

**ECE 536 – Integrated Optics and Optoelectronics**  
**Lecture 1 – January 18, 2022**

**Spring 2022**

Tu-Th 11:00am-12:20pm

Prof. Umberto Ravaioli

ECE Department, University of Illinois

# Lecture 1 Outline

- Course Purpose and Objectives
- Course Schedule
- Expectations and Policies
- Motivation
- Brief review of EM concepts

- Material posted at:

<https://ursemiconductors.web.illinois.edu/ECE536>

# Textbooks

## Primary Text:

S.L. Chuang, “Physics of Photonic Devices,” Wiley, 2<sup>nd</sup> Edition (2009)

<https://www.wiley.com/en-us/Physics+of+Photonic+Devices%2C+2nd+Edition-p-9780470293195>

## Supplementary Text:

L.A. Coldren, S.W. Corzine, M.L. Mašanović, “Diode Lasers and Photonic Integrated Circuits,” Wiley, 2<sup>nd</sup> Edition (2012)

[You can download pdf of this book from our library](#)

Many books on lasers and integrated optics are available for download from the digital library. I will suggest some during the course. For example:

R.G. Hunsperger, “Integrated Optics,” Springer, 6<sup>th</sup> Edition (2009)

M. Yamada, “Theory of Semiconductor Lasers,” Springer (2014)

## ECE 536 – SPRING 2022

Meeting Time 11:00am-12:20pm (synchronous)

### Lectures Calendar (List of topics is tentative and subject to change)

**January 18 Tuesday Lecture 1**

Course overview, Introduction to Optoelectronics & Communication, Refresher of Maxwell's equations

**January 20 Thursday Lecture 2**

Semiconductor electronics – Review of pertinent concepts

**January 25 Tuesday Lecture 3**

Semiconductor electronics – Review of pertinent concepts

**January 27 Thursday Lecture 4**

Basic quantum mechanics, Quantum wells

**February 1 Tuesday Lecture 5**

Time-dependent perturbation theory, Fermi's Golden Rule

**February 3 Thursday Lecture 6 Homework#1 due**

Symmetric Optical Waveguides, Dispersion relations

**February 8 Tuesday Lecture 7**

Optical transitions using Fermi's Golden Rule

**February 10 Thursday Lecture 8 Homework#2 due**

Interband absorption and gain of bulk semiconductors and quantum wells

**February 15 Tuesday Lecture 9**

Quantum dots and wires, intersubband absorption

**February 17 Thursday Lecture 10 Homework#3 due**

Double-heterojunction semiconductor lasers

**February 22 Tuesday Lecture 11**

Waveguiding in material with gain or loss, Gain-guided and Index-guided Lasers

**February 24 Thursday Lecture 12 Homework#4 due**

Quantum-well Lasers, Scaling laws, Semiconductor optical amplifiers

**March 1 Tuesday Lecture 13 (This week - Selection of final project topics)**

Strain effects on band structures, Strained quantum well lasers

**March 3 Thursday Lecture 14 Homework#5 due**

Strained quantum dot lasers, Direct modulation of semiconductor lasers

**March 8 Tuesday Lecture 15**

Distributed feedback structures and lasers

**March 10 Thursday Lecture 16 Homework#6 due**

Vertical cavity surface emitting lasers (VCSEL's)

**SPRING BREAK March 12-20**

<b>March 22</b>	<b>Tuesday</b>	<b>Lecture 17</b>	
Chirped Gratings, Tunable lasers			
<b>March 24</b>	<b>Thursday</b>	<b>Lecture 18</b>	
Coupled mode theory, Waveguide couplers, MMIs, AWGs			
<b>March 29</b>	<b>Tuesday</b>	<b>Lecture 19</b>	
Reciprocal and non-reciprocal polarization rotators			
<b>March 31</b>	<b>Thursday</b>	<b>Lecture 20</b>	<b>Homework #7 due</b>
Franz-Keldysh and exciton effects			
<b>April 5</b>	<b>Tuesday</b>	<b>Lecture 21</b>	
Quantum-confined Stark effect, EA modulators, EMLs, Mach-Zender modulators			
<b>April 7</b>	<b>Thursday</b>	<b>Lecture 22</b>	<b>Homework #8 due</b>
Photoconductors			
<b>April 12</b>	<b>Tuesday</b>	<b>Lecture 23</b>	
p-n junction photodiodes, p-i-n photodiodes			
<b>April 14</b>	<b>Thursday</b>	<b>Lecture 24</b>	
Avalanche photodiodes, intersubband quantum-well photodetectors			
<b>April 19</b>	<b>Tuesday</b>	<b>Lecture 25</b>	<b>Homework #9 due</b>
Special topics or catch up			
<b>April 21</b>	<b>Thursday</b>	<b>Lecture 26</b>	
Special topics or catch up			
<b>April 26</b>	<b>Tuesday</b>	<b>Lecture 27</b>	
Special topics			
<b>April 28</b>	<b>Thursday</b>	<b>Lecture 28</b>	
Special topics			
<b>May 3</b>	<b>Tuesday</b>	<b>Lecture 29</b>	<b>Last Class</b>
Special topics/Class discussion/Wrap-up			
<b>May 5</b>	<b>Thursday</b>	<b>Reading Day</b>	
<b>May 12</b>	<b>Thursday</b>	<b>8:00-11:00am</b>	<b>FINAL EXAM (consists of Final Project presentations) TAKE-HOME Exam due</b>

# Assignments/Grading

I am planning for activities that maximize learning and exploration but do not add to the stress of the ongoing pandemic

- 9 HW assignments (30%)
- A substantial Term Project (exploring in depth a topic of interest or developing a computational application) including final presentation (20%)
- A substantial Term Project Report (20%)
- A take-home exam assignment probing your understanding of the material covered (20%)
- Engagement, participation, punctuality (10%)

# Computational component

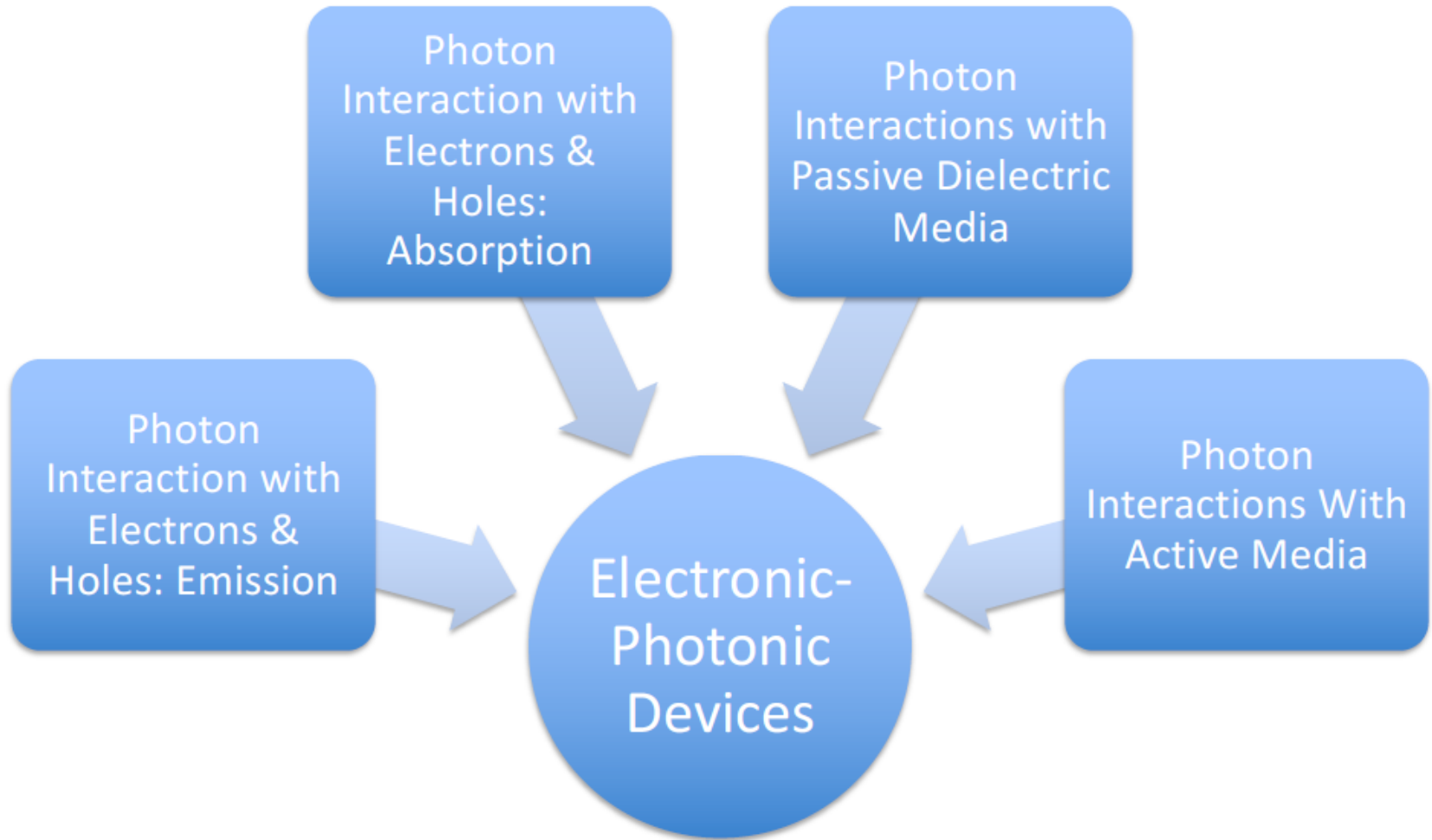
- Students have different backgrounds and exposure to computing
- Some discussions on simulations in photonics and optoelectronics will be introduced to complement the lectures. This may create the opportunity for some optional readings, investigations, term projects, etc.
- Except for calculations needed for homework, advanced computing will not be mandatory and much will depend on the interest expressed by the class.
- Activities that may complement your area of research can also be considered.

# Other Policies and Expectations

- Homework submission is personal (exercise social distance...).
- You can consult and research any available academic source but you should always provide appropriate citations in your HW, project, final presentation, etc.
- Maturity is expected of a graduate student in all circumstances.
- Where applicable, general university policies on academic affairs will be used.
- Always bring up any issues and discuss with me as soon as a problem arise.



# Device Application of Light-Matter Interactions



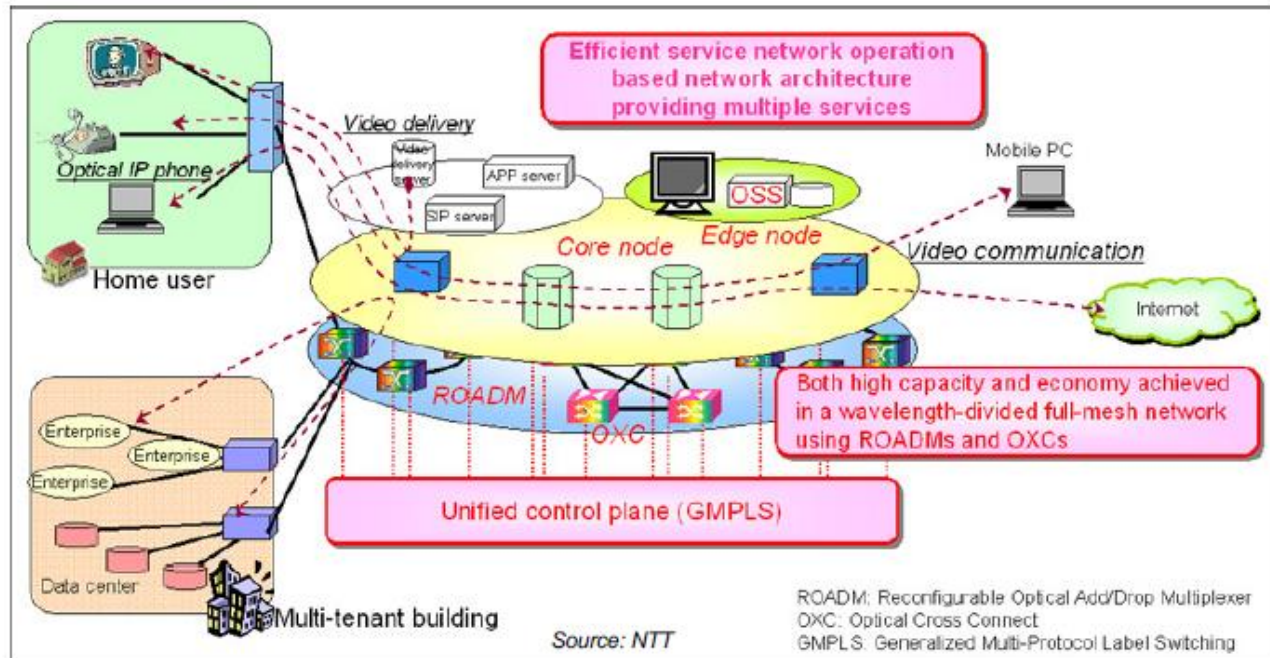
# Motivation

Photonic Devices, and Photonic  
Systems for Optical Data  
Communication, LEDs

# Applications of Integrated Optics

- Long-Haul Telecommunications
- Optical Links in Data Centers
- Optical Links in Enterprise Networks
- Optical Links in Storage Area Networks
- 3-D Imaging (Smart Phone)
- LIDAR (Self-Driving Cars)

# Elements of an Optical Network



## Electronics

- CDR (Clock and Data Recovery)
- SERDES (Serializer/Deserializer)
- Protocol Conversion
- Framers
- Switching/Routing

## Optics

- Lasers (Fixed  $\lambda$  and Tunable  $\lambda$ )
- Modulators
- Optical Mux / DeMux
- Switches (Cross Connect, ROADM, etc.)
- Amplifiers/Attenuators
- Dispersion Compensation Modules
- Detectors

**1 Petabyte**  
1,000 Terabytes or  
250,000 DVDs

**480 Terabytes**

A digital library of all of the world's catalogued books in all languages

**100 Petabytes**

The amount of data produced in a single minute by the new particle collider at CERN

**1 Exabyte**  
1,000 Petabytes or  
250 million DVDs

**5 Exabytes**

A text transcript of all words ever spoken †

**100 Exabytes**

A video recording of all the meetings that took place last year across the world

**400 Exabytes**

The amount of data that will cross the Internet in 2012 alone

**1 Zettabyte**  
1,000 Exabytes or  
250 billion DVDs

**1 Zettabyte**

The amount of data that has traversed the Internet since its creation

**300 Zettabytes**

The amount of visual information conveyed from the eyes to the brain of the entire human race in a single year ‡

**1 Yottabyte**  
1,000 Zettabytes or  
250 trillion DVDs

**20 Yottabytes**

A holographic snapshot of the earth's surface

# The Scale of “Big Data”

† Roy Williams, "Data Powers of Ten," 2000

‡ Based on a 2006 estimate by the University of Pennsylvania School of Medicine that the retina transmits information to the brain at 10 Mbps.



