6th edition of the biennial African School of Fundamental Physics and Applications.

Optics and Photonics

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What is the difference between Optics and Photonics?

- Optics is a general area of physics manipulating light through optical grade materials made from glass, plastic, or metallic/dielectric coatings.


Optical Lenses


Optical Mirrors

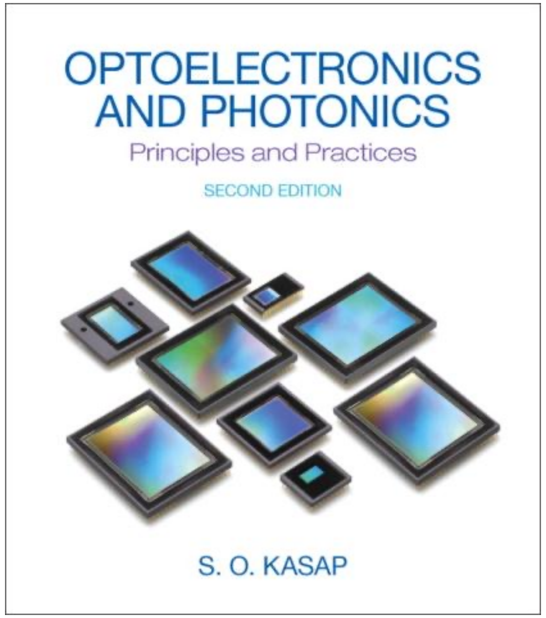

Windows and Diffusers

- Photonics is primarily concerned with the generation, "processing", and sensing of light.

Outline

Part 1. Wave nature of light

Part 2. Applications



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What is Light?

1. Ray

The basic element in geometrical optics is the light ray, a hypothetical construct that indicates the direction of the propagation of light at any point in space.

2. Wave

A wave is an undulation that propagates from one point to another, and as it travels it carries the energy of the electromagnetic spectrum.

3. Particle

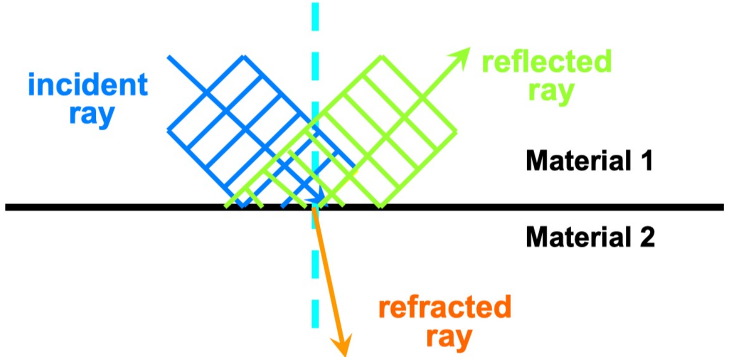
A *photon* is the smallest possible particle of electromagnetic energy.

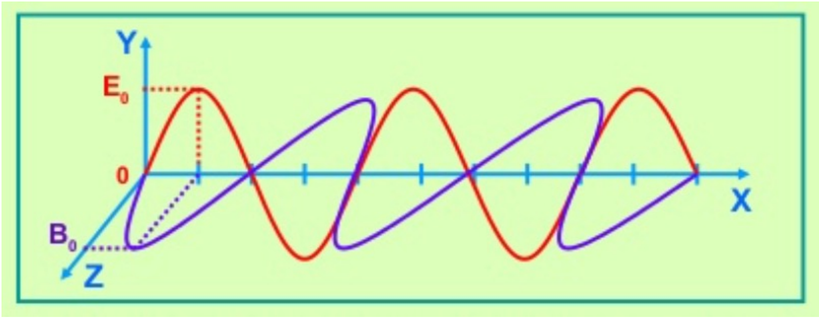
How to study light propagation?

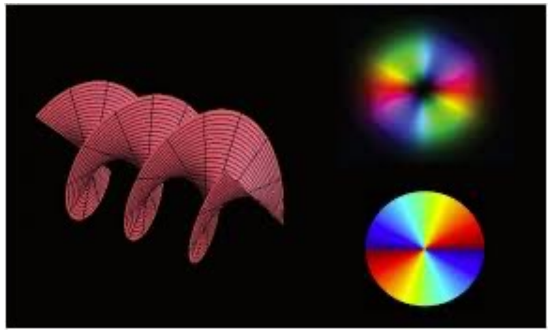
Geometric Optics

Wave Optics

Quantum Optics







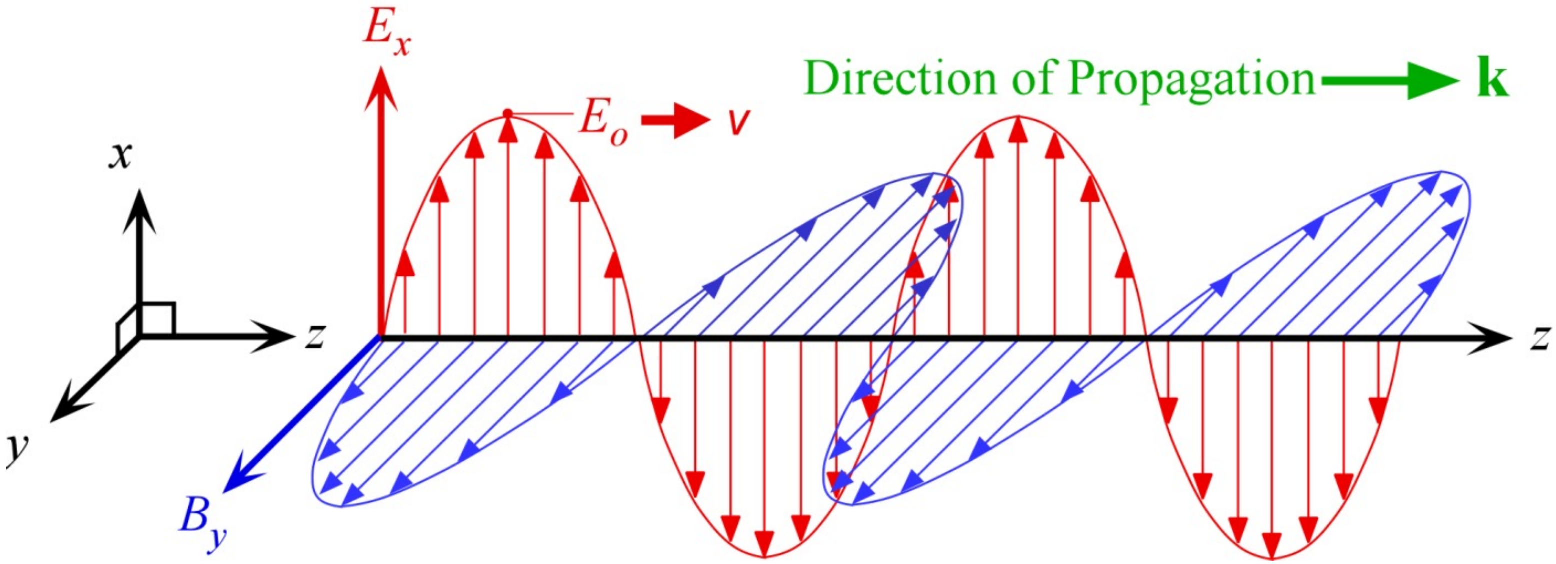
Light is an electromagnetic wave

$$E_x = E_o \cos(\omega t - kz + \phi_o)$$

E_x = Electric field along x at position z at time t
k = **Propagation constant** = $2\pi/\lambda$
λ = Wavelength
ω = Angular frequency = $2\pi\upsilon$ (υ = frequency)
E_o = Amplitude of the wave
ϕ_o = Phase constant; at $t = 0$ and $z = 0$, E_x may or may not necessarily be zero depending on the choice of origin.

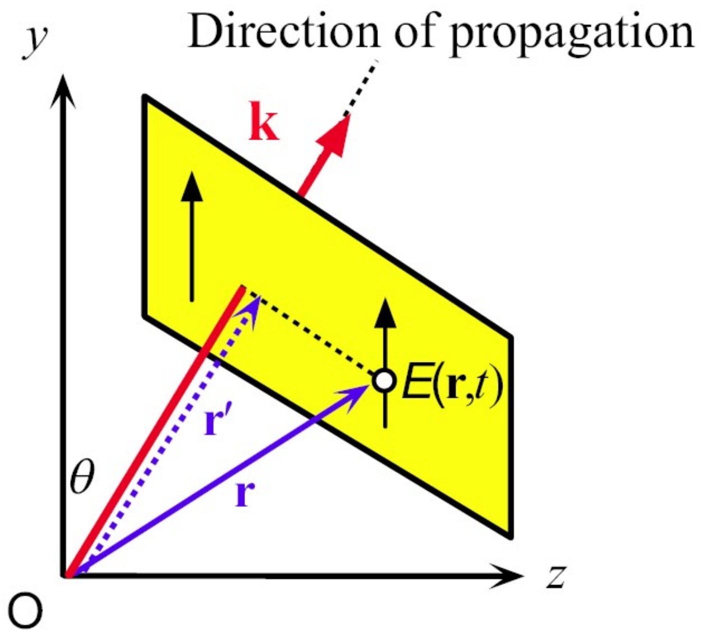
$(\omega t - kz + \phi_o) = \phi$ = **Phase of the wave**

This is a **monochromatic plane wave** of *infinite extent* traveling in the positive *z* direction.



An electromagnetic wave is a traveling wave that has time-varying electric and magnetic fields that are perpendicular to each other and the direction of propagation z.

Wave Vector or Propagation Vector



Direction of propagation is indicated with a vector **k**, called the **wave vector**, whose magnitude is the *propagation constant*, $k = 2\pi/\lambda$. **k** is *perpendicular* to constant phase planes.

When the electromagnetic (EM) wave is propagating along some arbitrary direction **k**, then the electric field $E(\mathbf{r},t)$ at a point **r** on a plane perpendicular to **k** is

$$E(\mathbf{r},t) = E_o \cos(\omega t - \mathbf{k}\cdot\mathbf{r} + \phi_o)$$

The equations of Optics are Maxwell's Equations

(first written down in 1864)

$$\vec{\nabla} \cdot \vec{E} = \rho / \varepsilon \qquad \vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\vec{\nabla} \cdot \vec{B} = 0 \qquad \vec{\nabla} \times \vec{B} = \mu \vec{J} + \mu\varepsilon \frac{\partial \vec{E}}{\partial t}$$


James Clerk Maxwell
(1831-1879)

where E is the electric field, B is the magnetic field, ρ is the charge density, J is the current density, ε is the permittivity, and μ is the permeability of the medium.

Often, in optics, there are no free charges or currents, so mostly we can assume that $\rho = 0$ and J = 0.

A vector wave equation for the electric field

A light wave can propagate in any direction in space. So we must allow the space derivative to be 3D:

in one dimension:

$$\frac{\partial^2 E}{\partial x^2} - \mu\varepsilon \frac{\partial^2 E}{\partial t^2} = 0$$

$\Longrightarrow$

in three dimensions:

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

Note the vector symbol over the E.

Questionnaire:

1. Prove this equation ?? →Need to know Div, grad, curl and all that
2. If E and B satisfy the same equation; does that mean they're equal?
3. How E and B fields are aligned always?

Derivation of the 3D wave equation

Steps involved:

1) Take cross product of “Del” with “Curl of E”.

2) Change the differentiation on the RHS and substitute the value of “Curl of B” on RHS.

3) Substitute LHS to be:

$$\vec{\nabla}(\vec{\nabla}\cdot\vec{E})-\nabla^2\vec{E}$$

For any function at all,

$$\vec{\nabla}(\vec{\nabla}\cdot\vec{F})-\nabla^2\vec{F}=\vec{\nabla}\times\left[\vec{\nabla}\times\vec{F}\right]$$

See: https://www.youtube.com/watch?v=P4edqL1r4DQ

Here assuming zero charge density,

Permeability and permittivity to be independent of time

We’re left with the WAVE EQUATION !!

1.

Expanding the Laplacian, we find:

$$\frac{\partial^2 \vec{E}}{\partial x^2} + \frac{\partial^2 \vec{E}}{\partial y^2} + \frac{\partial^2 \vec{E}}{\partial z^2} - \mu\varepsilon \frac{\partial^2 \vec{E}}{\partial t^2} = 0$$

2.

