OPTI510R: Photonics

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Announcements

- Homework #4 is assigned, due March 26th
- Start discussion on optical fibers
**Problem 1:** (15 points)

A femtosecond Er-doped fiber laser (working at 1560 nm center wavelength) emits a pulse train at 50 MHz repetition rate. The energy of each laser pulse is 20 pJ.

a) What is the distance between neighboring pulses in space (assuming the laser beam is in air)? (5 points)
b) What is the average power that the laser generates? (5 points)
c) What is the FWHM spectral bandwidth of the laser pulse if the duration of the pulse is ~100 fs (you can assume Gaussian shape and transform-limited pulse)? (5 points)
Problem 2: (20 points)

A ring resonator can be used to drop a channel in a communication system as shown below. The channel with wavelength which is on resonant with the ring resonator is dropped to the drop port, the off-resonant channels will just go through without any significant loss. Using the information given in the figures below:

a) Calculate the Free Spectral Range and the Finesse of the ring laser cavity (10 points)

b) Estimate the refractive index of the material used to make the ring resonator (10 points)

Figure 1: left) Off-resonant wavelength; right) On-resonant wavelength

Figure 2: The spectral response of the device at through and drop ports
Problem 3: (40 points)

Yttrium Orthovanadate (YVO$_4$) is a transparent uniaxial crystal that is used in many applications such as polarizing prisms, polarization independent isolators, or in divided-pulse amplification (DPA) of ultra-short optical pulses (which is a technique used to avoid nonlinear optical effects in high peak power fiber amplifiers). The Sellmeier equations for YVO$_4$ ($\lambda$ has unit in $\mu$m) are:

\begin{align*}
n_e^2 &= 4.59905 + 0.110534/(\lambda^2 - 0.04813) - 0.012267612 \lambda^2 \quad \text{(for extraordinary wave)} \\
n_o^2 &= 3.77834 + 0.069736/(\lambda^2 - 0.04724) - 0.0108133 \lambda^2 \quad \text{(for ordinary wave)}
\end{align*}

An unpolarized ultrashort Gaussian pulse (the electric field $E(t)$ of the pulse as the function of time is shown above on the right) propagates through a 10 cm thick YVO$_4$ crystal as shown. The speed of light in vacuum is $2.9979 \times 10^8$ m/s. The center wavelength of the pulse is 1.56 $\mu$m.

Give numerical answers to the following questions:

a) What is the FWHM duration of the input ultrashort Gaussian pulse? (10pts)
b) What are the phase velocities of the ordinary and extraordinary waves? (5pts)
c) What are the group velocities of the ordinary and extraordinary waves? (5pts)
d) The pulse will be divided into two pulses as shown. Assuming a walk off angle of 5 degrees, what is the delay time between the two pulses? (5pts)
e) Indicate the polarization of each pulse (5pts)
f) What are the durations of the pulses when they exit the crystal? (10pts)
**Problem 4:** (25 points)

Light of free-space wavelength $\lambda_0 = 1.56 \, \mu\text{m}$ is guided by a thin planar film of width $d = 5 \, \mu\text{m}$ and refractive index $n_1 = 1.5$ surrounded by a medium of refractive index $n_2 = 1.46$.

a) Determine the number of TE modes. (5pts)

b) Determine the bounce angle $\theta_0$ and the group velocity $v_g$ of the $m = 0$ TE mode (10pts)

c) Calculate the propagation constants $\beta_m$ for all supported TE modes (10pts)
Planar dielectric waveguide

Symmetric waveguide

Reflection due to TIR

(similar to planar mirror waveguide)

\[
\sin \frac{c}{2} = \frac{n_2}{n_1}
\]

\[
\frac{\sin \frac{c}{2}}{2} = \frac{\sin 1}{n_2} \frac{1}{n_1} = \cos 1 \frac{n_2}{n_1}
\]

Self Consistency

\[
\frac{2\pi}{\lambda} 2d \sin \theta - 2\varphi_r = 2\pi m
\]

\[
2k_y d - 2\varphi_r = 2\pi m
\]
Transcendental equation for modes

\[
\tan\left(\frac{\pi d}{\lambda} \sin \theta - \frac{m \pi}{2}\right) = \sqrt{\frac{\sin^2 \theta_c}{\sin^2 \theta}} - 1
\]

dielectric waveguide

mirror waveguide \( \phi_r = \pi \), or \( \tan(\phi_r / 2) = \infty \)
Number of modes

\[ M \doteq \frac{\sin \theta_c}{\lambda/2d} \], or \[ M \doteq \frac{2d}{\lambda_0} NA \], where \[ NA = \sqrt{n_1^2 - n_2^2} \]

Single mode \[ \frac{2d}{NA} < 1 \]
Universal dispersion curve

Solid lines ($\delta = 5$); dashed lines ($\delta = 0$)
Introduction to optical fibers

Outline:

• Introduction

• Geometrical optics description

• Wave optics description

• Fiber modes
THE GLOBAL TELECOMMUNICATIONS NETWORK

From “Understanding Fiber Optics” by Jeff Hecht

= Optical Fiber
Introduction to optical fibers

Figure 1: Location of physical conduits for networks considered in the continental United States.

