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

Waveguide dispersion

In single-mode fibers the group delay, τ_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:

Normalized propagation constant: $$b = \frac{\beta / k_0 - n_{clad}}{n_{core} - n_{clad}}.$$

Normalized frequency: $$V = \frac{2\pi a}{\lambda_0}\sqrt{n_{core}^2 - n_{clad}^2}$$

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

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 : $\tau_g = \frac{1}{c}\frac{d\beta}{dk_0} = \frac{1}{c}\frac{V}{k_0}\frac{d\beta}{dV}.$

Waveguide dispersion

Defining $\Delta = \dfrac{n_{core} - n_{clad}}{n_{core}}$ and with $\beta = \left[b(n_{core} - n_{clad}) + n_{clad}\right]k_0 \approx k_0 n_{clad}(1 + b\Delta)$ (when Δ is small).

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

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

τ_w : waveguide delay

τ_m : material delay

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

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

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

we finally get :

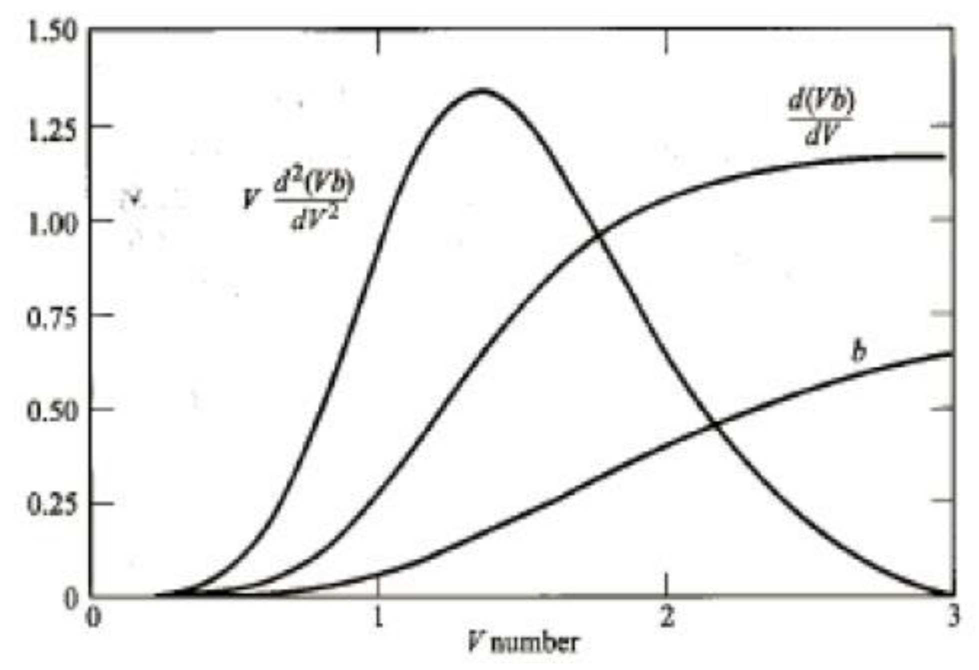
$$\frac{d\tau_W}{d\lambda} = -\frac{n_{clad}\Delta}{c\lambda} V \frac{d^2(bV)}{dV^2}.$$

Waveguide dispersion!

Note: Here we have neglected the dependence of Δ on k_0, which is negligibly small.

Waveguide dispersion

b, $d(Vb)/dV$ and $V\dfrac{d^2(Vb)}{dV^2}$ as a function of the V number:



Page 113, in *Optical Fiber Communications*, Gerd Keiser, third edition, McGraw Hill, 2000.

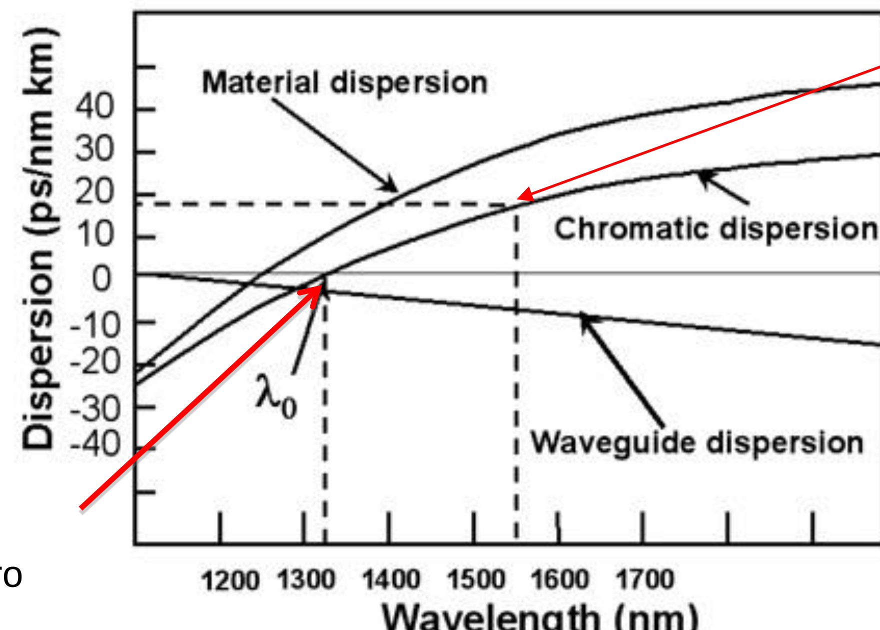
Chromatic dispersion of SMF

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

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

$$(D_{Material}) \qquad (D_{Waveguide})$$

at 1.55 μm,
D=+17ps/km-nm



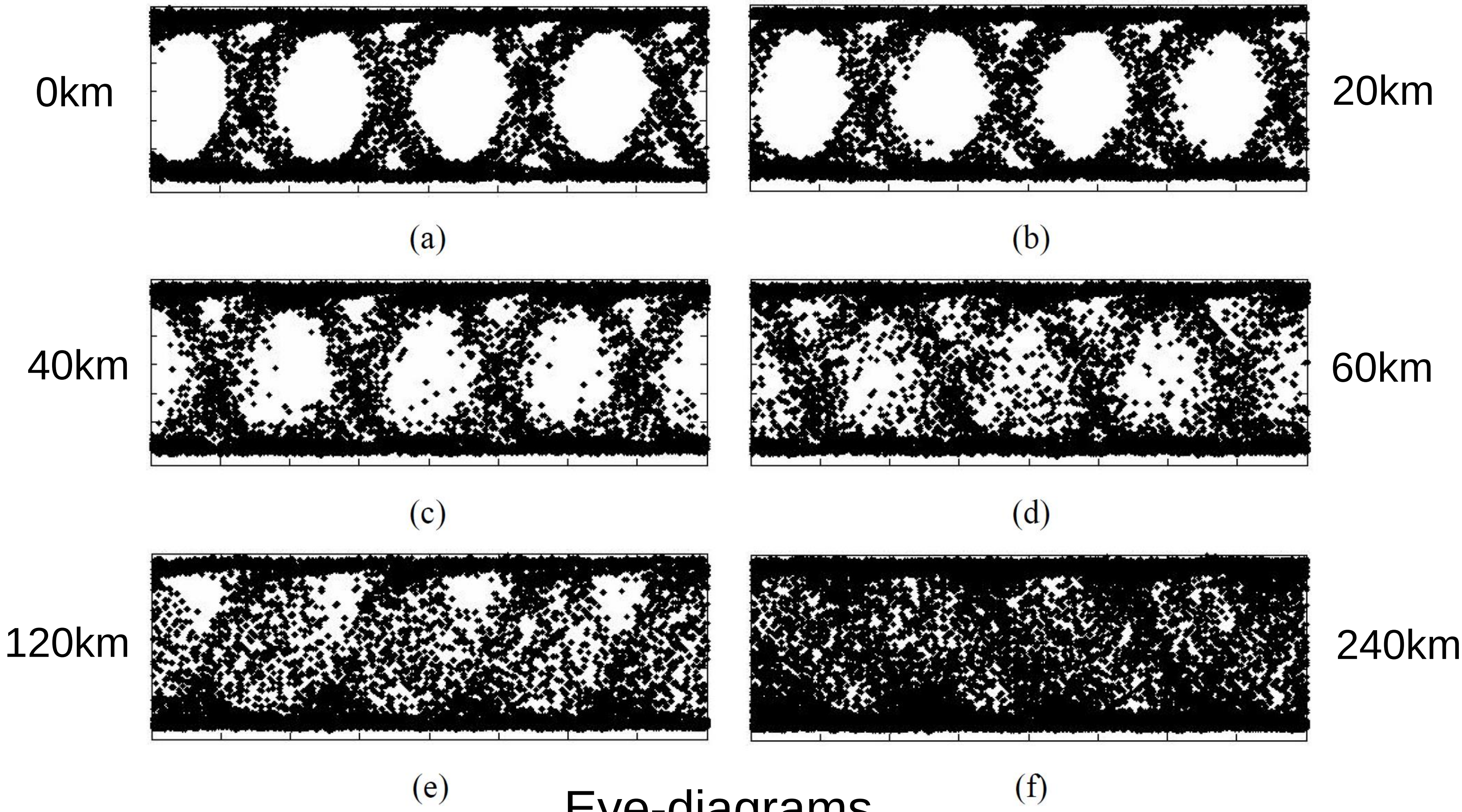
at 1.312 μm,
dispersion is zero

GVD

$$D = \frac{d}{d\lambda}\left(\frac{1}{v_g}\right) = -\frac{2\pi c}{\lambda^2}\frac{d^2\beta}{d\omega^2}$$

