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, 2nd 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, 2nd 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, 6th 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

March 22 **Tuesday** **Lecture 17**
Chirped Gratings, Tunable lasers

March 24 **Thursday** **Lecture 18**
Coupled mode theory, Waveguide couplers, MMIs, AWGs

March 29 **Tuesday** **Lecture 19**
Reciprocal and non-reciprocal polarization rotators

March 31 **Thursday** **Lecture 20** **Homework #7 due**
Franz-Keldysh and exciton effects

April 5 **Tuesday** **Lecture 21**
Quantum-confined Stark effect, EA modulators, EMLs, Mach-Zender modulators

April 7 **Thursday** **Lecture 22** **Homework #8 due**
Photoconductors

April 12 **Tuesday** **Lecture 23**
p-n junction photodiodes, p-i-n photodiodes

April 14 **Thursday** **Lecture 24**
Avalanche photodiodes, intersubband quantum-well photodetectors

April 19 **Tuesday** **Lecture 25** **Homework #9 due**
Special topics or catch up

April 21 **Thursday** **Lecture 26**
Special topics or catch up

April 26 **Tuesday** **Lecture 27**
Special topics

April 28 **Thursday** **Lecture 28**
Special topics

May 3 **Tuesday** **Lecture 29** **Last Class**
Special topics/Class discussion/Wrap-up

May 5 **Thursday** **Reading Day**
May 12 **Thursday** **8:00-11:00am** **FINAL EXAM (consists of Final Project presentations)**
TAKE-HOME Exam due

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%)

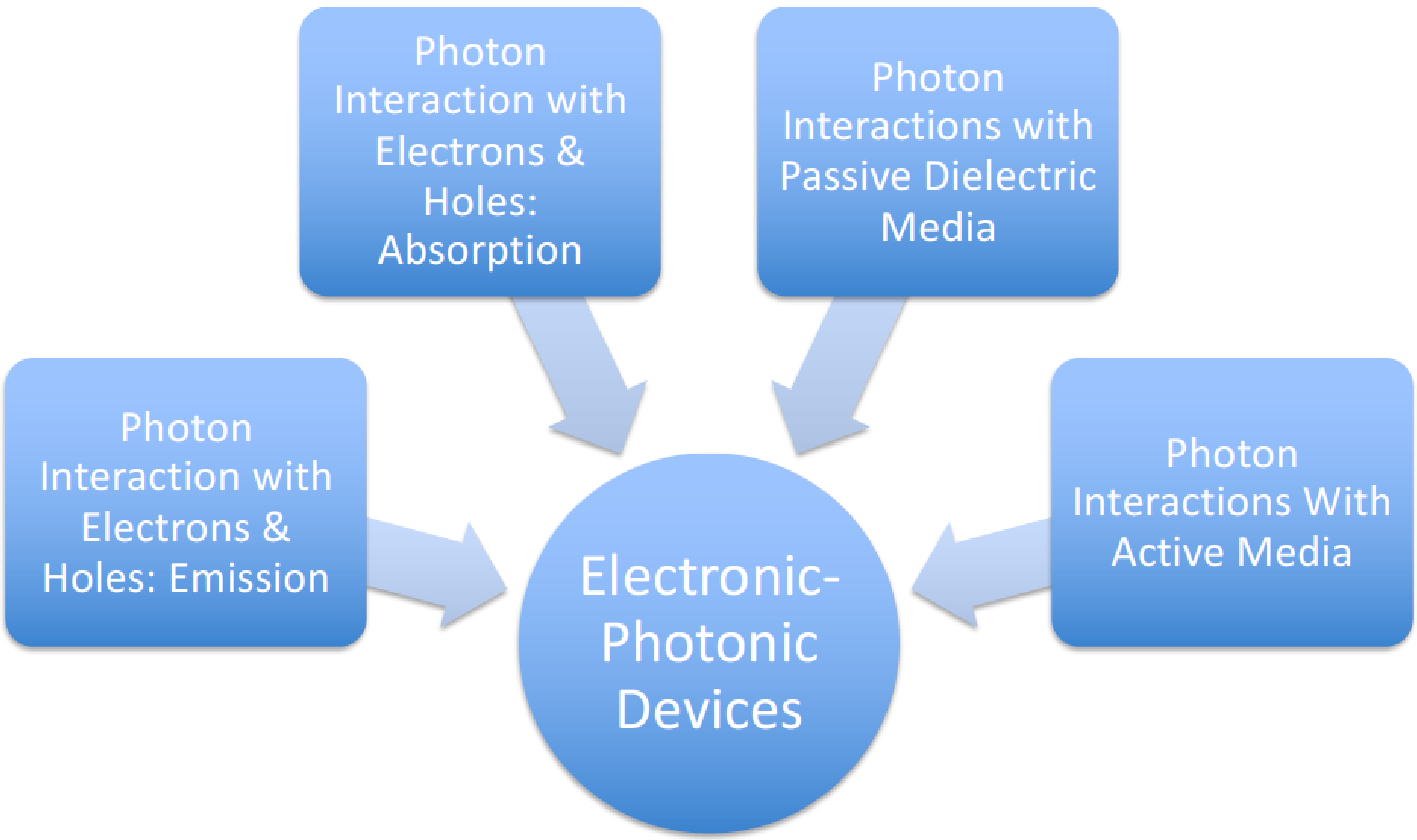
Computational component

- 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



(Thanks to Prof. Dallesasse for providing presentation material in this and future lectures)

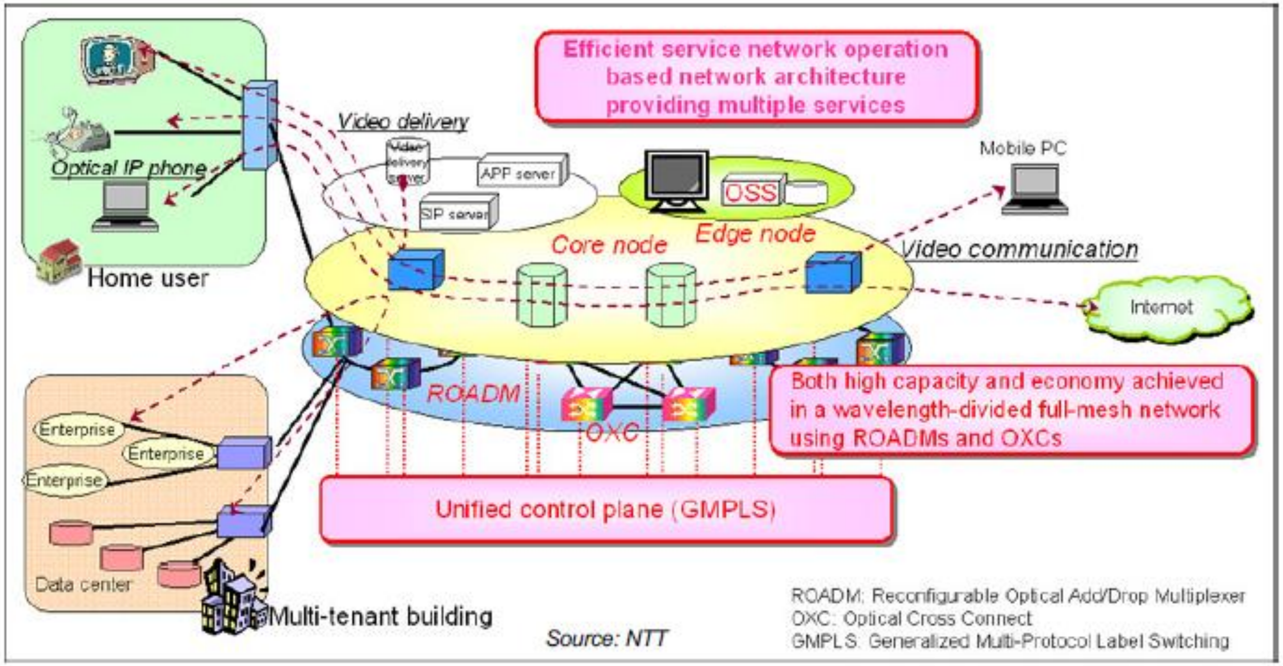
Motivation

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

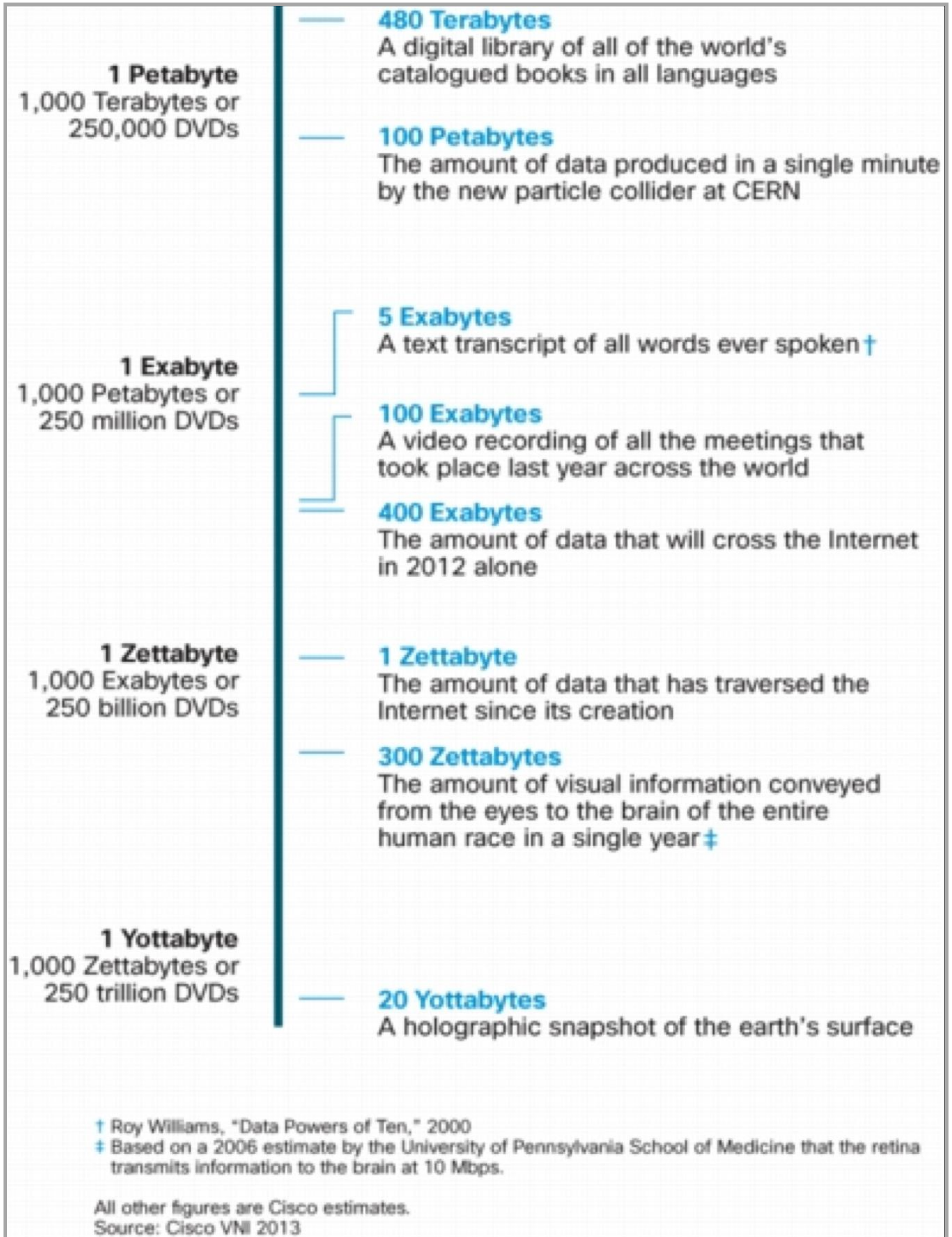


Electronics

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

Optics

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



The Scale of "Big Data"

https://www.cisco.com/c/en/us/solutions/executive-perspectives/annual-internet-report/index.html