## By The Numbers

Projecting the future of digital transformation (2018–2023)



## Global

### Internet users by 2023



66%

of the population will be using the Internet  
*up from 51% in 2018*

### Mobile devices/connections by 2023



1.6

networked devices and connections per person  
*up from 1.2 in 2018*

### Total devices/connections by 2023



3.6

networked devices and connections per person  
*up from 2.4 in 2018*

### Fixed speed by 2023



110 Mbps

average broadband speed  
*up from 46 Mbps in 2018*

### Wi-Fi speed by 2023



92 Mbps

average Wi-Fi speed  
*up from 30 Mbps in 2018*

### Mobile (cell) speed by 2023



44 Mbps

average mobile speed  
*up from 13 Mbps in 2018*

**Full report:**

<https://www.cisco.com/c/en/us/solutions/collateral/executive-perspectives/annual-internet-report/white-paper-c11-741490.html>



# Optical Links in Data Centers and Supercomputers



Supercomputer Optical Interconnects

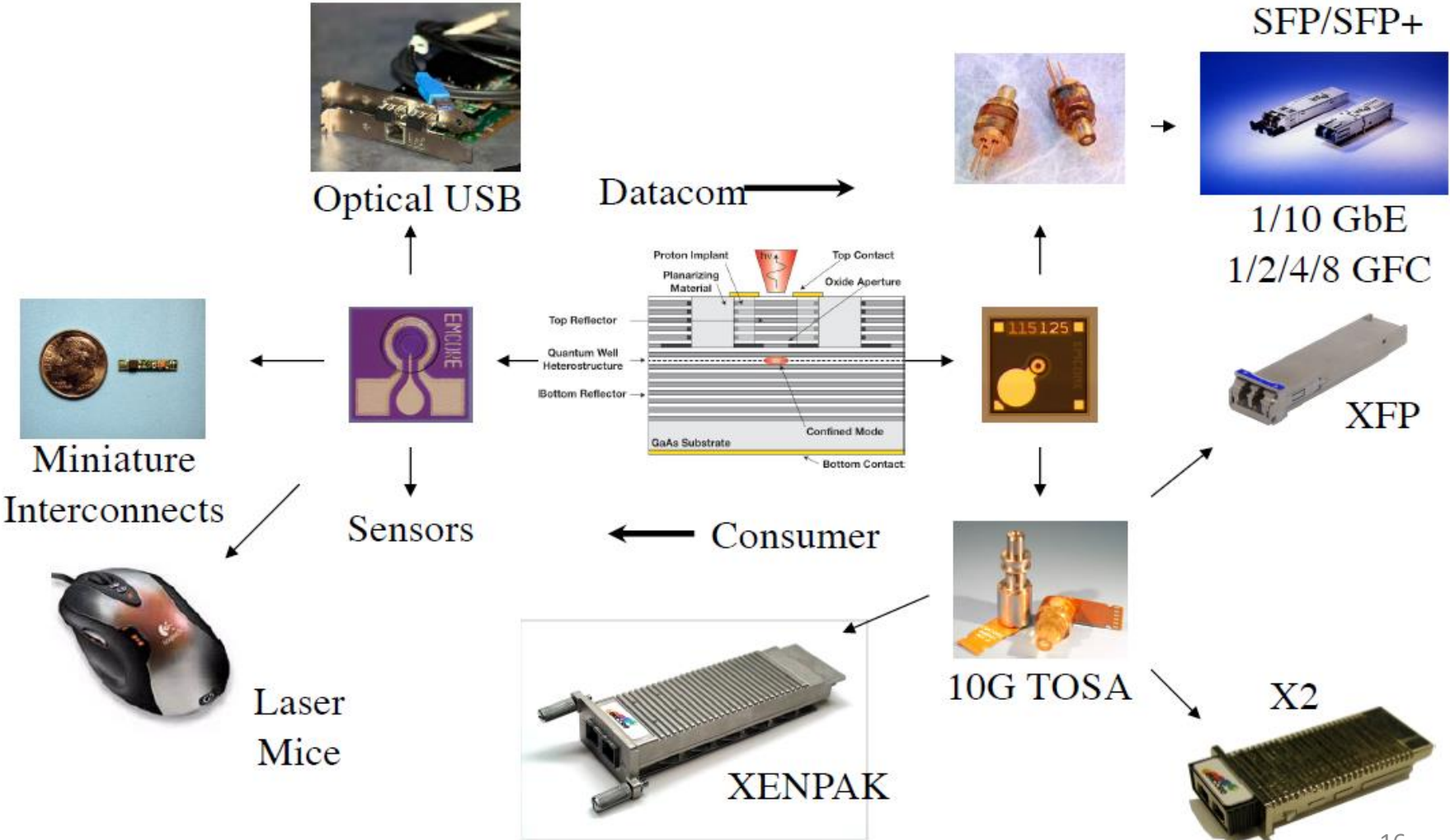


Server Room

Data Center

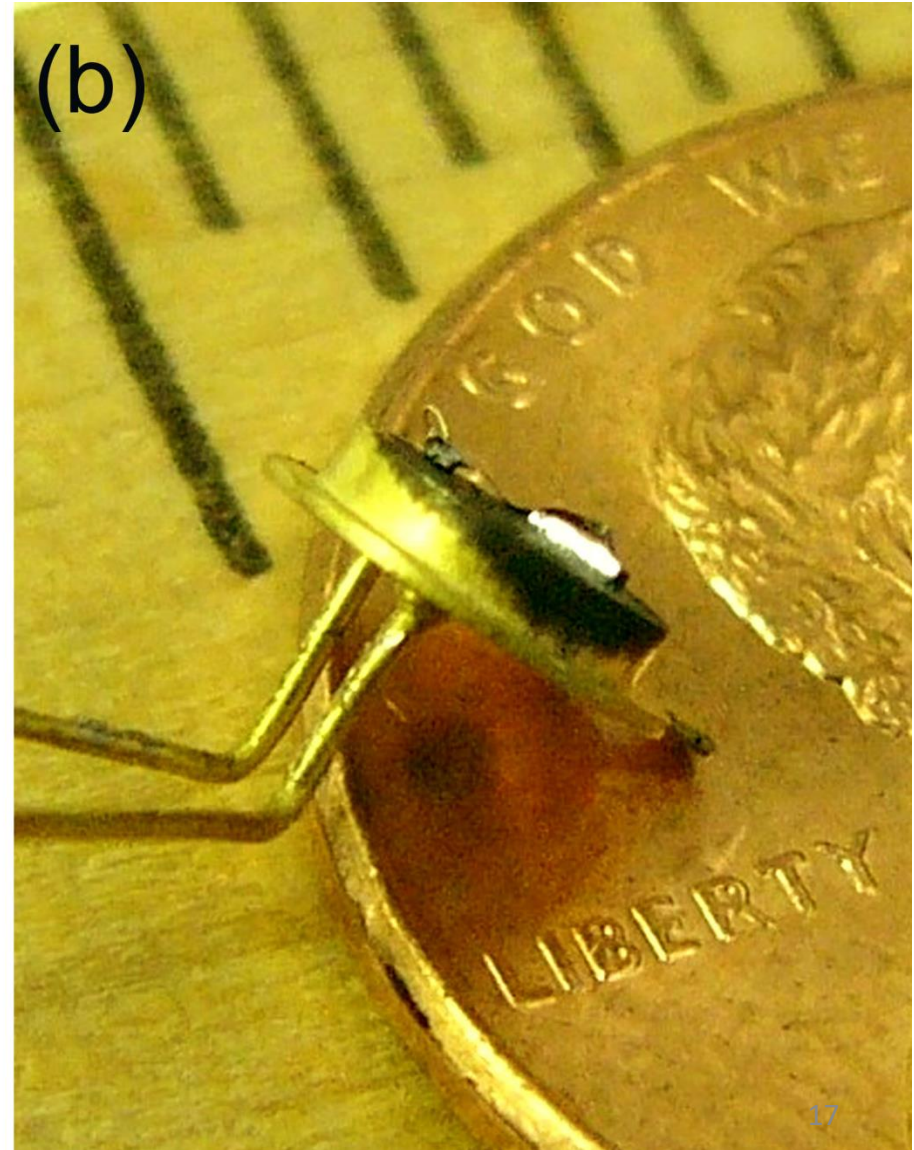
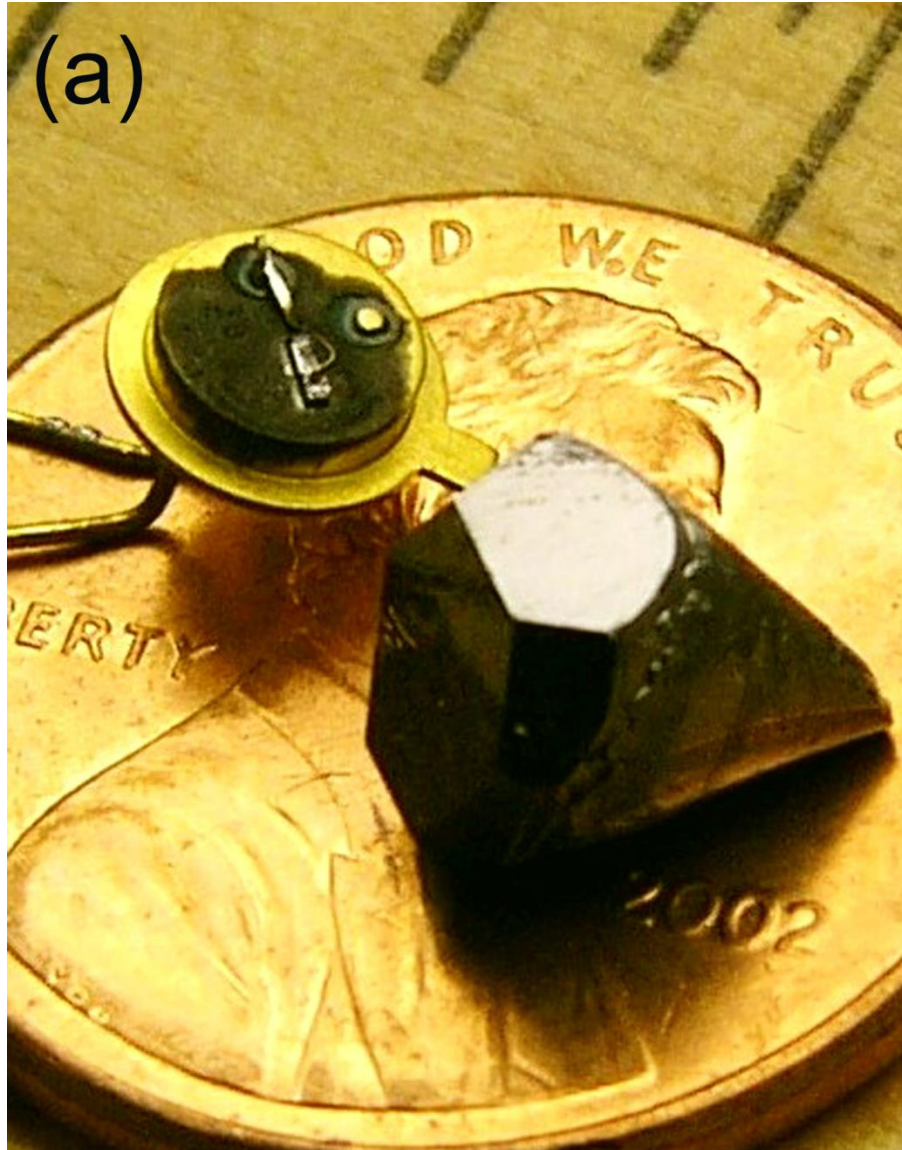


