eye-line measurements



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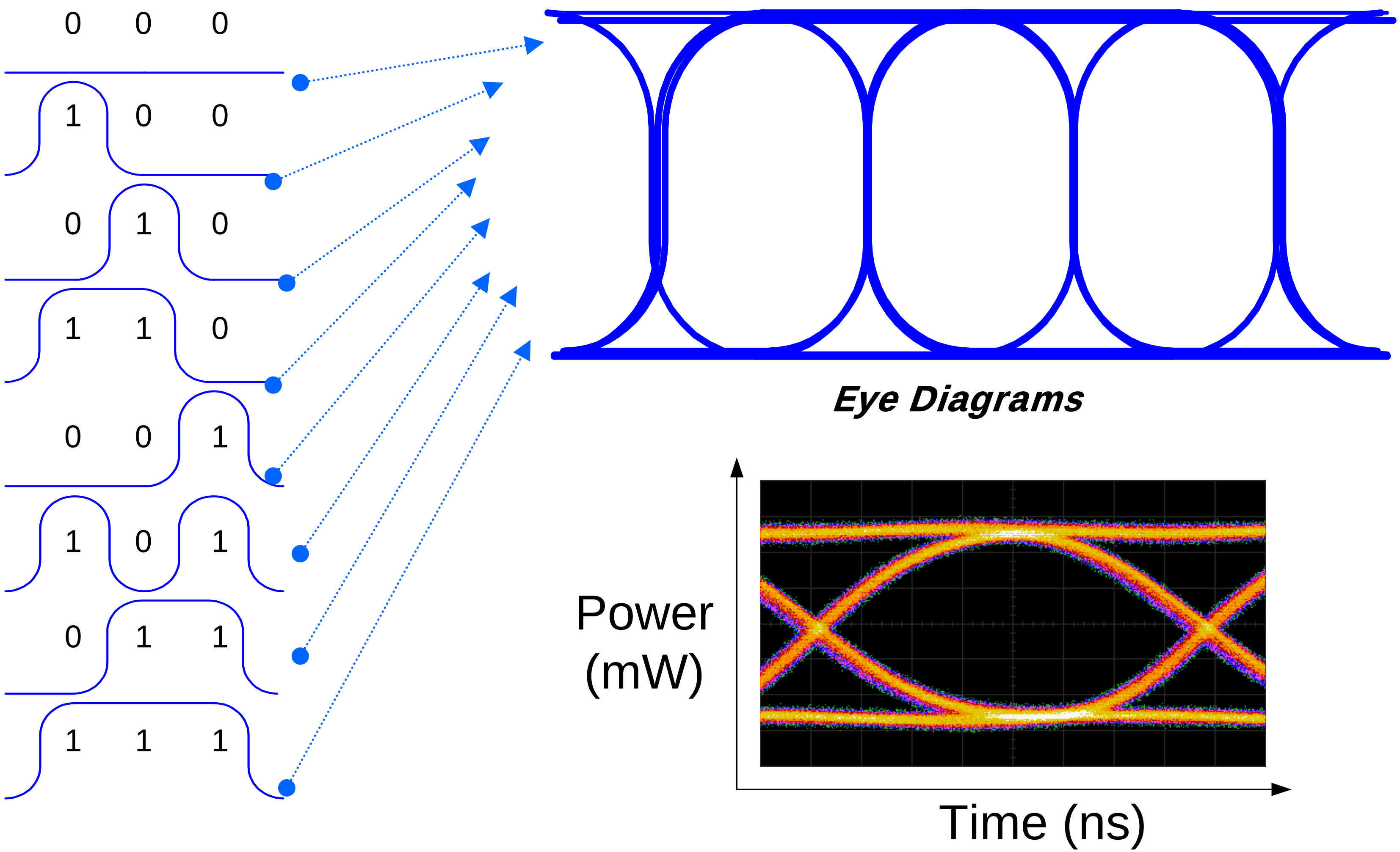
The Eye Diagram