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 from13 Mbps in 2018

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

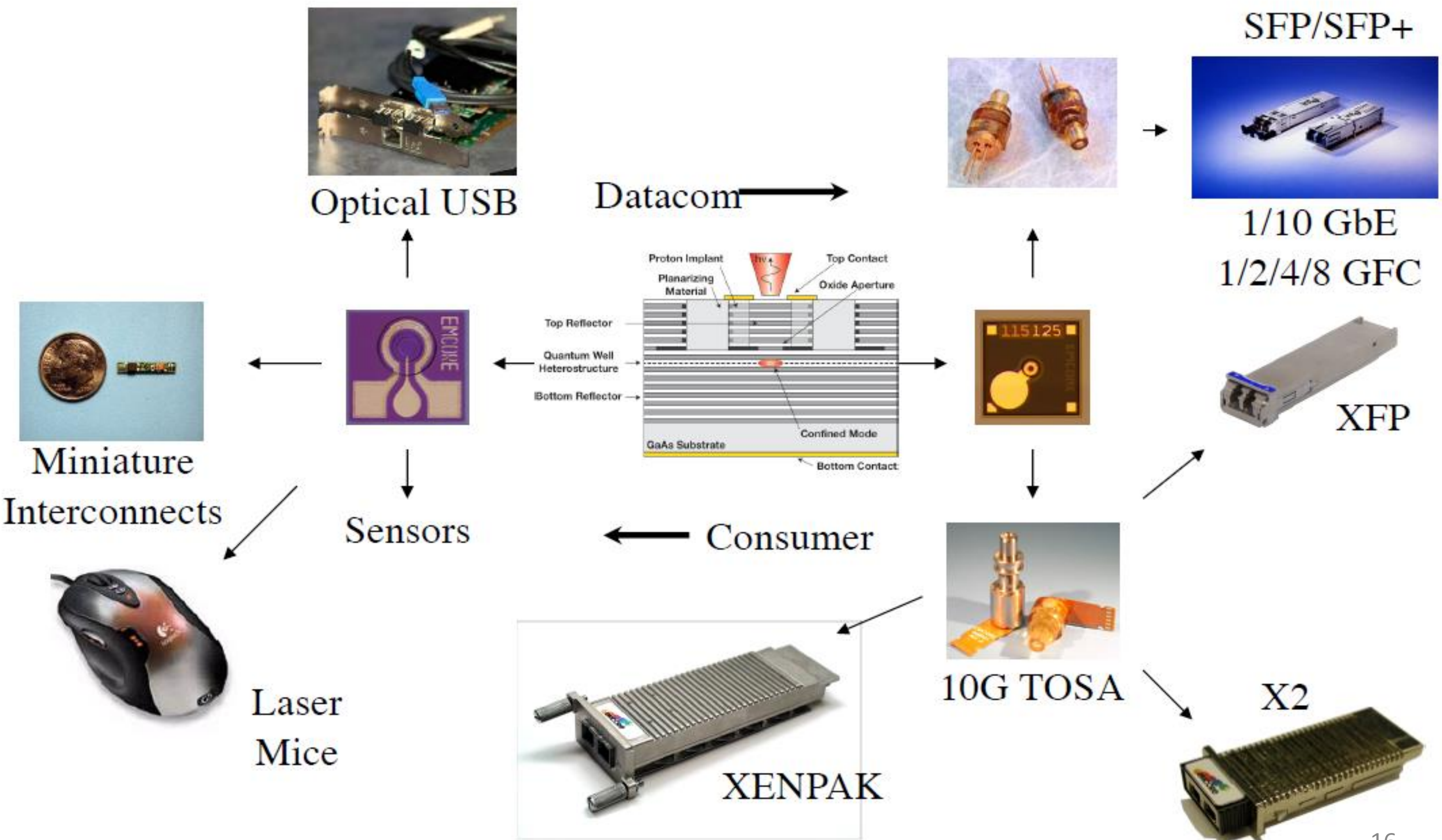
Optical Links in Data Centers and Supercomputers