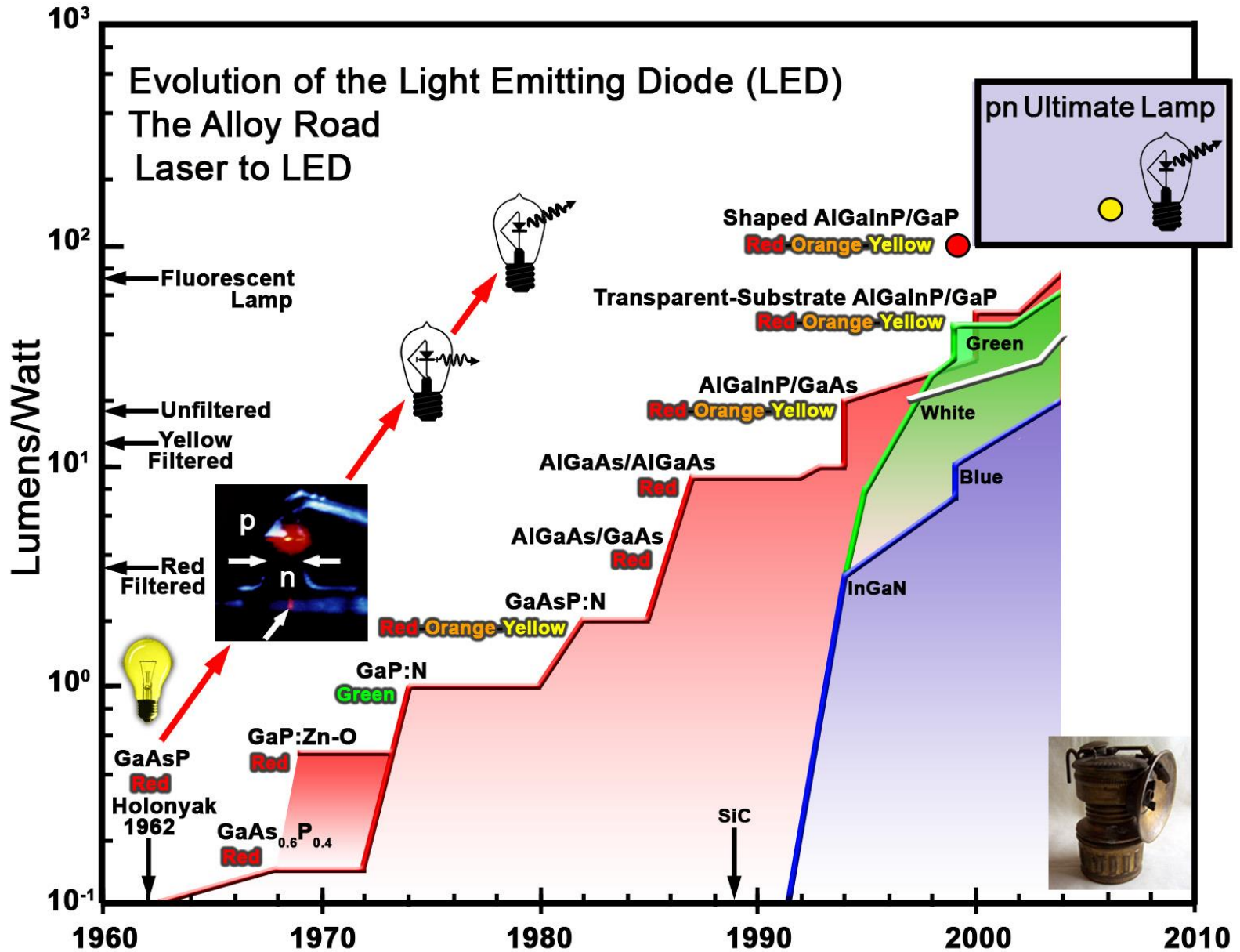
# VCSELs are revolutionizing optical interconnects





# The First GaAsP Diode Laser







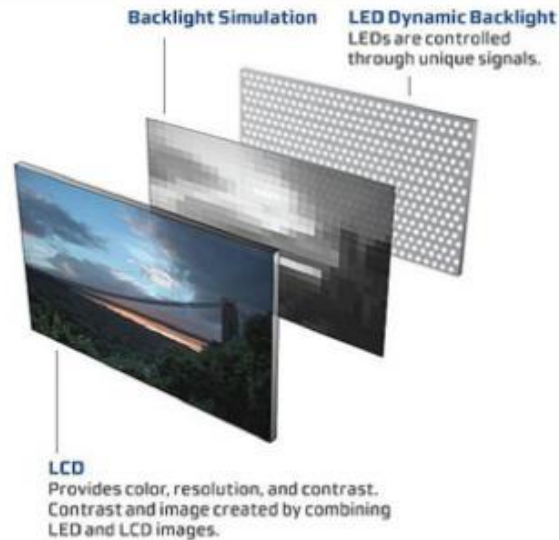
# LED Applications

## LED Traffic Signals



Source: [gelightingsolutions.com](http://gelightingsolutions.com)

## LED Backlit TV



Source: [digitaltrends.com](http://digitaltrends.com)

## Architectural Lighting



Source: [vividleds.us](http://vividleds.us)

## LED General Lighting



Source: [led-resource.com](http://led-resource.com)

## Automotive



Source: [spie.org](http://spie.org)

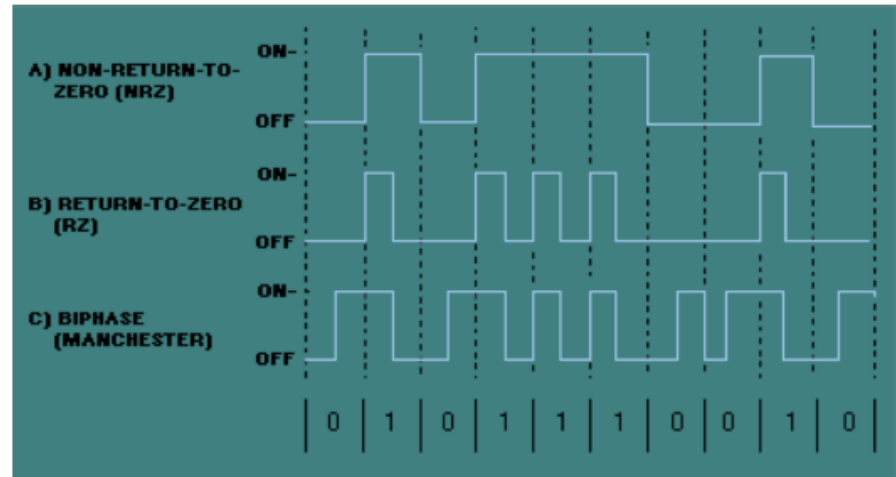
# TV screens are developing rapidly

- CCFL (cold cathode fluorescent lamp – now obsolete for the most part)
- OLED (Organic Light Emitting Diodes)
- QLED (Quantum-dot Light Emitting Diode)
  - Backlighting: Full-array or edge lighting
  - Local dimming
- 4K and 8K
- Marketing and Hype...

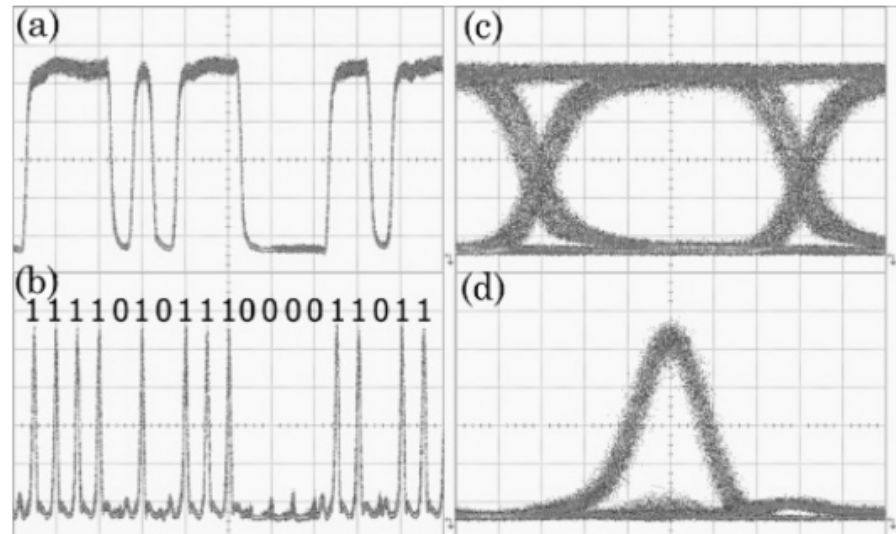
# Evolution of Optical System Complexity

# On-Off Keying

- Not Return to Zero (NRZ)
  - Simplest method of sending data
  - A “1” has light present for the entire clock interval
  - More adversely affected by nonlinearities (self phase modulation, cross phase modulation, etc.)
    - Higher optical power
- Return to Zero (RZ)
  - If a “1” is being sent, it is only present for a portion of the clock interval
  - More affected by dispersion
    - Larger BW required



<http://www.tpub.com/neets/tm/30NVM124.GIF>

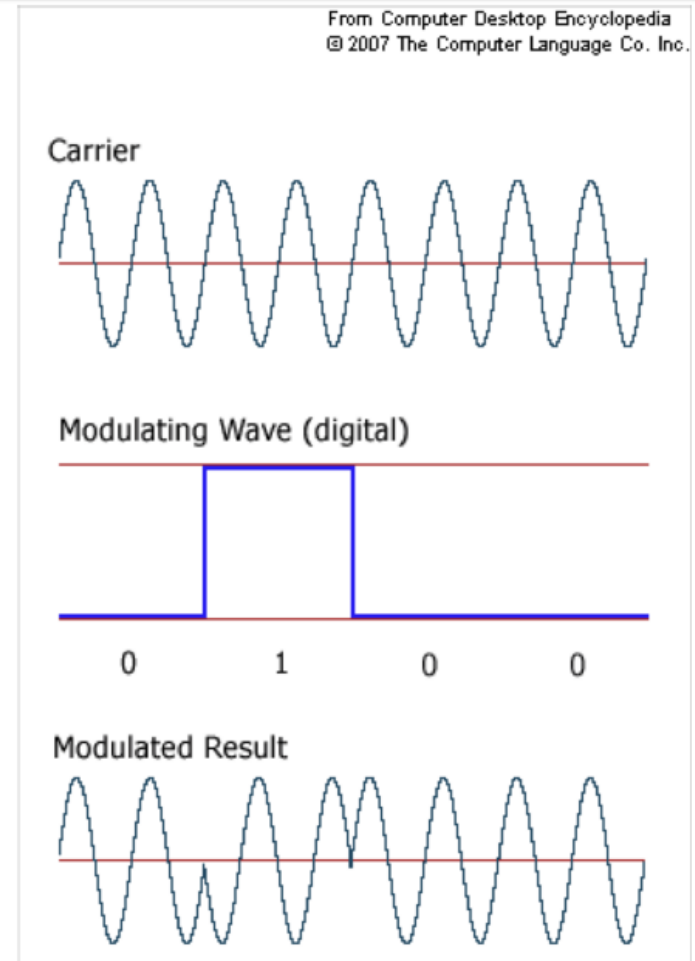
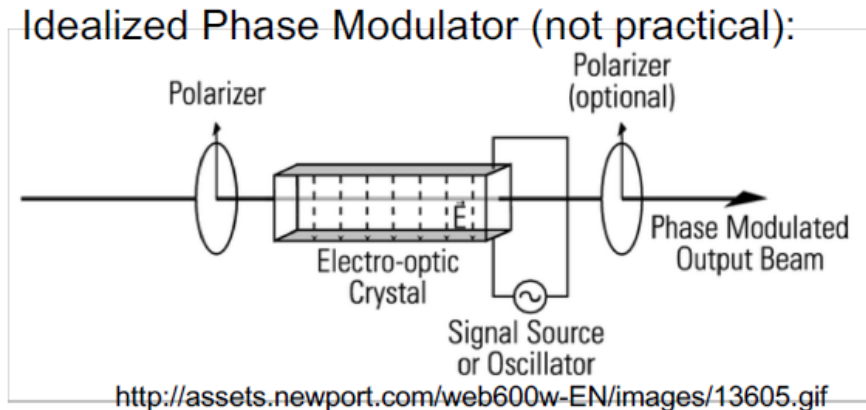


