OPTI510R: Photonics

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Announcements

- Homework #4 is assigned, due March 25th
Fiber fabrication

Outline:

- Fiber dispersion

- Fiber fabrication
  - Types of optical fibers
  - Fiber materials
  - Fabrications techniques
  - Specialty optical fibers
In single-mode fibers the group delay, \( \tau_g \), determines the transit time of a pulse traveling through a unit length of fiber. To get the waveguide dispersion we want to express the group delay in terms of normalized parameters, \( b \) and \( V \):

\[
\tau_g = \frac{d\beta}{d\omega} = \frac{d\beta}{dk_0} \frac{dk_0}{d\omega} = \frac{1}{c} \frac{d\beta}{dk_0}.
\]

Using normalized parameters:

\[
\frac{d\beta}{dk_0} = \frac{d\beta}{dV} \frac{dV}{dk_0} = \frac{d\beta}{dV} \frac{V}{k_0}.
\]

We get:

\[
\tau_g = \frac{1}{c} \frac{d\beta}{dk_0} = \frac{1}{c k_0} \frac{V}{dV} \frac{d\beta}{dV}.
\]
Waveguide dispersion

Defining $\Delta = \frac{n_{\text{core}} - n_{\text{clad}}}{n_{\text{core}}}$ and with $\beta = [b(n_{\text{core}} - n_{\text{clad}}) + n_{\text{clad}}]k_0 \approx k_0 n_{\text{clad}} (1 + b\Delta)$ (when $\Delta$ is small),

$$\tau_g = \frac{1}{c} \frac{V}{k_0} \frac{d}{dV} \left[k_0 n_{\text{clad}} (1 + b\Delta)\right]$$

$$= \frac{1}{c} \frac{V}{k_0} \frac{d(k_0 n_{\text{clad}})}{dV} + \frac{1}{c} \frac{V}{k_0} \frac{d(b\Delta k_0 n_{\text{clad}})}{dV}$$

$\tau_w$ : waveguide delay

$\tau_m$ : material delay

$$\tau_w = \frac{1}{c} \frac{V}{k_0} \frac{d(b\Delta k_0 n_{\text{clad}})}{dV}.$$ Noting that $V = \sqrt{2\Delta n_{\text{clad}} k_0 a}$, we get:

$$\tau_w = \frac{1}{c} n_{\text{clad}} \Delta \frac{d(bV)}{dV},$$ from which we get the waveguide dispersion

$$d\tau_k = \frac{1}{c} n_{\text{clad}} \Delta \frac{d^2(bV)}{dV^2}.$$ With $dV = a\sqrt{n_{\text{core}}^2 - n_{\text{clad}}^2} dk_0$ and $d\lambda = -\frac{\lambda}{k_0} dk_0$,

we finally get:

$$d\tau_k = -\frac{n_{\text{clad}} \Delta}{c\lambda} \frac{d^2(bV)}{dV^2}.$$ Note: Here we have neglected the dependence of $\Delta$ on $k_0$, which is negligibly small.
Waveguide dispersion

\[ b, \frac{d(Vb)}{dV} \text{ and } V \frac{d^2(Vb)}{dV^2} \text{ as a function of the V number:} \]

Chromatic dispersion of SMF

- Chromatic dispersion is the combination of material and waveguide dispersion in single-mode fiber (SMF)

\[
D = -\frac{\lambda}{c} \frac{d^2 n_{\text{core}}}{d\lambda^2} - \frac{n_{\text{core}} \Delta V}{c \lambda} \frac{d^2 (Vb)}{dV^2}
\]

\[
(D_{\text{Material}}) \quad (D_{\text{Waveguide}})
\]

at 1.55 μm, 
D=+17ps/km-nm

at 1.312 μm, dispersion is zero

Dispersive pulse broadening

Eye-diagrams

Lee’s PhD thesis
Dispersion compensation

- Pre-chirp technique
- Dispersion engineered fibers
- Dispersion compensating fibers
- Chirped fiber Bragg grating
- Tunable dispersion compensation
Dispersion engineered fiber