First: take $\vec{\nabla}\times$ of this one: $\vec{\nabla}\times\vec{E} = -\frac{\partial \vec{B}}{\partial t}$

$$\vec{\nabla}\times[\vec{\nabla}\times\vec{E}] = \vec{\nabla}\times[-\frac{\partial \vec{B}}{\partial t}]$$

Next: change the order of differentiation on the right-hand side:

$$\vec{\nabla}\times[\vec{\nabla}\times\vec{E}] = -\frac{\partial}{\partial t}[\vec{\nabla}\times\vec{B}]$$

3.

But: $\vec{\nabla}\times\vec{B} = \mu\varepsilon\frac{\partial \vec{E}}{\partial t}$

Next: substituting for $\vec{\nabla}\times\vec{B}$, we have:

$$\vec{\nabla}\times[\vec{\nabla}\times\vec{E}] = -\frac{\partial}{\partial t}[\vec{\nabla}\times\vec{B}] \quad \Rightarrow \quad \vec{\nabla}\times[\vec{\nabla}\times\vec{E}] = -\frac{\partial}{\partial t}[\mu\varepsilon\frac{\partial \vec{E}}{\partial t}]$$

Or: $$\vec{\nabla}\times[\vec{\nabla}\times\vec{E}] = -\mu\varepsilon\frac{\partial^2 \vec{E}}{\partial t^2}$$

assuming that μ and ε are both independent of time.

4.

We are up to here: $\vec{\nabla}\times[\vec{\nabla}\times\vec{E}] = -\mu\varepsilon\frac{\partial^2 \vec{E}}{\partial t^2}$

Now, it can be shown that this: $\vec{\nabla}\times[\vec{\nabla}\times\vec{E}]$

is the same as this: $\vec{\nabla}(\vec{\nabla}\cdot\vec{E}) - \nabla^2\vec{E}$

For any function at all,

$$\vec{\nabla}(\vec{\nabla}\cdot\vec{F}) - \nabla^2\vec{F} = \vec{\nabla}\times\left[\vec{\nabla}\times\vec{F}\right]$$

See: https://www.youtube.com/watch?v=P4edqL1r4DQ

If we now assume zero charge density: $\rho = 0$, then

$$\vec{\nabla}\cdot\vec{E} = 0$$

and we're left with the Wave Equation! $\nabla^2\vec{E} = \mu\varepsilon\frac{\partial^2 \vec{E}}{\partial t^2}$

EM propagation in homogeneous materials

- The speed of an EM wave in free space is given by: $c = \dfrac{1}{\sqrt{\mu_0 \varepsilon_0}}$

ε_0 = permittivity of free space, μ_0 = magnetic permeability of free space

- **How are Maxwell's equations in matter different?**
  - $\varepsilon_0 \rightarrow \varepsilon$, $\mu_0 \rightarrow \mu$
    - *Generally increased by the presence of matter – <u>especially ε</u>*
  - => Speed of light in matter v related to the speed of light in vacuum c by:

$$v_{medium} = \frac{c}{n_{medium}}$$

What is n ?

Refractive Index

TABLE 1.1 Low-frequency (LF) relative permittivity ε_r(LF) and refractive index n

Material	ε_r(LF)	$[\varepsilon_r(\text{LF})]^{1/2}$	n (at λ)	Comment
Si	11.9	3.44	3.45 (at 2.15 μm)	Electronic bond polarization up to optical frequencies
Diamond	5.7	2.39	2.41 (at 590 nm)	Electronic bond polarization up to UV light
GaAs	13.1	3.62	3.30 (at 5 μm)	Ionic polarization contributes to ε_r(LF)
SiO_2	3.84	2.00	1.46 (at 600 nm)	Ionic polarization contributes to ε_r(LF)
Water	80	8.9	1.33 (at 600 nm)	Dipolar polarization contributes to ε_r(LF), which is large

n depends on the wavelength λ

Dispersion relation: $n = n(\lambda)$

The simplest electronic polarization gives

$$n^2 = 1 + \left(\frac{N_{at} Z e^2}{\varepsilon_o m_e}\right)\left(\frac{\lambda_o}{2\pi c}\right)^2 \frac{\lambda^2}{\lambda^2 - \lambda_o^2}$$

N_{at} =Number of atoms per unit volume
Z = Number of electrons in the atom (atomic number)

λ_o = A "resonant frequency"

Sellmeier Equation

$$n^2 = 1 + \frac{A_1 \lambda^2}{\lambda^2 - \lambda_1^2} + \frac{A_2 \lambda^2}{\lambda^2 - \lambda_2^2} + \frac{A_3 \lambda^2}{\lambda^2 - \lambda_3^2}$$

n depends on the wavelength λ

TABLE 1.2 Sellmeier and Cauchy coefficients

Sellmeier	A_1	A_2	A_3	λ_1 (μm)	λ_2 (μm)	λ_3 (μm)
SiO_2 (fused silica)	0.696749	0.408218	0.890815	0.0690660	0.115662	9.900559
86.5%SiO_2-13.5%GeO_2	0.711040	0.451885	0.704048	0.0642700	0.129408	9.425478
GeO_2	0.80686642	0.71815848	0.85416831	0.068972606	0.15396605	11.841931
Sapphire	1.023798	1.058264	5.280792	0.0614482	0.110700	17.92656
Diamond	0.3306	4.3356	–	0.1750	0.1060	–

Cauchy	Range of $h\nu$ (eV)	n_{-2} (eV^2)	n_0	n_2 (eV^{-2})	n_4 (eV^{-4})
Diamond	0.05–5.47	-1.07×10^{-5}	2.378	8.01×10^{-3}	1.04×10^{-4}
Silicon	0.002–1.08	-2.04×10^{-8}	3.4189	8.15×10^{-2}	1.25×10^{-2}
Germanium	0.002–0.75	-1.0×10^{-8}	4.003	2.2×10^{-1}	1.4×10^{-1}

Source: Sellmeier coefficients combined from various sources. Cauchy coefficients from D. Y. Smith *et al.*, *J. Phys. CM*, *13*, 3883, 2001.

EXAMPLE 1.2.1 Sellmeier equation and diamond

Using the Sellmeier coefficients for diamond in Table 1.2, calculate its refractive index at 610 nm (red light) and compare with the experimental quoted value of 2.415 to three decimal places.

Solution

The Sellmeier dispersion relation for diamond is

$$n^2 = 1 + \frac{0.3306\lambda^2}{\lambda^2 - 175\text{ nm}^2} + \frac{4.3356\lambda^2}{\lambda^2 - 106\text{ nm}^2}$$

$$n^2 = 1 + \frac{0.3306(610\text{ nm})^2}{(610\text{ nm})^2 - (175\text{ nm})^2} + \frac{4.3356(610\text{ nm})^2}{(610\text{ nm})^2 - (106\text{ nm})^2} = 5.8308$$

So that

$$n = 2.4147$$

which is 2.415 to three decimal places and matches the experimental value.

Diffraction

Interference

Reflection

Refraction

Dispersion

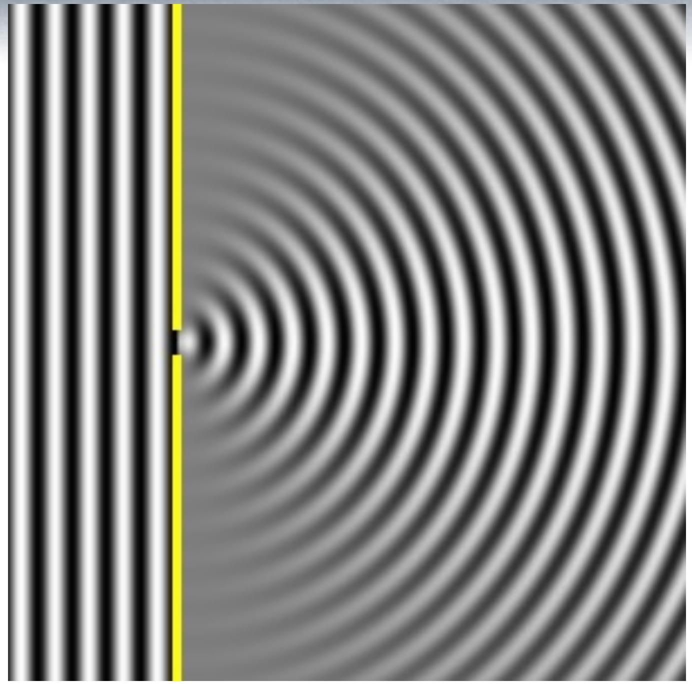
Polarization

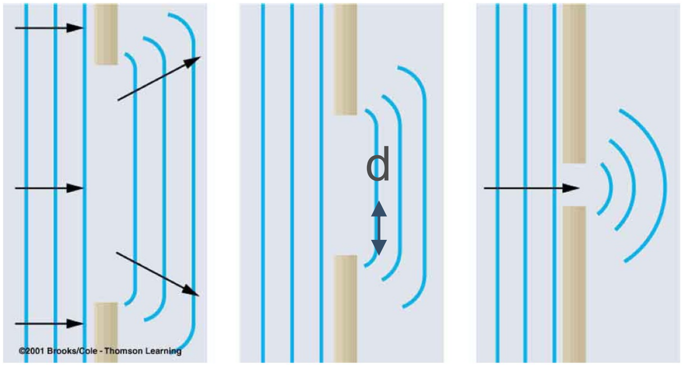
Characteristic of waves: Diffraction

- Diffraction refers to various phenomena that occur when a wave encounters an obstacle or opening (slit).

- It is defined as the bending of waves around the corners of an obstacle or through an aperture into the region of geometrical shadow of the obstacle/aperture.

- Diffraction depends on slit width: the smaller the width, relative to wavelength, the more bending and diffraction.





Young’s double slit interference

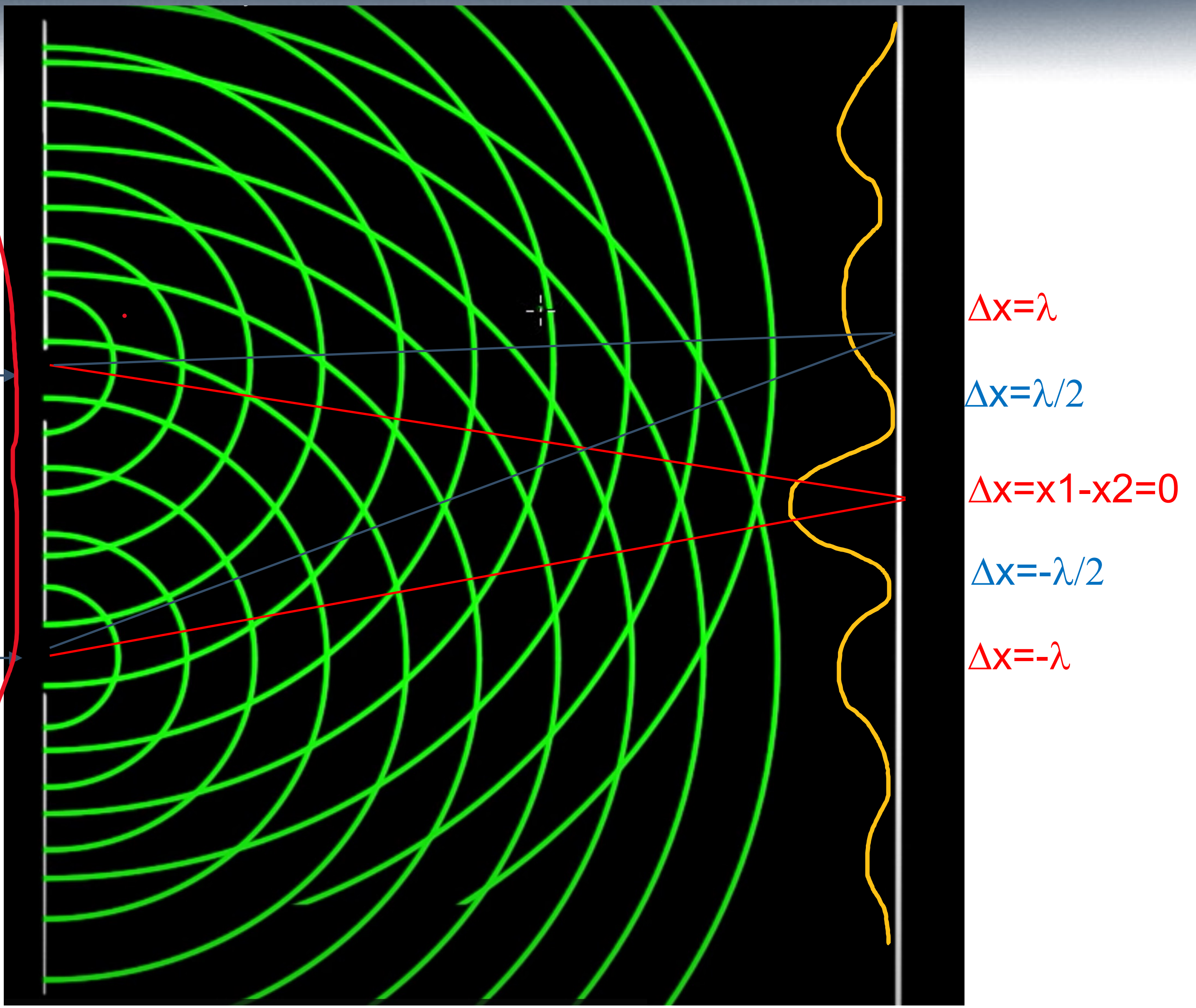
How the two waves will overlap?