Supercomputer Optical Interconnects

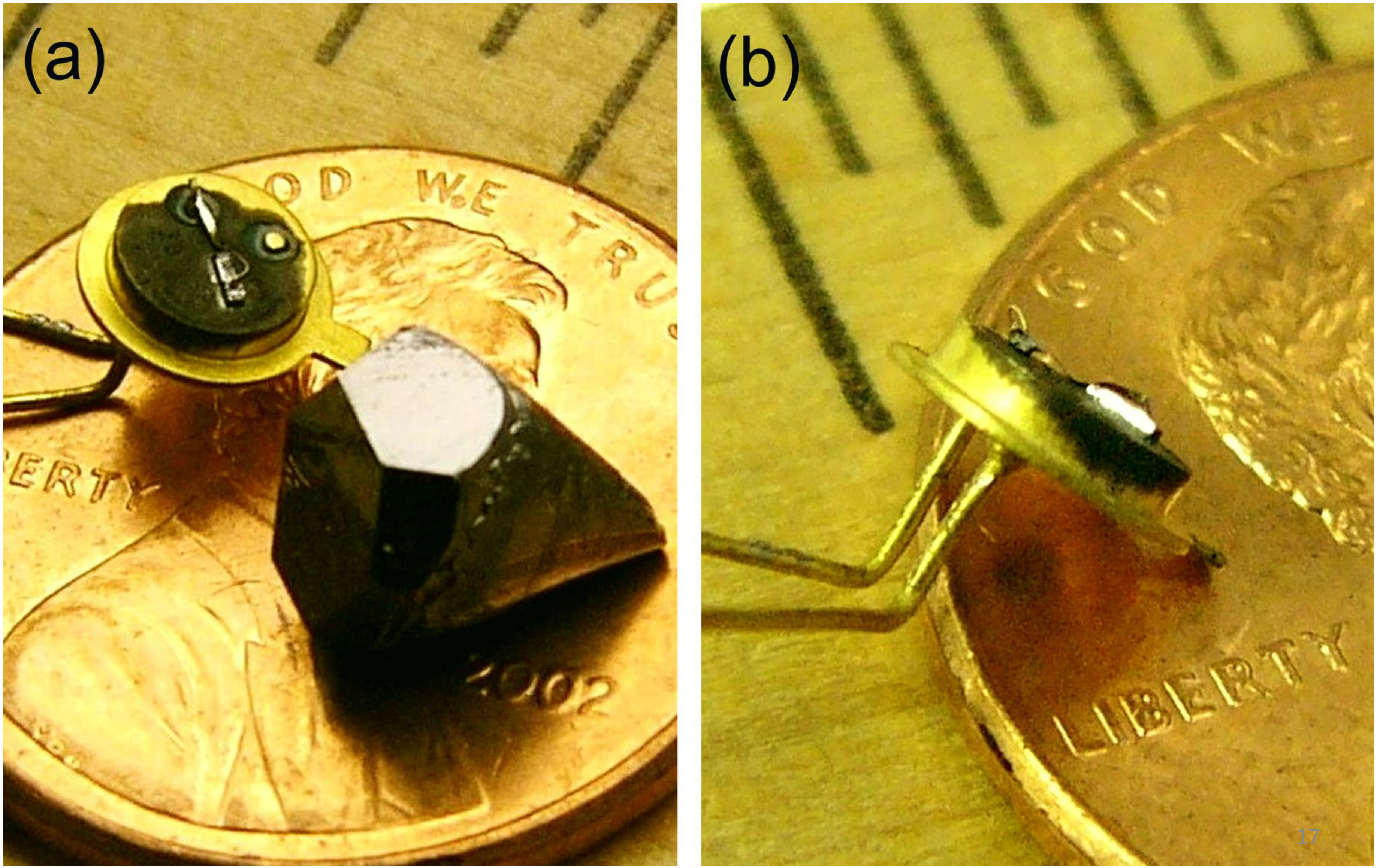
Server Room

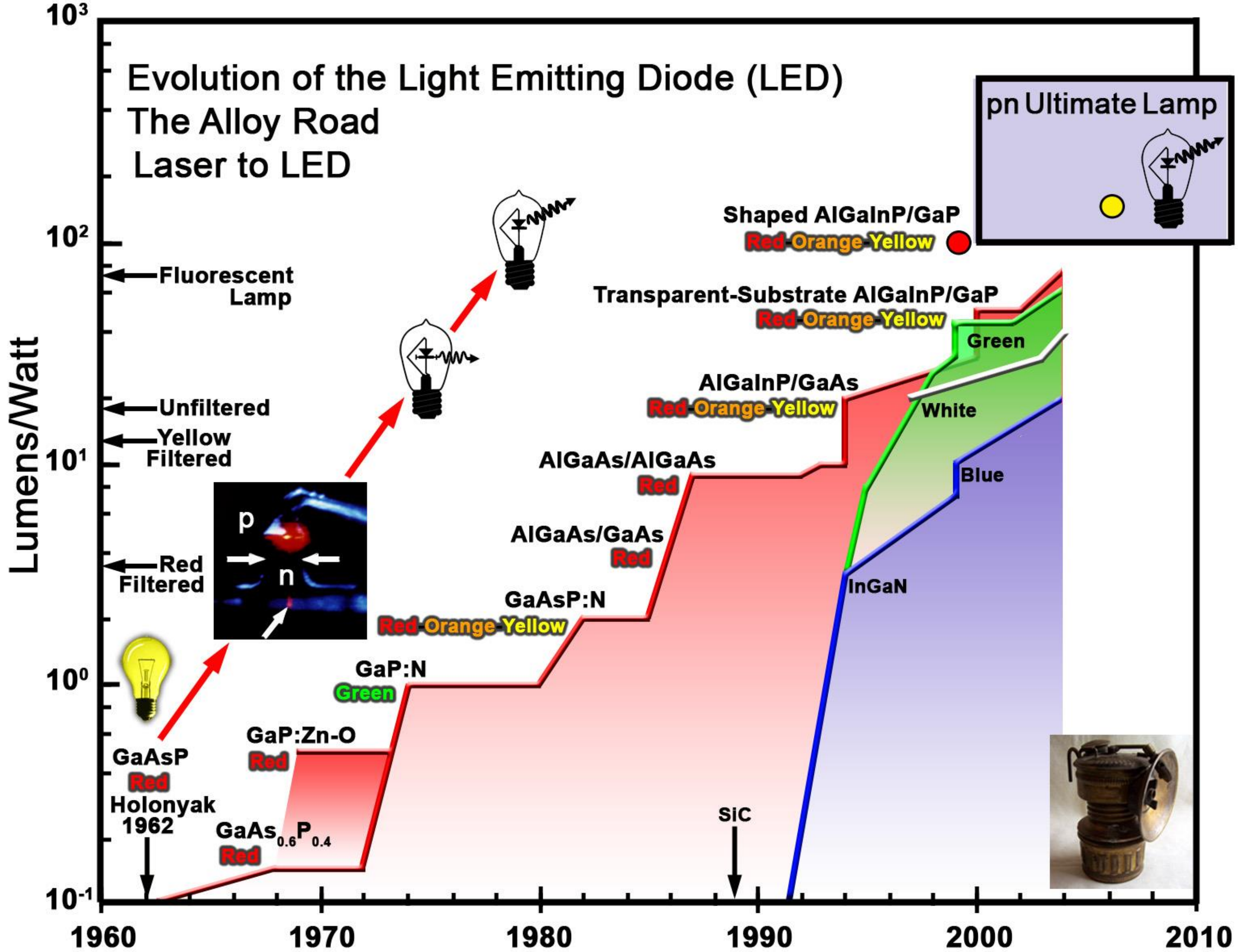
Data Center

VCSELs are revolutionizing optical interconnects



The First GaAsP Diode Laser





Evolution of the Light Emitting Diode (LED)
The Alloy Road
Laser to LED
pn Ultimate Lamp
Lumens/Watt
10³
10²
10¹
10⁰
10⁻¹
Fluorescent Lamp
Unfiltered
Yellow Filtered
Red Filtered
p
n
GaAsP
Red
Holonyak
1962
GaAs0.6P0.4
Red
GaP:Zn-O
Red
GaP:N
Green
GaAsP:N
Red-Orange-Yellow
AlGaAs/GaAs
Red
AlGaAs/AlGaAs
Red
AlGaInP/GaAs
Red-Orange-Yellow
Transparent-Substrate AlGaInP/GaP
Red-Orange-Yellow
Shaped AlGaInP/GaP
Red-Orange-Yellow
Green
White
Blue
InGaN
SiC
1960
1970
1980
1990
2000
2010

LED Applications

LED Traffic Signals

Source: gelightingsolutions.com

LED General Lighting

Source: led-resource.com

LED Backlit TV

Source: digitaltrends.com

Architectural Lighting

Source: vividleds.us

Automotive

Source: spie.org

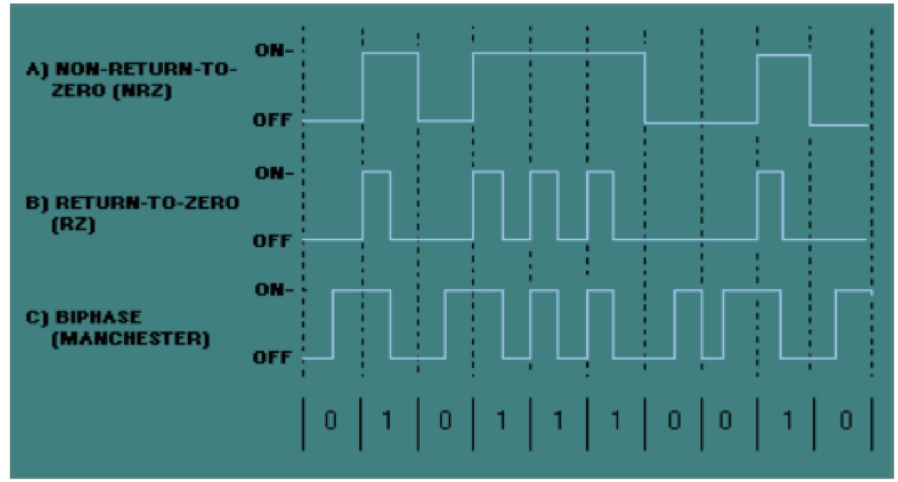
TV screens are developing rapidly

- 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…

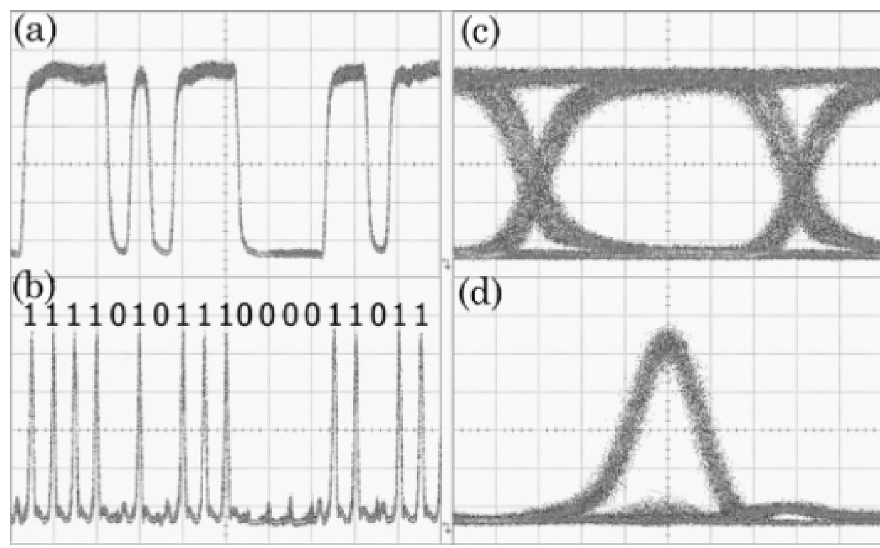
Evolution of Optical System Complexity

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



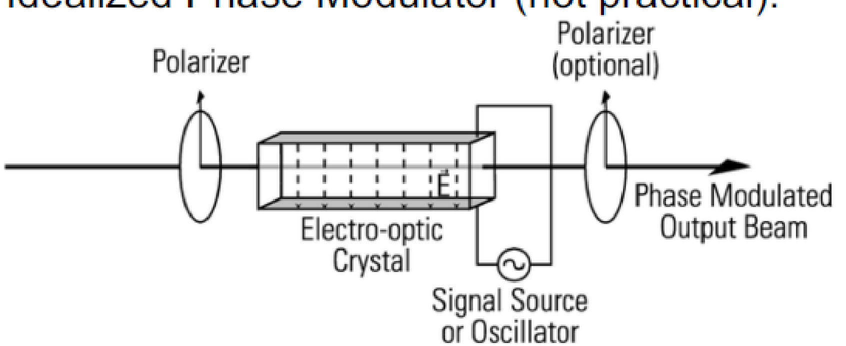
http://imagebank.osa.org/getImage.xqy?img=OG0kcC5sYXJnZSxhby00OS03LTExNTgtZzAwMg

Phase-Shift Keying

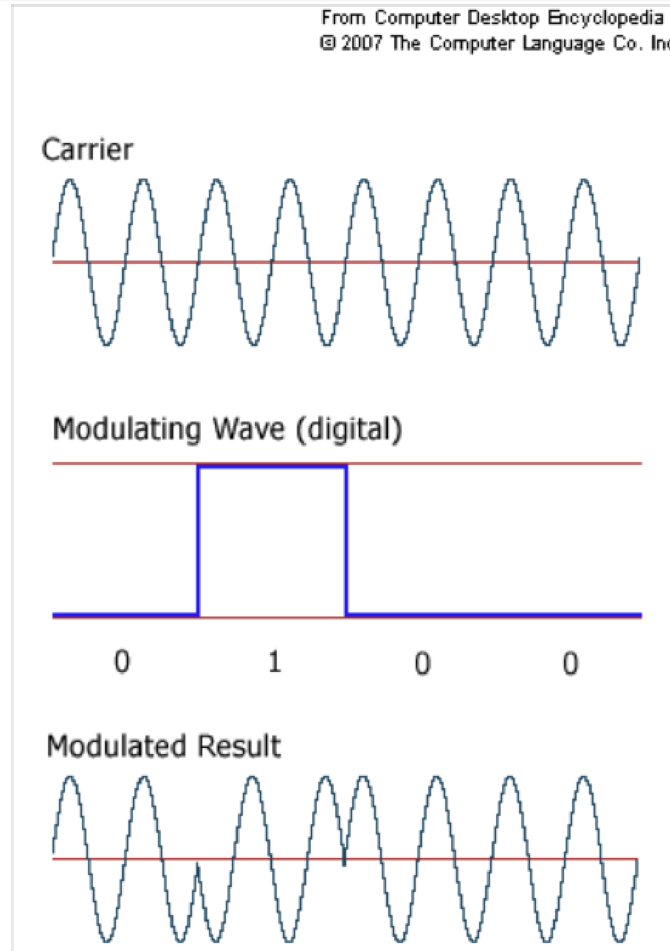
Phase-Shift Keying

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

Idealized Phase Modulator (not practical):



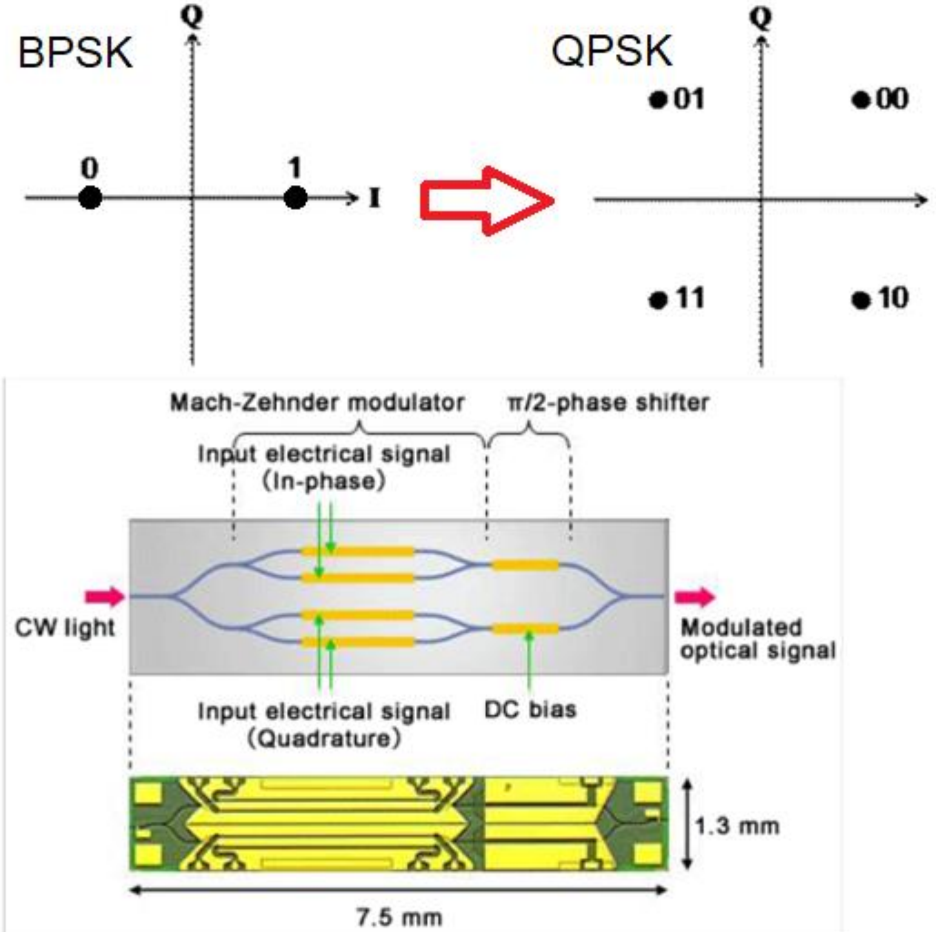
http://assets.newport.com/web600w-EN/images/13605.gif



http://img.tfd.com/cde/_PSK.GIF

Differential Quadrature Phase Shift Keying

- Constant-intensity modulation format
- Data is encoded into one of 4 phase states that are 90° 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