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# Phase-Shift Keying

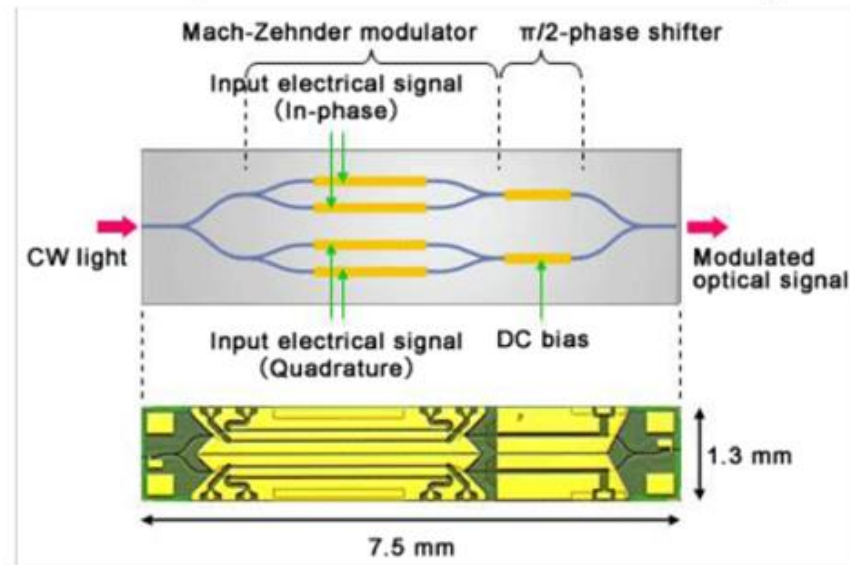
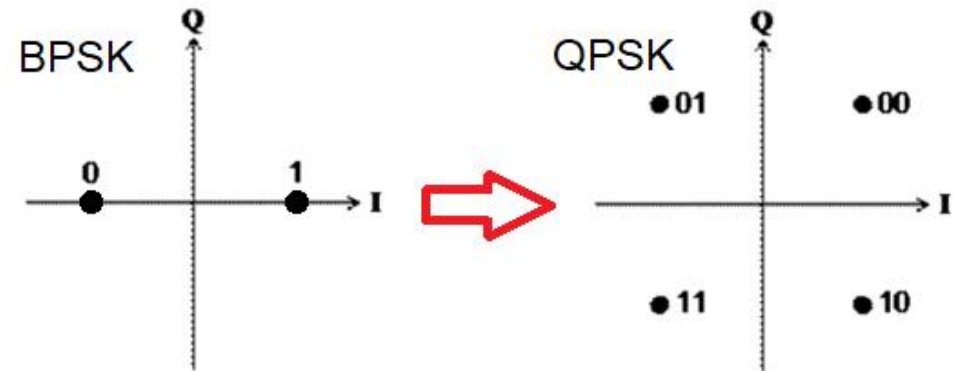
## Phase-Shift Keying

- Data is encoded in the phase of the transmitted signal
- Field-controlled refractive index results in optical path length difference



# Differential Quadrature Phase Shift Keying

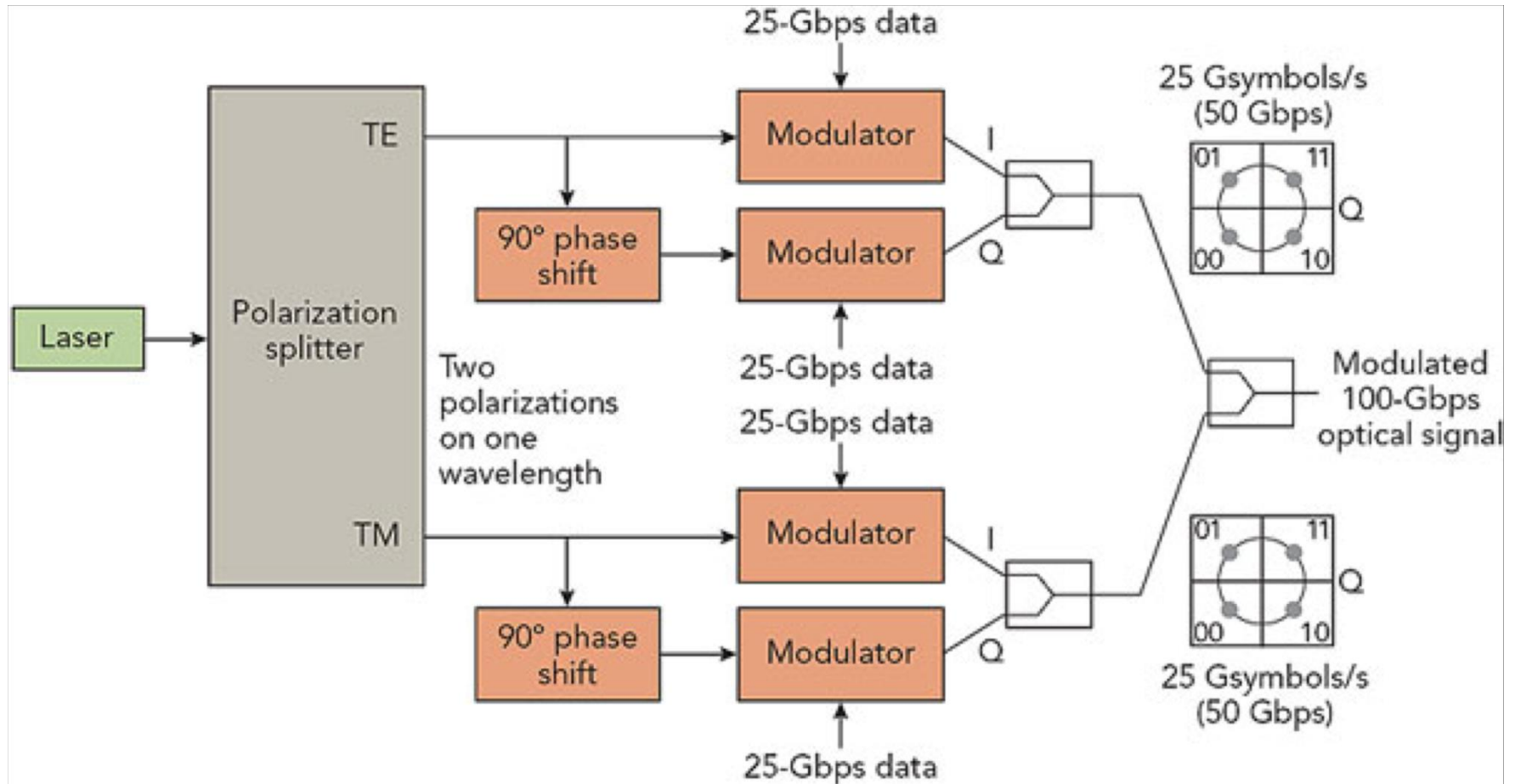
- Constant-intensity modulation format
- Data is encoded into one of 4 phase states that are  $90^\circ$  apart
- Each symbol carries 2 bits (baud rate is half the bit rate)



[http://www.phlab.ecl.ntt.co.jp/eng/organ/images/img02ph\\_2e.gif](http://www.phlab.ecl.ntt.co.jp/eng/organ/images/img02ph_2e.gif)

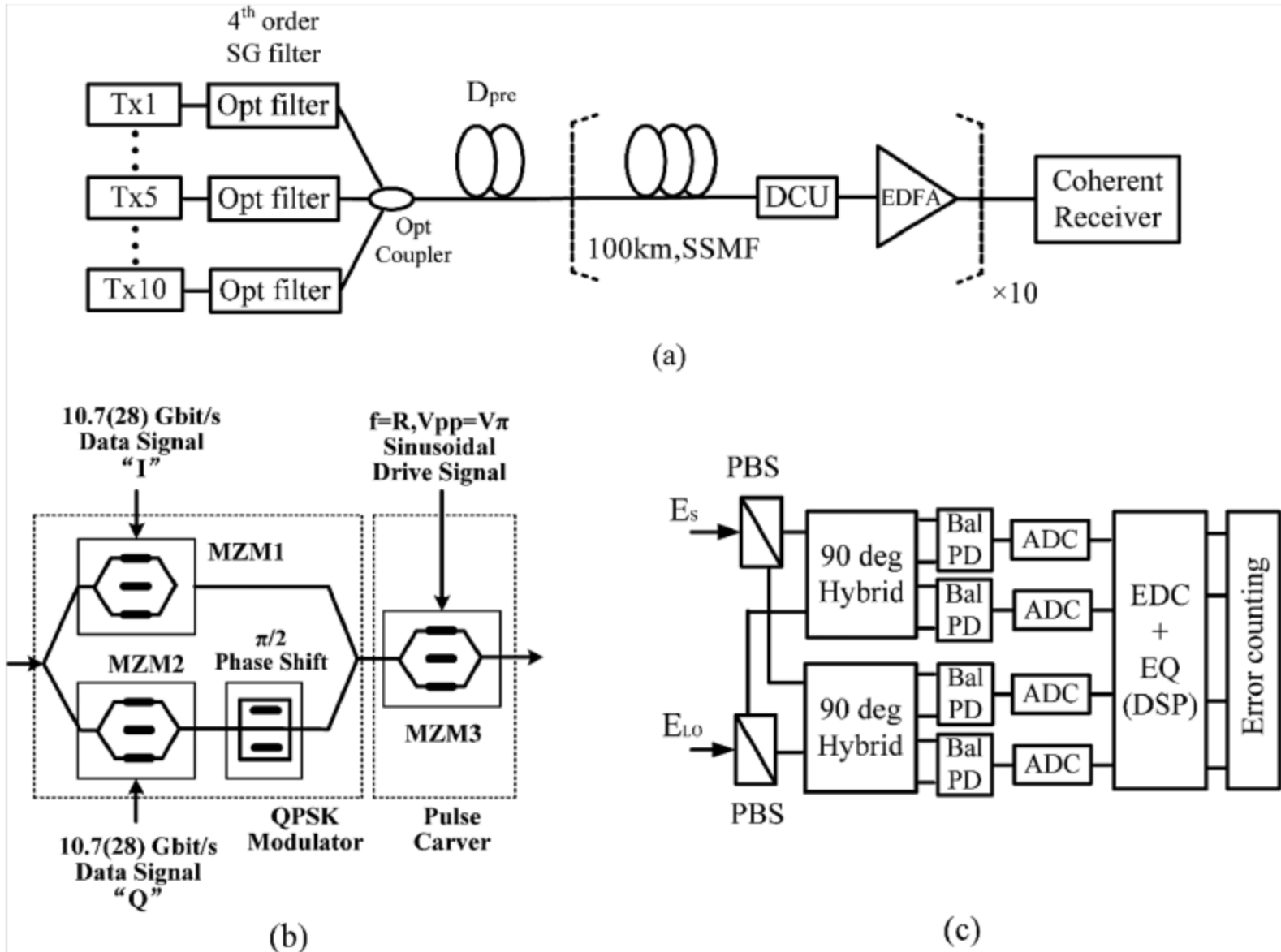


# Polarization Multiplexing



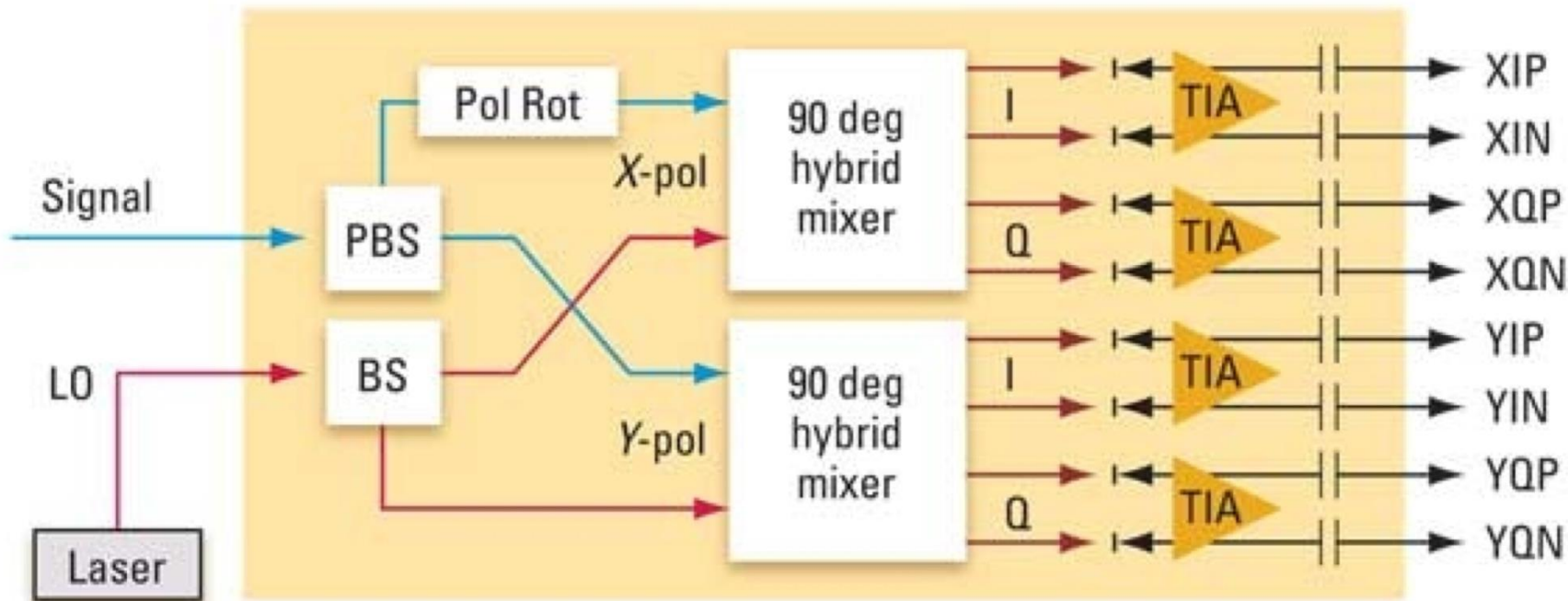
**Figure 2** A 100-Gbps transmitter splits a laser into two polarizations and then modulates four 25-Gbps data streams onto a single fiber at a single wavelength.