1. Locate the bright spots
2. Locate the dark spots
3. Trace the path length difference:

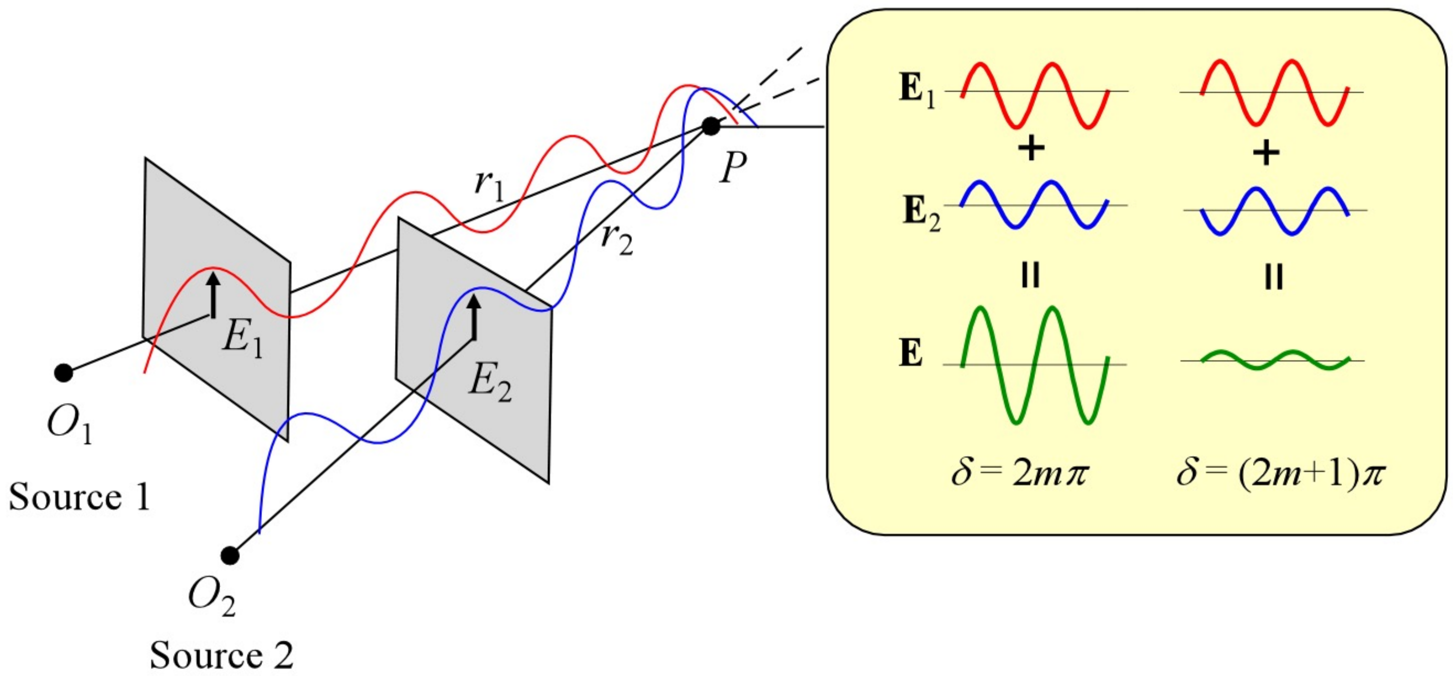
$\Delta x = X1 - X2$

- Constructive interference (bright fringes) at: **$\Delta x = 0, \lambda, 2\lambda \ldots$**

- Destructive interference (dark fringes) at: **$\Delta x = \lambda/2, 3\lambda/2 \ldots$**



Interference

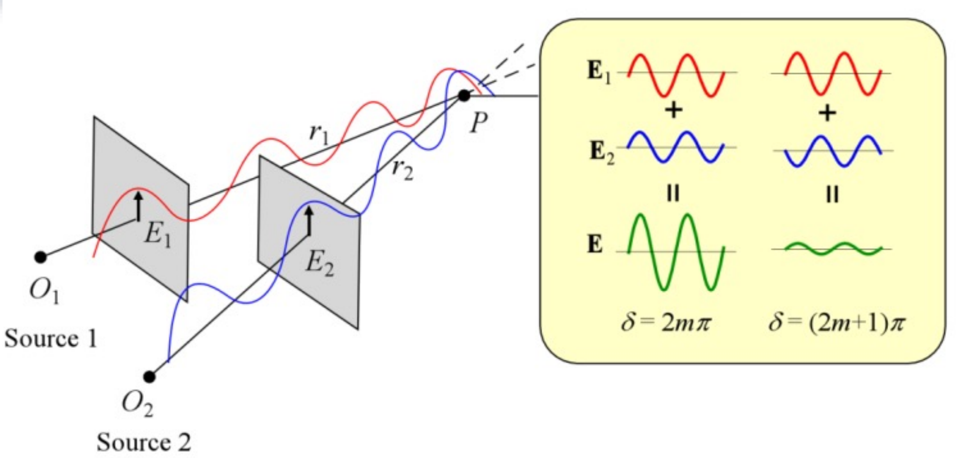


$\mathbf{E}_1 = \mathbf{E}_{o1}\sin(\omega t - kr_1 - \phi_1)$ and $\mathbf{E}_2 = \mathbf{E}_{o2}\sin(\omega t - kr_2 - \phi_2)$

Interference results in $\mathbf{E} = \mathbf{E}_1 + \mathbf{E}_2$

$$\overline{\mathbf{E}\cdot\mathbf{E}} = \overline{(\mathbf{E}_1 + \mathbf{E}_2)\cdot(\mathbf{E}_1 + \mathbf{E}_2)} = \overline{\mathbf{E}_1^2} + \overline{\mathbf{E}_2^2} + 2\overline{\mathbf{E}_1\mathbf{E}_2}$$

Interference



Resultant intensity I is

$$I = I_1 + I_2 + 2(I_1 I_2)^{1/2} \cos\delta$$

$$\delta = k(r_2 - r_1) + (\phi_2 - \phi_1)$$

Phase difference due to optical path difference

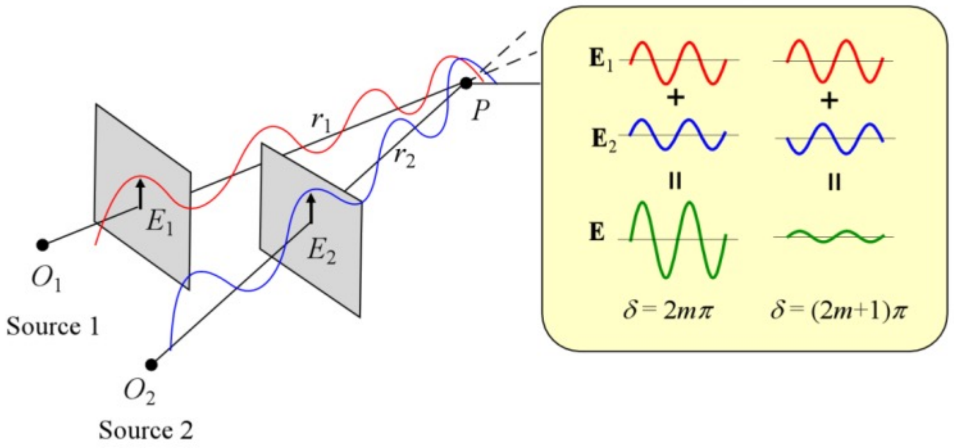
Constructive interference **Destructive interference**

$$I_{\max} = I_1 + I_2 + 2(I_1 I_2)^{1/2}$$ and $$I_{\min} = I_1 + I_2 - 2(I_1 I_2)^{1/2}$$

If the interfering beams have equal irradiances, then

$$I_{\max} = 4I_1$$ $$I_{\min} = 0$$

Interference between coherent waves



Resultant intensity I is

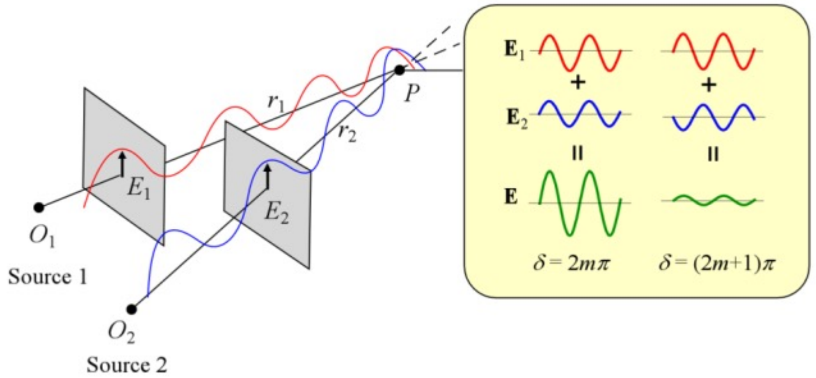
$$I = I_1 + I_2 + 2(I_1 I_2)^{1/2}\cos\delta$$