Polarization Multiplexing

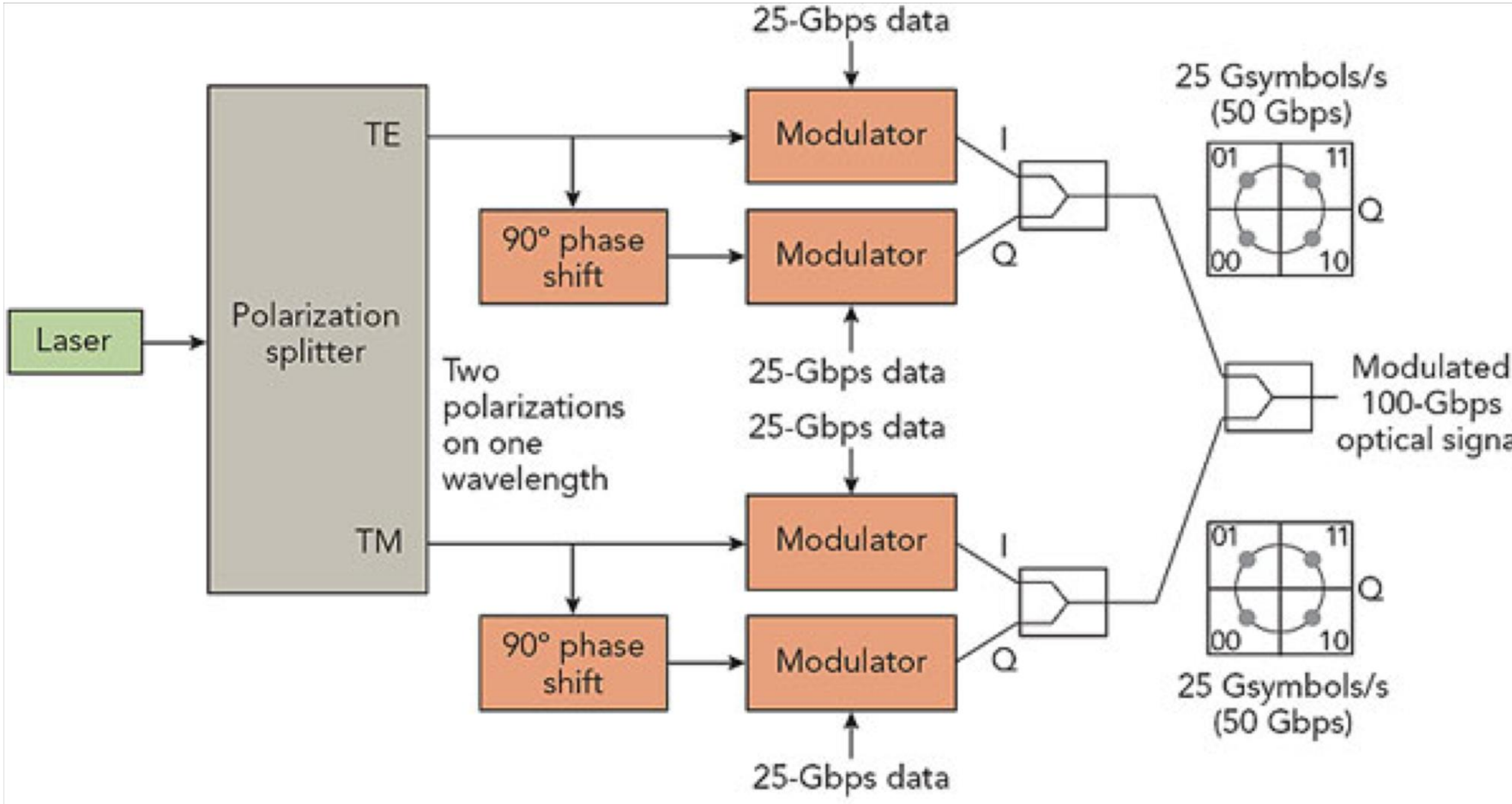
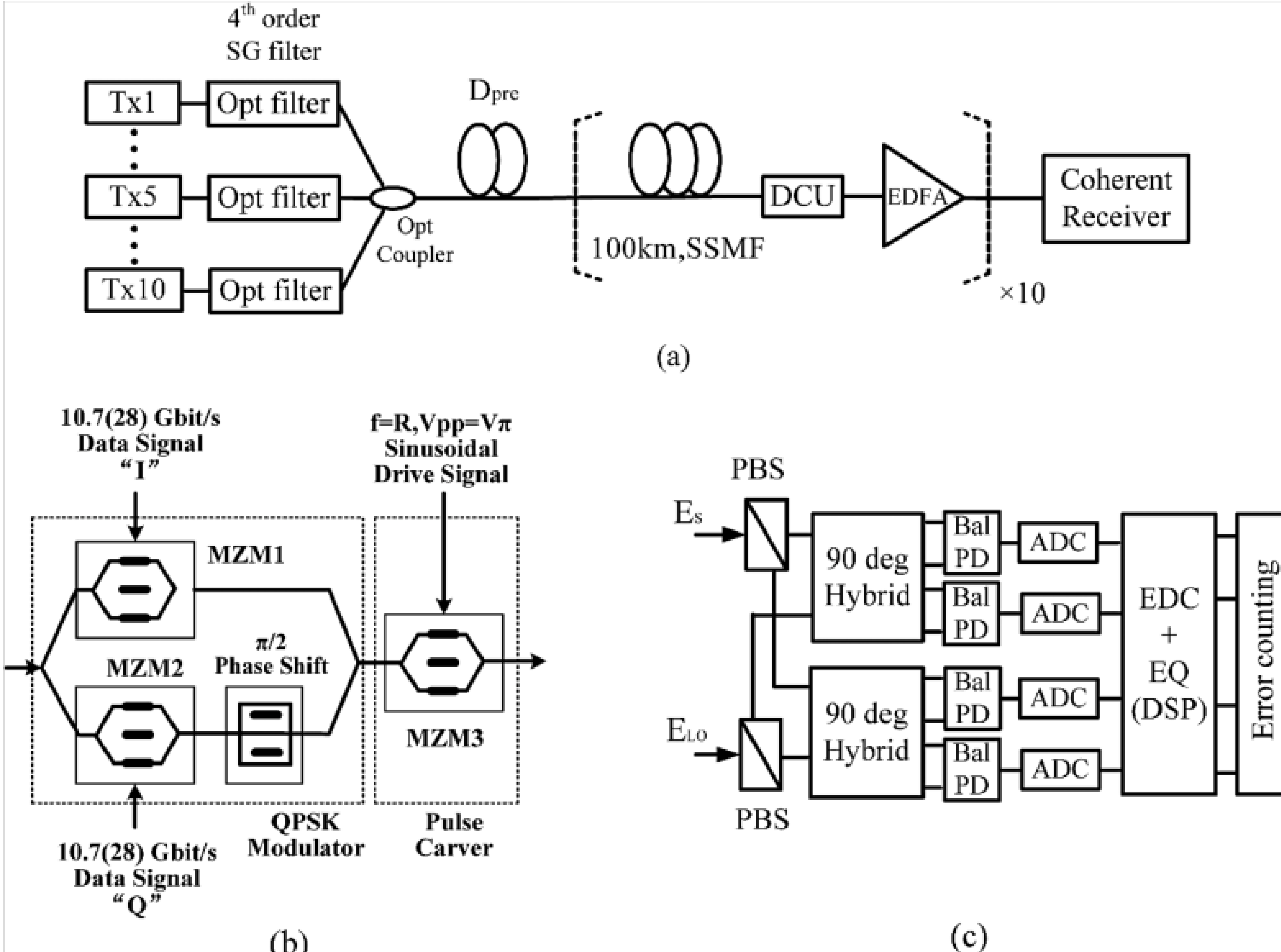


Figure 2 A 100-Gbps transmitter splits a laser into two polarizations and then modulates four 25-Gbps data streams onto a single fiber at a single wavelength.

http://www.edn-europe.com/cmsimages/0410/20f2.jpg

RZ DQPSK for long haul transmission



http://opticalengineering.spiedigitallibrary.org/data/Journals/OPTICE/24718/OE_51_7_075003_f001.png