Engineer the index profile around the core region to modify dispersion properties
Dispersion engineered fiber

- No dispersion at 1550nm
- But strong Four-Wave-Mixing cross-talk
- Need non-zero dispersion shifted fibers
Dispersion engineered fiber

Non-zero dispersion shifted fibers

Diagram showing dispersion vs wavelength with two lines: one with a dispersion of approximately +3 ps/nm-km and another with approximately -3 ps/nm-km. The wavelength is labeled as $\lambda$ and the dispersion is measured in ps/nm-km.
Dispersion compensating fibers

Total Dispersion in Several Fiber Types

- Standard Single Mode: Zero at 1.3 μm
- Nonzero Dispersion-Shifted: Zero at 1.5 μm

Dispersion-Compensating
Dispersion compensating fibers

- **Standard fiber**
- **Dispersion compensating fiber**

Advantage:
- Fiber format
- Low cost
- Broadband

Disadvantage:
- Small mode field diameter
- Higher loss

\[
\beta_{21}L_1 + \beta_{22}L_2 = 0, \quad \text{or} \quad D_1L_1 + D_2L_2 = 0.
\]
Tunable dispersion compensation

- Provide adjustable dispersion
- Compensate residual dispersion
Tunable dispersion compensation

• Provide adjustable dispersion

• Compensate residual dispersion
Tunable dispersion compensation
Tunable dispersion compensation

VIPA variable dispersion compensator

Optical circulator

Collimating lens

Line-focusing lens

Glass plate

Focusing lens

3-Dimensional Mirror

$D_c > 0$

Variable x-axis

$D_c < 0$

VIPA: Virtually Imaged Phased Array

Semi-Cylindrical Lens

Input

AR (R= 0%)$

$\theta$

Outputs

Virtual Images

$R = 100\%$

$R \approx 95\%$

Fujitsu
Tunable dispersion compensation

Eye-diagrams
Optical fibers fabrication

- Types of optical fibers
- Fiber materials
- Fabrications techniques
- Specialty optical fibers
Optical Fibers

Light is kept in the core by total internal reflection (TIR is not the only mechanism - PCF)
Types of optical fiber

Types of fiber by construction:

- step index
- graded index
- PM fiber
- photonic crystal fiber
- multi-core fiber
Types of optical fiber

Types of fiber by material:

- Glass fibers
- Plastic fibers
- Liquid fibers
- Crystalline fibers?

UA integrated liquid-core optical fiber
Types of optical fiber

Types of fiber by functionality:

- passive fibers
- active fibers

![Graph showing best average output power (W) for different fiber types and wavelengths.]

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

- Numerical aperture: 
  \[ NA = \sqrt{n_1^2 - n_2^2}, \]

- V number:
  \[ V = \frac{2\pi}{\lambda} a NA = \frac{2\pi}{\lambda} a \sqrt{n_{\text{core}}^2 - n_{\text{cladding}}^2} \]

- Core size, MFD

- Polarization maintaining or not polarization maintaining

- Dispersion

- Attenuation

- Nonlinear coefficient
Optical fiber materials

Requirements:

- Low propagation loss
- Low dispersion
- Easy to process
- High mechanical strength
- High chemical stability
- Low cost

Glassy materials (fused silica, polymer)
Glassy materials

American Society for Testing Materials (1945):
“Glass is an inorganic product of fusion which has cooled to a rigid condition without crystallization”

Satisfactory for glasses most familiar to us: windows, containers … But new methods other than cooling a melt were developed: sputtering, sol gels…

1976:
“Glass is an X-ray amorphous material which exhibits the glass transition, this is being defined as the phenomenon in which a solid amorphous phase exhibits with changing temperature a more or less sudden change in the derivative thermodynamic properties, such as heat capacity and expansion coefficient, from crystal-like to liquid like values.”
Glasses have the mechanical rigidity of crystals, but the random disordered arrangement of molecules that characterizes liquids.
Properties of glassy state

- Lack of long range repeatable order, non-crystalline structure
- Typically produced from the liquid state by continuous cooling
- Exhibits what is known as the glass transition
- Can be formed from most liquids, provided cooling rate is sufficiently high
How to make glass?