$$\delta = k(r_2 - r_1) + (\phi_2 - \phi_1)$$

Interference between incoherent waves

$$I = I_1 + I_2$$

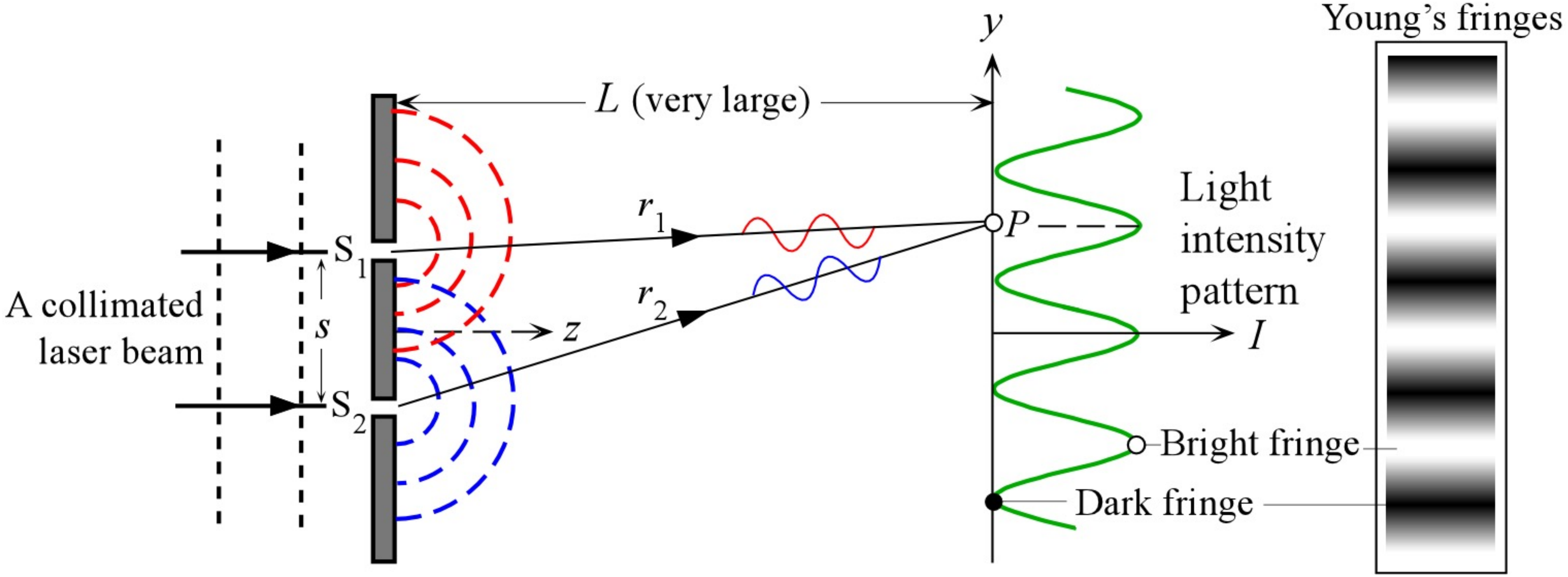
Interference between coherent waves



Resultant intensity I is

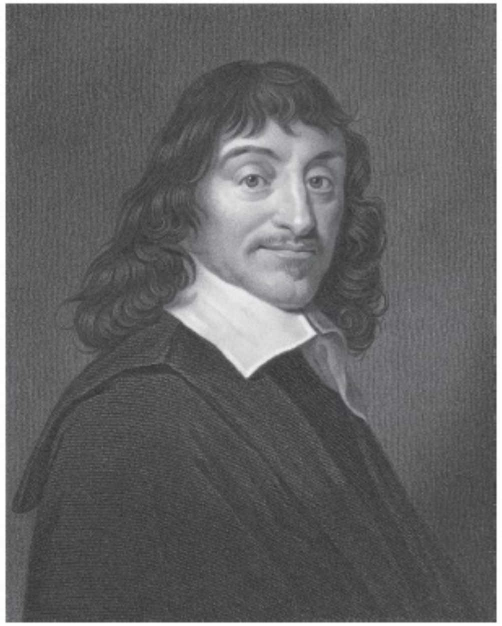
$$I = I_1 + I_2 + 2(I_1 I_2)^{1/2}\cos\delta$$

$$\delta = k(r_2 - r_1) + (\phi_2 - \phi_1)$$



Snell's Law or Descartes's Law?

Willebrord Snellius (Willebrord Snel van Royen, 1580–1626) was a Dutch astronomer and a mathematician, who was a professor at the University of Leiden. He discovered his law of refraction in 1621 which was published by Réne Descartes in France 1637; it is not known whether Descartes knew of Snell's law or formulated it independently. *(Courtesy of AIP Emilio Segre Visual Archives, Brittle Books Collection.)*



René Descartes (1596–1650) was a French philosopher who was also involved with mathematics and sciences. He has been called the "Father of Modern Philosophy." Descartes was responsible for the development of Cartesian coordinates and analytical geometry. He also made significant contributions to optics, including reflection and refraction. *(Courtesy of Georgios Kollidas/Shutterstock.com.)*

Fermat's principle of least time

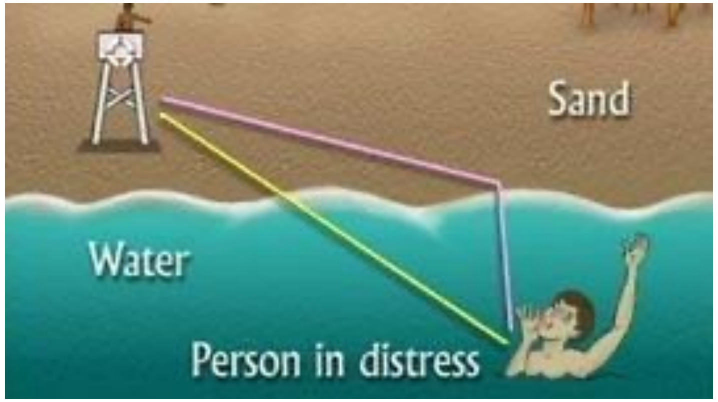
Fermat's principle of least time in simple terms states that:

When light travels from one point to another it takes a path that has the shortest time.

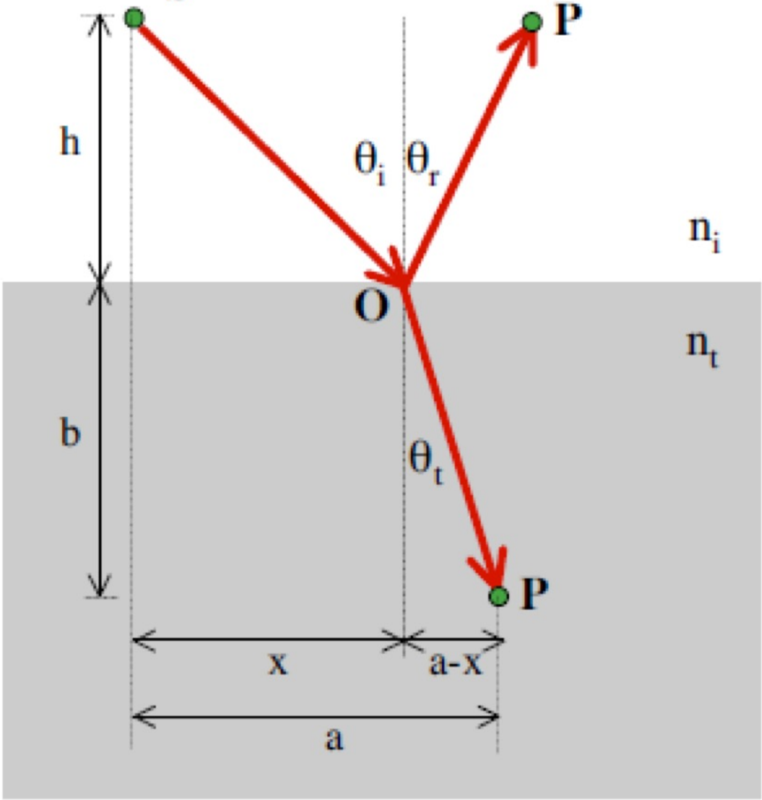
Pierre de Fermat (1601–1665) was a French mathematician who made many significant contributions to modern calculus, number theory, analytical geometry, and probability. *(Courtesy of Mary Evans Picture Library/Alamy.)*

Fermat's Principle and the laws of Reflection and Refraction

The path actuallty taken by light in going from point S to a point P is the shortest optical path length (OPL)



Refraction



$$OPL = n_i \cdot \overline{SO} + n_t \cdot \overline{OP}$$
$$= n_i \cdot \sqrt{h^2 + x^2} + n_t \cdot \sqrt{b^2 + (a-x)^2}$$

$$\frac{dOPL}{dx} = 0 \text{ to minimize } OPL$$

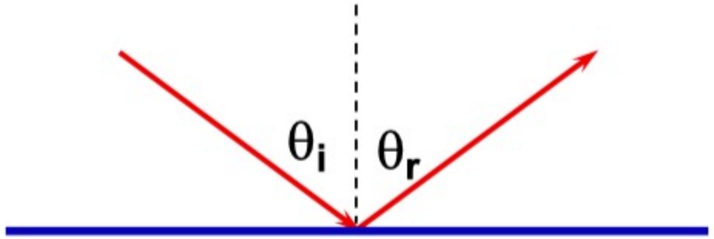
$$n_i \cdot \frac{x}{\sqrt{h^2 + x^2}} + n_t \cdot \frac{-(a-x)}{\sqrt{b^2 + (a-x)^2}} = 0$$

$$\frac{n_i}{n_t} = \frac{\sin(\theta_t)}{\sin(\theta_i)}$$

Snell's law

Reflection

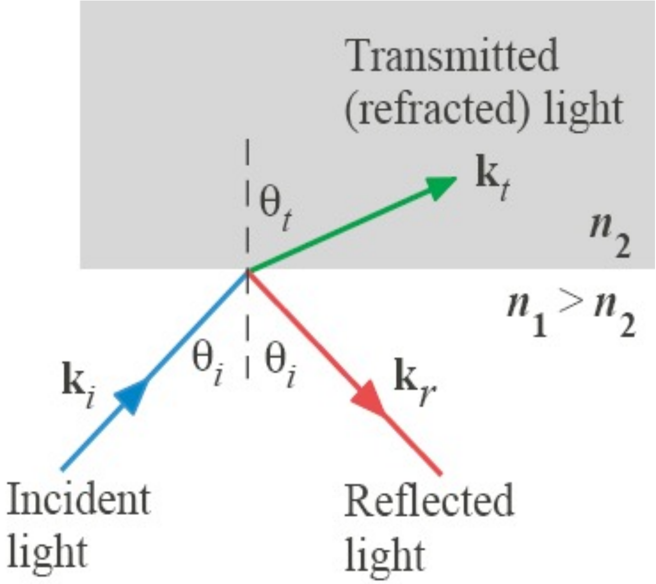
• Angle of incidence = angle of reflection both angles are measured from the normal



$$\theta\, i = \theta r$$

Refraction

• How is the angle of refraction related to the angle of incidence?



$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

Thin films interference

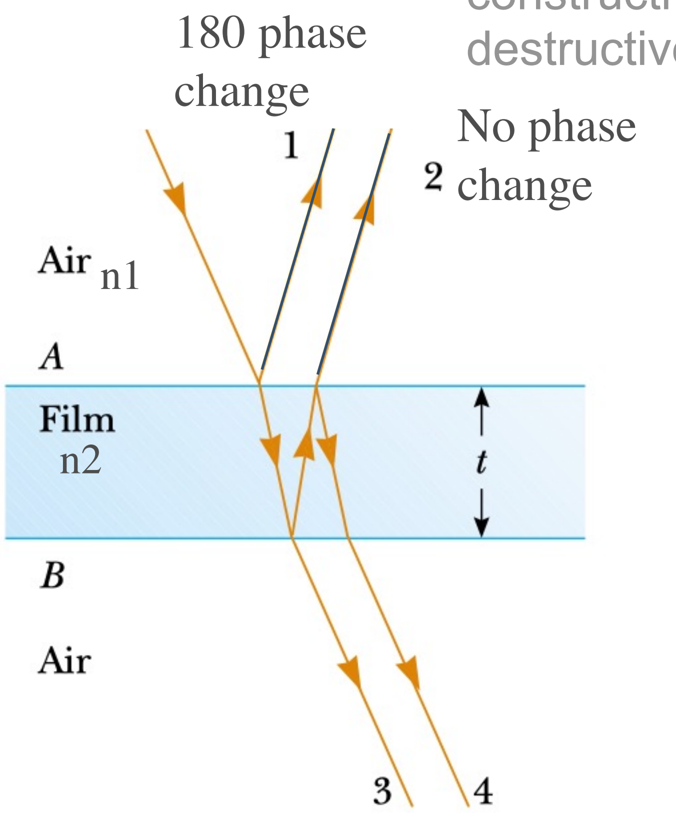
- A wave traveling from a medium of index of refraction n1 toward a medium of index of refraction n2 undergoes a 180°phase change upon reflection when n2 > n1 and undergoes no phase change if n2 < n1 .
- The wavelength of light λn in a medium whose index of refraction is n is: $\lambda_n = \dfrac{\lambda}{n}$

$\Delta x = L2 - (L1 + \lambda/2)$

- For constructive interference: $\Delta x = m\lambda$

$$2t = (m + \tfrac{1}{2})\lambda_n \qquad (m = 0, 1, 2, \ . \ . \ .)$$

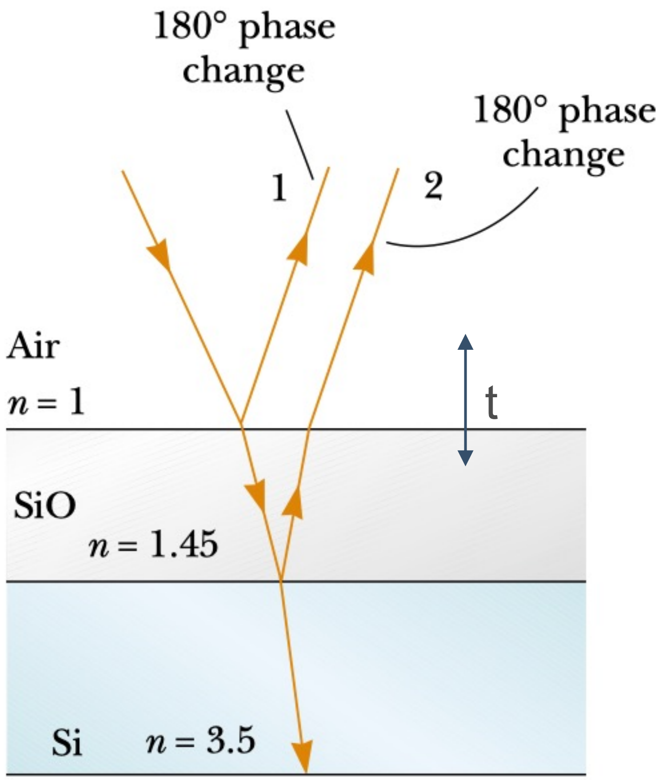
These two rays interfere constructively or destructivey



Approximation: we are considering light rays that are close to normal to the surface

Problem

We consider a solar cells which generates electricity when exposed to sunlight. They are coated with a transparent thin film of SiO to minimize reflective losses from the surface. Suppose that a silicon solar cell (n=3.5) is coated with a thin film of SiO for this purpose, determine the minimum film thickness that produces the least reflection at a wavelength of 550 nm, near the center of the visible spectrum.