# RZ DQPSK for long haul transmission



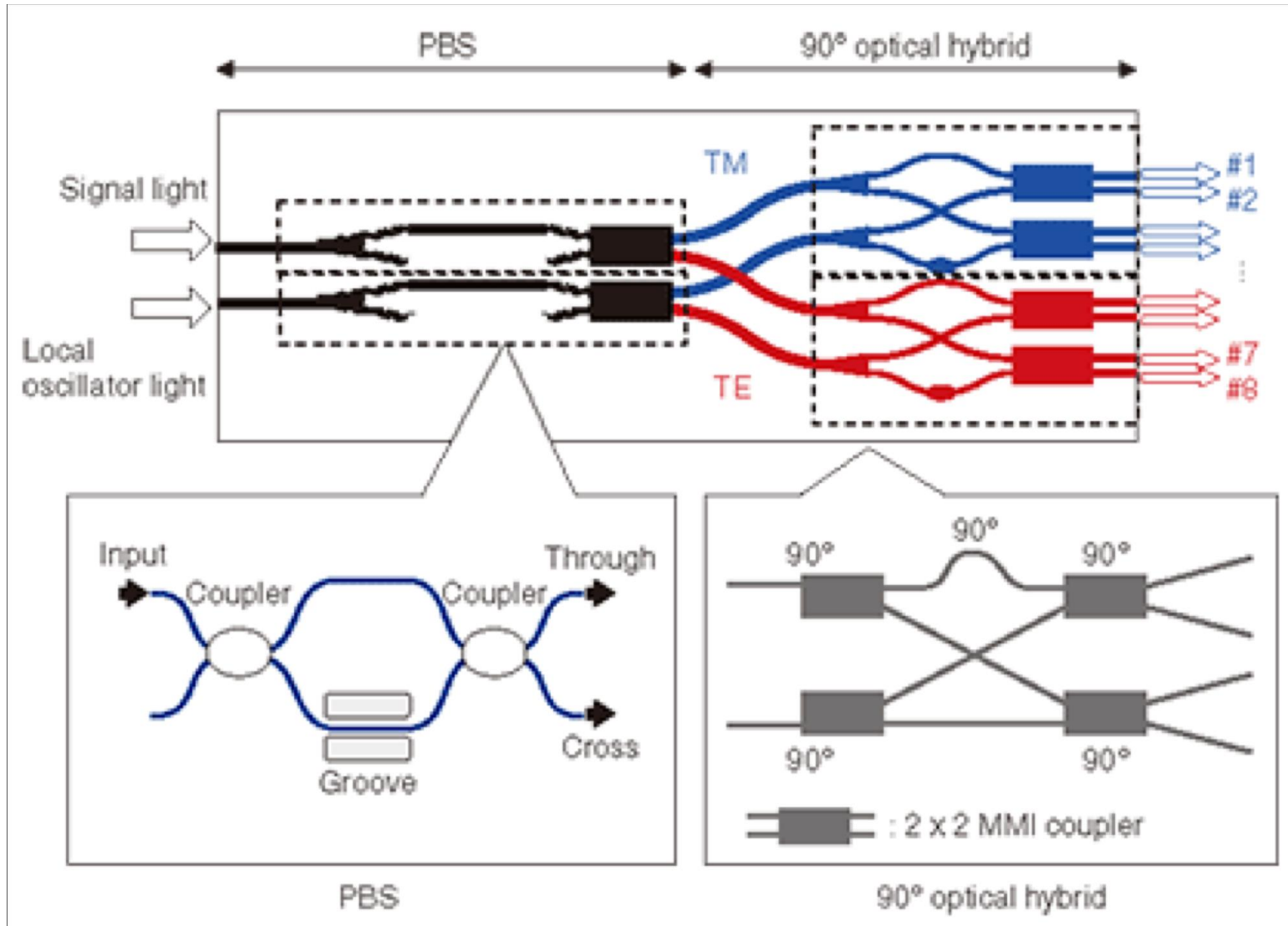
# Dual Polarization

## DP-DQPSK for long haul transmission



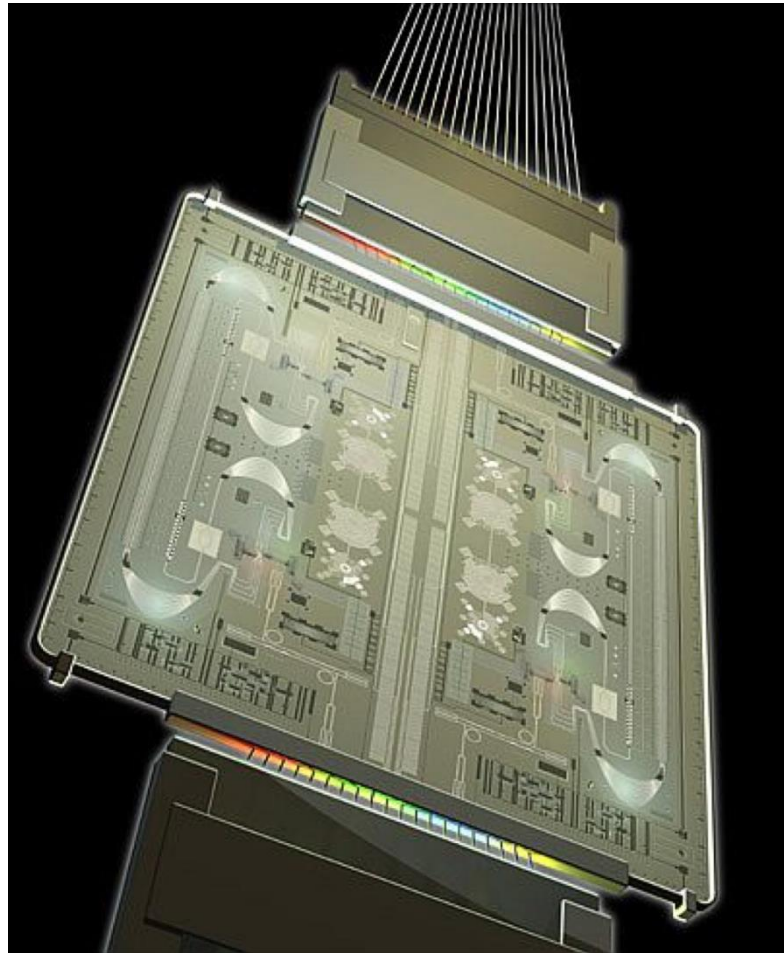
**FIGURE 3.** Block diagram of the optical receiver proposed for 100-Gbps DP-QPSK. (Source: OIF 100G Ultra Long Haul DWDM Framework Document.)

# 90° Optical Hybrid Mixer



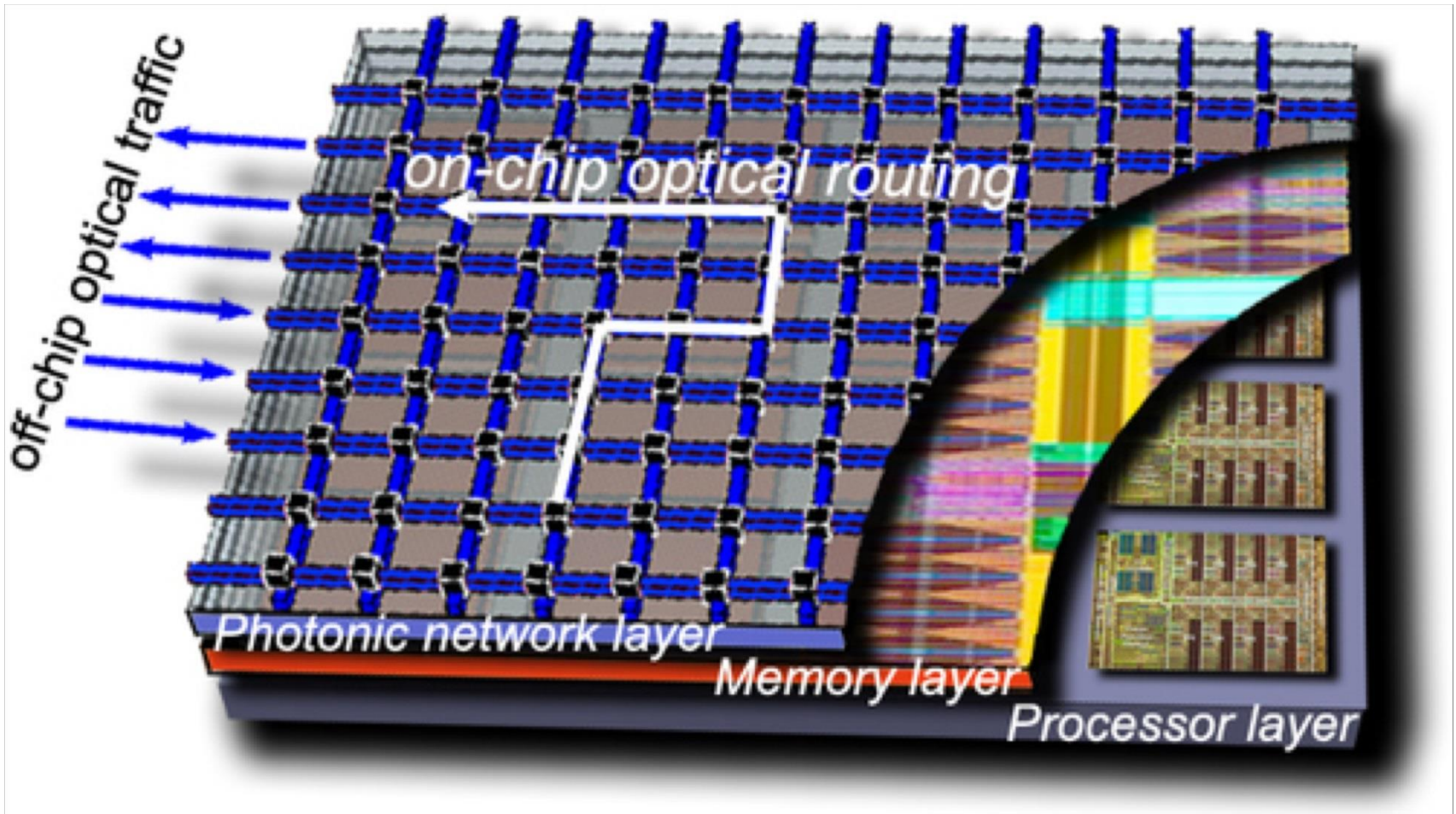
# Photonic Integrated Circuit

Photonic integration solves practical issues associated with discrete implementations





# On-Chip Optics?



# Course Purpose

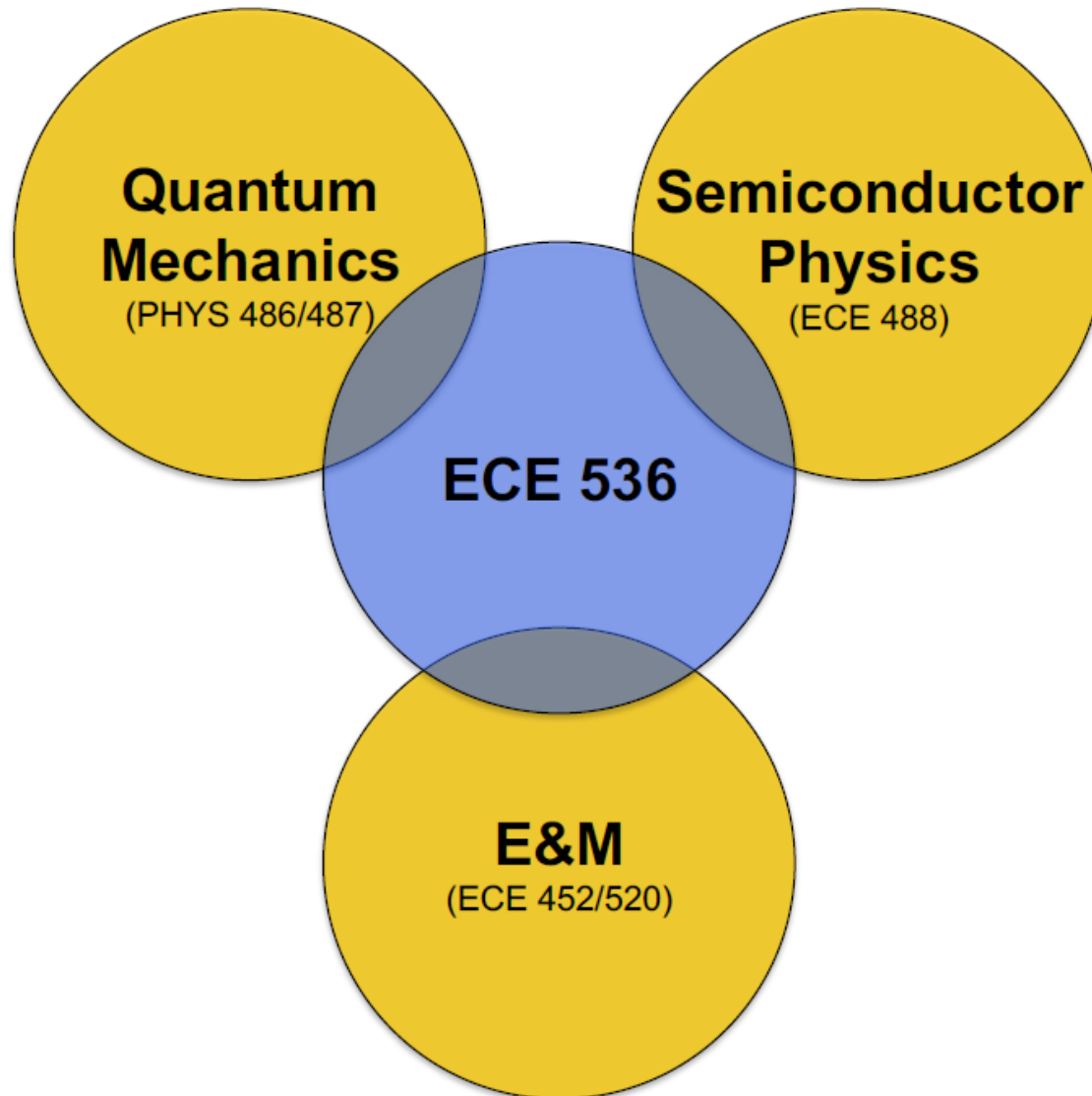
- Cover the theory and design of semiconductor devices used in optical communication systems and electronic-photonic integrated circuits