D. Gloge, "Dispersion in weakly guiding fibers," *Appl. Opt.* **10**, pp. 2442-2445, 1971

Dispersive pulse broadening



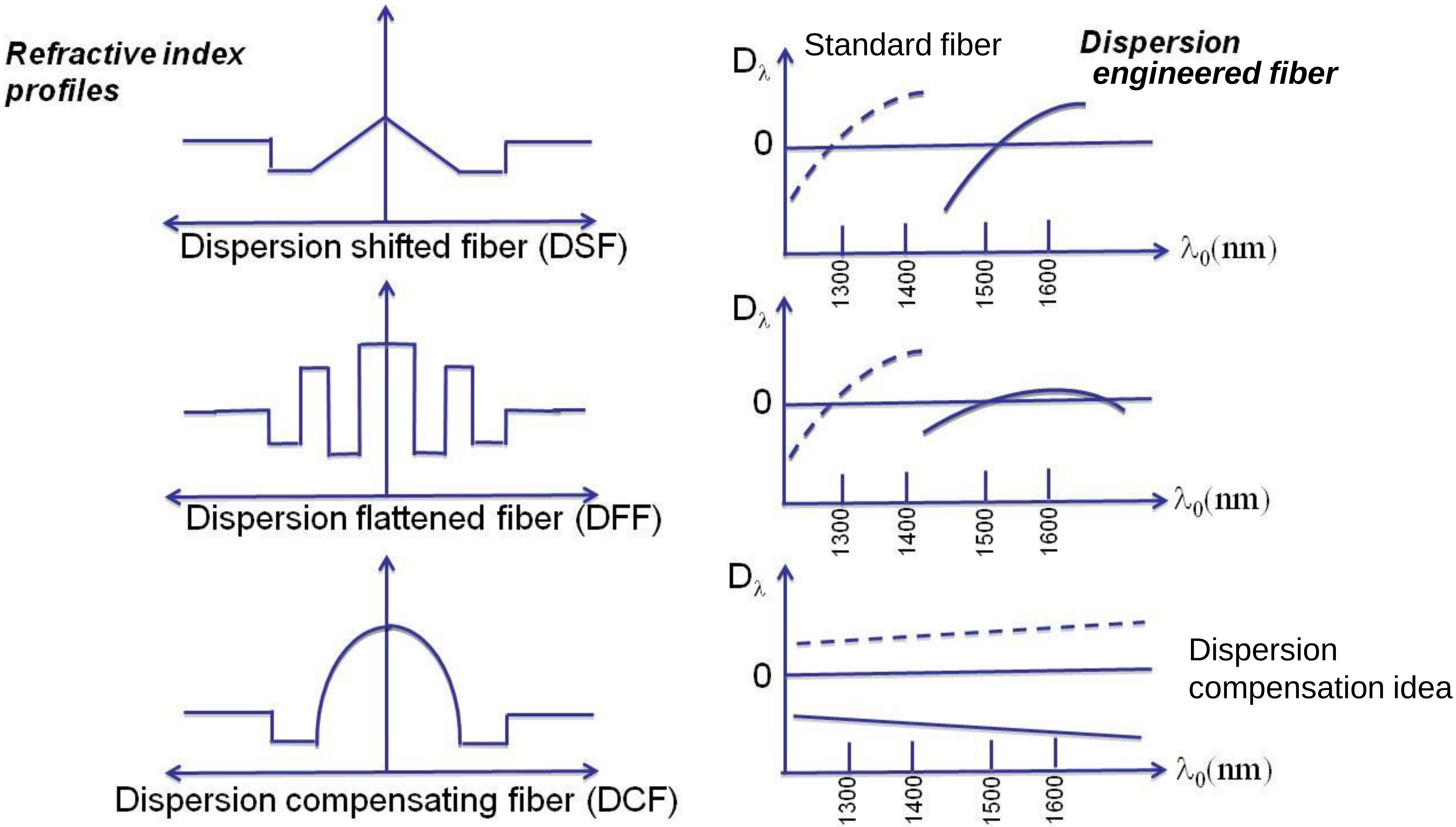
Eye-diagrams

Lee's PhD thesis

Dispersion compensation

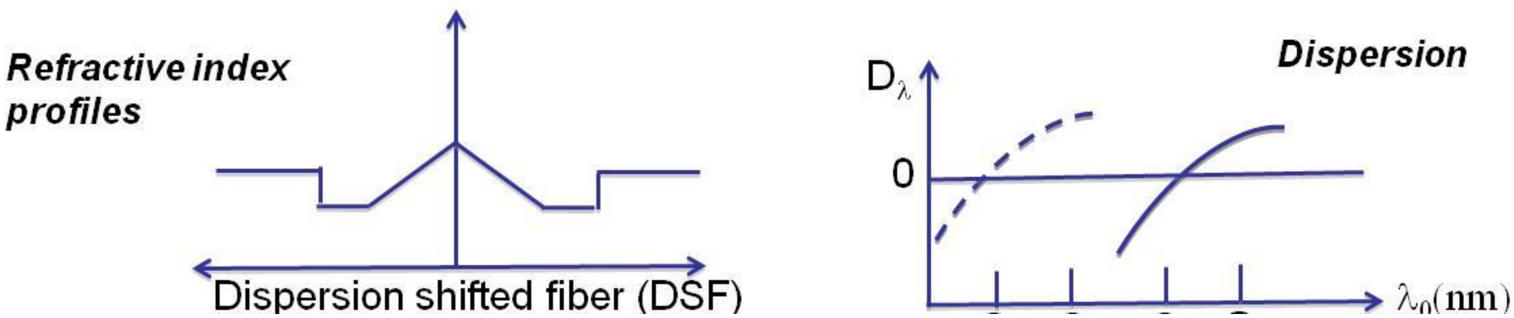
- Pre-chirp technique
- Dispersion engineered fibers
- Dispersion compensating fibers
- Chirped fiber Bragg grating
- Tunable dispersion compensation

Dispersion engineered fiber

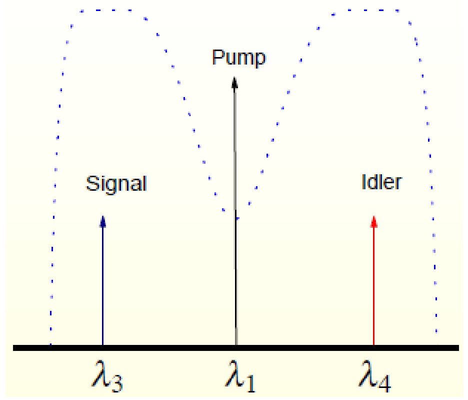


Engineer the index profile around the core region to modify dispersion properties

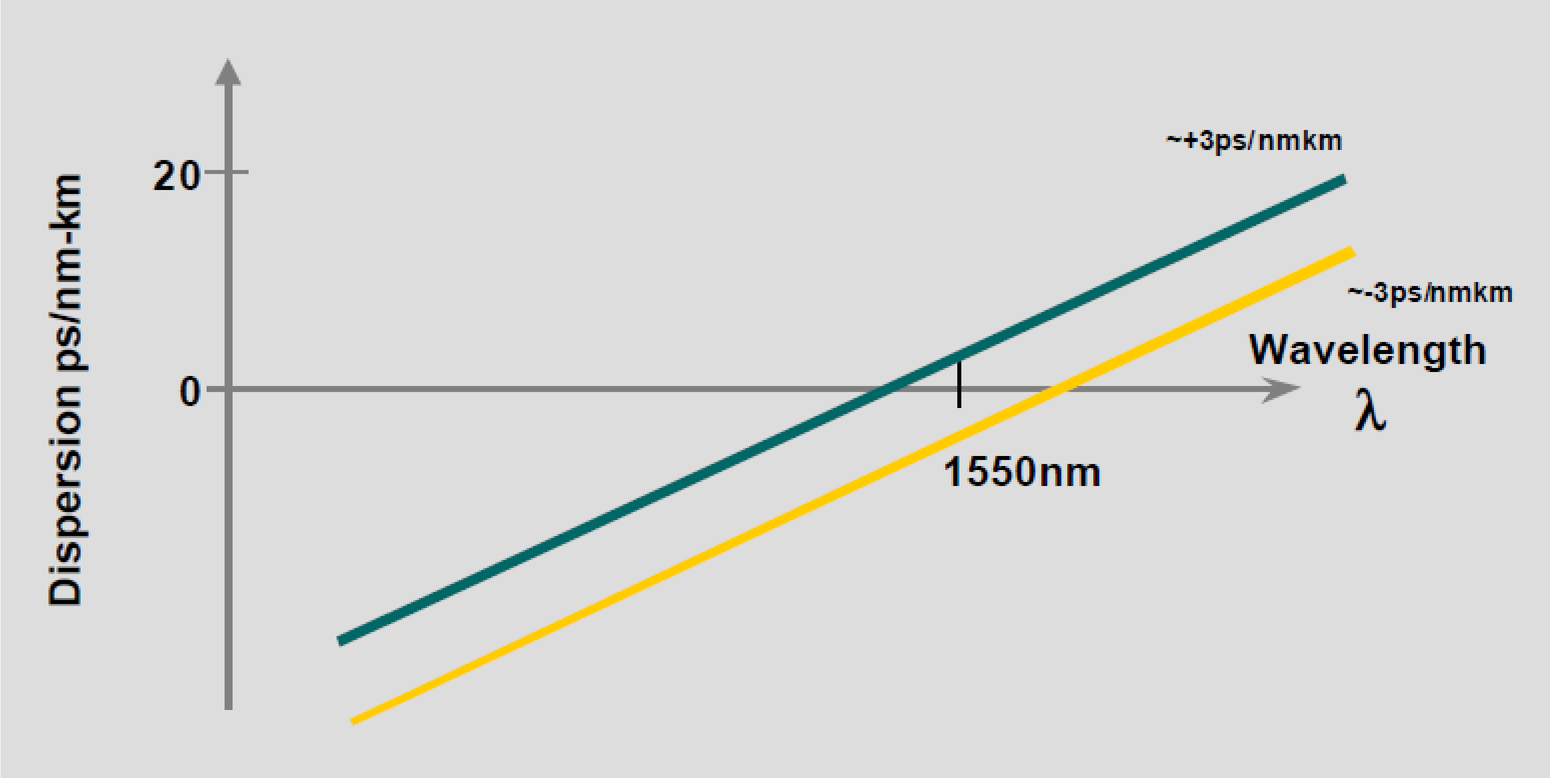
Dispersion engineered fiber



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

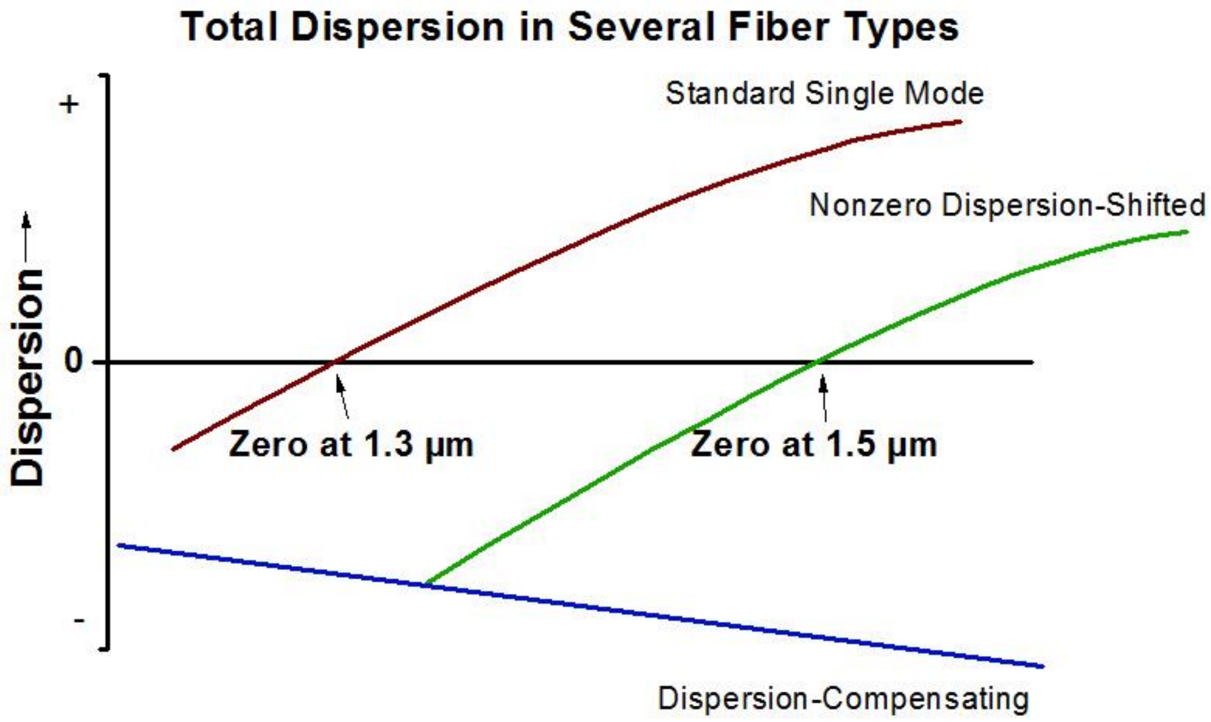


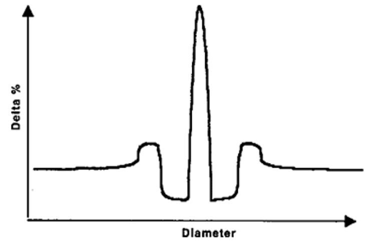
Dispersion engineered fiber



Non-zero dispersion shifted fibers

Dispersion compensating fibers





Dispersion compensating fibers

$$\beta_{21} L_1 + \beta_{22} L_2 = 0, \text{ or}$$

$$D_1 L_1 + D_2 L_2 = 0.$$

DCF modules

Advantage:

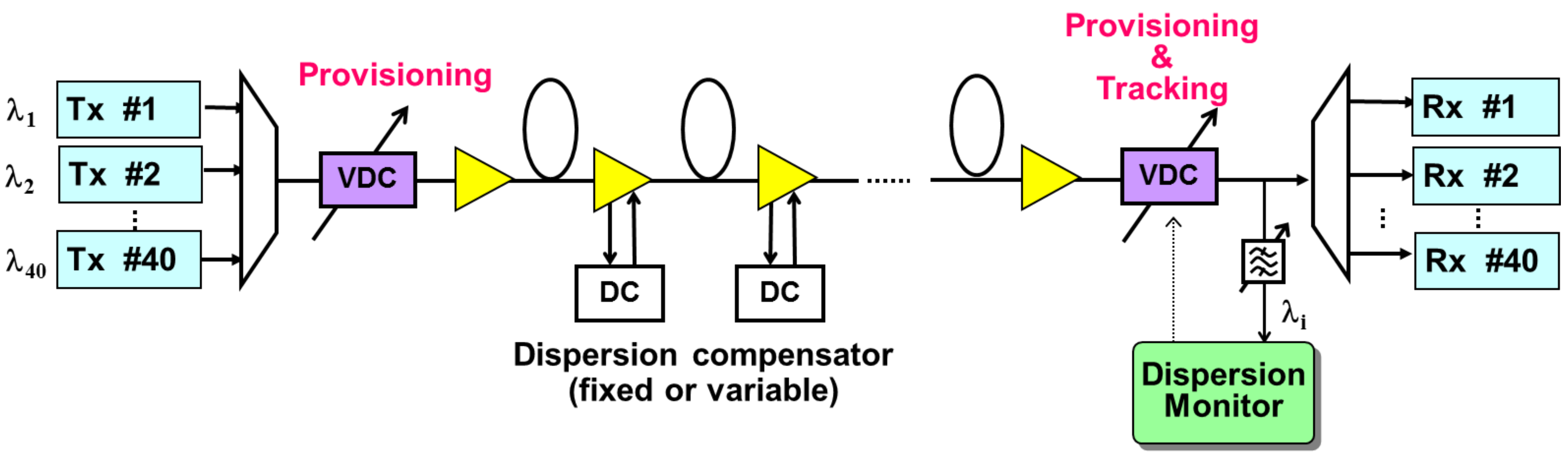
- Fiber format
- Low cost
- Broadband

Disadvantage:

- Small mode field diameter
- Higher loss

Tunable dispersion compensation

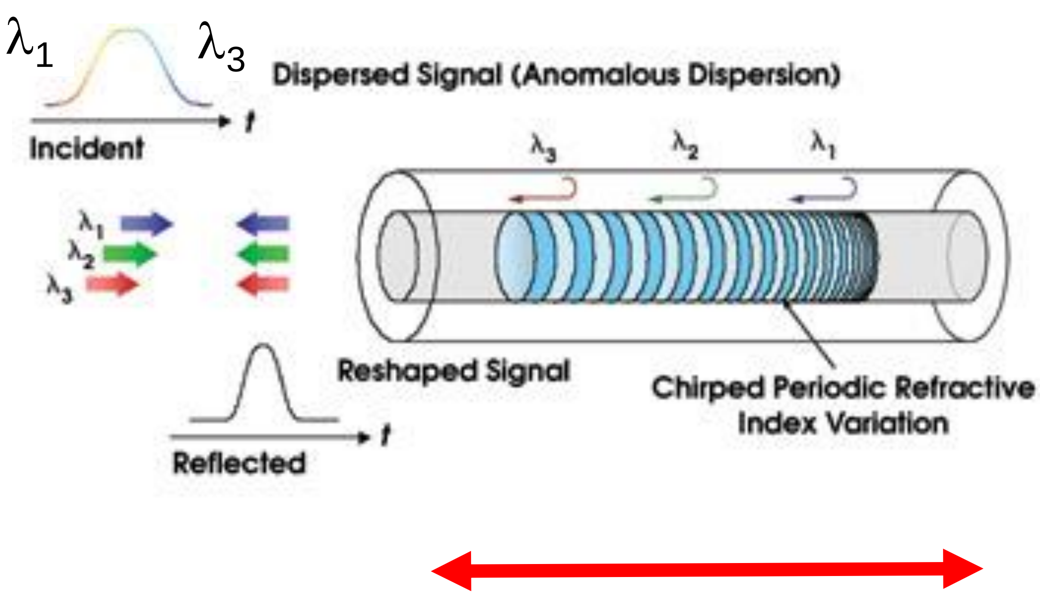
- Provide adjustable dispersion
- Compensate residual dispersion