Solution

The reflected light is a minimum when rays 1 and 2 meet the condition of destructive interference.

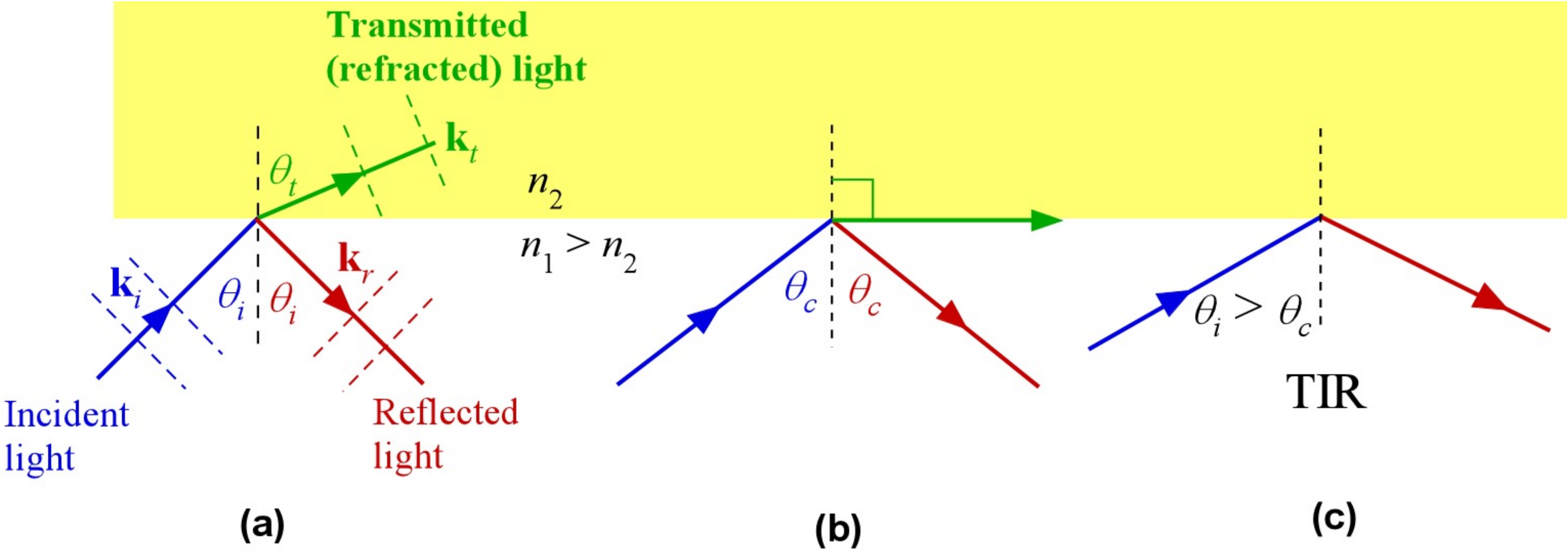
In this situation, both rays undergo a 180°phase change upon reflection—ray 1 from the upper SiO surface and ray 2 from the lower SiO surface. The net change in phase due to reflection is therefore zero, and the condition for a reflection minimum requires a path difference of $\lambda_n/2$, where λ_n is the wavelength of the light in SiO.

Hence $2t= \lambda/2n$, where λ is the wavelength in air and n is the index of refraction of SiO.

The required thickness is:

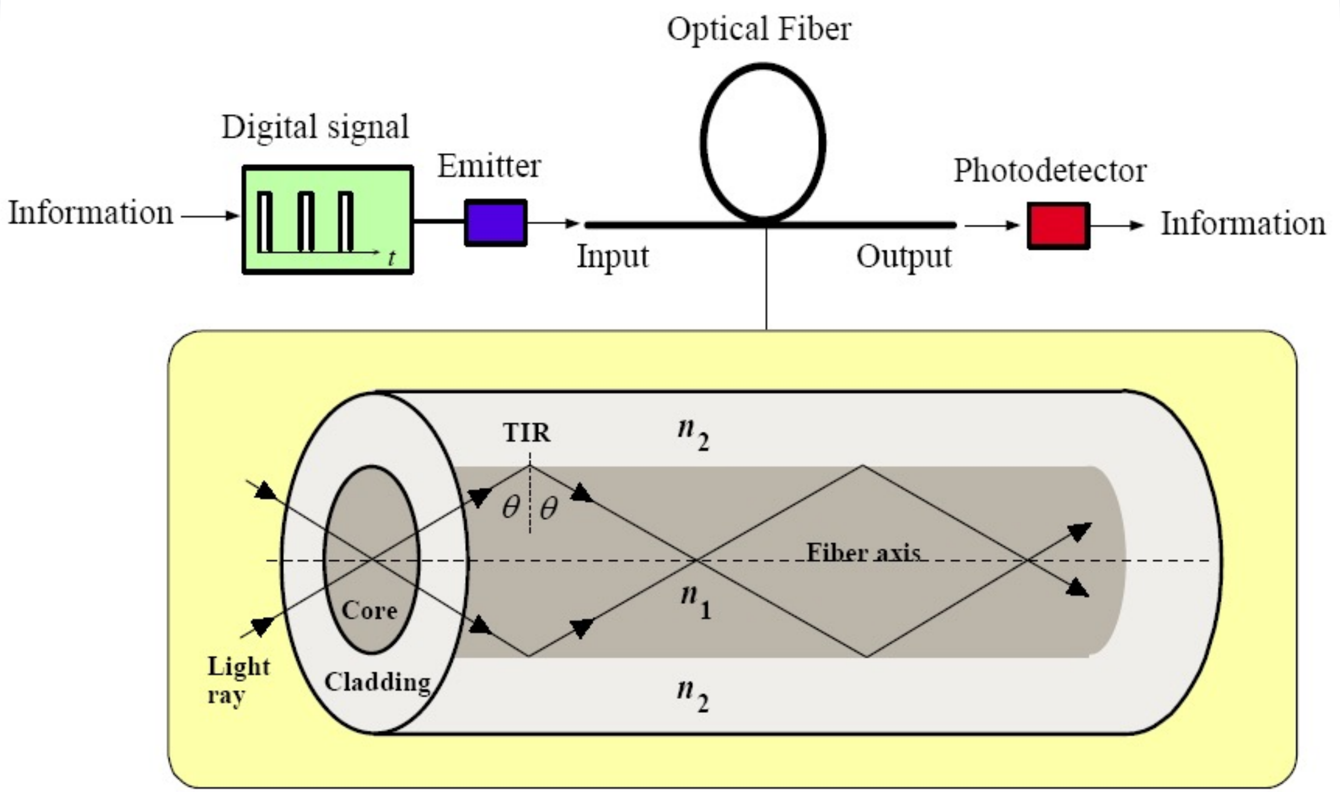
$$t = \frac{\lambda}{4n} = \frac{550\text{ nm}}{4(1.45)} = \boxed{94.8\text{ nm}}$$

Total Internal Reflection



Light wave traveling in a more dense medium strikes a less dense medium. Depending on the incidence angle with respect to θ_c, which is determined by the ratio of the refractive indices, the wave may be transmitted (refracted) or reflected. (a) $\theta_i < \theta_c$ (b) $\theta_i = \theta_c$ (c) $\theta_i > \theta_c$ and total internal reflection (TIR).

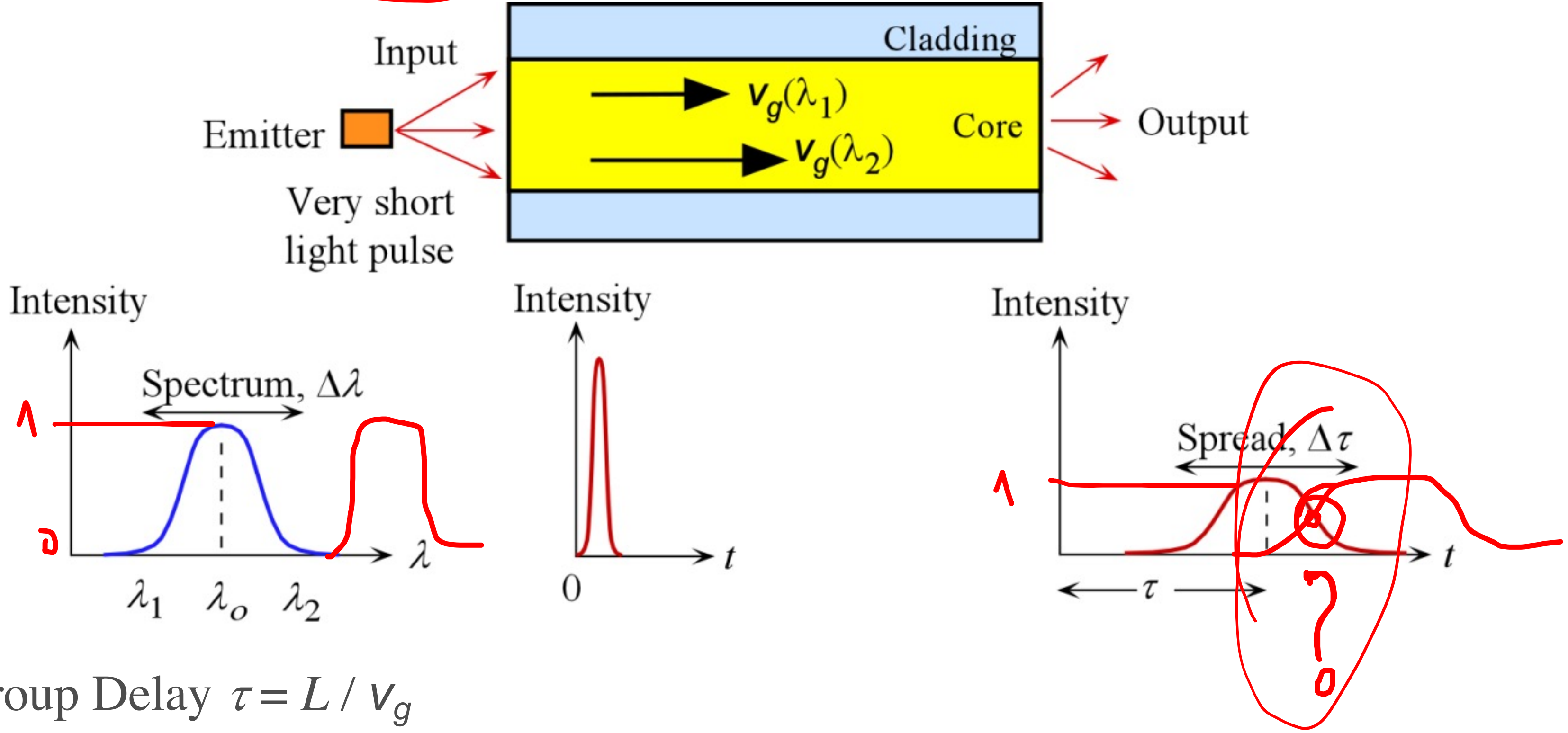
Light travels by TIR in optical fibers



An optical fiber link for transmitting digital information in communications. The fiber core has a higher refractive index so that the light travels along the fiber inside the fiber core by total internal reflection at the core-cladding interface.