# Course Objectives

- Discuss, at a graduate level, key topics in semiconductor physics
- Discuss, at a graduate level, key topics in electromagnetics as applied to photonic devices
- Provide an understanding of active photonic devices used in optical communication systems and photonic integrated circuits
- Provide an understanding of passive photonic devices used in optical communication systems and photonic integrated circuits



# Overlap With ECE/PHYS Courses



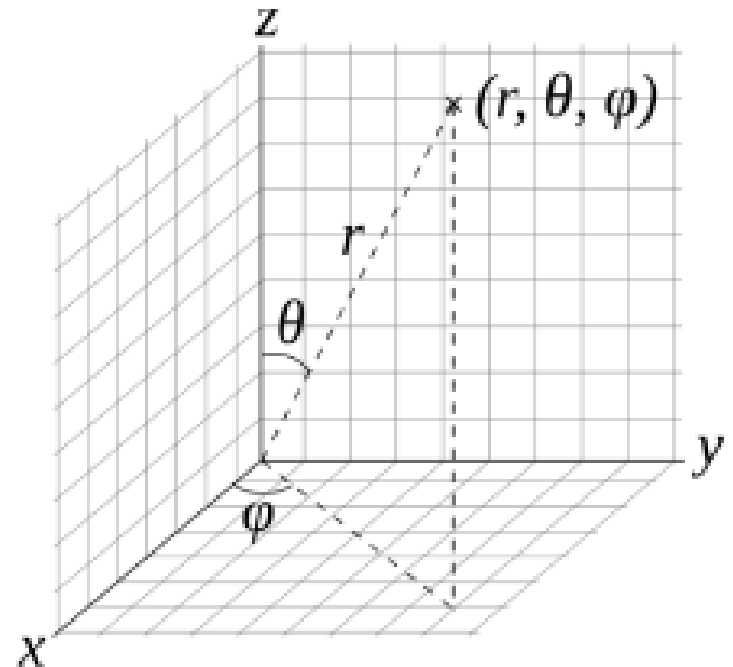
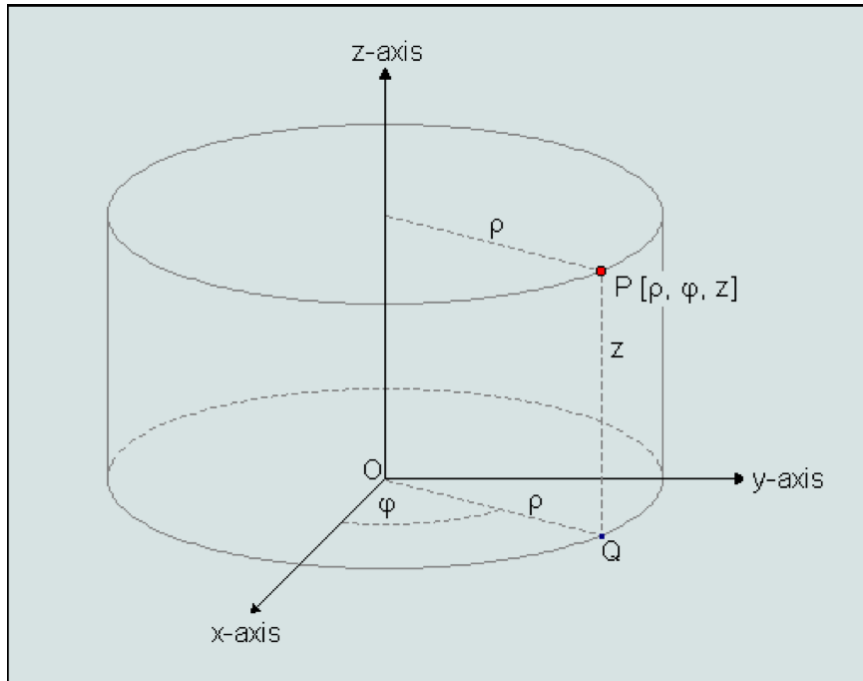
# Important points (Chapter 1)

- Semiconductor Crystal Structures and Bonding Diagrams
- Relationship Between Photon Energy and Wavelength
- History of the Semiconductor Laser
- Evolution of LED Technology
- Condition for Lasing: Gain and Phase
- Mode Spacing in a FP Laser
- Heterojunctions
- Lattice Constant and Energy Gap in Alloy Semiconductors
- Strain

# This is a good time to refresh basic EM

- Divergence
- Curl
- Maxwell's equations
- EM vector fields
- Wave (Helmholtz) equation
- Constitutive relations in materials
- Boundary conditions

# Cylindrical and Spherical Coordinates



# Curl

In Cartesian Coordinates:

$$\nabla \times \mathbf{A} = \left( \frac{\partial A_z}{\partial y} - \frac{\partial A_y}{\partial z} \right) \hat{x} + \left( \frac{\partial A_x}{\partial z} - \frac{\partial A_z}{\partial x} \right) \hat{y} + \left( \frac{\partial A_y}{\partial x} - \frac{\partial A_x}{\partial y} \right) \hat{z}$$

In Cylindrical Coordinates:

$$\nabla \times \mathbf{A} = \left( \frac{1}{\rho} \frac{\partial A_z}{\partial \phi} - \frac{\partial A_\phi}{\partial z} \right) \hat{\rho} + \left( \frac{\partial A_\rho}{\partial z} - \frac{\partial A_z}{\partial \rho} \right) \hat{\phi} + \frac{1}{\rho} \left( \frac{\partial(\rho A_\phi)}{\partial \rho} - \frac{\partial A_\rho}{\partial \phi} \right) \hat{z}$$

In Spherical Coordinates:

$$\nabla \times \mathbf{A} = \frac{1}{r \sin \theta} \left( \frac{\partial}{\partial \phi} (A_\phi \sin \theta) - \frac{\partial A_\theta}{\partial \phi} \right) \hat{r} + \frac{1}{r} \left( \frac{1}{\sin \theta} \frac{\partial A_r}{\partial \phi} - \frac{\partial}{\partial r} (r A_\phi) \right) \hat{\theta} + \frac{1}{r} \left( \frac{\partial}{\partial r} (r A_\theta) - \frac{\partial A_r}{\partial \theta} \right) \hat{\phi}$$

# Divergence

In Cartesian Coordinates:

$$\nabla \cdot \mathbf{A} = \frac{\partial A_x}{\partial x} + \frac{\partial A_y}{\partial y} + \frac{\partial A_z}{\partial z}$$

In Cylindrical Coordinates:

$$\nabla \cdot \mathbf{A} = \frac{1}{\rho} \frac{\partial}{\partial \rho} (\rho A_\rho) + \frac{1}{\rho} \frac{\partial}{\partial \phi} (A_\phi) + \frac{\partial A_z}{\partial z}$$

In Spherical Coordinates:

$$\nabla \cdot \mathbf{A} = \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 A_r) + \frac{1}{r \sin \theta} \frac{\partial}{\partial \theta} (\sin \theta A_\theta) + \frac{1}{r \sin \theta} \frac{\partial}{\partial \phi} (A_\phi)$$

# Maxwell's Equations

$$\nabla \times \vec{E}(t) = -\frac{\partial \vec{B}(t)}{\partial t}$$

$$\nabla \times \vec{H}(t) = \frac{\partial \vec{D}(t)}{\partial t} + \vec{J}$$

$$\nabla \cdot \vec{D}(t) = \rho$$

$$\nabla \cdot \vec{B}(t) = 0$$

$$\vec{D}(t) = \epsilon \vec{E}(t)$$

$$\vec{B}(t) = \mu \vec{H}(t)$$

# In material media

$$\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}_r \boldsymbol{\varepsilon}_0 \quad ; \quad \boldsymbol{\mu} = \boldsymbol{\mu}_r \boldsymbol{\mu}_0$$

**If the medium is anisotropic, the relative quantities are tensors:**

$$\boldsymbol{\varepsilon}_r = \begin{bmatrix} \varepsilon_{xx} & \varepsilon_{xy} & \varepsilon_{xz} \\ \varepsilon_{yx} & \varepsilon_{yy} & \varepsilon_{yz} \\ \varepsilon_{zx} & \varepsilon_{zy} & \varepsilon_{zz} \end{bmatrix} \quad ; \quad \boldsymbol{\mu}_r = \begin{bmatrix} \mu_{xx} & \mu_{xy} & \mu_{xz} \\ \mu_{yx} & \mu_{yy} & \mu_{yz} \\ \mu_{zx} & \mu_{zy} & \mu_{zz} \end{bmatrix}$$



In phasor form

$$\nabla \times \vec{\mathbf{E}} = -j\omega\mu\vec{\mathbf{H}}$$

$$\nabla \times \vec{\mathbf{H}} = \vec{\mathbf{J}} + j\omega\epsilon\vec{\mathbf{E}}$$

$$\nabla \cdot \vec{\mathbf{D}} = \rho$$

$$\nabla \cdot \vec{\mathbf{B}} = 0$$

$$\vec{\mathbf{D}} = \epsilon\vec{\mathbf{E}}$$

$$\vec{\mathbf{B}} = \mu\vec{\mathbf{H}}$$

# General wave equations

$$\nabla^2 \vec{E}(t) - \nabla \nabla \cdot \vec{E}(t) - \mu \varepsilon \frac{\partial^2 \vec{E}(t)}{\partial t^2} = \mu \frac{\partial \vec{J}(t)}{\partial t}$$

$$\nabla^2 \vec{H}(t) - \mu \varepsilon \frac{\partial^2 \vec{H}(t)}{\partial t^2} = -\nabla \times \vec{J}(t)$$

Away from charges

$$\nabla^2 \vec{E}(t) - \mu \varepsilon \frac{\partial^2 \vec{E}(t)}{\partial t^2} = \mathbf{0}$$

$$\nabla^2 \vec{H}(t) - \mu \varepsilon \frac{\partial^2 \vec{H}(t)}{\partial t^2} = \mathbf{0}$$

# Helmholtz equations (phasors)

$$\nabla^2 \vec{E} + \omega^2 \mu_0 \epsilon_0 \vec{E} = 0$$

$$\nabla^2 \vec{H} + \omega^2 \mu_0 \epsilon_0 \vec{H} = 0$$

(vacuum)

In material medium (phasors)

$$\nabla \times \vec{E} = -j\omega\mu \vec{H}$$

$$\nabla \times \vec{H} = \sigma \vec{E} + j\omega\epsilon \vec{E} = j\omega\left(\epsilon - j\frac{\sigma}{\omega}\right)\vec{E}$$

$$\begin{aligned}\nabla \times \nabla \times \vec{E} &= \nabla \nabla \cdot \vec{E} - \nabla^2 \vec{E} = -j\omega\mu \nabla \times \vec{H} \\ &= -j\omega\mu(\vec{J}_c + j\omega\epsilon \vec{E})\end{aligned}$$

$$\Rightarrow \nabla^2 \vec{E} = j\omega\mu(\sigma + j\omega\epsilon)\vec{E}$$

# Reading Assignments

Chuang – Chapter 1, Section 2.1

Consider spending some time to review “visually” some of the EM fundamentals which are important in optics.

Several Java applications have been posted for you to download and keep (developed for the textbook Ulaby and Ravaioli, “Fundamentals of Applied Electromagnetics,” Pearson, 8<sup>th</sup> edition, 2020).

These applications run on any desktop computer with the Java Runtime Environment installed. They have been tested on Windows and Mac OSX, but do not run on Android or iOS.