Dual Polarization
DP-DQPSK for long haul transmission

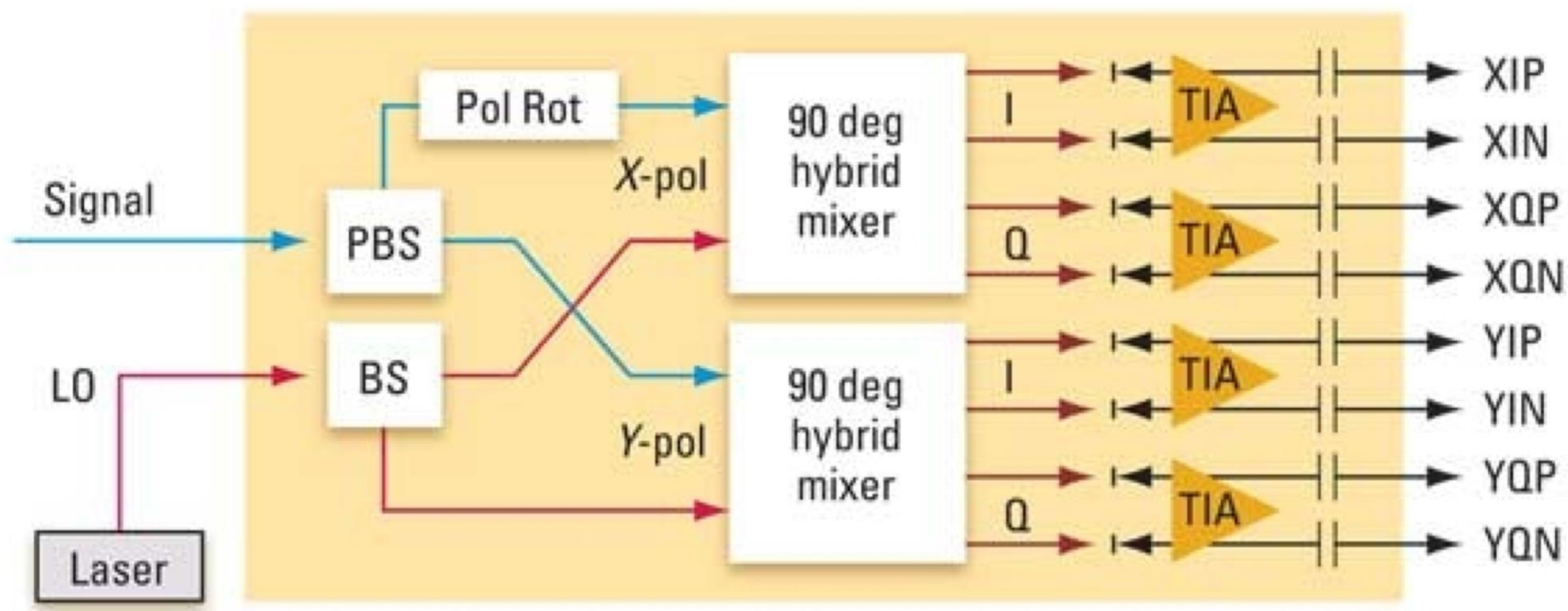
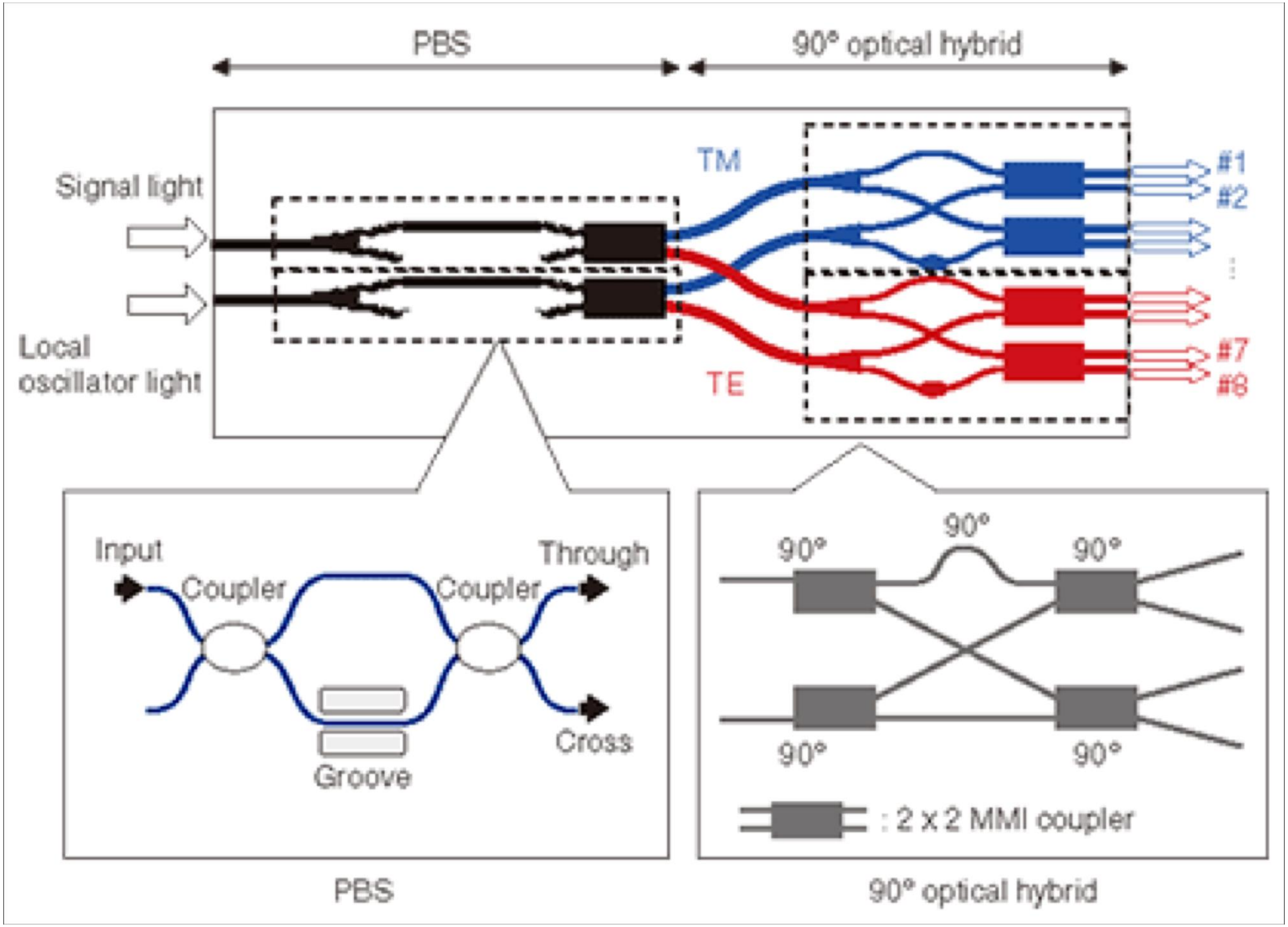


FIGURE 3. Block diagram of the optical receiver proposed for 100-Gbps DP-QPSK. (Source: OIF 100G Ultra Long Haul DWDM Framework Document.)

http://www.lightwaveonline.com/content/dam/etc/medialib/new-lib/lw/print-articles/lw/volume-27/issue-3/pg8a.jpg/_jcr_content/renditions/pennwell.web.600.302.jpg

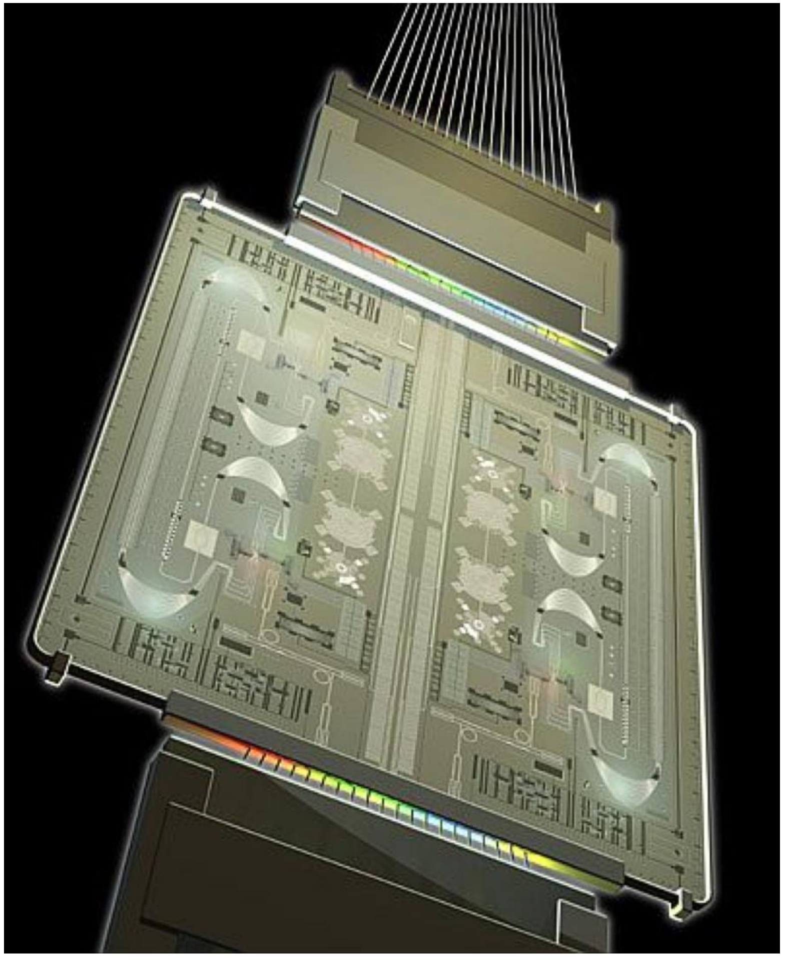
90° Optical Hybrid Mixer



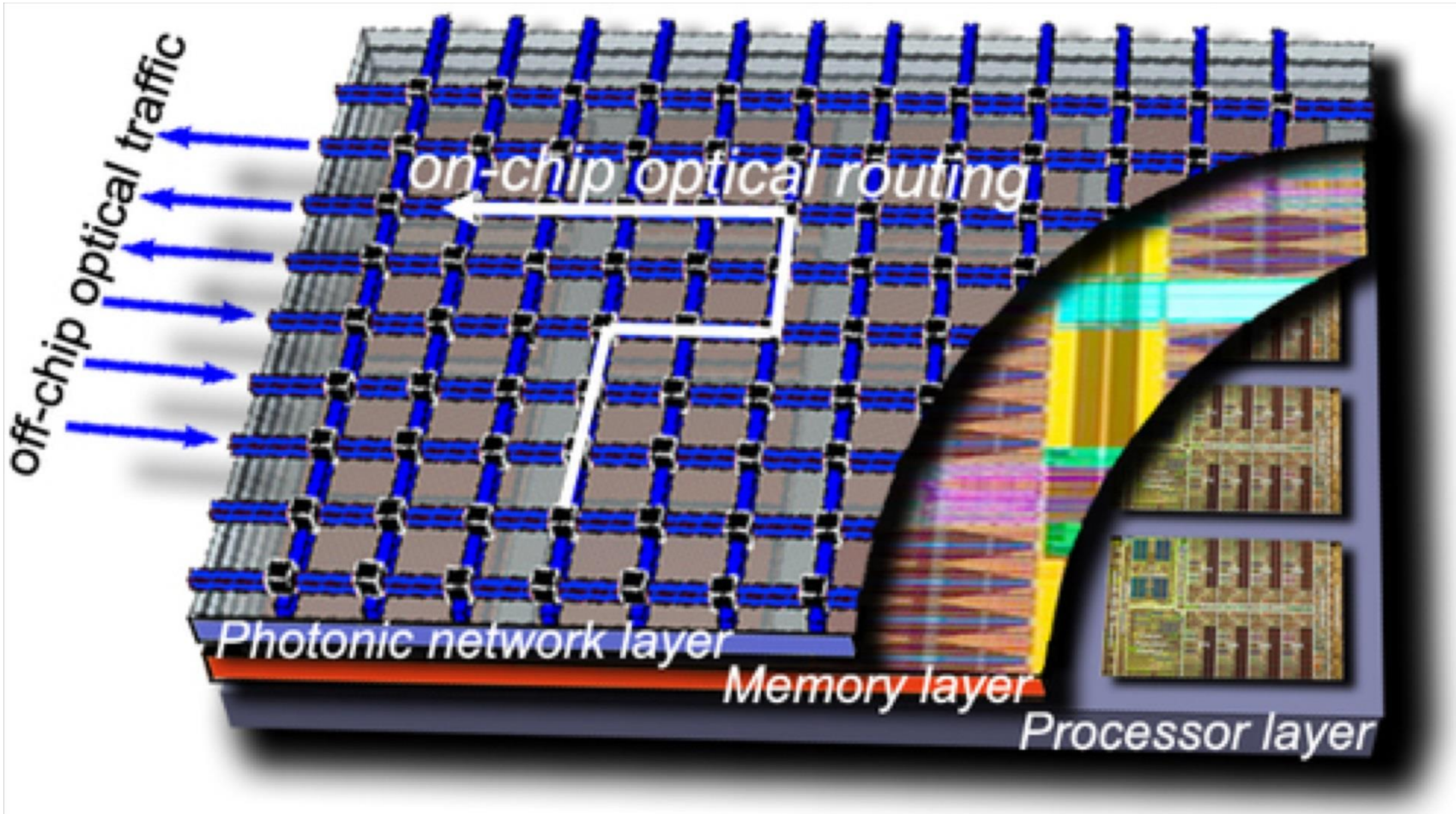
https://www.ntt-review.jp/archive_html/201103/images/fa9_fig04.gif