Intramode Dispersion (SMF)

Dispersion in the fundamental mode



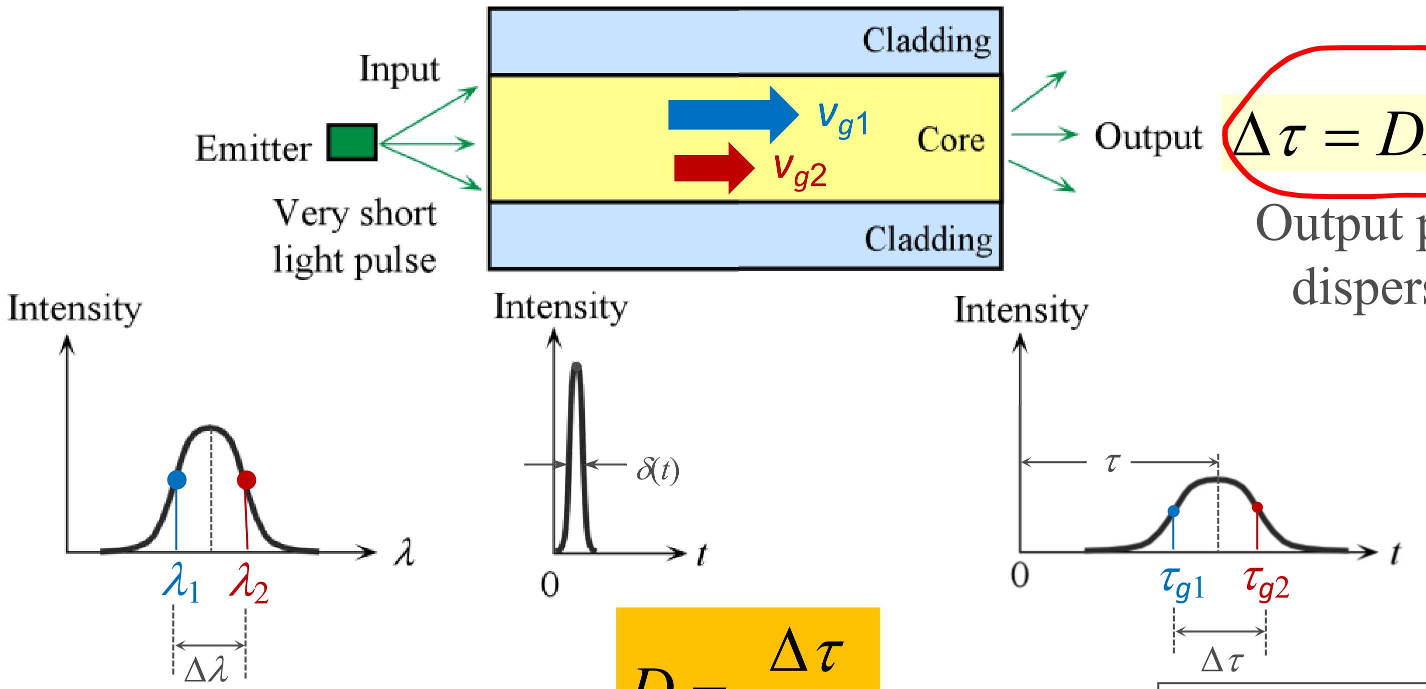
Group Delay $\tau = L / v_g$

Group velocity v_g depends on

Refractive index = $n(\lambda)$	**Material Dispersion**
V-number = $V(\lambda)$	**Waveguide Dispersion**
$\Delta = (n_1 - n_2)/n_1 = \Delta(\lambda)$	**Profile Dispersion**

Intramode Dispersion (SMF)

Chromatic dispersion in the fundamental mode



$$\Delta\tau = DL\Delta\lambda$$

Output pulse dispersed

$$\Delta\lambda = \lambda_2 - \lambda_1$$

Chromatic spread

$$\Delta\tau = \tau_{g1} - \tau_{g2}$$

Dispersion

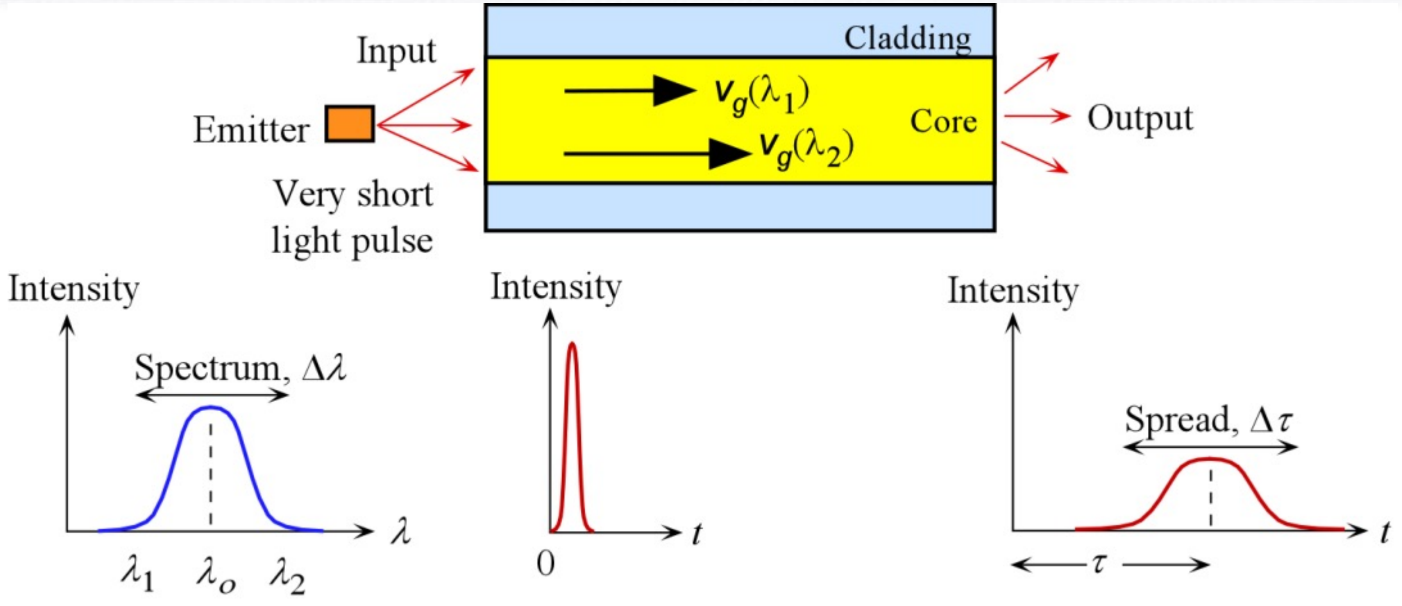
$$D = \frac{\Delta\tau}{L\Delta\lambda}$$

OR

$$D = \frac{d\tau}{Ld\lambda}$$

Definition of Dispersion Coefficient

Material Dispersion



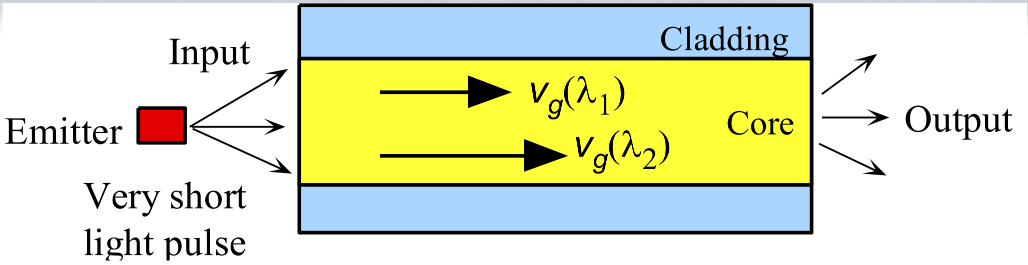
Emitter emits a spectrum $\Delta\lambda$ of wavelengths.

Waves in the guide with different free space wavelengths travel at different group velocities due to the wavelength dependence of n_1. The waves arrive at the end of the fiber at different times and hence result in a broadened output pulse.