# Plane Wave in material medium

Module 7.2

Plane Wave

$t = 0.0T$

$\omega t = 0^\circ$

START

STOP

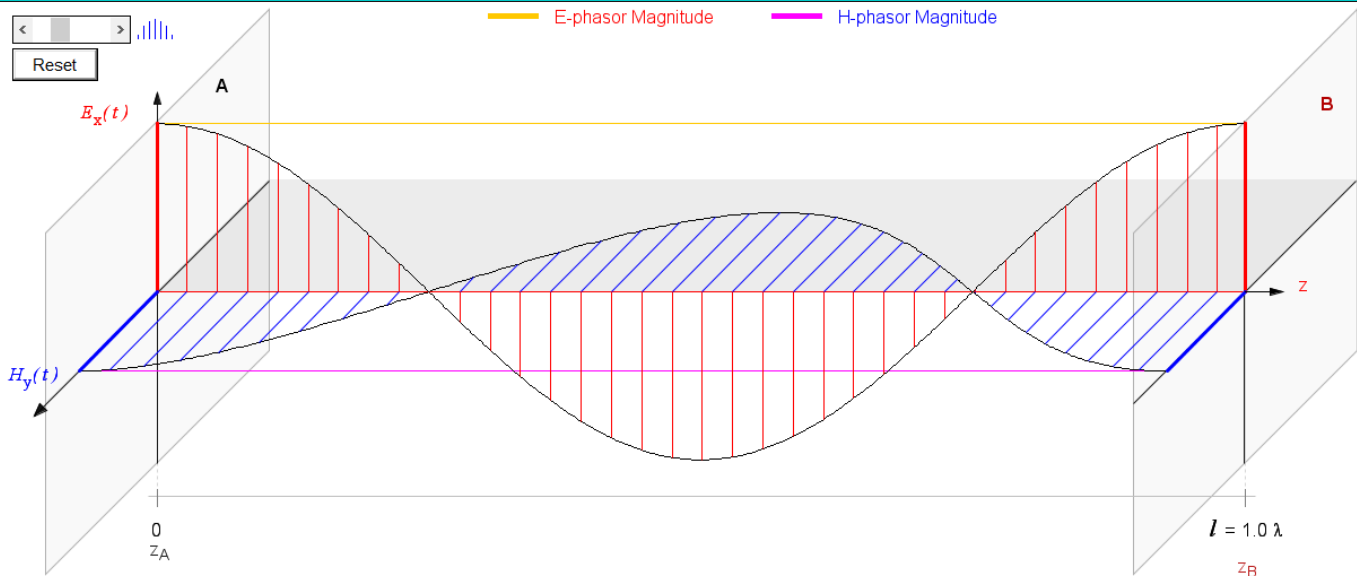


Input/Output

Phase Planes

Instructions

| Phasors |



Input

Frequency  $f = 1.0E9$  Hz

Conductivity  $\sigma = 0.0$  S/m

Relative Permittivity  $\epsilon_r = 1.0$

Relative Permeability  $\mu_r = 1.0$

E-field Amplitude ( $z=0$ )  $E_o = 1.0$  V/m

E-field Phase ( $z=0$ )  $\phi = 0.0$  rad

Length Displayed  $l = 1.0$   $\lambda$

[A] & [B] Windows  $Area = 1.0$   $m^2$

Update

Animation speed

Output Wave Properties

WaveLength  $\lambda = 30.0$  [cm]

Phase Velocity  $u_p = 3.0 \times 10^8$  [m/s]

Period  $T = 1.0 \times 10^{-9}$  [s]

Impedance of the Medium [ $\Omega$ ]

$\eta = 376.991118 + j0.0$

$= 376.991118 \angle 0.0$  rad

$= 376.991118 \angle 0.0^\circ$

Penetration (Skin) Depth

$\delta_s = \infty$

Phase and Attenuation Constants

$\beta = 20.94395$  [ $m^{-1}$ ]

$\alpha = 0.0$  [Ne/m]

$\sigma / \omega \epsilon = 0.0$

The material is vacuum (perfect dielectric)

A  B

B  A

A)  $z_A = 0.0 \lambda = 0.0$  [m]

$|E_A| = 1.0$  [V/m]

$\angle E_A = 0.0$  [rad]

$|H_A| = 2.65258 \times 10^{-3}$  [A/m]

$\angle H_A = 0.0$  [rad]

$f = 1.0$  GHz

$l = 1.0 \lambda = 30.0$  [cm]

Phasor fields on selected phase planes

$E_x(t)$    $H_y(t)$

B)  $z_B = 1.0 \lambda = 30.0$  [cm]

$|E_B| = 1.0$  [V/m]

$\angle E_B = -6.28319$  [rad]

$|H_B| = 2.65258 \times 10^{-3}$  [A/m]

$\angle H_B = -6.28319$  [rad]

# Polarization

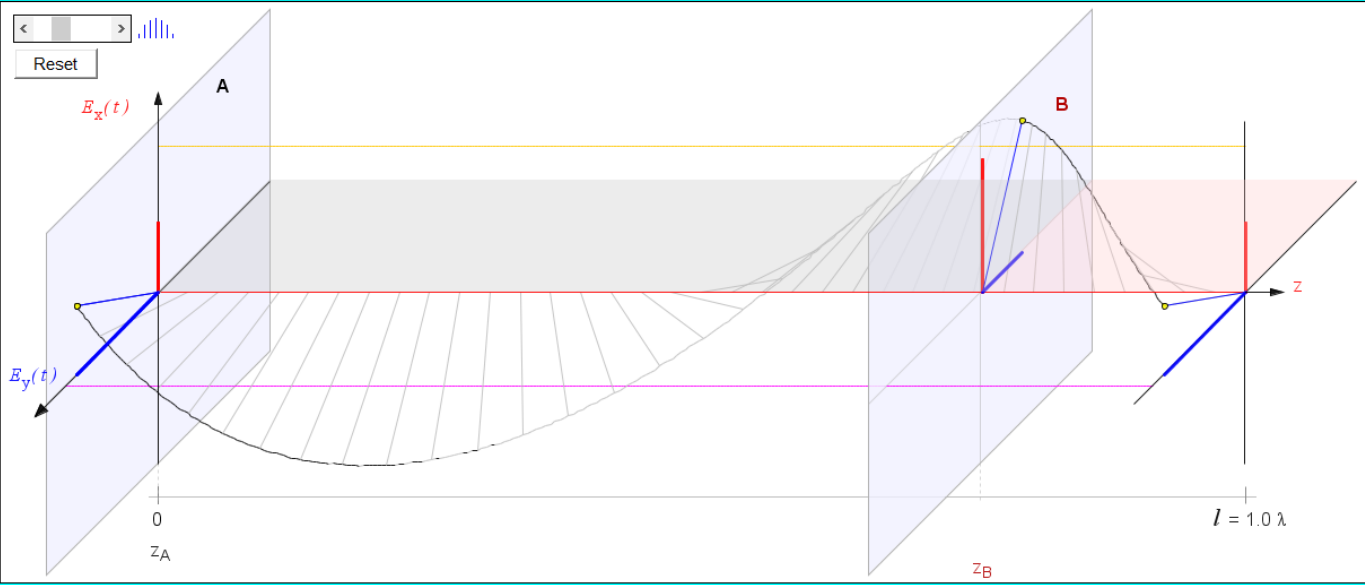
## Module 7.4 Polarization II

$t = 0.831T + 1T$        $\omega t = 299^\circ + 2\pi$



Input/Output    Phase Planes    Instructions

Animation speed



A <-----> A

B <-----> B

A)  $z_A = 0.0 \lambda = 0.0$  [m]  
 $|E_x| = 1.0$  [V/m]  
 $\angle E_x = 0.0$  [rad]  
 $|E_y| = 1.0$  [V/m]  
 $\angle E_y = 1.5708$  [rad]

$f = 1.0$  GHz  
 $l = 1.0 \lambda = 30.0$  [cm]

$E_x(t)$       $E_y(t)$       $E_{tot}(t)$

B)  $z_B = 0.75 \lambda = 22.71$  [cm]  
 $|E_x| = 1.0$  [V/m]  
 $\angle E_x = -4.75637$  [rad]  
 $|E_y| = 1.0$  [V/m]  
 $\angle E_y = -3.18557$  [rad]

**Input**      Update

Frequency  $f = 1.0E9$  [Hz]

Relative Permittivity  $\epsilon_r = 1.0$

Relative Permeability  $\mu_r = 1.0$

Reference Amplitude  $E_o = 1.0$  [V/m]

Reference Phase (z=0)  $\phi = 0.0$  [rad]

Length Displayed  $l = 1.0$  [ $\lambda$ ]

$E_x = 1.0 E_o$        $E_y = 1.0 E_o$

$\phi(E_y) - \phi(E_x) = 90.0^\circ$

**Output**

WaveLength  $\lambda = 30.0$  [cm]

Phase Velocity  $v_p = 3.0 \times 10^8$  [m/s]

Period  $T = 1.0 \times 10^{-9}$  [s]

Impedance of the Medium [ $\Omega$ ]  
 $\eta = 376.991118$

Phase Constant [ $m^{-1}$ ]  
 $\beta = 20.94395$

**CIRCULAR POLARIZATION  
LEFT HANDED**

# Wavelength Calculator


Electromagnetic Waves **Wavelength Calculator** Select: Visible Spectrum About

$\lambda = 749.481144 \times 10^{-9} \text{ [m]}$

km **m** cm mm  $\mu\text{m}$  nm A

Phase velocity  $v_p = 2.99792458 \times 10^8 \text{ m/s}$   
Wave Period  $T_p = 2.5 \times 10^{-15} \text{ s}$   
Photon Energy  $E_{ph} = 1.65426708 \text{ [eV]}$

meters



400 THz 450 THz 500 THz 550 THz 600 THz 650 THz 700 THz 750 THz

< >

Frequency  $f = 400.0 \times 10^{12} \text{ [Hz]}$   
 $= 400.0 \text{ [THz]}$  **tera-Hertz =  $10^{12}$  Hertz**

**VISIBLE SPECTRUM**  
400 THz - 789 THz

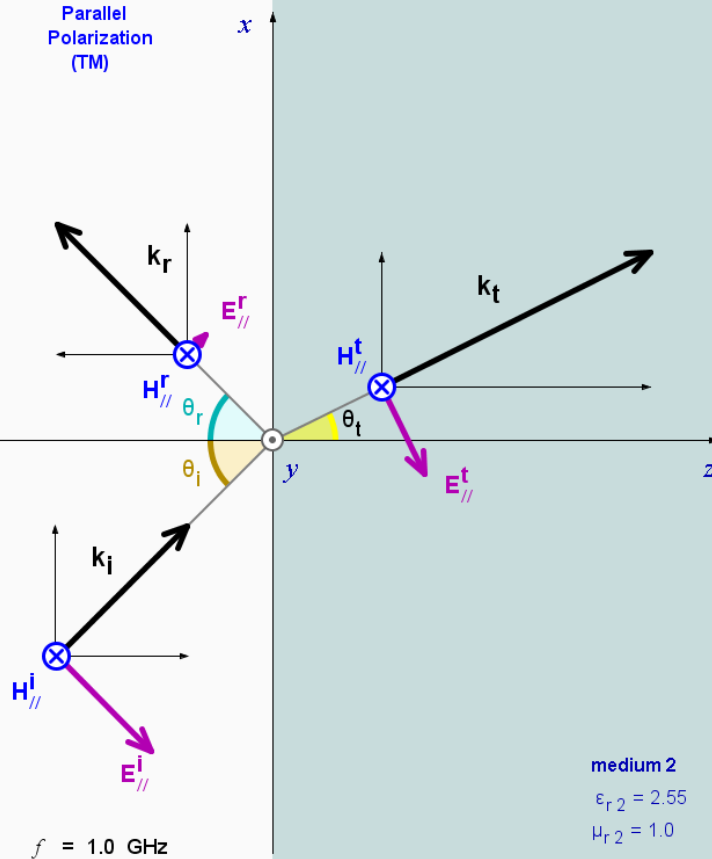
**Red Band:** 400 THz - 484 THz (750 nm - 620 nm)  
AlGaAs - AlGaInP Lasers (~ 630 to 900 nm)

Relative Dielectric Constant  $\epsilon_r = 1.0$  Conductivity  $\sigma = 0.0 \text{ S/m}$  UPDATE