Superimposed Bit Sequences

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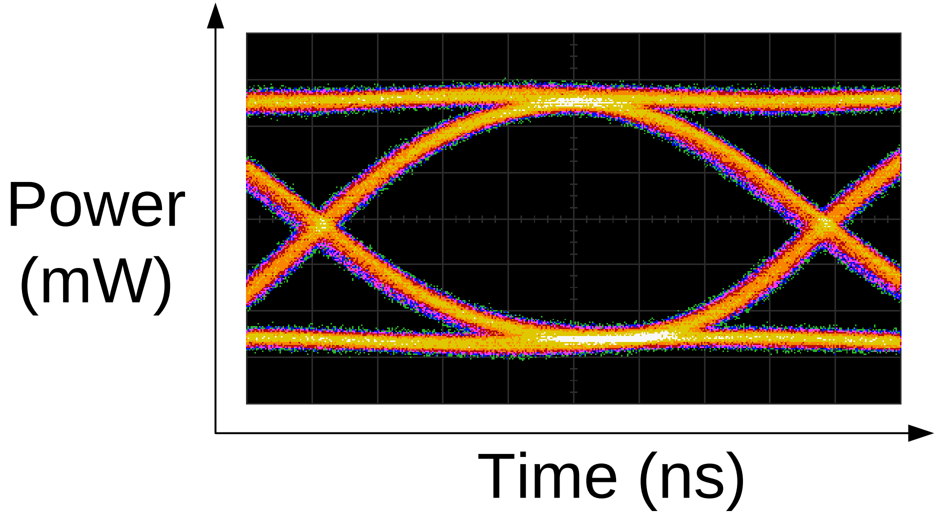
Digital Communications Analyzer
A sampling oscilloscope for very high rates

- Logic power levels, P_0 and P_1
- Average Power, $P_{avg} = \frac{1}{2}(P_{1\text{-level}} + P_{0\text{-level}})$
- Extinction Ratio, $E = \dfrac{P_{1\text{-level}}}{P_{0\text{-level}}}$
- Pulse width/height
- Rise/fall times
- Undershoot/overshoot
- Ringing frequency



Superimposed Bit Sequences

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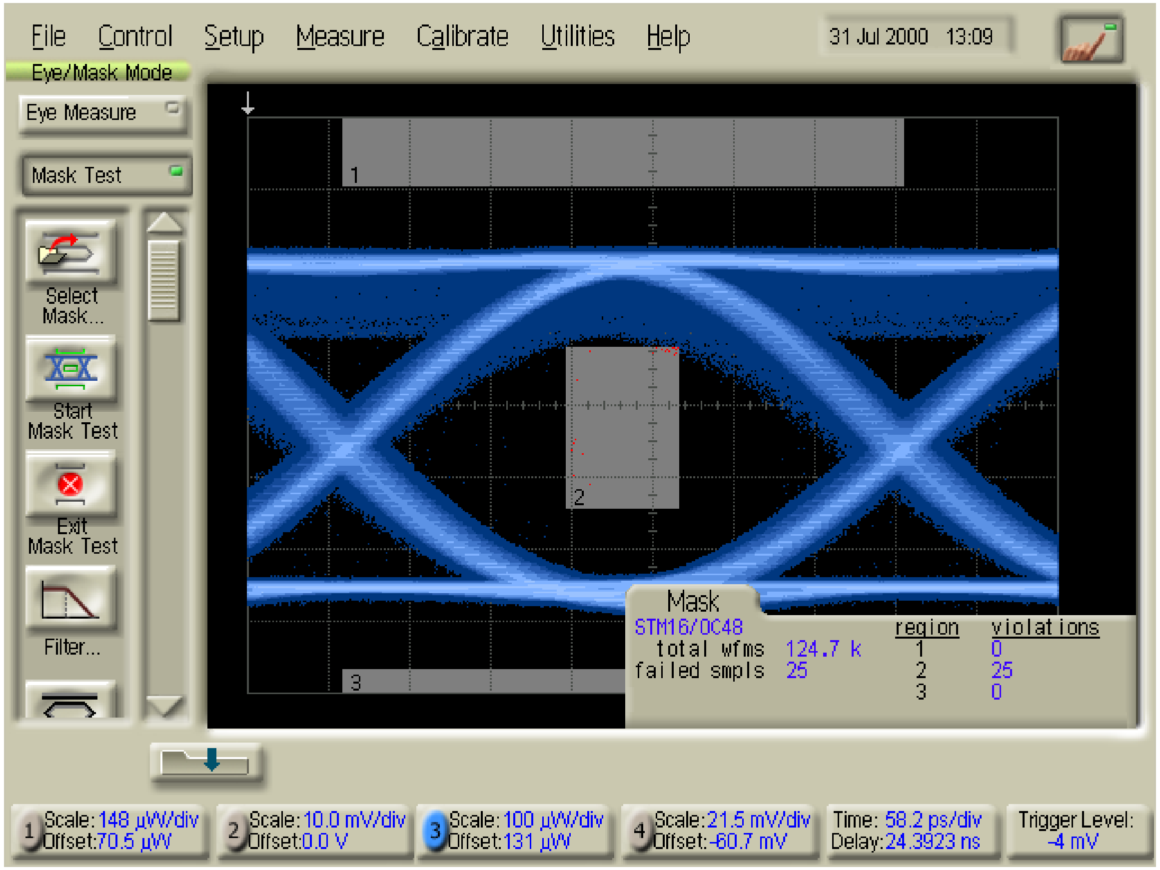
Mask Tests
On the DCA