$$\boxed{\frac{\Delta\tau}{L} = D_m \Delta\lambda}$$

D_m = Material dispersion coefficient, ps nm^{-1} km^{-1}

Material Dispersion



$$v_g = c / N_g$$

Group velocity

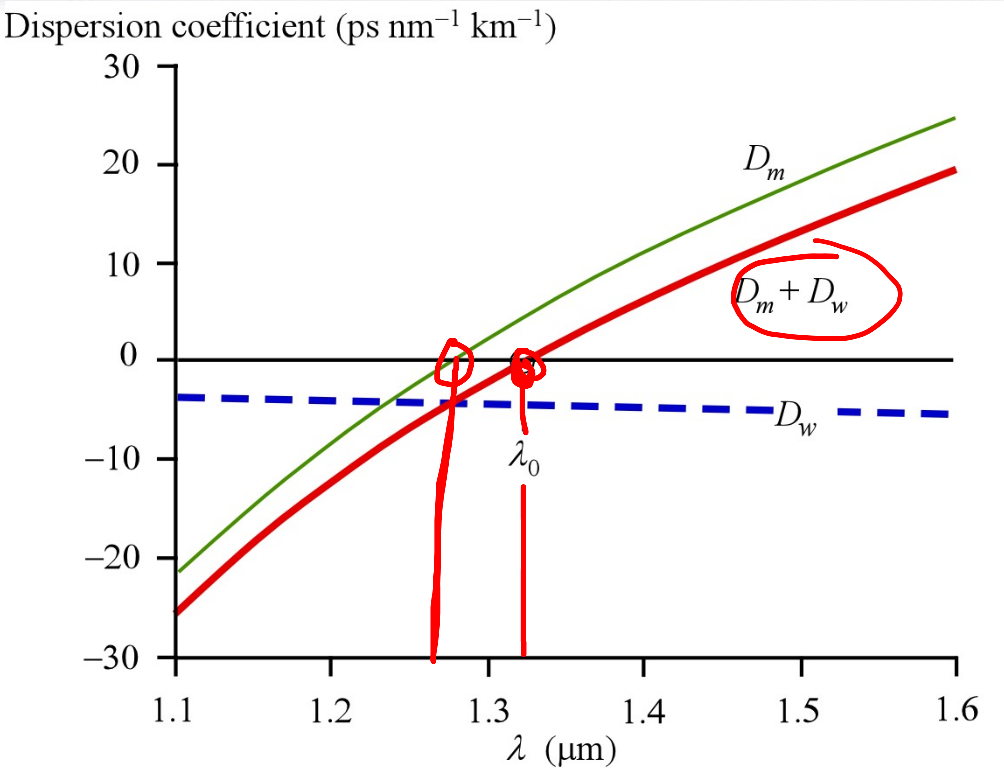
Depends on the wavelength

$$\frac{\Delta\tau}{L} = D_m \Delta\lambda$$

D_m = Material dispersion coefficient, ps nm^{-1} km^{-1}

$$D_m \approx -\frac{\lambda}{c}\left(\frac{d^2 n}{d\lambda^2}\right)$$

Chromatic Dispersion



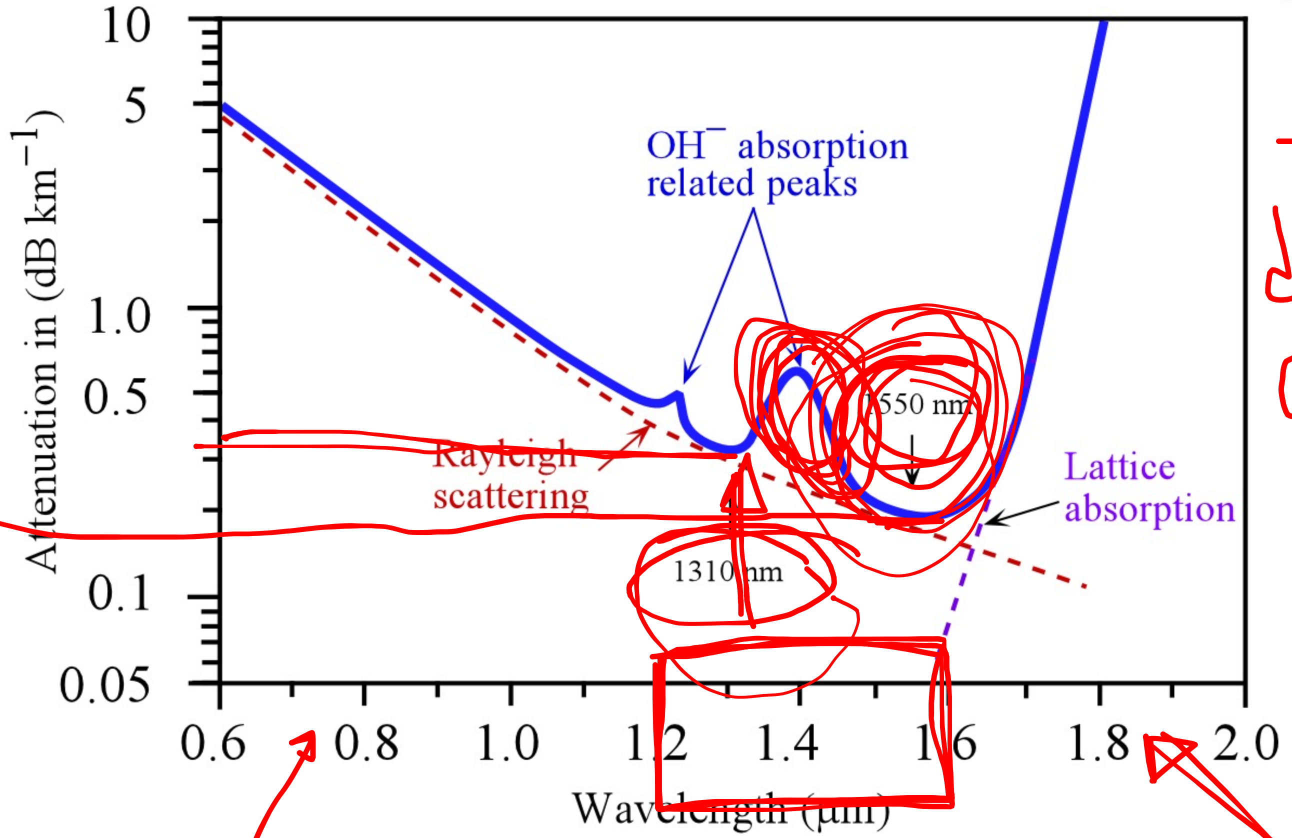
Material dispersion coefficient (D_m) for the core material (taken as SiO_2), waveguide dispersion coefficient (D_w) (a = 4.2 μm) and the total or chromatic dispersion coefficient D_{ch} (= $D_m + D_w$) as a function of free space wavelength, λ

$\lambda = 1.32\ \mu m$?

Chromatic = Material + Waveguide

$$\frac{\Delta\tau}{L} = (D_m + D_w)\Delta\lambda$$

Attenuation in Optical Fibers



Attenuation vs. wavelength for a standard silica based fiber.

D | α

dist ↓ | amplif

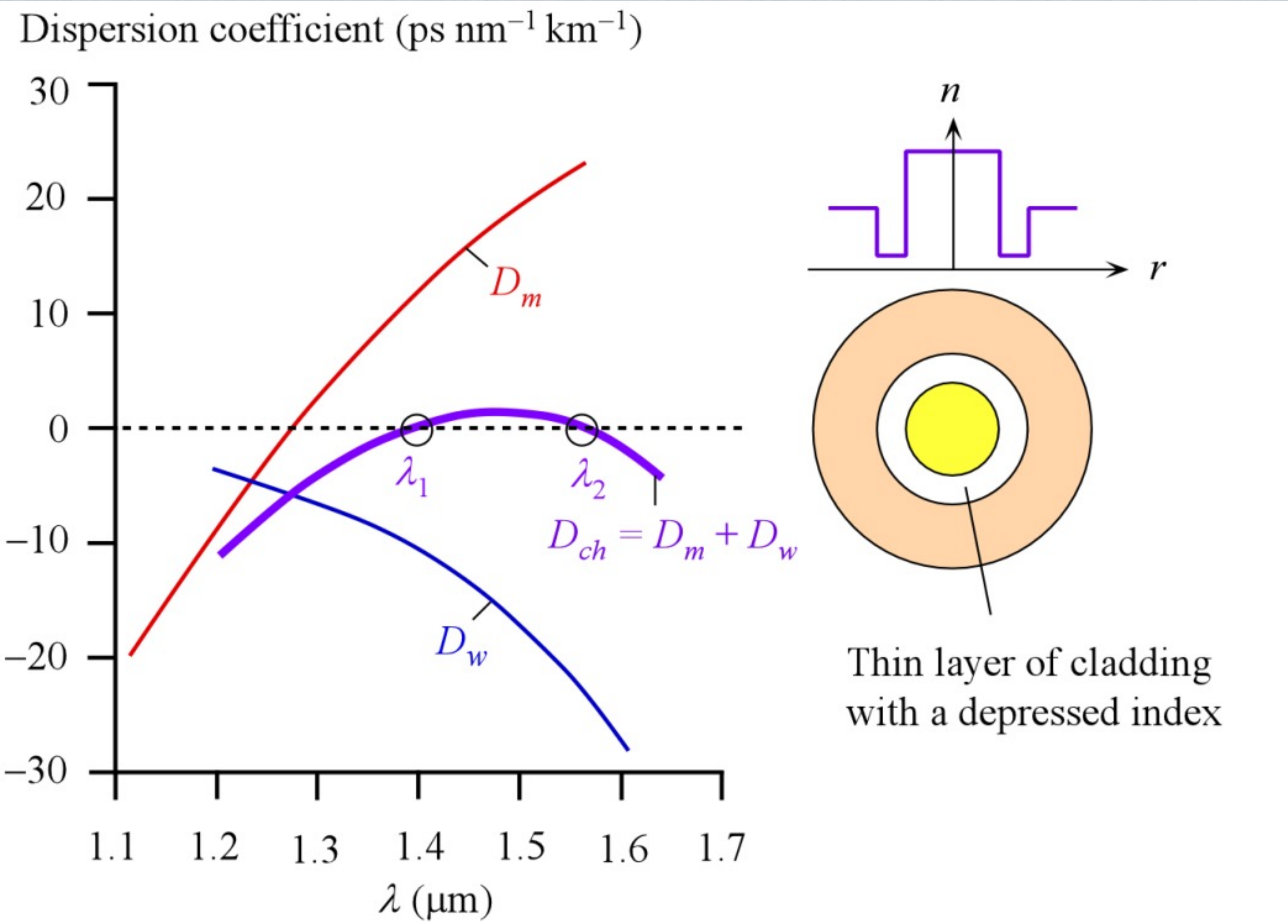
Comp fiber

Cost?

Summary

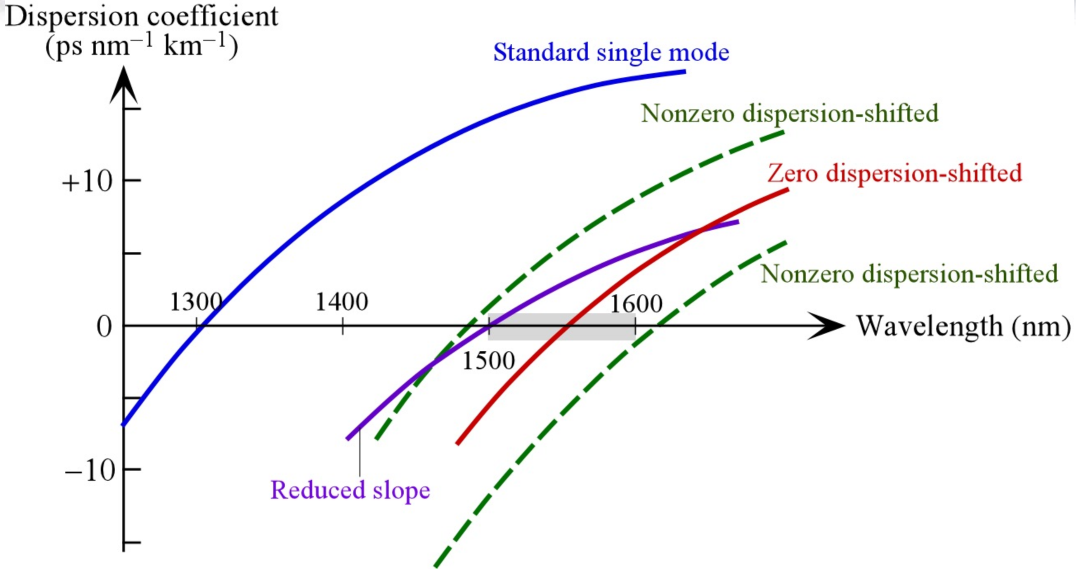
1. What is light
2. How can we study light propagation in a meduim
3. Optical fibers

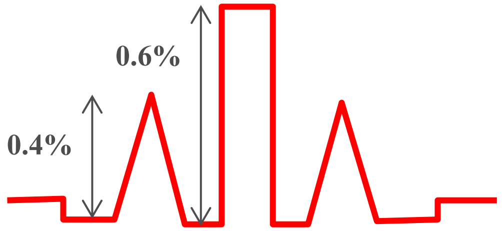
Dispersion Flattened Fiber



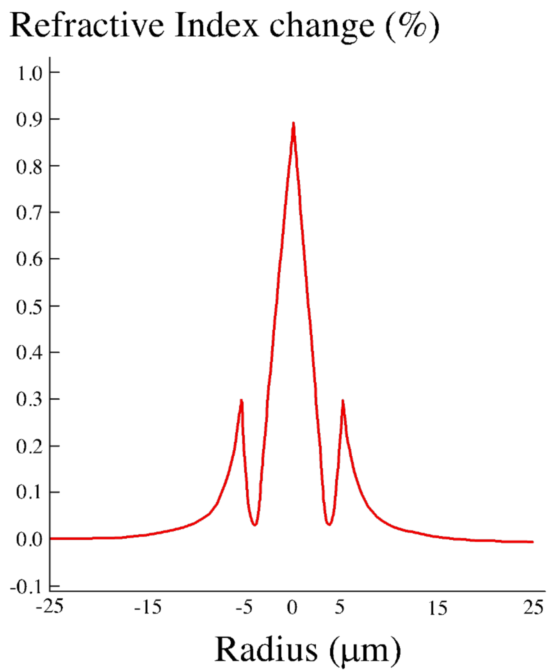
Dispersion flattened fiber example. The material dispersion coefficient (D_m) for the core material and waveguide dispersion coefficient (D_w) for the doubly clad fiber result in a flattened small chromatic dispersion between λ_1 and λ_2.

Nonzero Dispersion Shifted Fiber: More Examples





Fiber with flattened dispersion slope (schematic)



Nonzero dispersion shifted fiber (Corning)

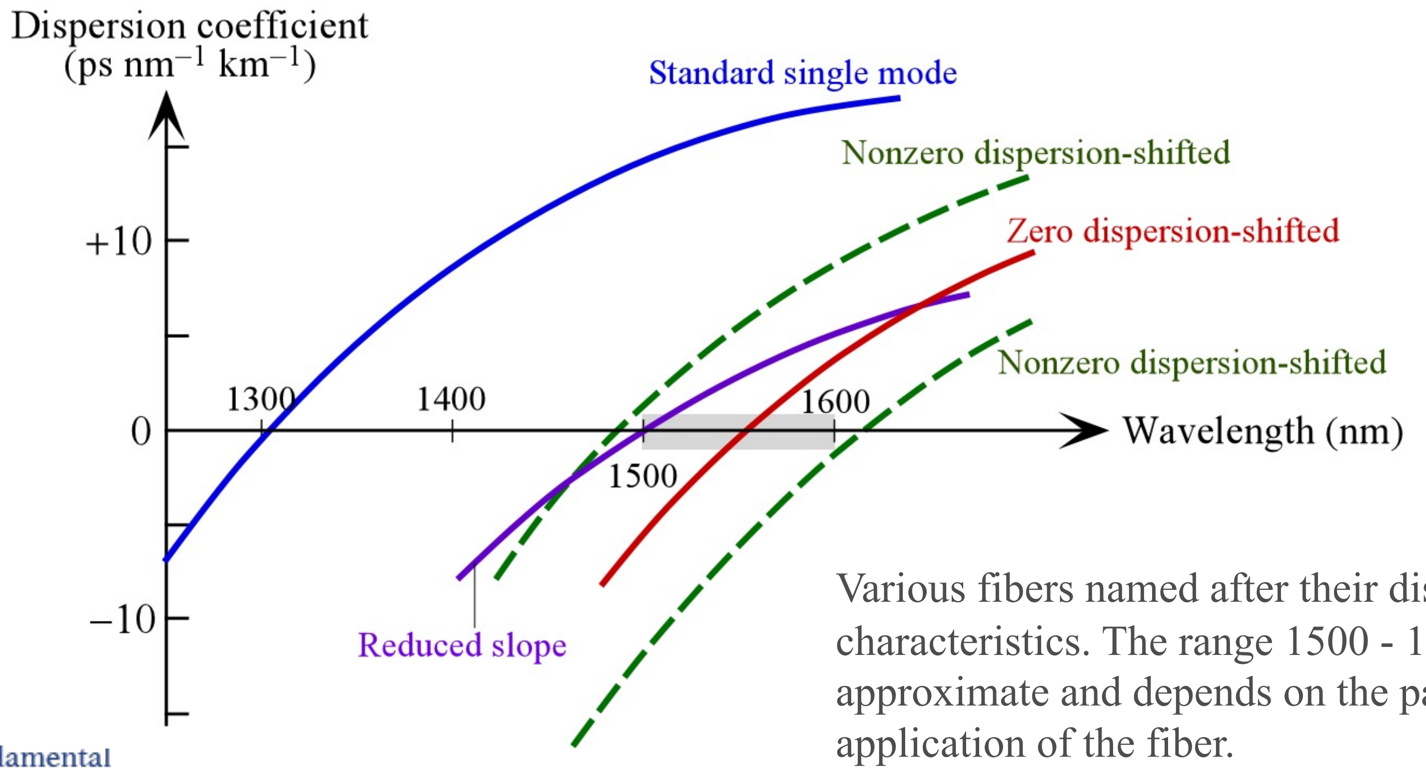
Nonzero Dispersion Shifted Fiber

For Wavelength Division Multiplexing (WDM) avoid 4 wave mixing: cross talk.