Fujitsu

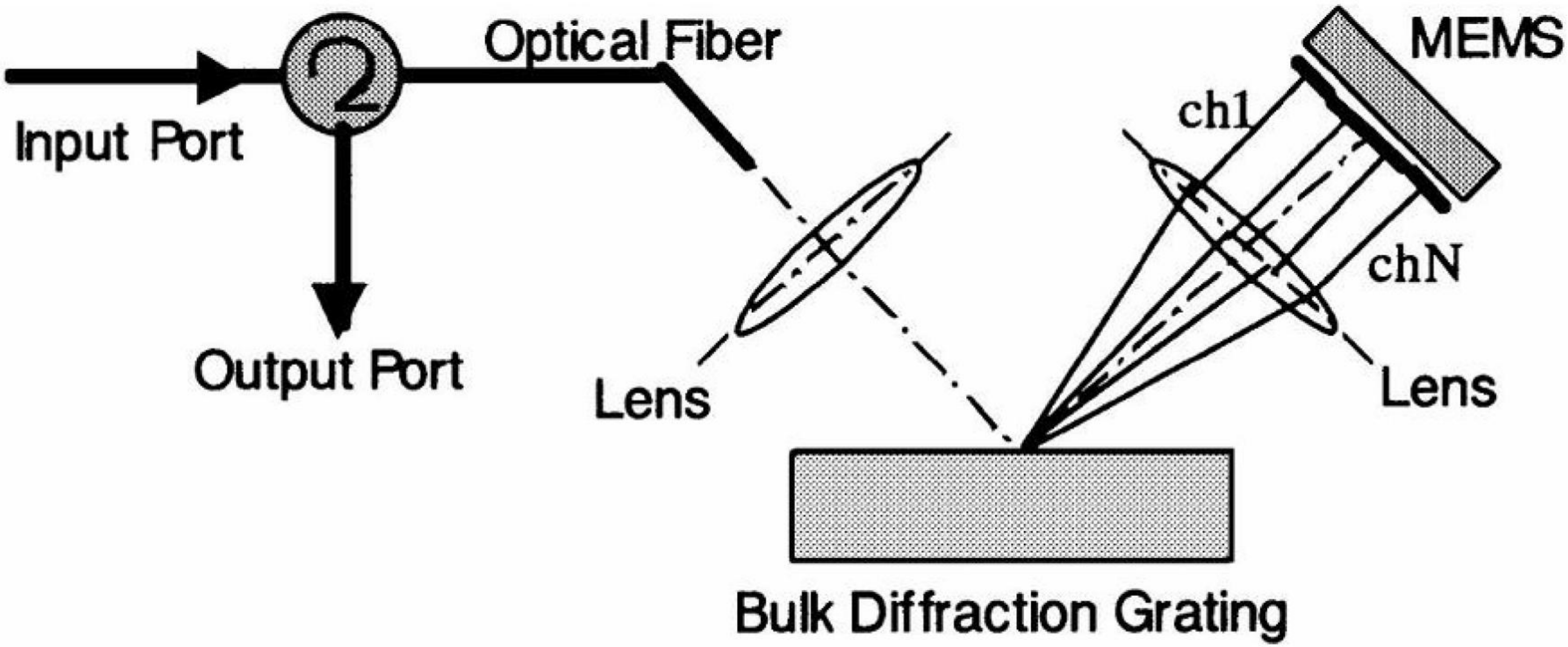
Tunable dispersion compensation

- Provide adjustable dispersion
- Compensate residual dispersion



Mechanical stretching

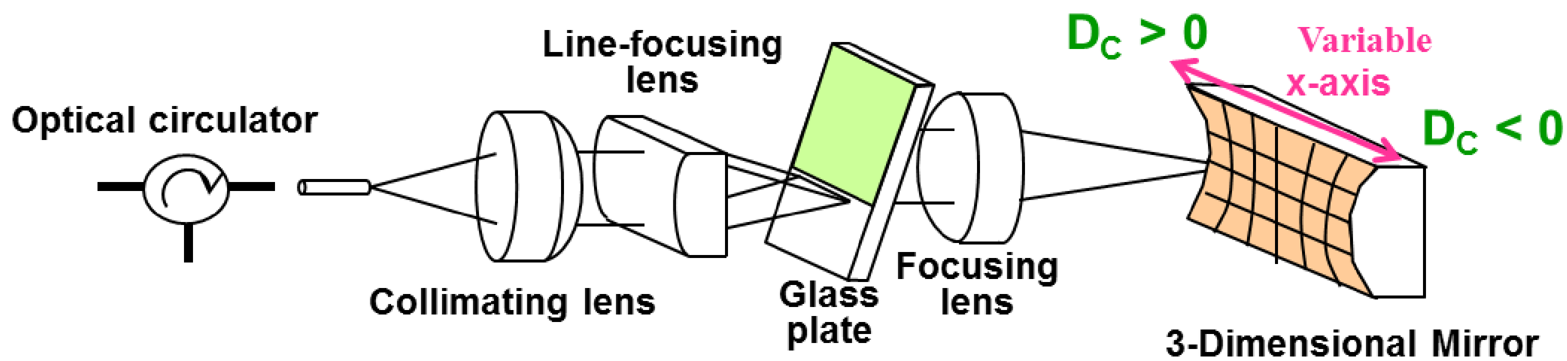
Tunable dispersion compensation



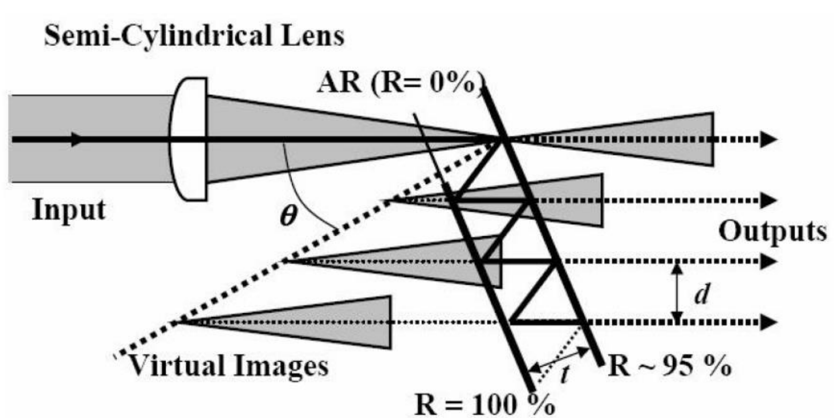
Lee’s PhD thesis

Tunable dispersion compensation

VIPA variable dispersion compensator



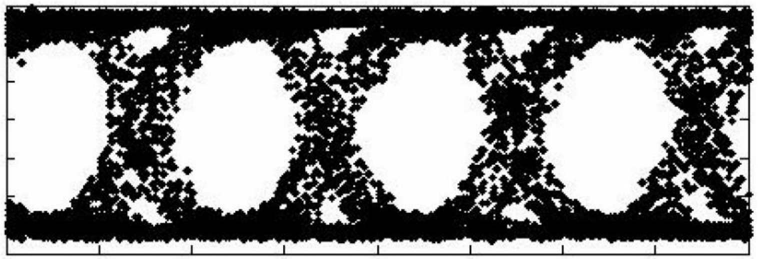
VIPA : Virtually Imaged Phased Array



Fujitsu

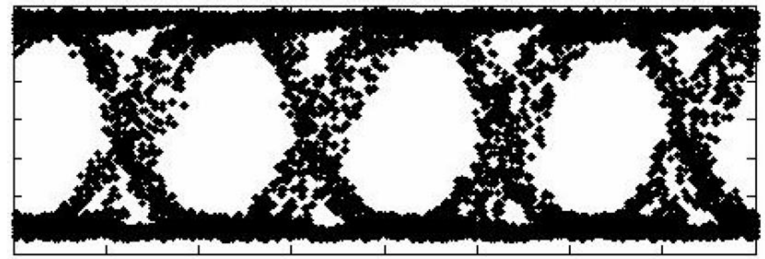
Tunable dispersion compensation

20km



(a)

40km

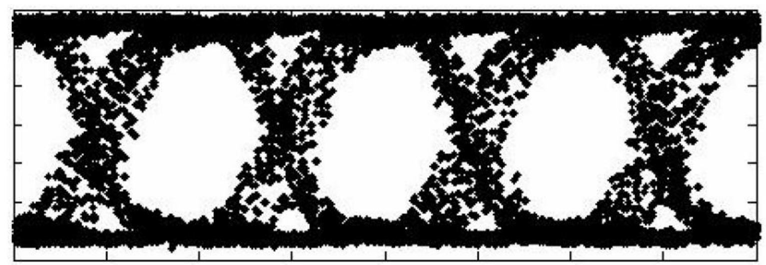


(b)

60km

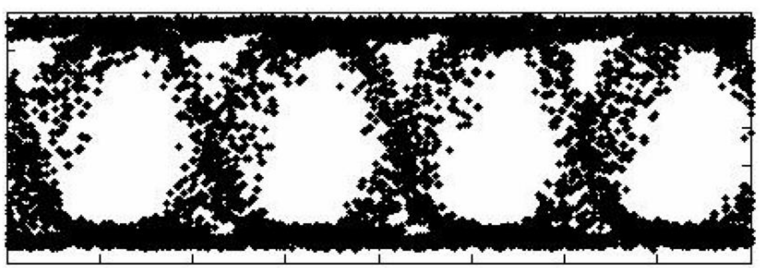
(c)

120km



(d)

240km



(f)

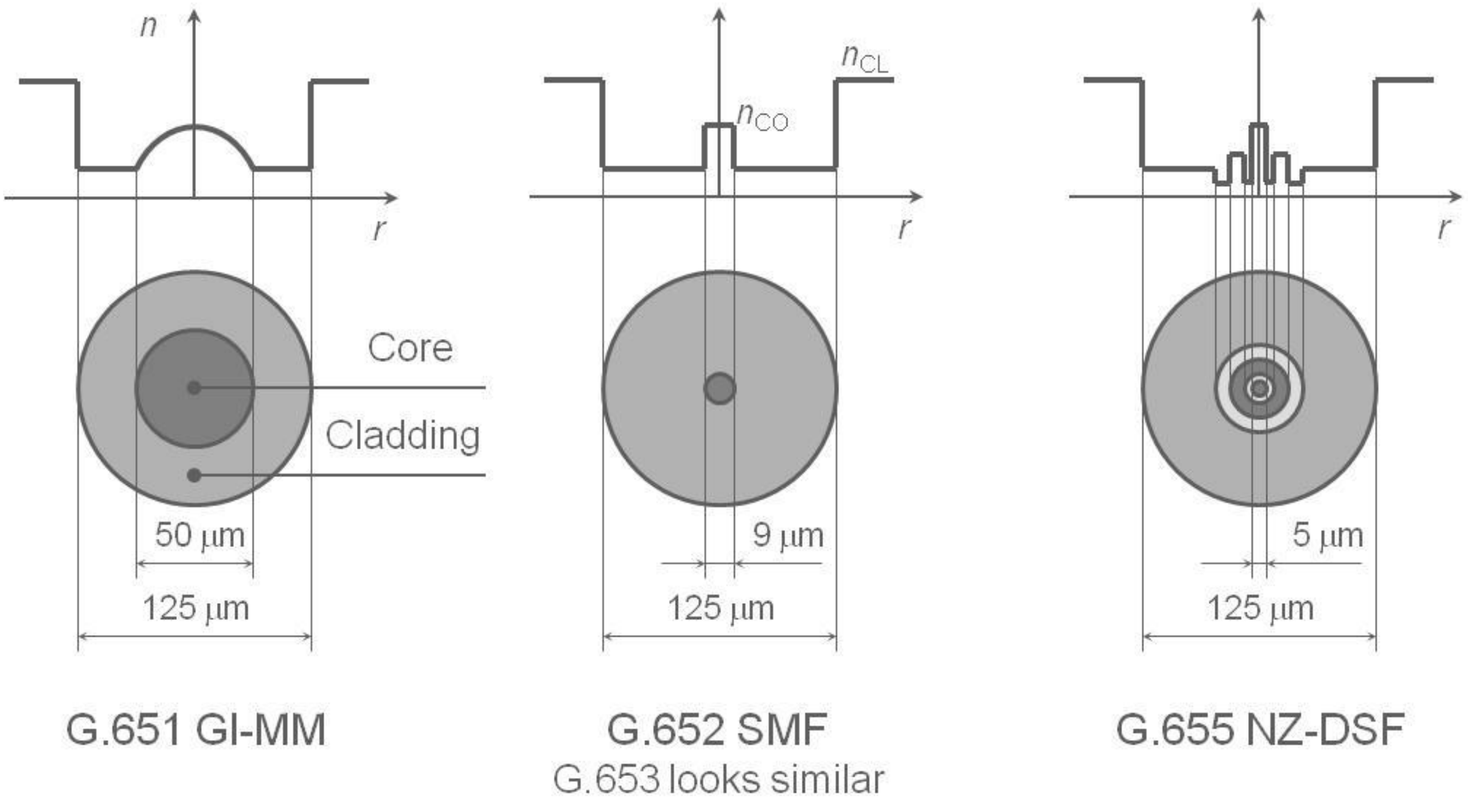
Eye-diagrams

Lee's PhD thesis

Optical fibers fabrication

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

Optical Fibers



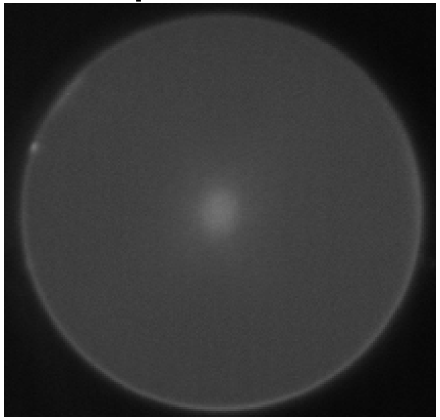
Light is kept in the core by total internal reflection (TIR is not the only mechanism- PCF)

Types of optical fiber

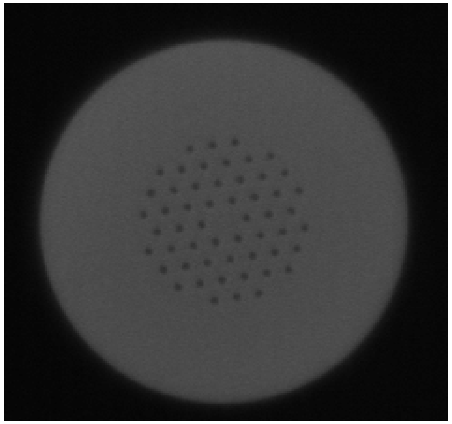
Types of fiber by construction:

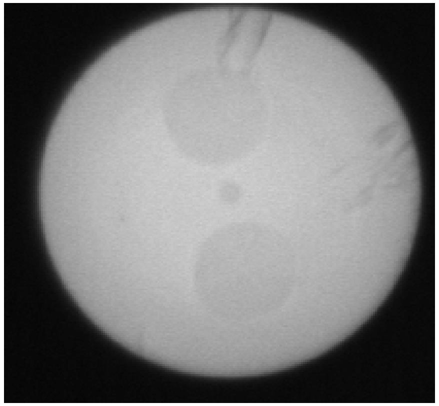
- step index
- graded index
- PM fiber
- photonic crystal fiber
- multi-core fiber

Step index fiber

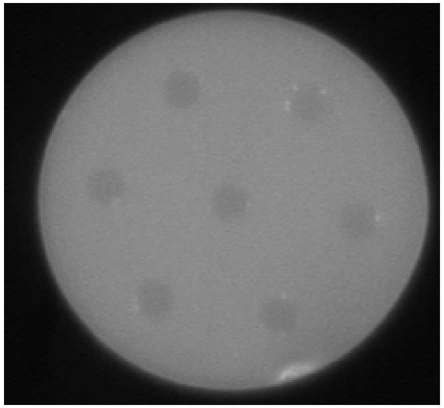


PCF fiber





PM fiber

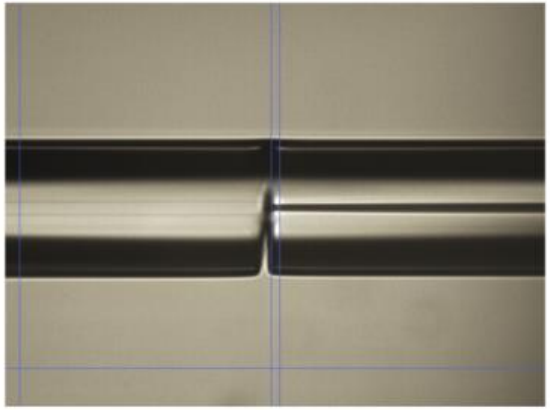


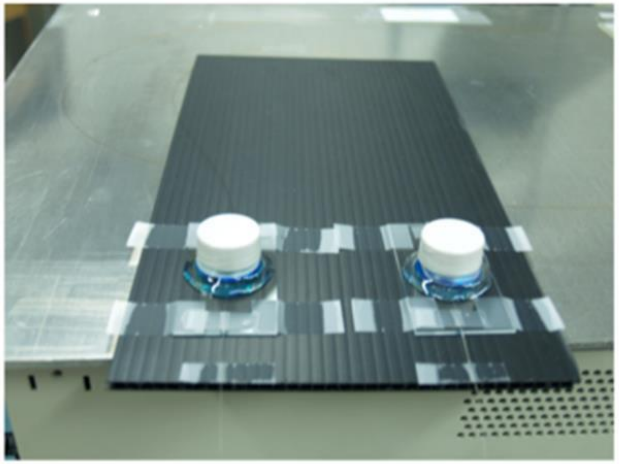
Multicore fiber

Types of optical fiber

Types of fiber by material:

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



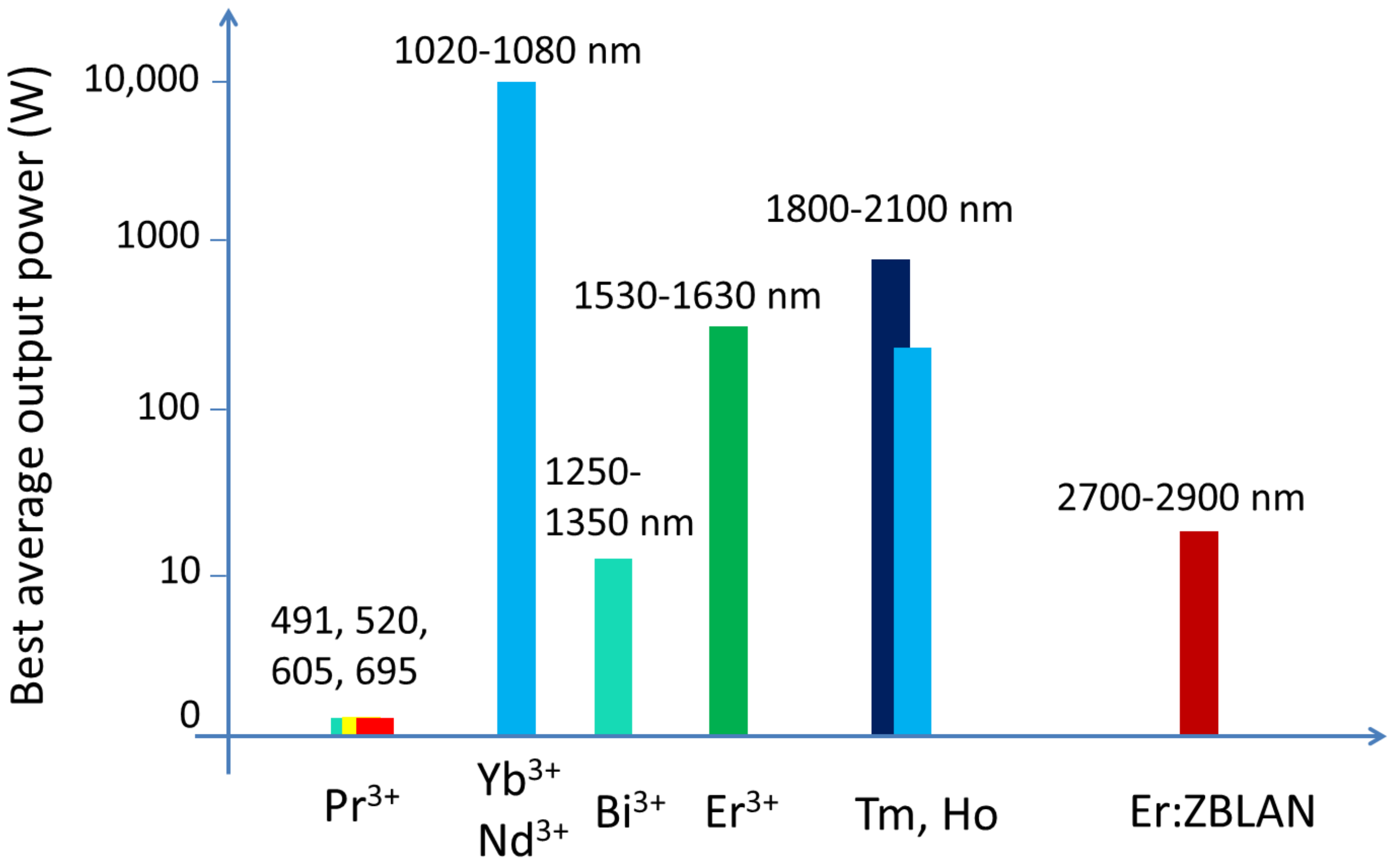


UA integrated liquid-core optical fiber

Types of optical fiber

Types of fiber by functionality:

- passive fibers
- active fibers



Important parameters

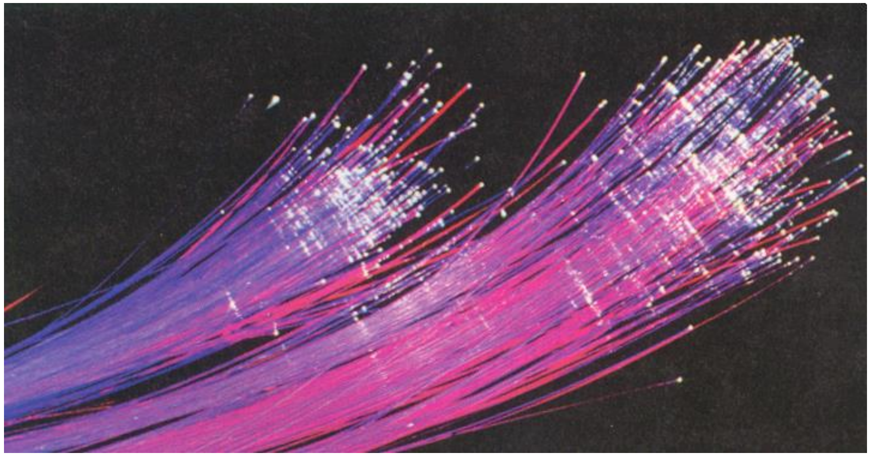
- Numerical aperture: $\mathrm{NA} = \sqrt{n_1^2 - n_2^2},$
- V number: $V = \frac{2\pi}{\lambda} a \, \mathrm{NA} = \frac{2\pi}{\lambda} a \sqrt{n_{\mathrm{core}}{}^2 - n_{\mathrm{cladding}}{}^2}$
- Core size, MFD
- Polarization maintaining or not polarization maintaining
- Dispersion
- Attenuation
- Nonlinear coefficient

Optical fiber materials

Requirements:

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

Glassy materials (fused silica, polymer)



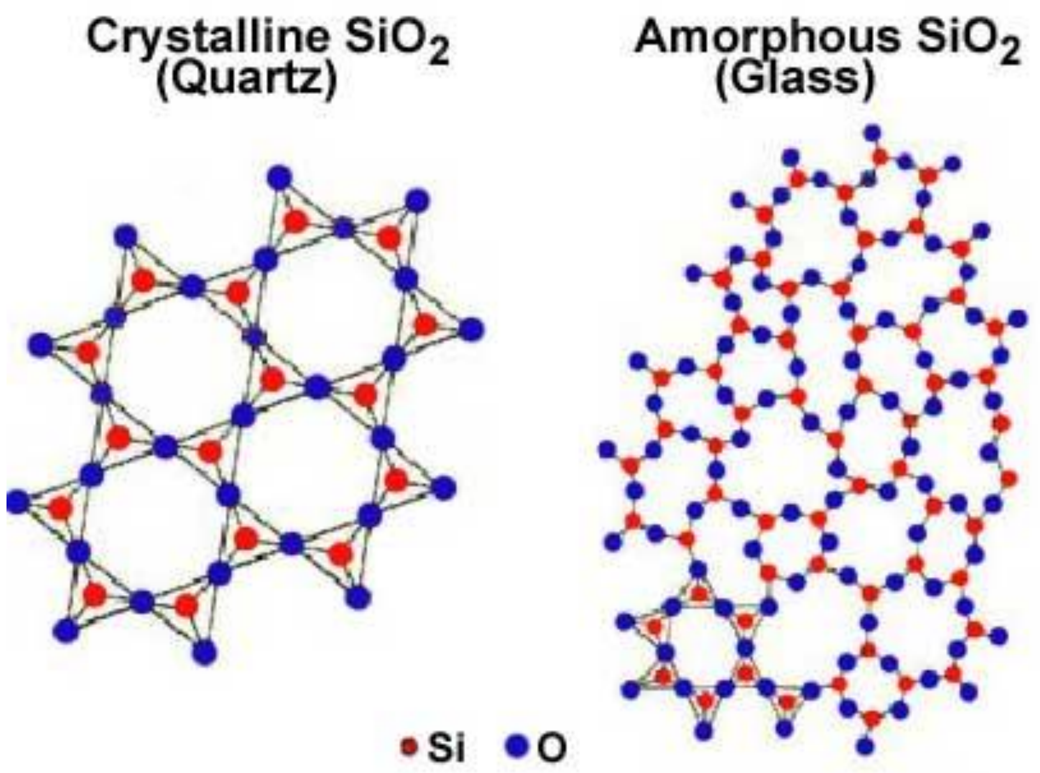
Glassy materials

American Society for Testing Materials (1945):
"Glass is a 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."

Glassy structure



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 (10-2Pas)

• Cooling melt → rapid crystallization ~ Tm

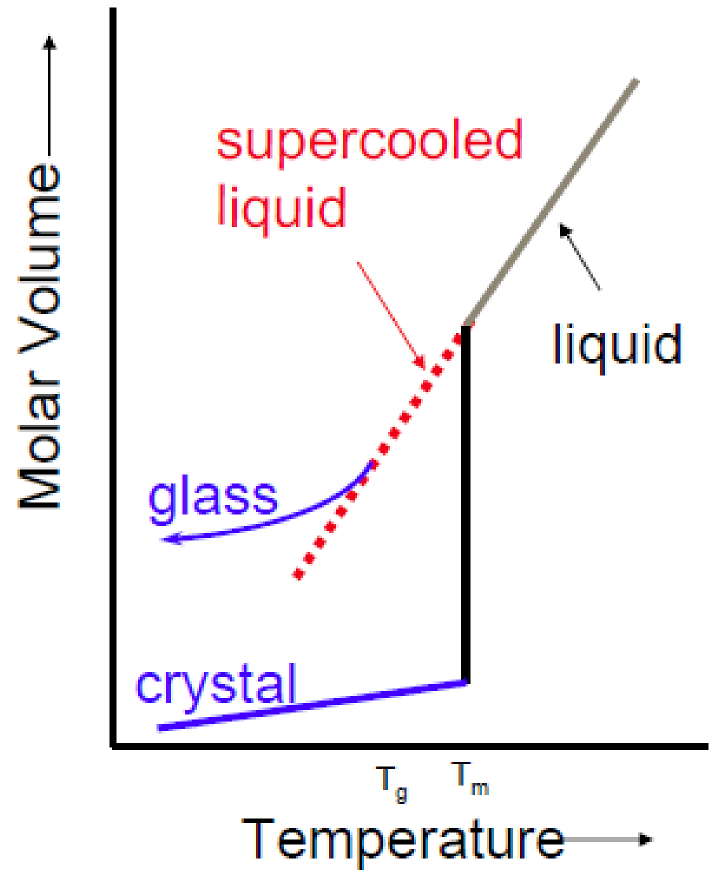
Glass forming materials:

• Melt with considerable higher viscosity

• Significantly less crystallization below Tm

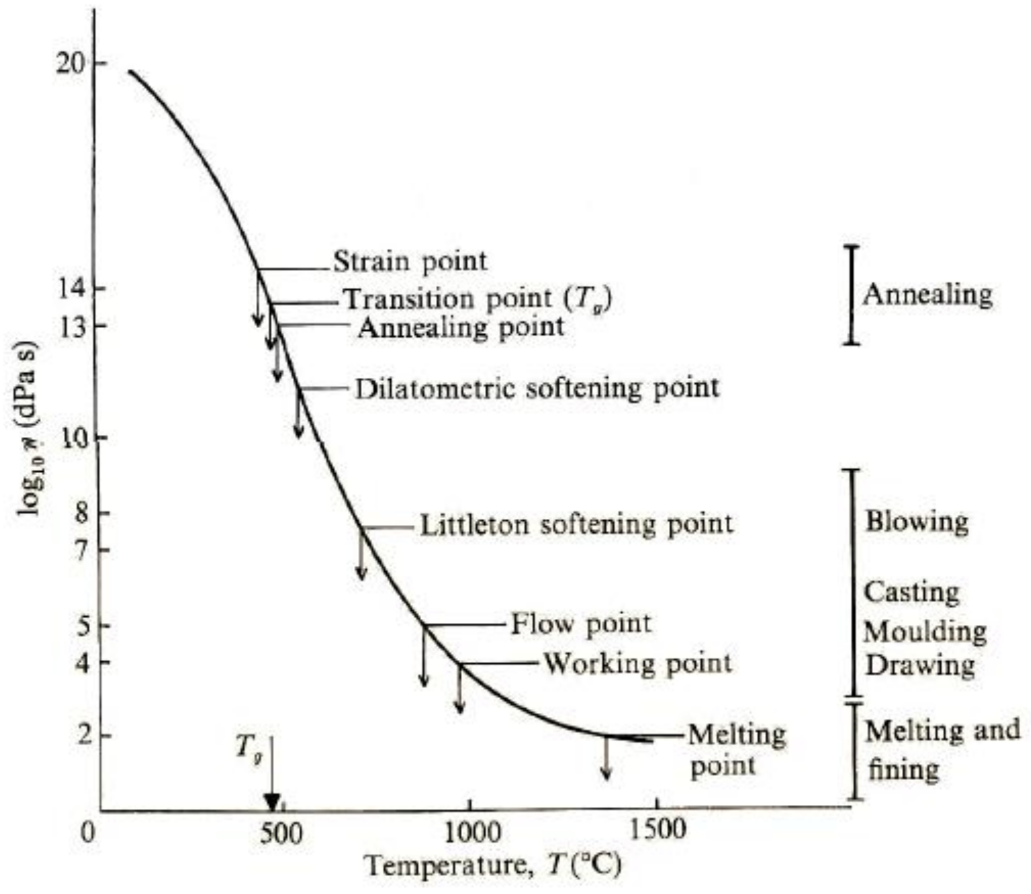
• If crystallization rate is low enough fast cooling below Tm w/o crystallization possible

• 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



Thermal properties

Typical thermal properties of fused silica

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

Thermal conductivity: 1.3 W/(m·K)

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

Softening point: 1665 ^{0}C

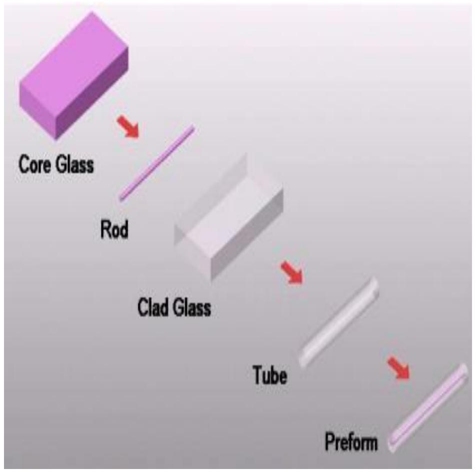
Annealing point: 1140 ^{0}C

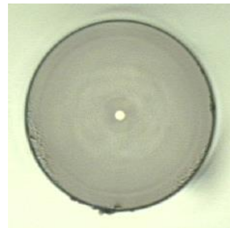
Fabrication techniques

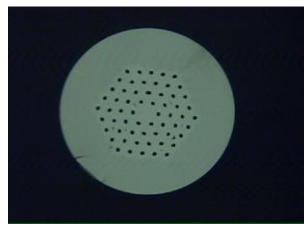
- Fiber preform fabrication
- Fiber pulling

Rod-in-tube technique

Rod-in-tube method: UA



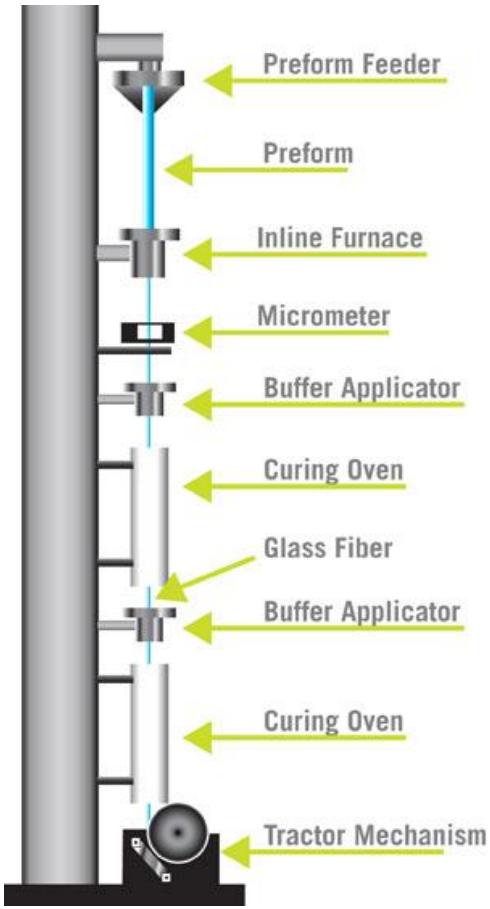


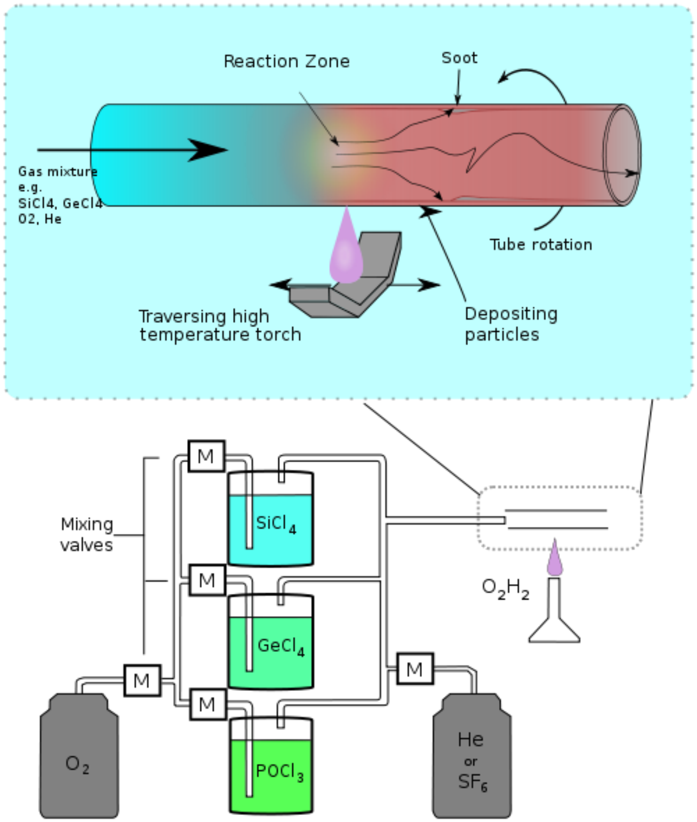


High precision ultrasonic drilling and grinding machines for glass rod processing

UA fiber drawing tower

Modified Chemical deposition

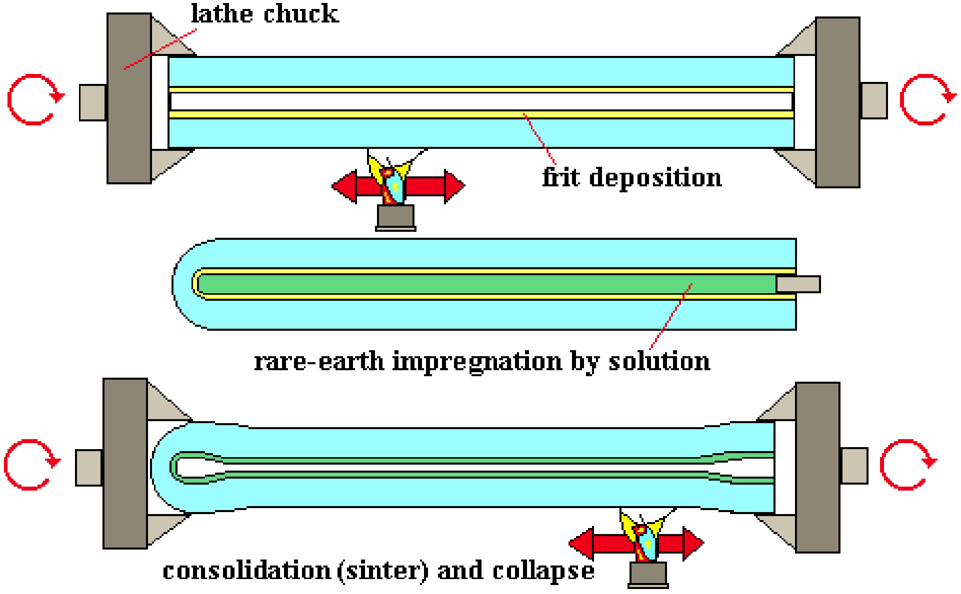




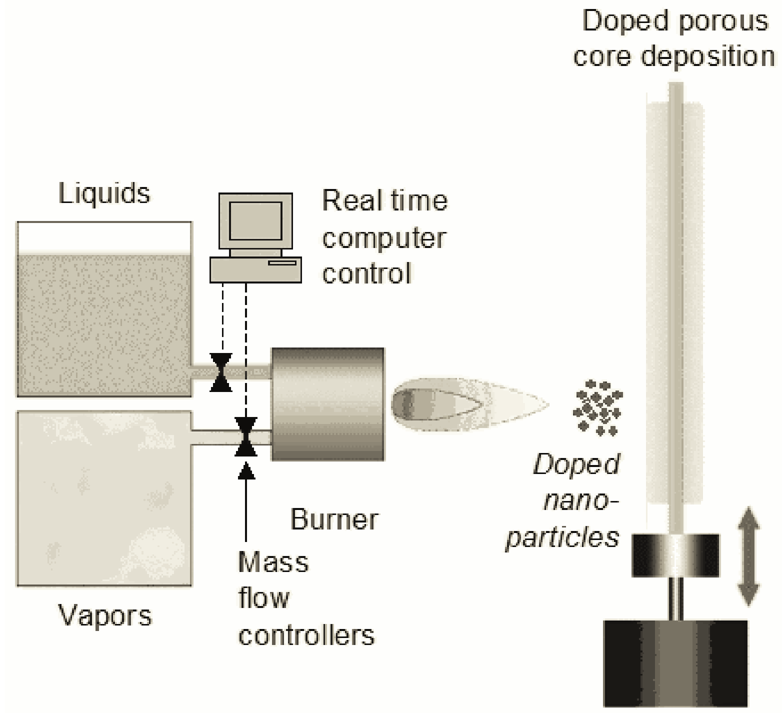
Modified chemical vapor deposition method

How fiber is made?