Defined masks allow conformance testing to standards

Mask ‘hits’ highlight problems with many signal parameters



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The Agilent 86100
Digital Communications Analyzer (DCA)

20 GHz - 50 GHz - 500 GHz bandwidth

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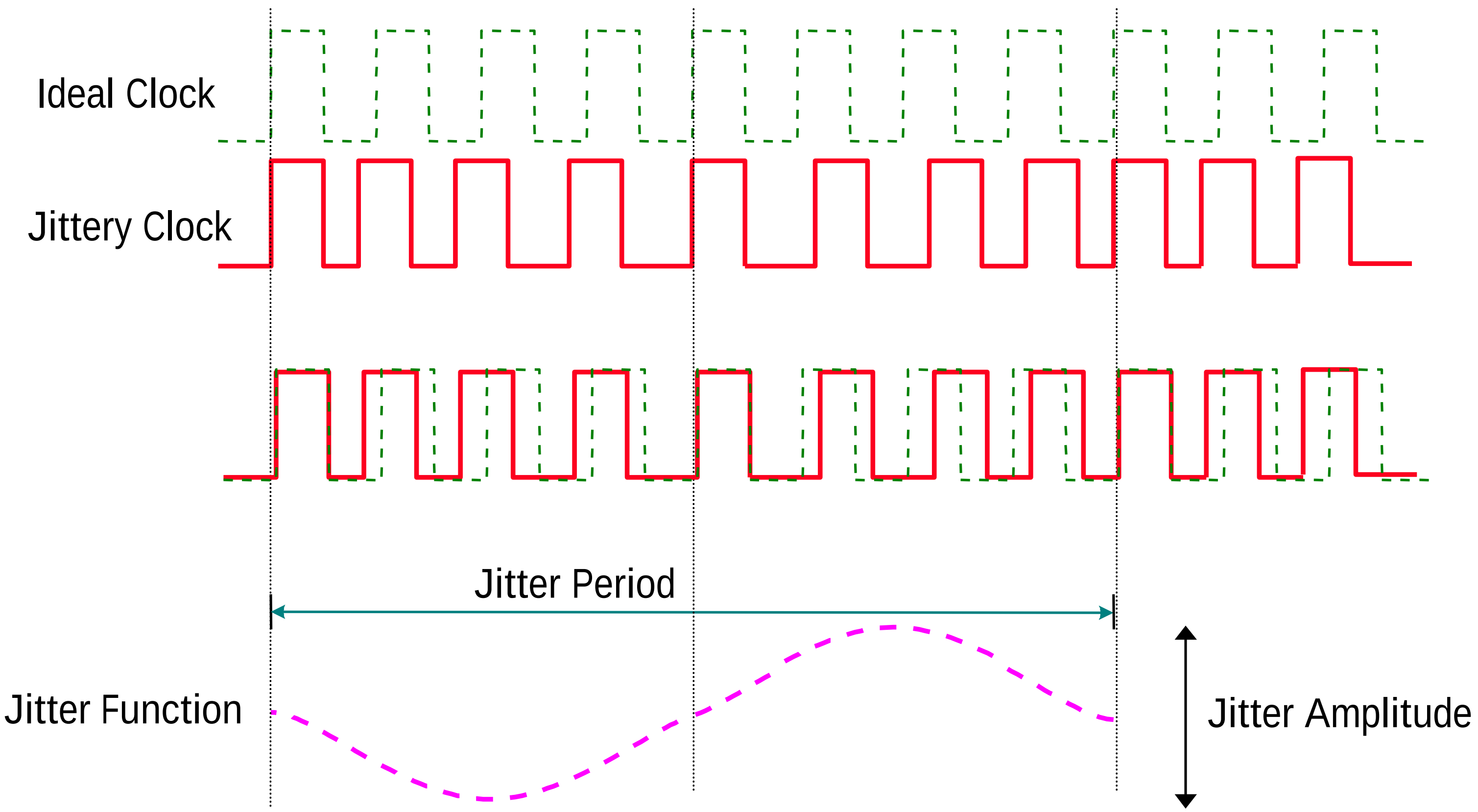
Jitter