Photonic Integrated Circuit

Photonic integration solves practical issues associated with discrete implementations



On-Chip Optics?



http://media.tumblr.com/L2LtU8zYIi2t7noh5m280xpUo1_500.jpg

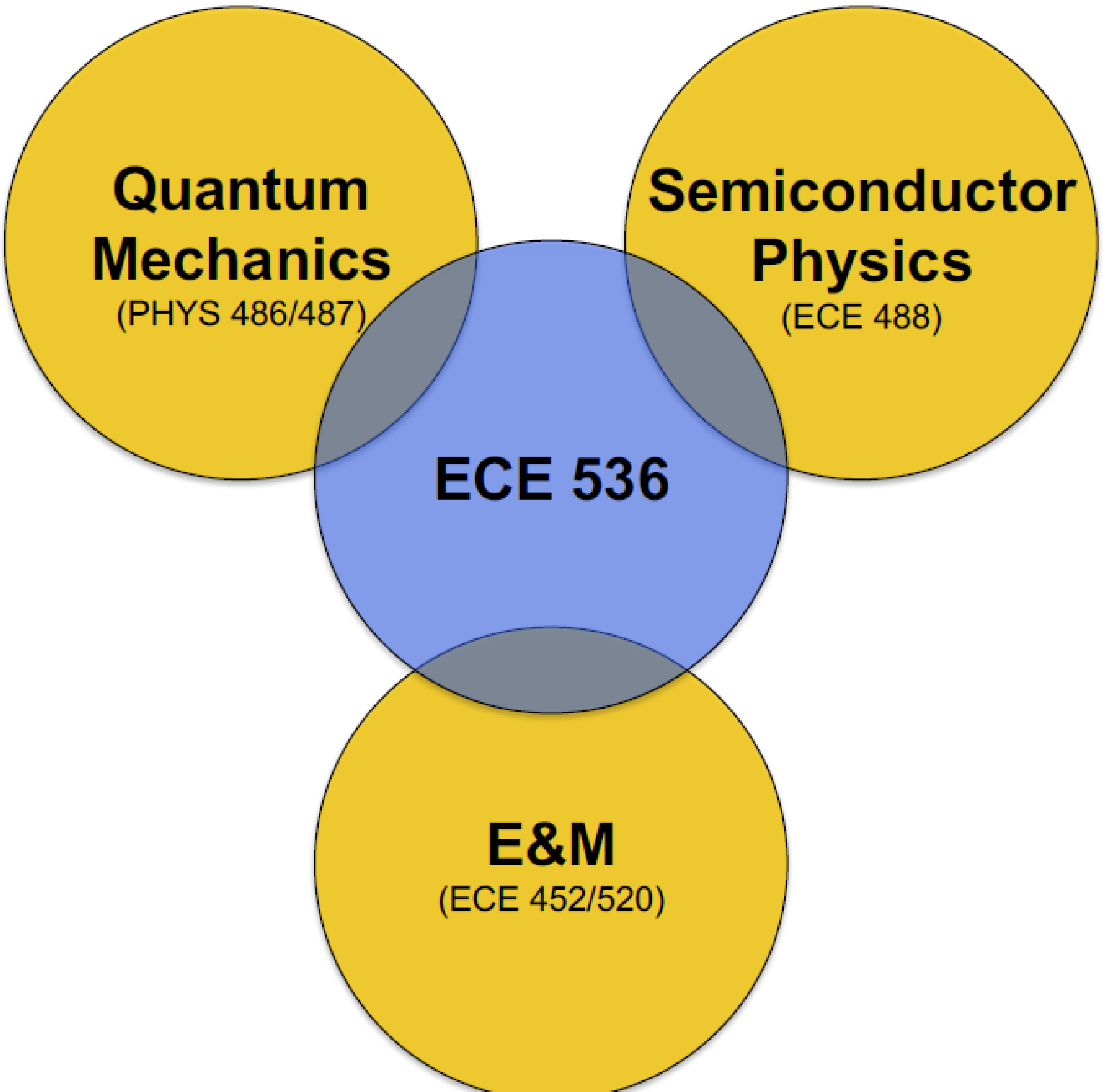
Course Purpose

- 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



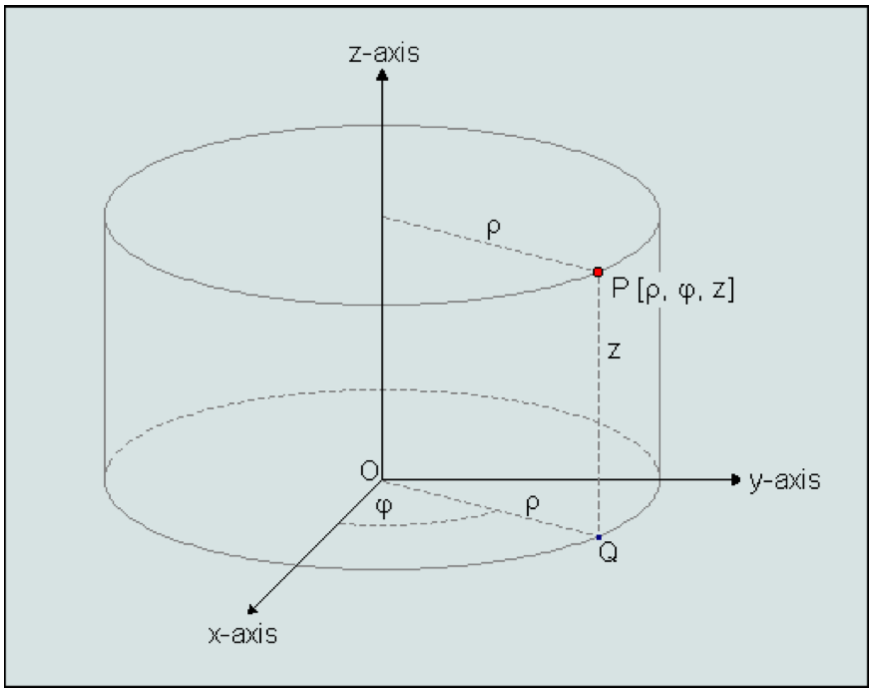
Important points (Chapter 1)

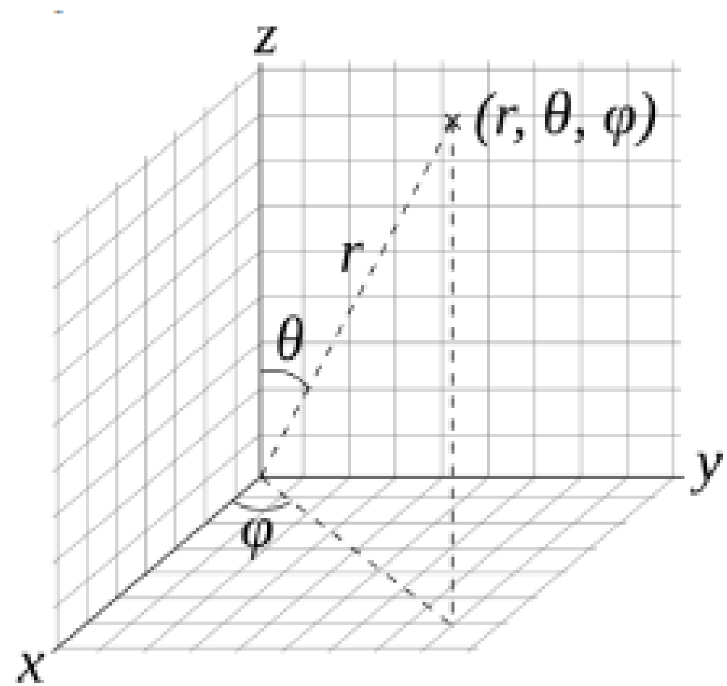
- Semiconductor Crystal Structures and Bonding Diagrams
- Relationship Between Photon Energy and Wavelength
- History of the Semiconductor Laser
- Evolution of LED Technology
- Condition for Lasing: Gain and Phase
- Mode Spacing in a FP Laser
- Heterojunctions
- Lattice Constant and Energy Gap in Alloy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

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

In Cylindrical Coordinates:

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

In Spherical Coordinates:

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

Maxwell’s Equations

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

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

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

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

$$\vec{D}(t) = \varepsilon \, \vec{E}(t)$$

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

In material media

$$\varepsilon = \varepsilon_r \, \varepsilon_0 \qquad ; \qquad \mu = \mu_r \, \mu_0$$

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

$$\varepsilon_r = \begin{bmatrix} \varepsilon_{xx} & \varepsilon_{xy} & \varepsilon_{xz} \\ \varepsilon_{yx} & \varepsilon_{yy} & \varepsilon_{yz} \\ \varepsilon_{zx} & \varepsilon_{zy} & \varepsilon_{zz} \end{bmatrix} \qquad ; \qquad \mu_r = \begin{bmatrix} \mu_{xx} & \mu_{xy} & \mu_{xz} \\ \mu_{yx} & \mu_{yy} & \mu_{yz} \\ \mu_{zx} & \mu_{zy} & \mu_{zz} \end{bmatrix}$$

In phasor form

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

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

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

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

$$\vec{\mathbf{D}} = \varepsilon\,\vec{\mathbf{E}}$$

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

General wave equations

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

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

Away from charges

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

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

Helmholtz equations (phasors)

$$\nabla^2 \vec{E} + \omega^2 \mu_0 \varepsilon_0 \vec{E} = 0$$

$$\nabla^2 \vec{H} + \omega^2 \mu_0 \varepsilon_0 \vec{H} = 0$$

(vacuum)

In material medium (phasors)

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

$$\nabla \times \vec{\mathbf{H}} = \sigma\,\vec{\mathbf{E}} + j\omega\varepsilon\,\vec{\mathbf{E}} = j\omega(\varepsilon - j\frac{\sigma}{\omega})\vec{\mathbf{E}}$$

$$\nabla \times \nabla \times \vec{\mathbf{E}} = \nabla\nabla \cdot \vec{\mathbf{E}} - \nabla^2\vec{\mathbf{E}} = -j\omega\mu\,\nabla \times \vec{\mathbf{H}}$$

$$= -j\omega\mu(\vec{\mathbf{J}}_{\mathbf{c}} + j\omega\varepsilon\,\vec{\mathbf{E}})$$