Active fiber fabrication



MCVD process



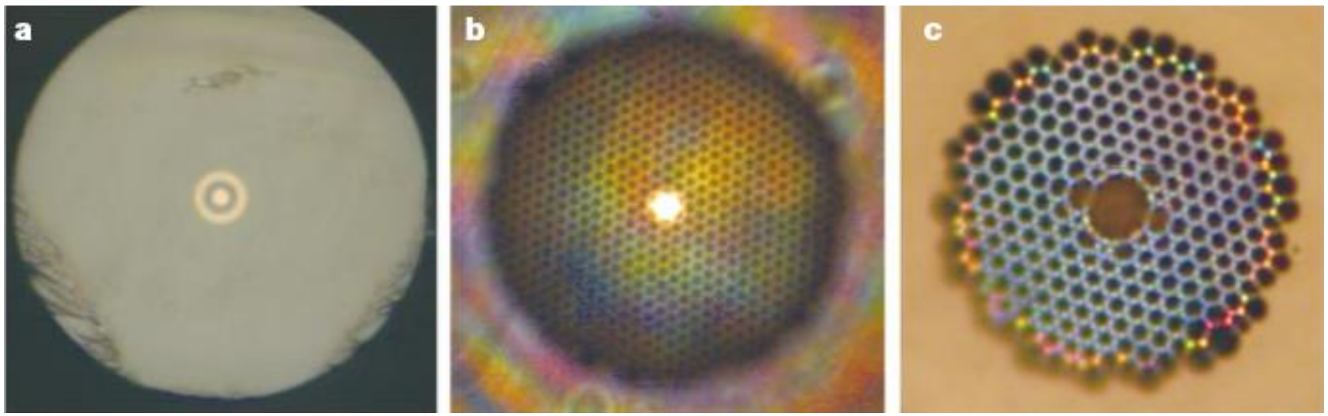
Nano-particle vapor deposition (Liekki)

Specialty optical fibers

There are a lot of specialty optical fibers!

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

Photonics crystal fibers



Standard fiber   PCF   HC-PCF

a PCF preform

J. C. Knight, “Photonic crystal fibers,” Nature **424**, 847-851 (2003)

Limitation of standard fibers

Loss: amplifiers every 50–100km

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

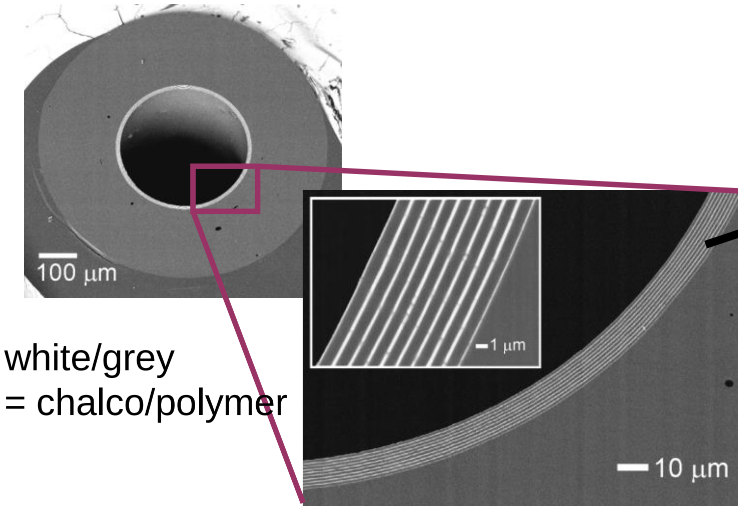
Nonlinearities: crosstalk, power limits

(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

[figs courtesy
Y. Fink *et al*., MIT]



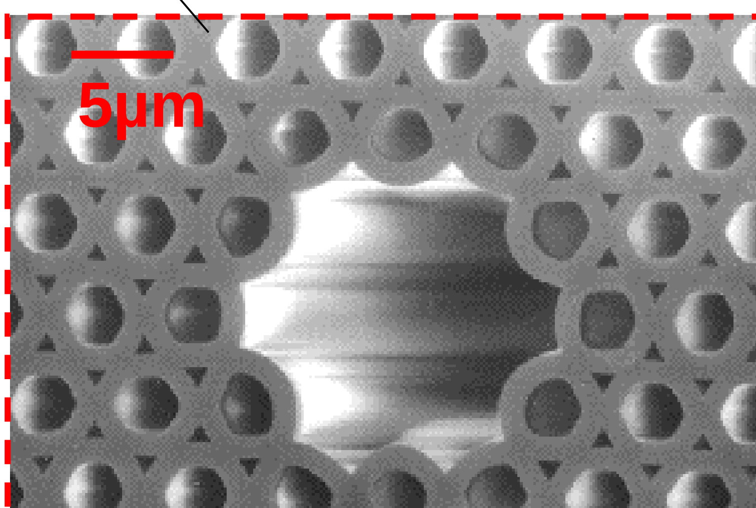
white/grey
= chalco/polymer

Guiding @ 10.6µm
(high-power CO_2 lasers)
loss < 1 dB/m
(material loss ~ 10^4 dB/m)

[Temelkuran *et al.*,
Nature **420**, 650 (2002)]

[R. F. Cregan
et al.,
Science **285**,
1537 (1999)]

silica

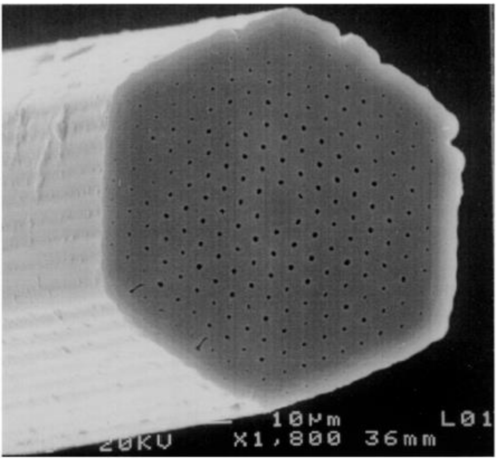


Guiding @ 1.55µm
loss ~ 13dB/km

[Smith, *et al.*,
Nature **424**, 657 (2003)]

OFC 2004: 1.7dB/km
BlazePhotonics

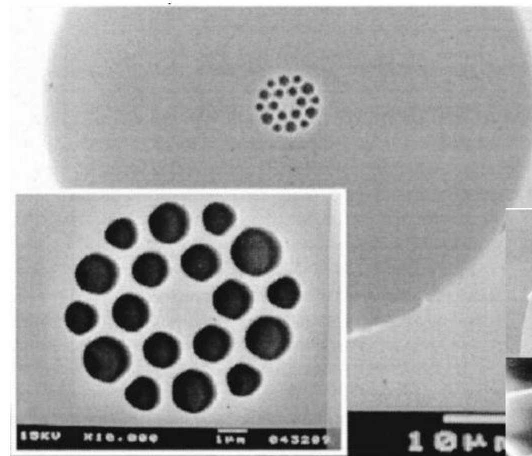
Interesting breakthroughs

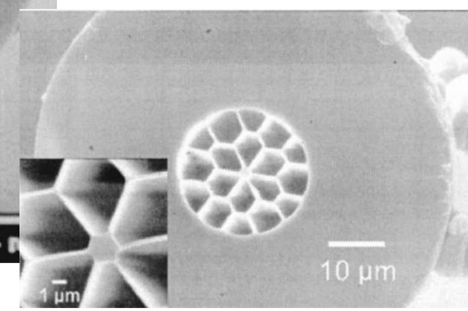


Endlessly single-mode

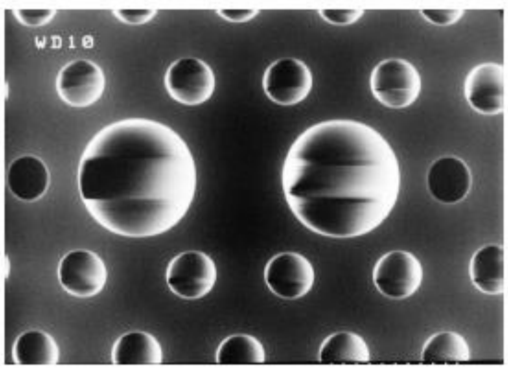
[T. A. Birks *et al.*, *Opt. Lett.* **22**, 961 (1997)]

Nonlinear fibers



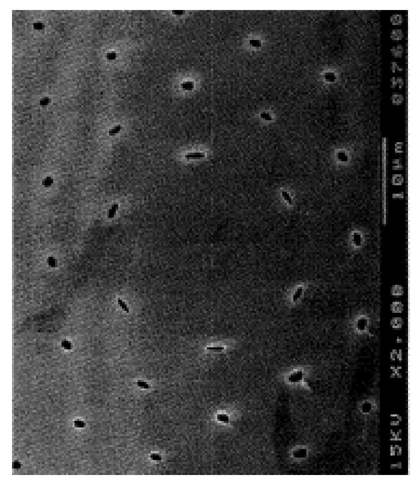


[Wadsworth *et al.*, *JOSA B* **19**, 2148 (2002)]



polarization -maintaining

[K. Suzuki, *Opt. Express* **9**, 676 (2001)]

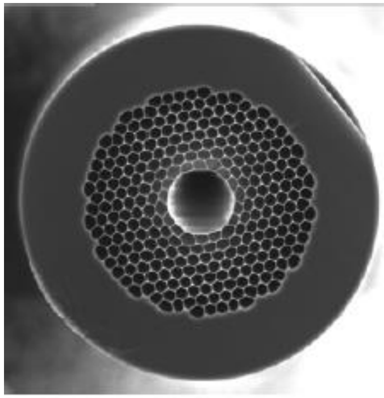


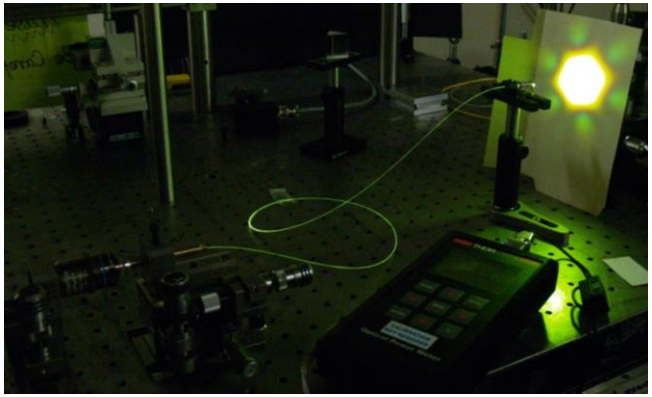
low-contrast *linear* fiber (large area)

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

Interesting Applications

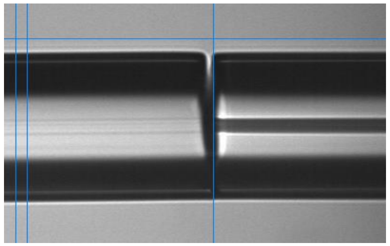
- Dispersion compensation
- Pulse compression and deliver
- Supercontinuum generation
- Gas, liquid sensing
- Telecommunication?
- …