The short-term, (>10Hz), variations in the time base of a signal



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Characterizing Jitter

Jitter can be measured either as RMS variations or peak-peak

- Jitter Tolerance = Amplitude of applied sinusoidal jitter to the device under test resulting in a certain Bit Error Rate
- Jitter Transfer = Ratio of the output jitter amplitude to the amplitude of applied sinusoidal jitter
- Jitter Generation/Intrinsic Jitter = Jitter produced by the device under test

Random Jitter - sum of small random processes resulting in jitter

Deterministic jitter - data dependent jitter, duty cycle distortion, etc resulting in jitter

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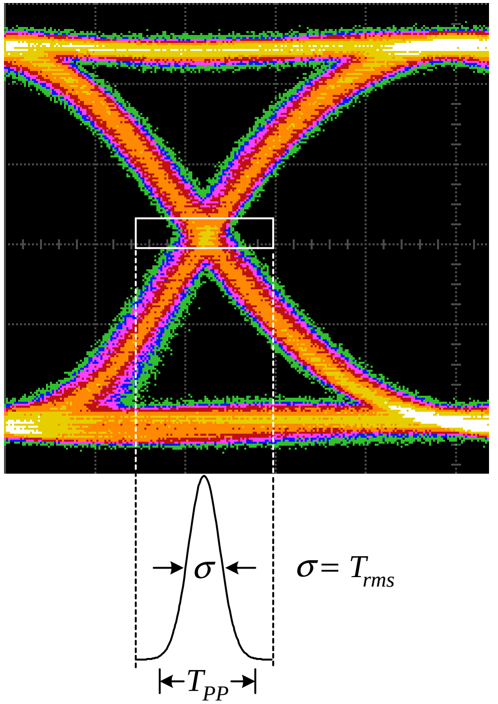
Measurement of Jitter
The Agilent 71501 Jitter Analysis System



Statistical analysis on a DCA
build a histogram window around samples

- Only measures jitter generation
- Limited to 1 UI peak-peak
- No jitter spectrum info