# Oblique Incidence at dielectric-dielectric interface

## Module 8.3 Oblique Incidence

Vector Diagrams

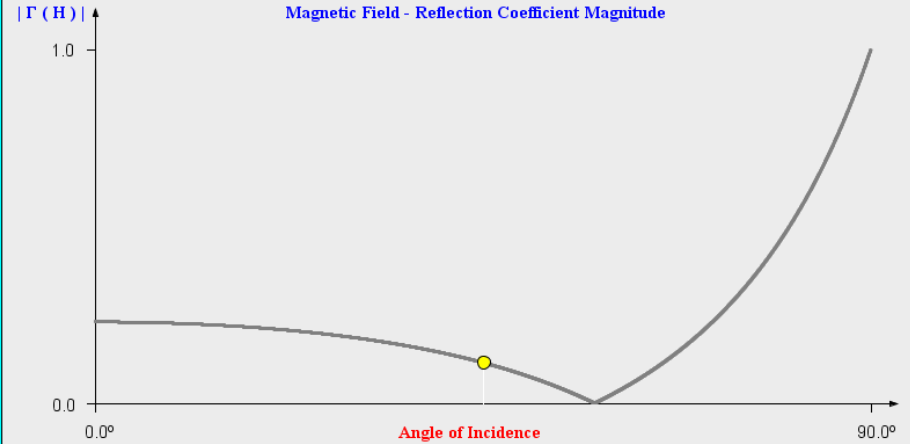


Click to Visualize Power Flow

| Reflection Coefficient |

| Transmission Coefficient |

Standing Wave



### Input

$f = 1.0\text{E}9$  Hz

$\epsilon_r = 1.0$   $\epsilon_r = 2.55$

$\mu_r = 1.0$   $\mu_r = 1.0$

Medium 1 Medium 2

Polarization: Incident Transverse Field

FIELD

PLOT

Angle of Incidence: 45°

### Output

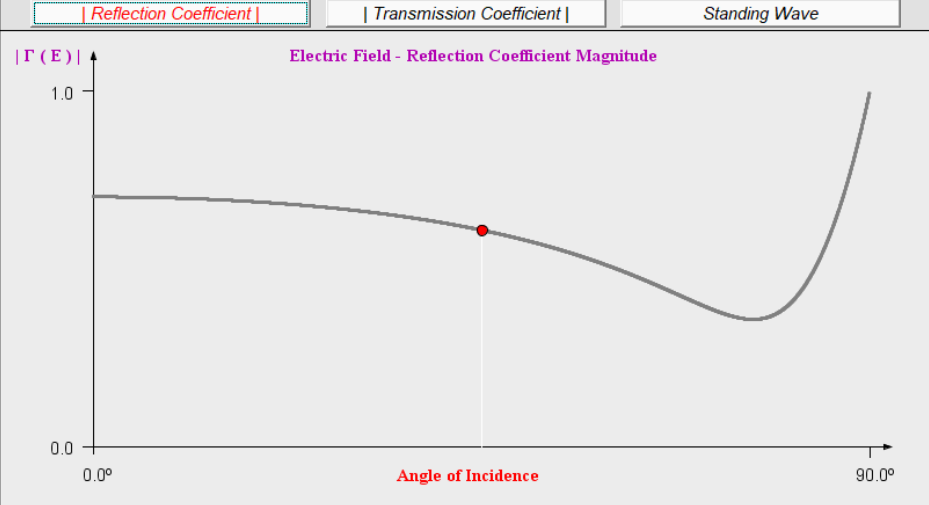
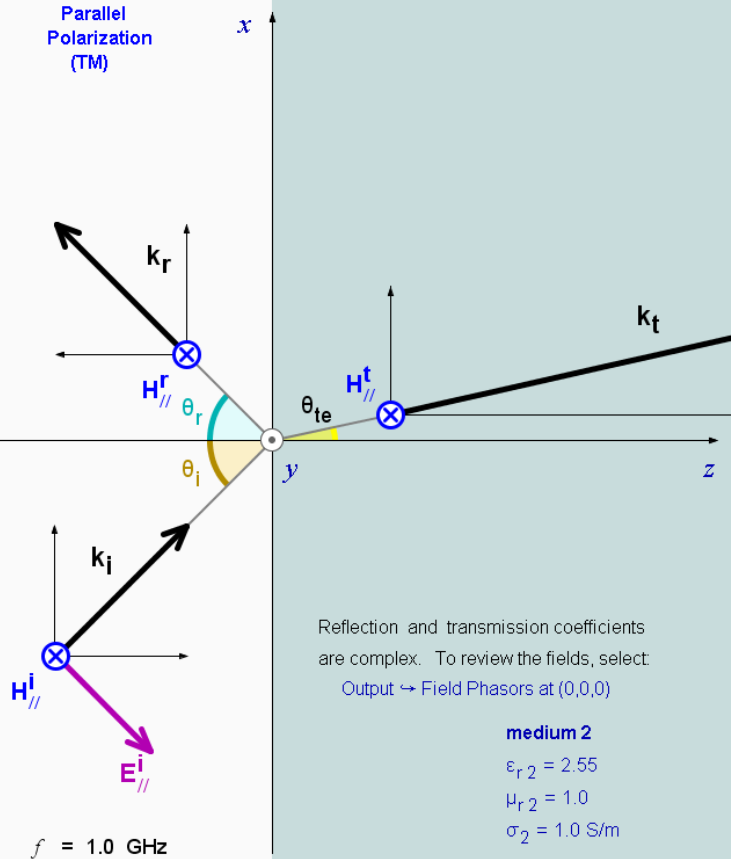
Refraction Behavior

Incident Angle	Refraction Angle
$\theta_i = 45.0^\circ$	$\theta_t = 26.2831^\circ$
<b>Electric Field</b>	
Reflection Coefficient	$\Gamma = -0.1148 + j 0.0$
Transmission Coefficient	$\tau = 0.6981 + j 0.0$
<b>Magnetic Field</b>	
Reflection Coefficient	$\Gamma = 0.1148 + j 0.0$
Transmission Coefficient	$\tau = 1.1148 + j 0.0$
<b>Power</b>	
Reflectivity	$R = 0.013177$
Transmissivity	$T = 0.986823$
Total Transmission Angle (Brewster Angle)	$\theta_B = 57.9442^\circ$
Total Reflection Angle (Critical Angle)	$\theta_c = \text{Undefined}$

# Oblique Incidence at dielectric-lossy medium interface

## Module 8.4 Oblique Incidence on Lossy Medium

Vector Diagrams



**Input**

UPDATE

$f = 1.0\text{E}9$  Hz  $\sigma = 1.0$  S/m

$\epsilon_r = 1.0$   $\epsilon_r = 2.55$

$\mu_r = 1.0$   $\mu_r = 1.0$

Medium 1 Medium 2

Polarization: Incident Transverse Field

⊥  //  In  ⊗  Out  ⊙

FIELD  Electric  Magnetic

PLOT  R, T  |Γ|, |τ|  Γ, τ

Angle of Incidence: 45°

**Output** Refraction Behavior 1

Incident Angle  $\theta_i = 45.0^\circ$  Effective Refraction Angle  $\theta_{te} = 12.5539^\circ$

Electric Field

Reflection Coefficient  $\Gamma = -0.5511 + j 0.2645$

Transmission Coefficient  $\tau = 0.3154 + j 0.1917$

Magnetic Field

Reflection Coefficient  $\Gamma = 0.5511 - j 0.2645$

Transmission Coefficient  $\tau = 1.5511 - j 0.2645$

Power

Reflectivity R = 0.373705

Transmissivity T = 0.626295

Angle of Maximum Transmission  $\theta_m = 76.51^\circ$

Total Reflection Angle (Medium 2 Lossless)  $\theta_c = \text{Undefined}$

# Step-index optical multimode waveguide (simple ray optics model)

Module 8.2

Multimode Step-Index Optical Fiber

Input

$\epsilon_{r0} = 1.0$

$\epsilon_{rf} = 2.55$

$\epsilon_{rc} = 2.40$

$\epsilon$

Angle of Entrance:  $\theta_i = 12^\circ$

$\mu = \mu_0$   $f = 350.0E12$  Hz

$R = 100.0E-6$  m

Update

n

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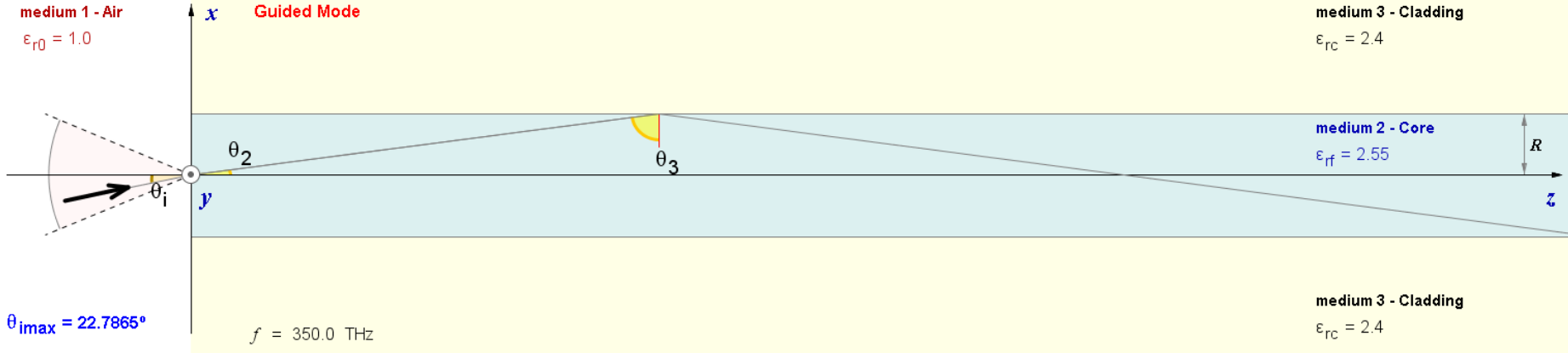
medium 1 - Air

$\epsilon_{r0} = 1.0$

Guided Mode

medium 3 - Cladding

$\epsilon_{rc} = 2.4$



$\theta_{imax} = 22.7865^\circ$

$f = 350.0$  THz

medium 2 - Core

$\epsilon_{rf} = 2.55$

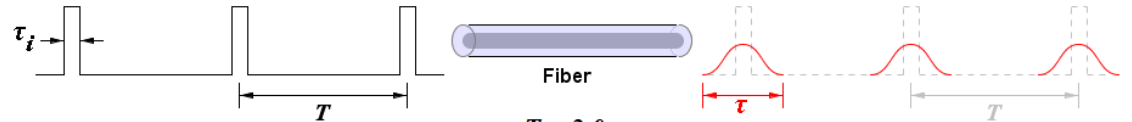
medium 3 - Cladding

$\epsilon_{rc} = 2.4$

Fiber Length = 1.0 km

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Modal Dispersion



$T = 2.0 \tau$

3.052 [Megabits/s]

Guided Rays

Axial Ray  $\theta_{2min} = 0.0^\circ$

Path Length  $l_{min} = 1.0$  [km]

Slowest Ray  $\theta_{2max} = 14.0362^\circ$

Path Length  $l_{max} = 1.030776$  [km]

Selected Ray  $\theta_2 = 7.4811^\circ$

Path Length  $l = 1.008585$  [km]

Axial Ray

Travel Time  $t_{min} = 5.322906$  [ $\mu$ s]

Slowest Ray

Travel Time  $t_{max} = 5.486725$  [ $\mu$ s]

Selected Ray

Travel Time  $t = 5.368605$  [ $\mu$ s]

**SAFETY MARGIN**  $T \geq 2 \tau$

The safety margin is used because of pulse spreading. Reduce T to observe how increased data rate may cause interference between consecutive pulses.

Pulse Spread

$\tau = t_{max} - t_{min} = 163.819$  [ns]

Minimum Pulse Period

$T = 2 \tau = 327.638$  [ns]

Maximum Data Rate

$f_p = (2 \tau)^{-1} = 3.052$  [Megabits/s]

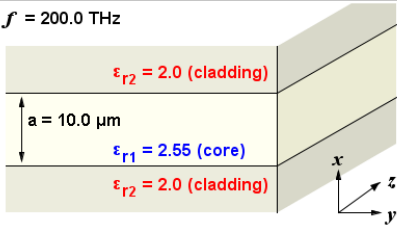
GO TO >> Propagation Properties

Instructions

# Dielectric Slab Waveguide (EM modes representation)

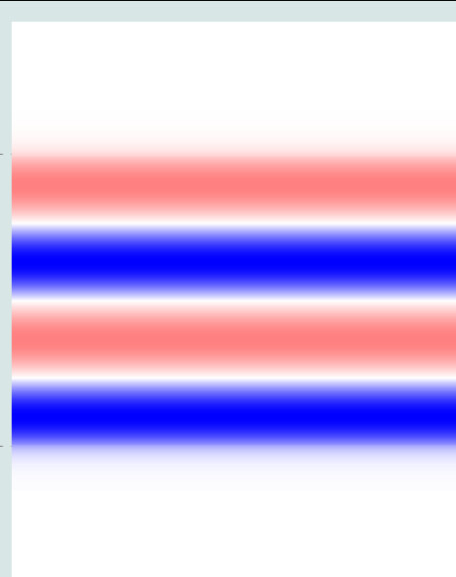
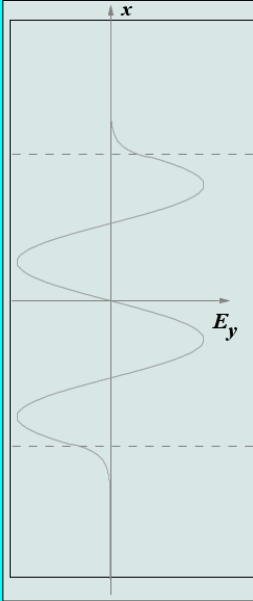
## Module 8.2B Dielectric Slab Waveguide

$f = 200.0$  THz



### Input

Width  $a$   [ m ]  
 Range <  >  
 Frequency  $f$   [ Hz ]  
 Range <  >  
 (Core)  $\epsilon_{r1}$    
 (Cladding)  $\epsilon_{r2}$

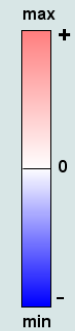


Electric Field

cladding

core

cladding



Plot:

Output Total propagating modes = 20

**TE<sub>3</sub>**

cut-off frequency  $f_c = 60.63601$  [ THz ]

cut-off wavelength  $\lambda_c = 3.096$  [  $\mu\text{m}$  ]

**At the frequency of operation:**

phase velocity  $v_{pz} = 1.90718$  [  $10^8$  m/s ]

group velocity  $v_{gz} = 1.84803$  [  $10^8$  m/s ]

guide wavelength  $\lambda_g = 954.0$  [ nm ]

**Wave vector components:**

$k_z = 6588970.147803771$  [  $\text{m}^{-1}$  ]

$k_x = 1178833.8402834912$  [  $\text{m}^{-1}$  ]

**Attenuation in cladding:**

$\alpha_x = 2876455.589836012$  [  $\text{Ne m}^{-1}$  ]

**Angle of incidence on interface:**

$\theta = 79.85652^\circ$



Mode Selector  TE  TM

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