Table 1: Number of nodes and long-haul fiber links included in the initial map for each ISP considered in step 1.

<table>
<thead>
<tr>
<th>ISP</th>
<th>AT&amp;T</th>
<th>Comcast</th>
<th>Cogent</th>
<th>EarthLink</th>
<th>Integra</th>
<th>Level 3</th>
<th>Suddenlink</th>
<th>Verizon</th>
<th>Zayo</th>
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<tr>
<td>Number of nodes</td>
<td>25</td>
<td>26</td>
<td>69</td>
<td>248</td>
<td>27</td>
<td>240</td>
<td>39</td>
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<tr>
<td>Number of links</td>
<td>57</td>
<td>71</td>
<td>84</td>
<td>370</td>
<td>36</td>
<td>336</td>
<td>42</td>
<td>151</td>
<td>111</td>
</tr>
</tbody>
</table>
Google Fiber starts with a connection that's up to 1,000 megabits per second.
Introduction to optical fibers

2014
Submarine Cable Map
www.telegeography.com | www.submarinecablemap.com
Cross Section: Deep-Sea Submarine Cable

- Thick Polyethylene Jacket
- Steel Wires
- Plastic Fill
- Optical Fiber
- Copper Tube (carries electric power)
- Copper-Clad Steel “King” Wire
- Nylon Jacket
Advantages

- Economics: Fewer repeaters
- Capacity: Much wider bandwidth (> 10 GHz)
- Distance
- Weight/size
- Freedom from interference
- Safety: Electrical isolation
- Security: More difficult to tap
Challenges

- Higher initial cost in installation
- More expensive to repair
- Strength: Lower tensile strength
Brief history

1841: Daniel Colladon demonstrates light guiding in jet of water
Geneva
1842: Jacques Babinet reports light guiding in water jets and bent
glass rods Paris
1880: William Wheeler invents system of light pipes to illuminate
homes from an electric arc lamp in basement, Concord, Mass.
January 2, 1954: Hopkins and Kapany and van Heel publish
separate papers in Nature. Hopkins and Kapany report imaging
bundles of unclad fibers; van Heel reports simple bundles of clad
fibers
December 8, 1956: Curtiss makes first glass-clad fibers by rod-in-
tube method
May 1961: Elias Snitzer of American Optical publishes theoretical
description of single-mode fibers
July 1966: Kao and Hockham publish paper outlining their proposal
in the Proceedings of the Institution of Electrical Engineers
Summer 1970: Maurer, Donald Keck, Peter Schultz, and Frank
Zimar at Corning develop a single-mode fiber with loss of 17 dB/km
at 633 nanometers by doping titanium into fiber core

(credit: J. Hecht)
Brief history

Figure 1.3: Increase in the capacity of lightwave systems realized after 1980. The dotted lines indicate a nearly exponential growth in the bit rate for both the research and commercial systems. Note the change in the slope after 2001.
Brief history

The Nobel Prize in Physics 2009

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

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

Charles K. Kao: 1/2 of the prize
Willard S. Boyle: 1/4 of the prize
George E. Smith: 1/4 of the prize
Geometrical description of fiber

- Contain a central core surrounded by a lower-index cladding
- Two-dimensional waveguides with cylindrical symmetry
- Step-index fiber: refractive index of the core is uniform
- Graded-index fibers: refractive index varies inside the core
Optical fibers

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

Photonics crystal fibers

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

Applications of optical fibers

- Telecommunication
- Lasers and amplifiers
- Sensors
- Light delivery and transportation
- Supercontinuum generation
- Pulse compression
- ...
Fiber Lasers

Best average output power (W)

- **Pr$^{3+}$**: 491, 520, 605, 695
- **Yb$^{3+}$**: 1020-1080 nm
- **Nd$^{3+}$**: 1250-1350 nm
- **Bi$^{3+}$**: 1530-1630 nm
- **Er$^{3+}$**: 1800-2100 nm
- **Tm, Ho**: 2700-2900 nm
- **Er:ZBLAN**
Fiber Lasers

CNN: The laser burning up the business world
Fiber Optics at COS

Groups at COS that use fiber optics:

- Khanh Kieu
- Naser Peyghambarian
- Jason Jones
- Bob Norwood
- Jim Burge
- Russell Chipman
- Poul Jessen
- Art Gmitro, Urs Utzinger
- Mahmoud Fallahi
- Milorad Cvijetic
- Rongguang Liang
- Tom Milster
- Brian Anderson
- Raymond Kostuk
- Jennifer Barton