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

Reading Assignments

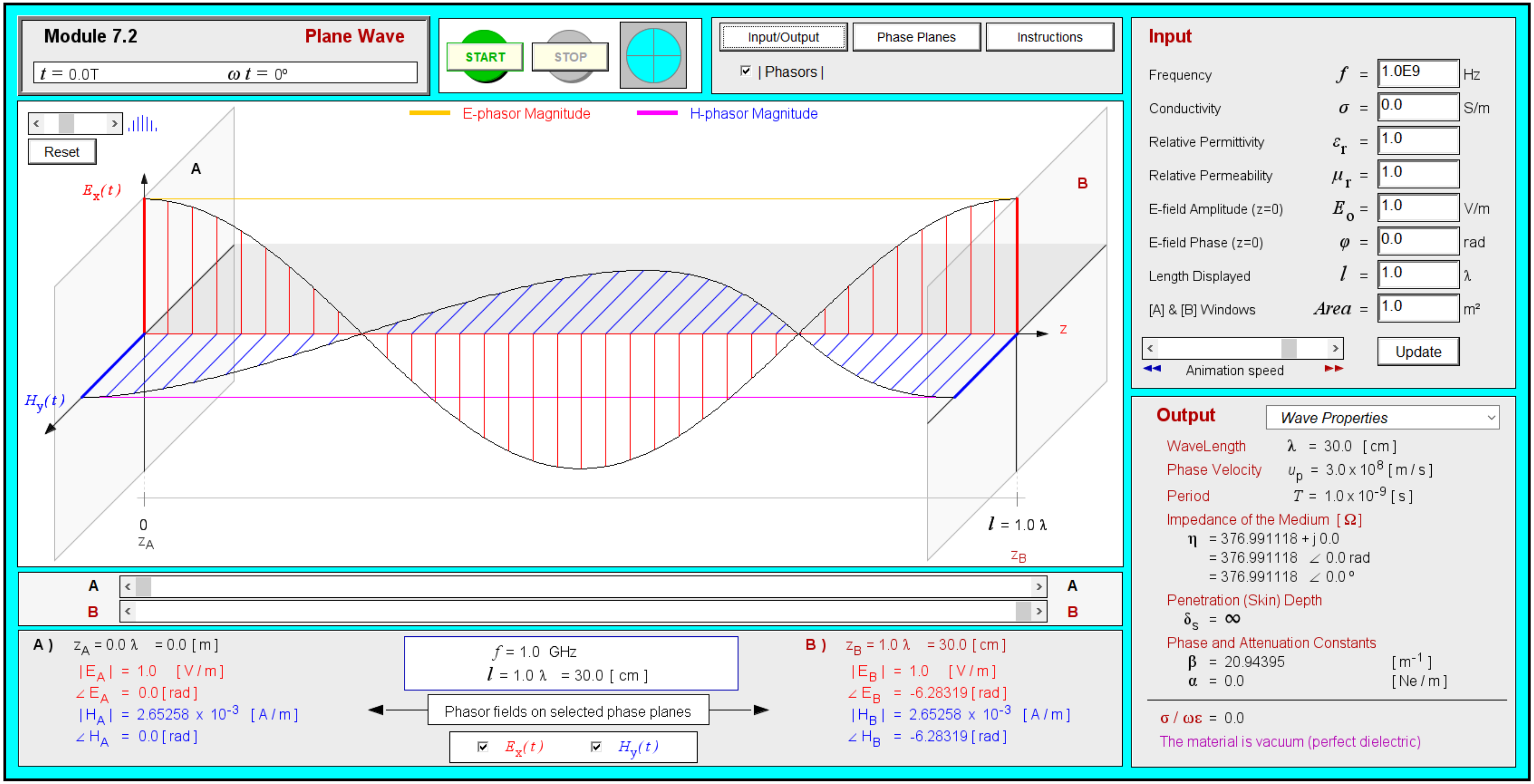
Chuang – Chapter 1, Section 2.1

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

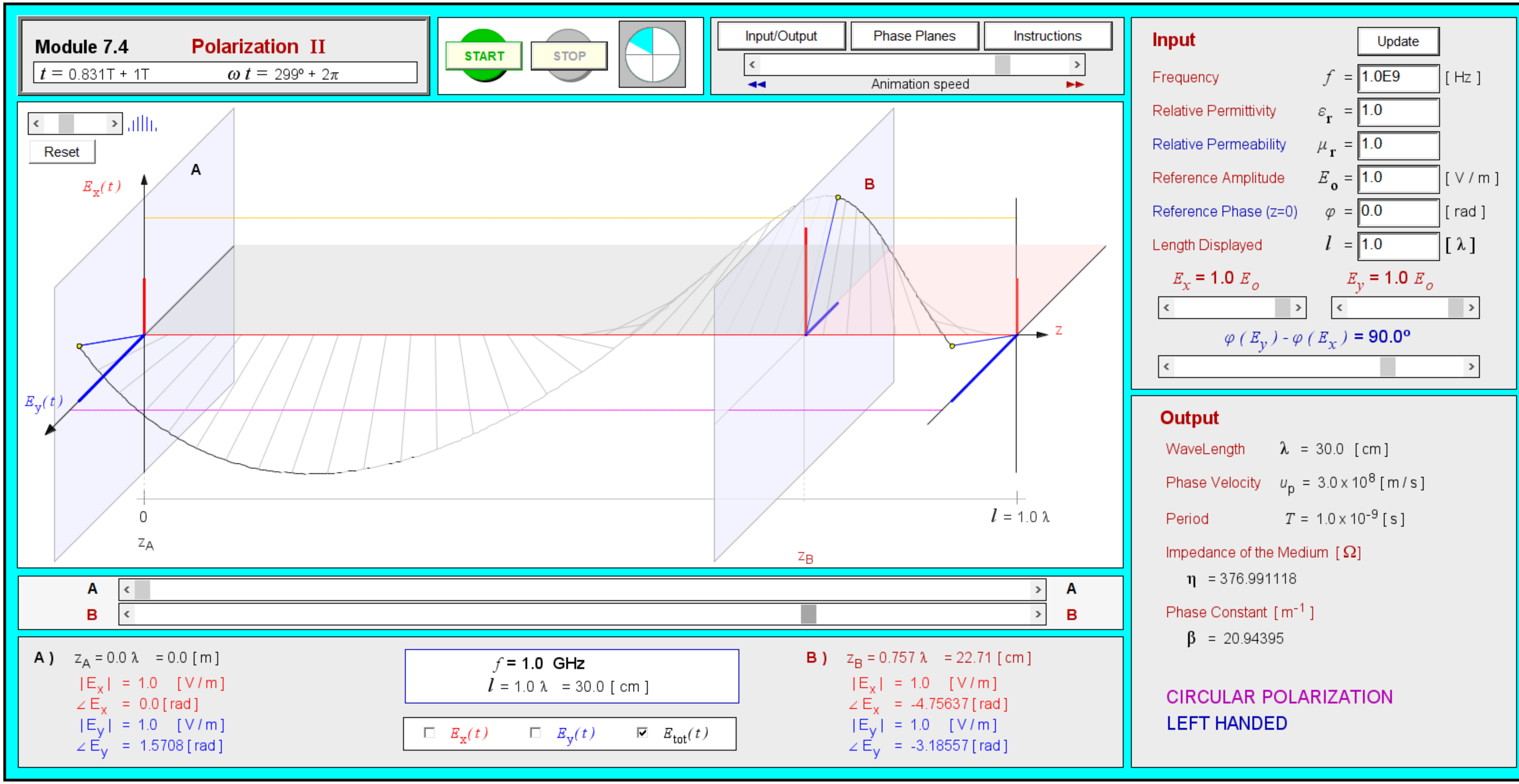
Several Java applications have been posted for you to download and keep (developed for the textbook Ulaby and Ravaioli, “Fundamentals of Applied Electromagnetics,” Pearson, 8th edition, 2020).

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.