Use a phase-detector to compare phase of jittery clock with ideal clock

- Usually used for fixed rates

Take FFT's of time-samples

- Frequency agile
- Extract eye-diagram information

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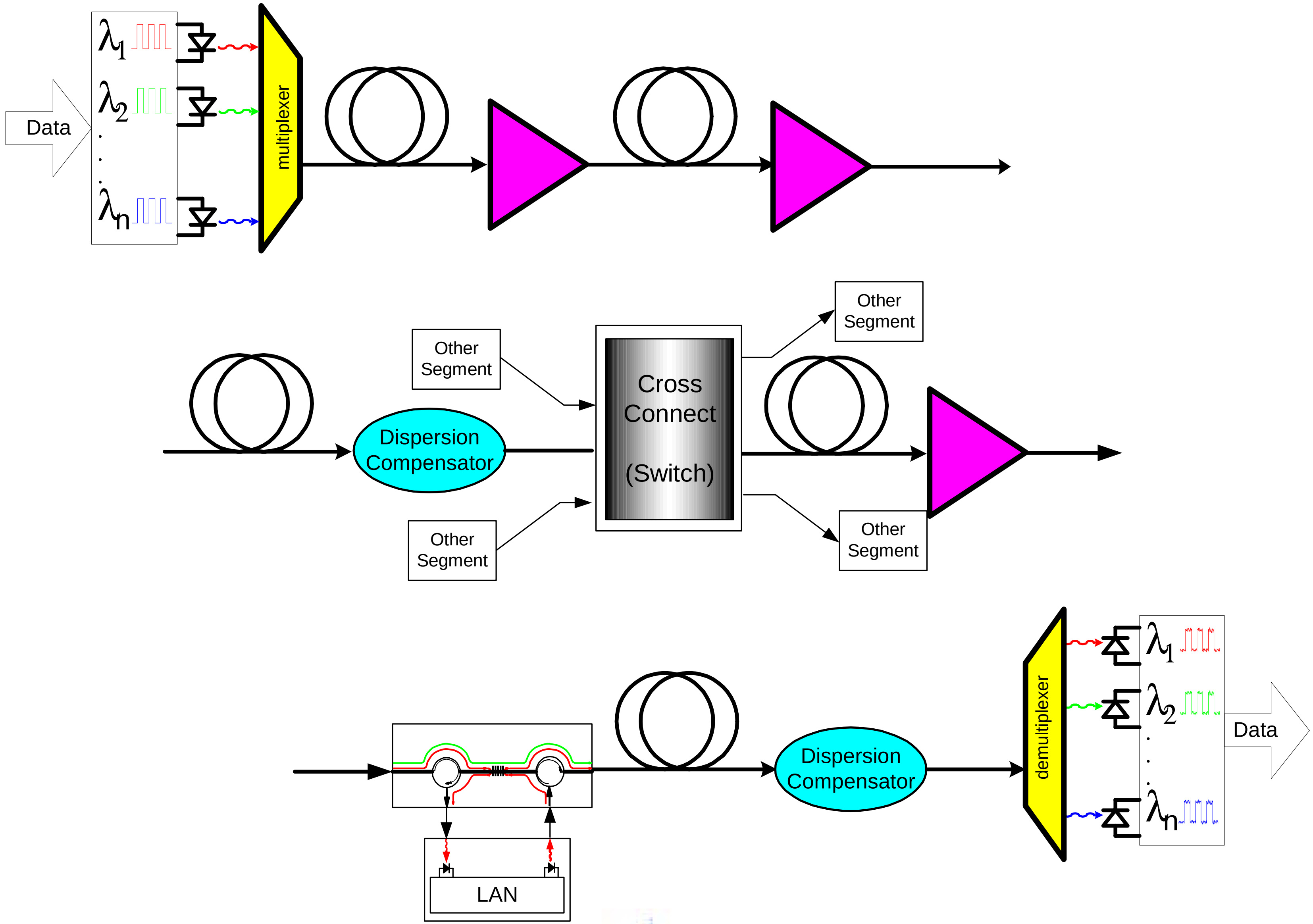
Optical Networking - The DWDM Forest



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Conclusion

A wealth of technologies have been developed for high speed networking based on a few simple physical phenomena:

- Reflection and refraction (geometric optics) ⇒
  Optic fibers
- Interference ⇒
  Optical Spectrum Analysis
  high resolution distance measurements
  Filters, mux/demux, isolators, et cetera
  external modulators
- Atomic transitions and Raman scattering ⇒
  LEDs, LASERs
  Light detectors - PIN diodes, APDs
  Optical Amplifiers
- Index of Refraction ⇒
  Chromatic and Polarization Mode Dispersion

Agilent develops technology that makes dreams real!

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s Agilent Technologies' Lightwave Training and Services

- Training

Fast Food Technician → Optical Engineering Nobel Laureate

Understanding Optical Networking

Understanding Lightwave Technology

Understanding DWDM

Understanding Optical Passive Device Characterization

Understanding Optical Transmitters and Receivers and Their Characterization

Optical Spectrum Analysis/OSA User's Course

Characterizing Polarization Effects

Eye Diagram Analysis

TDR in High-Speed Digital Design

Bit Error Rate Analysis

Digital Communications Analyzer User's Course

Design-to-Fit Training

- Consulting and Customizing

Test and Measurement Automation

Brilliant and talented Applications Engineers and Scientists at your every whim. . .

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