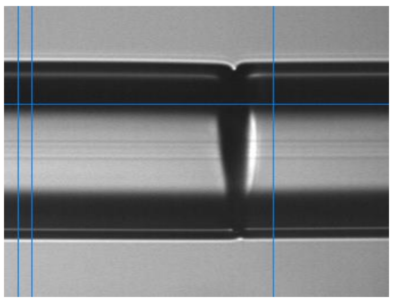


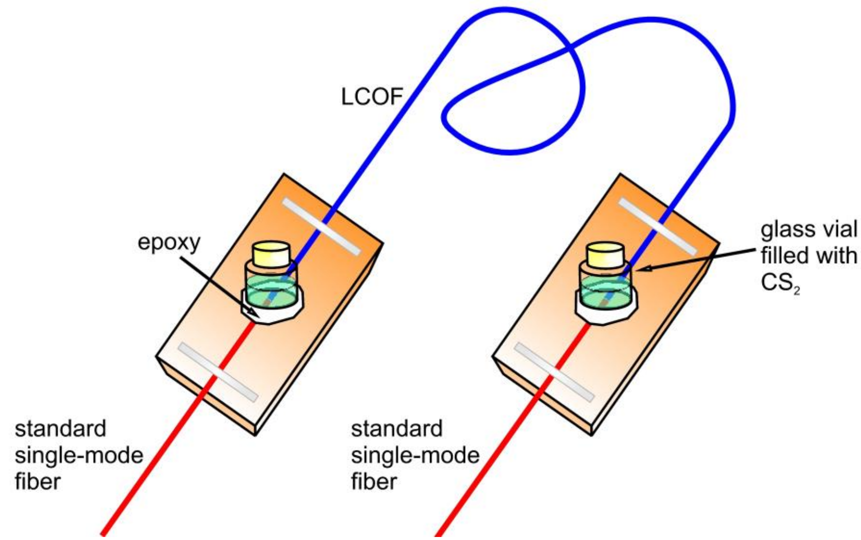
Integrated liquid-core optical fibers

SMF28-LCOF



SMF28-SMF28

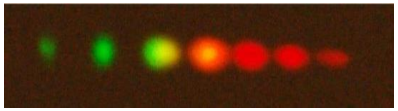




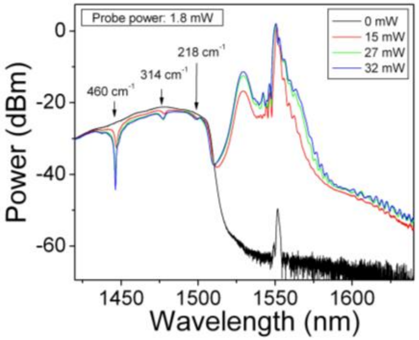
- Low insertion loss (< 1dB)
- Long interaction length
- No alignment or adjustment needed

What we can do with it?

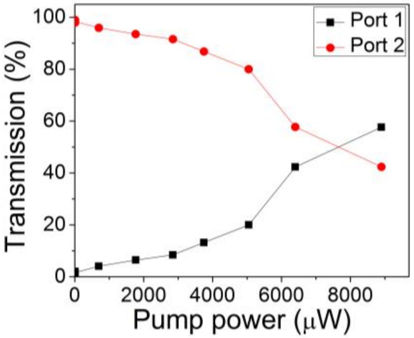
- Raman generation



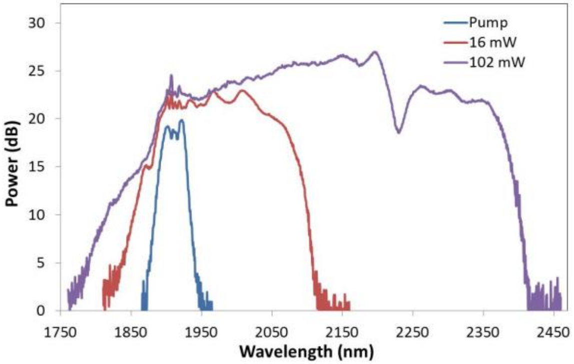
- Spectroscopy

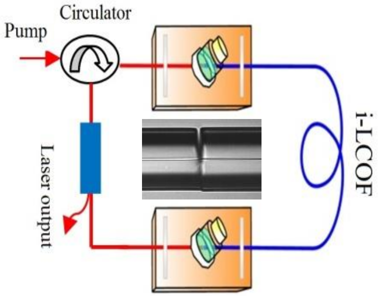


- All-optical switching

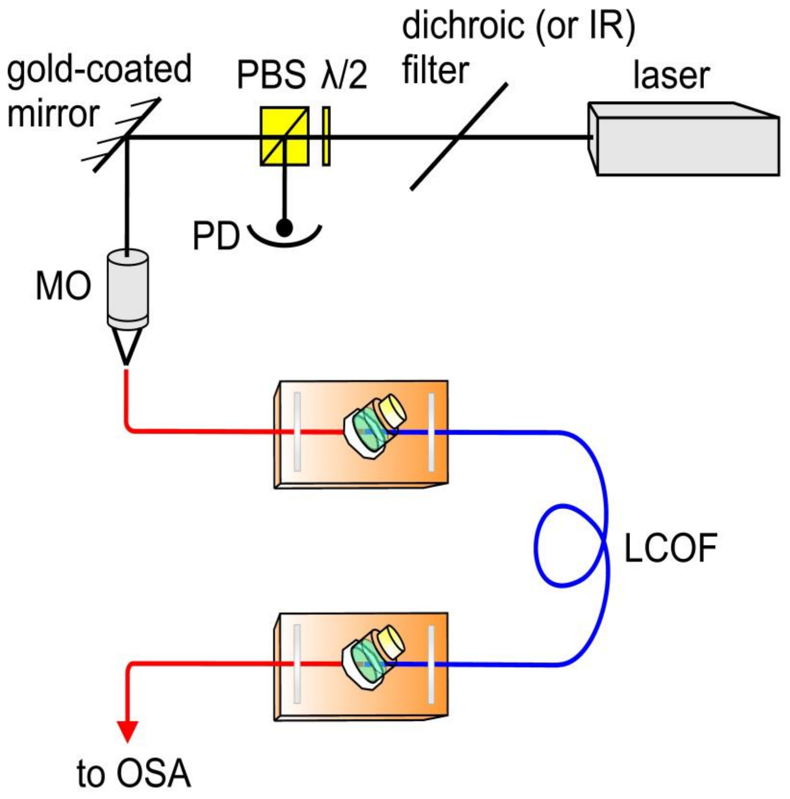


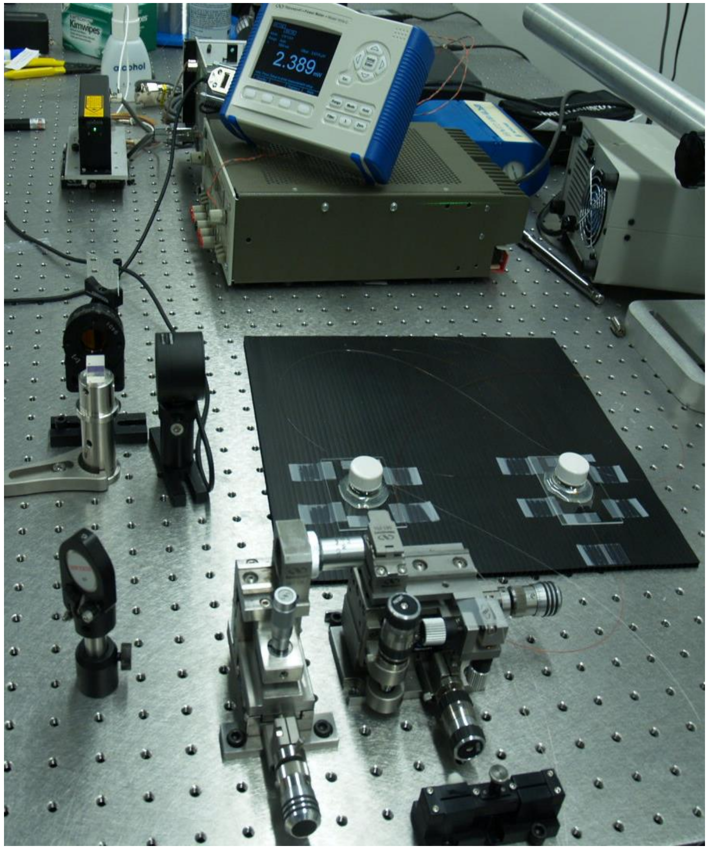
- Supercontinuum geneation
- Brillouin lasing
- …





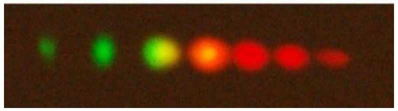
Ultra-efficient Raman generation

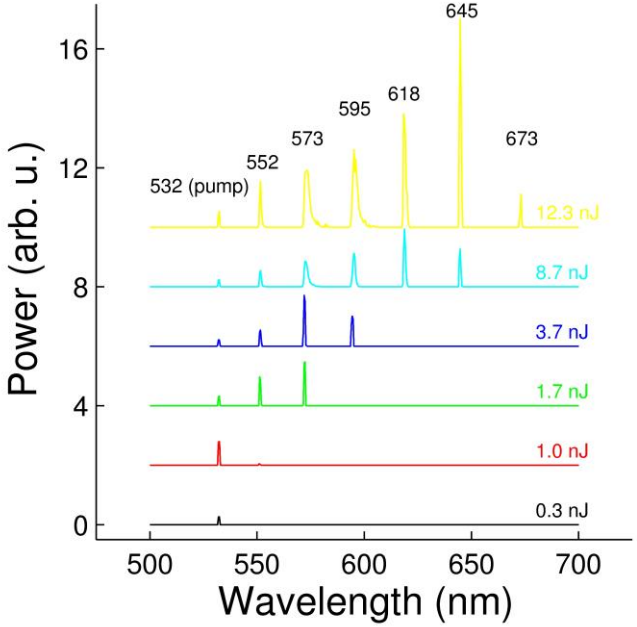


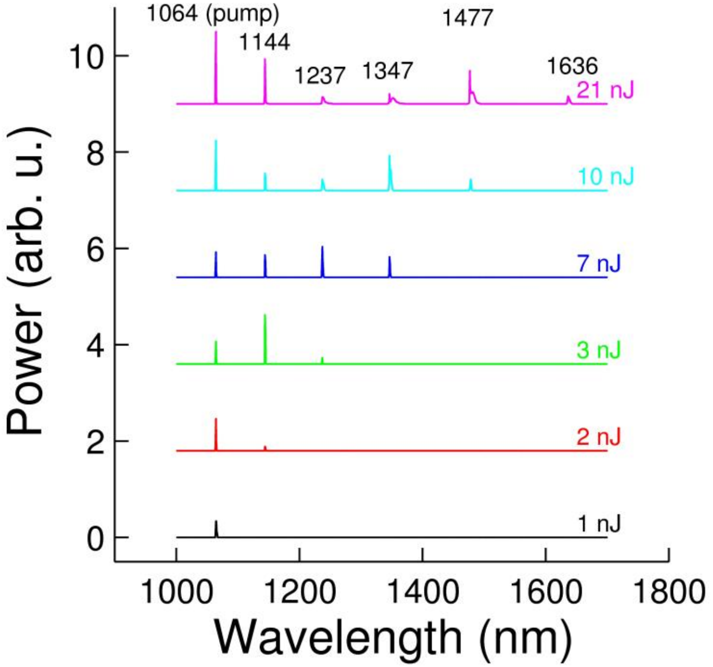


Laser source: microchip Nd:Yag, pulse duration ~ 700ps,
pulse repetition rate: 1.5kHz

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?