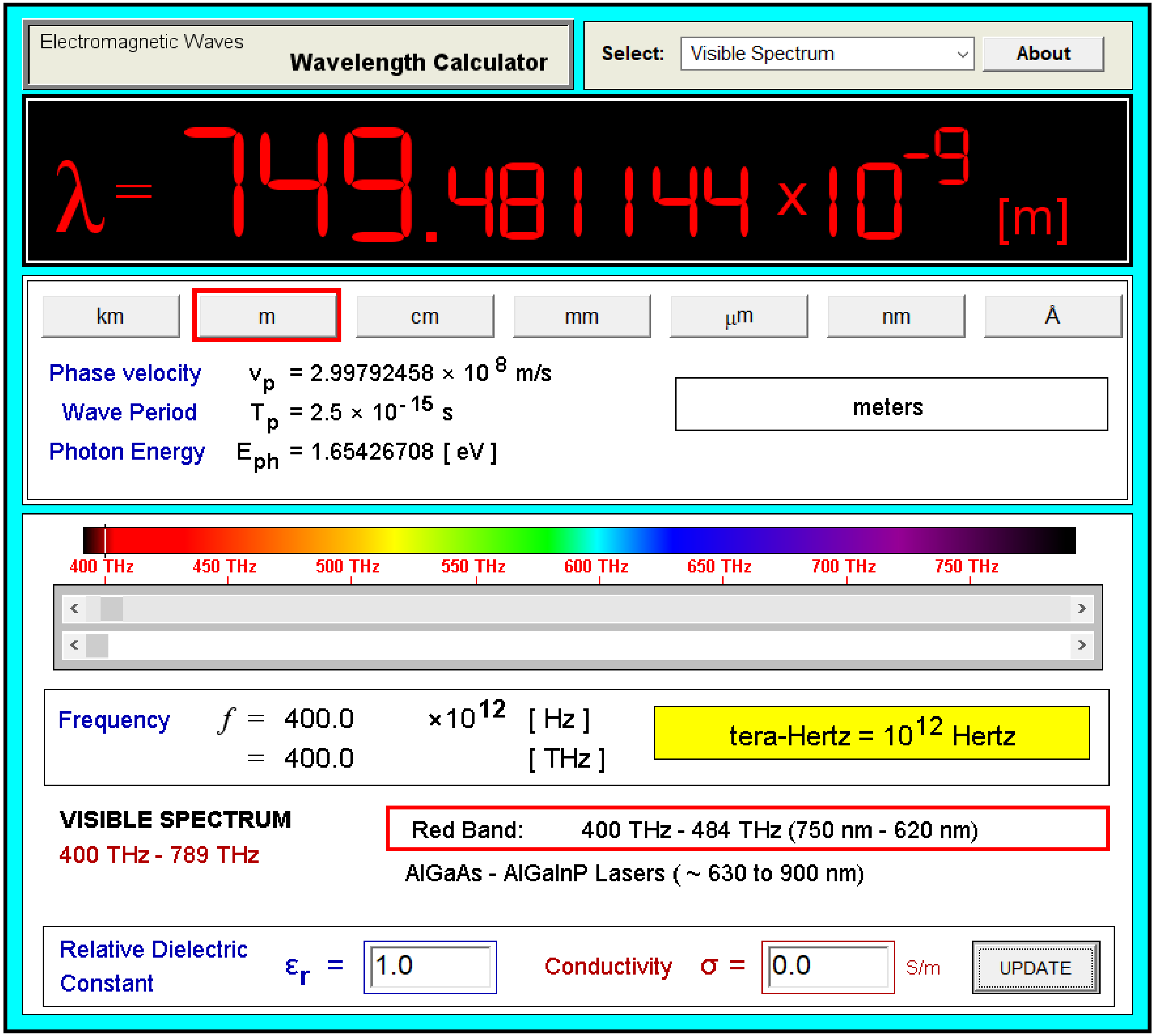
Plane Wave in material medium



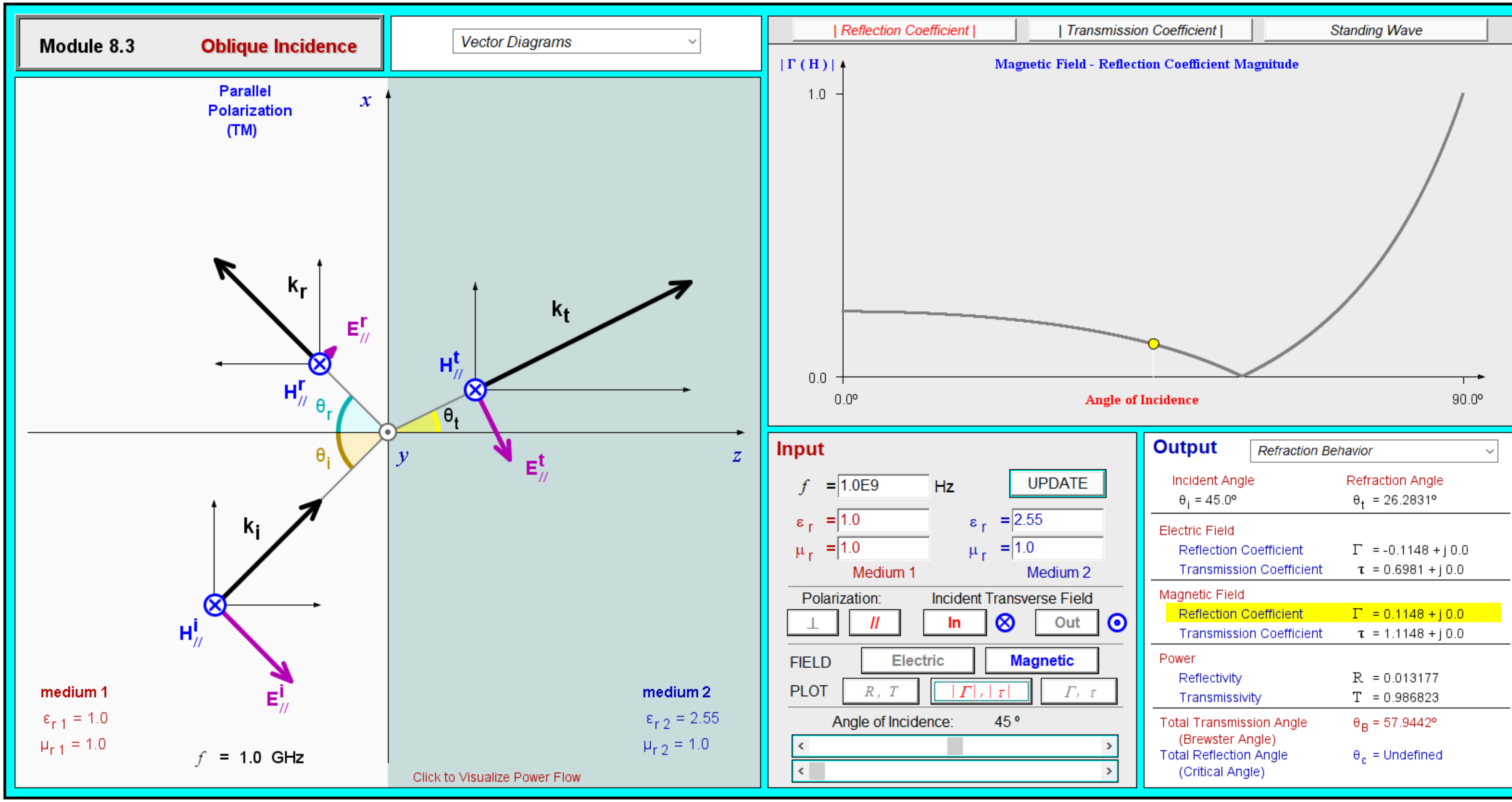
Polarization



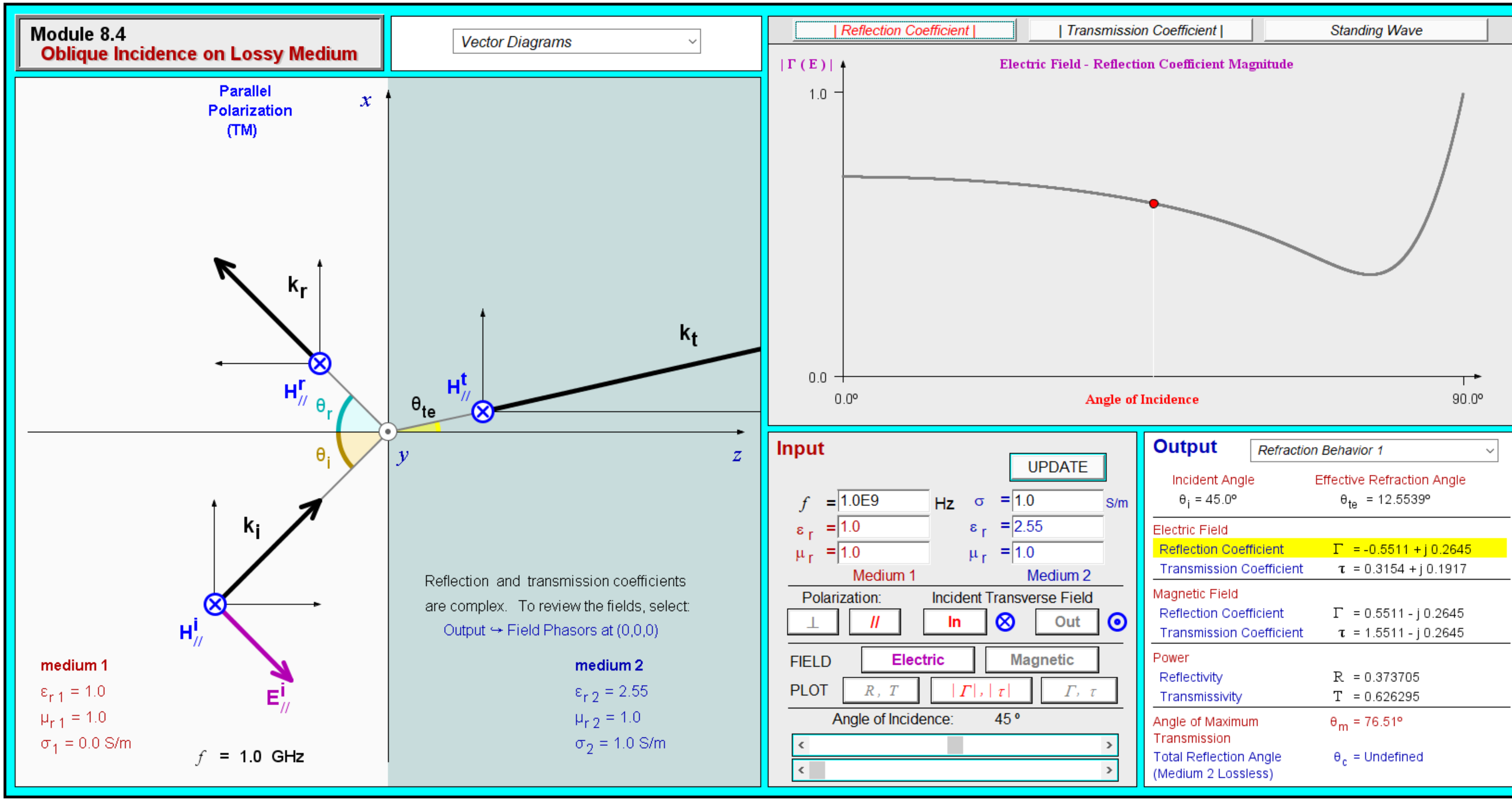
Wavelength Calculator



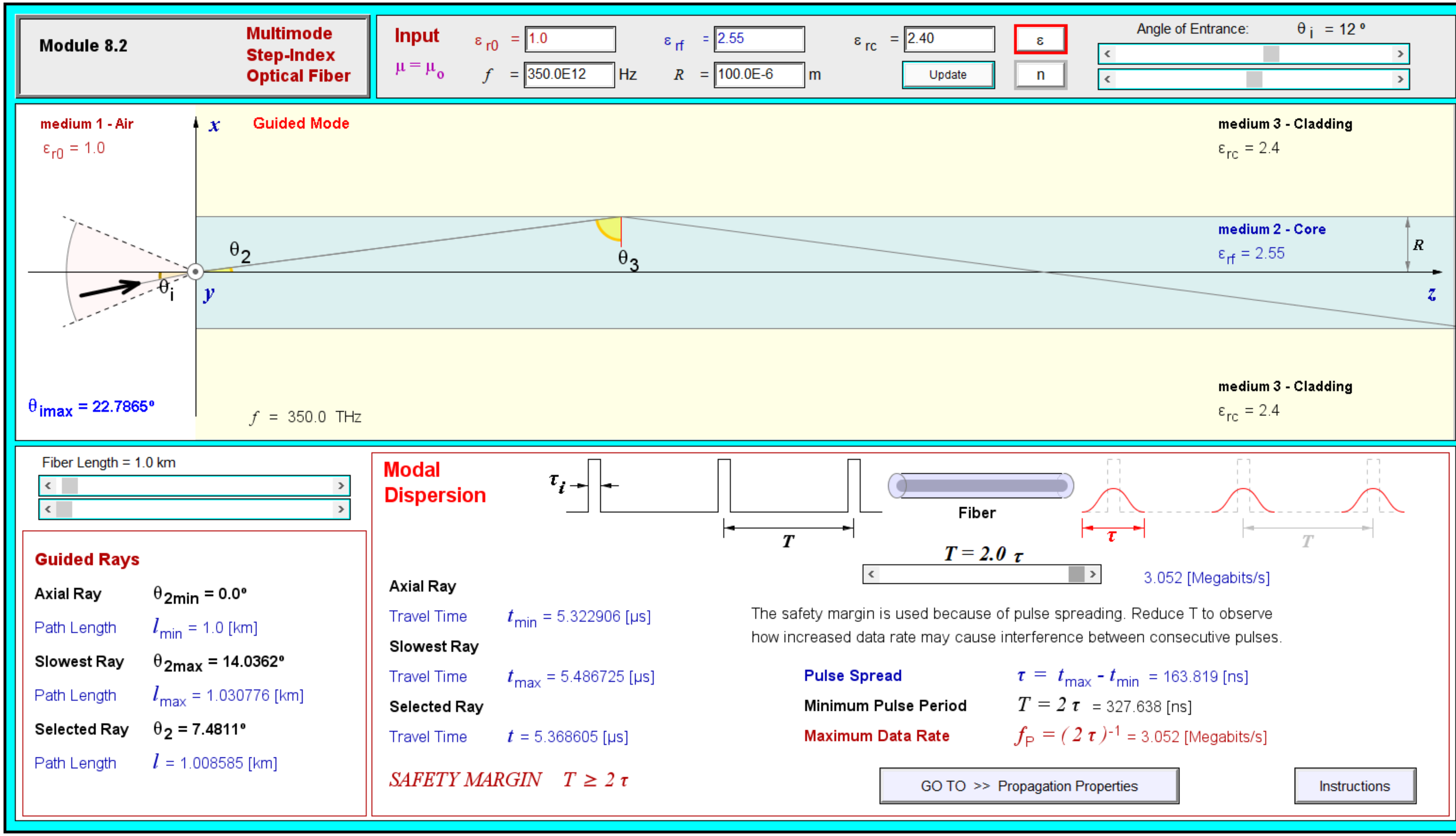
Oblique Incidence at dielectric-dielectric interface



Oblique Incidence at dielectric-lossy medium interface



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



Dielectric Slab Waveguide (EM modes representation)