- Mix and heat a composition of chemicals to high temperature
- Keep the mixture at high temperature for chemical reaction
- Quickly reduce the temperature to annealing point
- Anneal at moderate temperature to reduce internal stresses
- Slowly bring to room temperature

Recommend: Corning museum of glass
(http://www.cmog.org/)
Thermal properties

**Most materials:**
- Viscosity of melt ~ water (10-2 Pas)
- Cooling melt → rapid crystallization ~ Tm

**Glass forming materials:**
- Melt with considerable higher viscosity
- Significantly less crystallization below Tm
- If crystallization rate is low enough fast cooling below Tm w/o crystallization possible
- Further cooling: viscosity rising to such high values that the mechanical properties become similar to a solid
Thermal properties

Typical dependence of viscosity of a glass on temperature
Typical thermal properties of fused silica

Coefficient of thermal expansion: \(5.5 \times 10^{-7}/^\circ\text{C}\)
(average from 20 \(^{0}\text{C}\) to 320 \(^{0}\text{C}\))

Thermal conductivity: 1.3 W/(m·K)

Specific heat capacity: 45.3 J/(mol·K)

Softening point: 1665 \(^{0}\text{C}\)

Annealing point: 1140 \(^{0}\text{C}\)
Fabrication techniques

- Fiber preform fabrication
- Fiber pulling
Rod-in-tube technique

Rod-in-tube method: UA

High precision ultrasonic drilling and grinding machines for glass rod processing

UA fiber drawing tower
Modified Chemical deposition

Modified chemical vapor deposition method
How fiber is made?
Active fiber fabrication

MCVD process

Nano-particle vapor deposition (Liekki)
Specialty optical fibers

There are a lot of specialty optical fibers!

- Photonics crystal fibers
- Doped (active) optical fibers
- Liquid core optical fibers (*if have time*)
- Large mode area optical fibers
- Chiral core coupled optical fibers
- Polarizing fibers
- …
Photonics crystal fibers

Limitation of standard fibers

**Loss**: amplifiers every 50–100km

...limited by Rayleigh scattering
...cannot use “exotic” wavelengths like 10.6µm

**Nonlinearities**: crosstalk, power limits

(limited by mode area ~ single-mode, bending loss)
also cannot be made with (very) **large** core for high power operation

**Radical modifications to dispersion, polarization effects**?
...tunability is limited by low index contrast
Interesting breakthroughs

Guiding @ 10.6µm (high-power CO₂ lasers)
loss < 1 dB/m
(material loss ~ 10⁴ dB/m)

[ Temelkuran et al.,

Guiding @ 1.55µm
loss ~ 13dB/km

[ Smith, et al.,

OFC 2004: 1.7dB/km
BlazePhotonics
Interesting breakthroughs

Endlessly single-mode


Polarization-maintaining


Nonlinear fibers

[ Wadsworth et al., *JOSA B* 19, 2148 (2002) ]

Low-contrast linear fiber (large area)

[ J. C. Knight et al., *Elec. Lett.* 34, 1347 (1998) ]
Interesting Applications

- Dispersion compensation
- Pulse compression and deliver
- Supercontinuum generation
- Gas, liquid sensing
- Telecommunication?
- …
Integrated liquid-core optical fibers

- Low insertion loss (< 1dB)
- Long interaction length
- No alignment or adjustment needed
What we can do with it?

- Raman generation
- Spectroscopy
- All-optical switching
- Supercontinuum generation
- Brillouin lasing
- ...
Ultra-efficient Raman generation

Laser source: microchip Nd:Yag, pulse duration ~ 700ps, pulse repetition rate: 1.5kHz
Ultra-efficient Raman generation
Questions for thoughts

Can you come up with a new design of optical fiber that would work much better than existing ones?

New applications for optical fibers?

Do optical fibers exist in nature?