We need dispersion not zero but very small in Er-amplifer band (1525-1620 nm)

$D_{ch} = 0.1 - 6$ ps nm^{-1} km^{-1}.

Nonzero dispersion shifted fibers

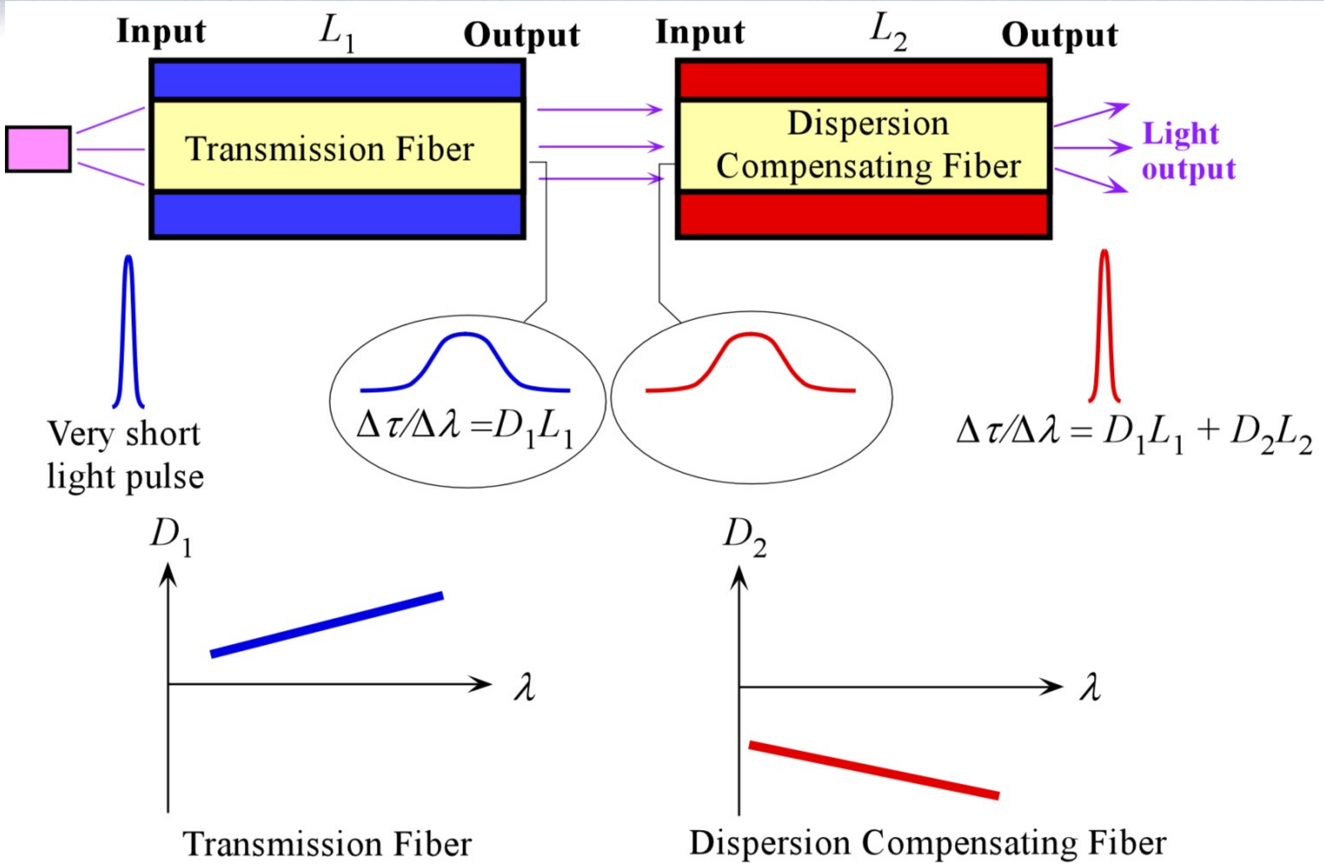


Various fibers named after their dispersion characteristics. The range 1500 - 1600 nm is only approximate and depends on the particular application of the fiber.

Commercial Fibers for Optical Communications

Fiber	D_{ch} ps nm^{-1} km^{-1}	S_0 ps nm^{-2} km^{-1}	D_{PMD} ps km$^{-1/2}$	**Some attributes**
Standard single mode, ITU-T G.652	17 (1550 nm)	≤ 0.093	< 0.5 (cabled)	$D_{ch} = 0$ at $\lambda_0 \approx 1312$ nm, MFD = 8.6 - 9.5 μm at 1310 nm. $\lambda_c \leq 1260$ nm.
Non-zero dispersion shifted fiber, ITU-T G.655	0.1 – 6 (1530 nm)	< 0.05 at 1550 nm	< 0.5 (cabled)	For 1500 - 1600 nm range. WDM application MFD = 8 – 11 μm.
Non-zero dispersion shifted fiber, ITU-T G.656	2 – 14	< 0.045 at 1550 nm	< 0.20 (cabled)	For 1460 - 1625 nm range. DWDM application. MFD = 7 – 11 μm (at 1550 nm). Positive D_{ch}. λ_c <1310 nm
Corning SMF28e+ (Standard SMF)	18 (1550 nm)	0.088	< 0.1	Satisfies G.652. $\lambda_0 \approx 1317$ nm, MFD = 9.2 μm (at 1310 nm), 10.4 μm (at 1550 nm); $\lambda_c \leq 1260$ nm.
OFS TrueWave RS Fiber	2.6 - 8.9	0.045	0.02	Satisfies G.655. Optimized for 1530 nm - 1625nm. MFD = 8.4 μm (at 1550 nm); $\lambda_c \leq 1260$ nm.
OFS REACH Fiber	5.5 -8.9	0.045	0.02	Higher performance than G.655 specification. Satisfies G.656. For DWDM from 1460 to 1625 nm. $\lambda_0 \leq 1405$ nm. MFD = 8.6 μm (at 1550 nm)

Dispersion Compensation

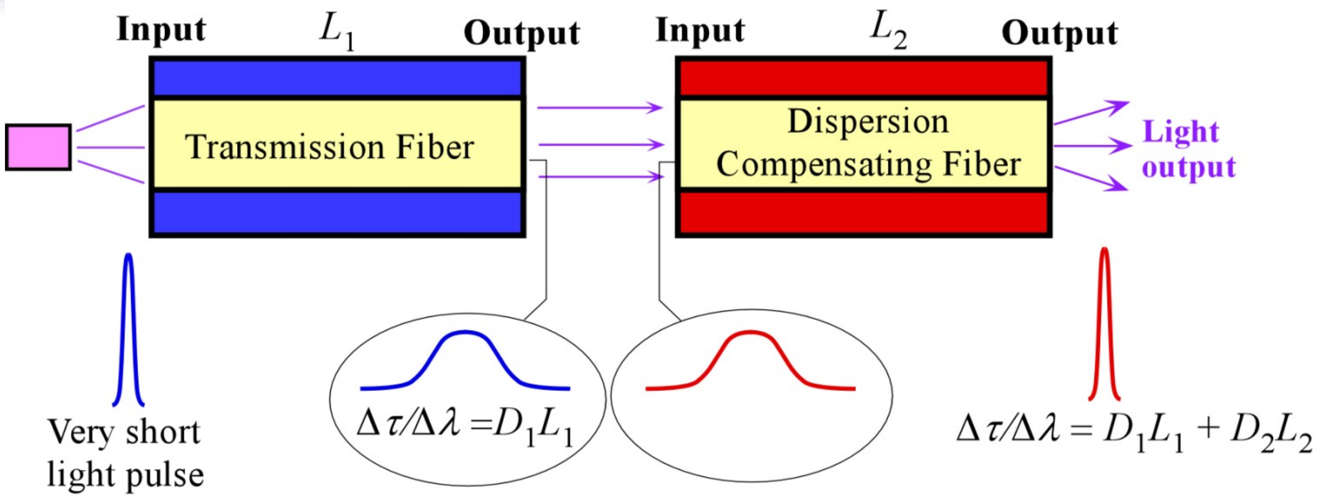


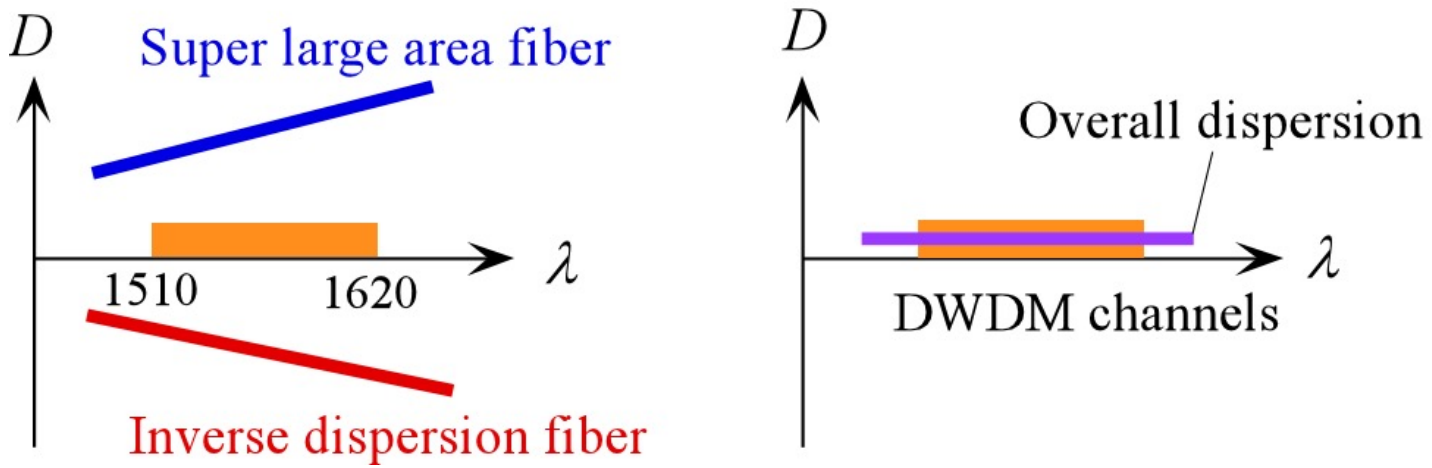
Total dispersion = $D_tL_t + D_cL_c$ = (10 ps nm^{-1} km^{-1})(1000 km) + (–100 ps nm^{-1} km^{-1})(80 km)

= 2000 ps/nm for 1080 km

$D_{effective}$ = 1.9 ps nm^{-1} km^{-1}

Dispersion Compensation



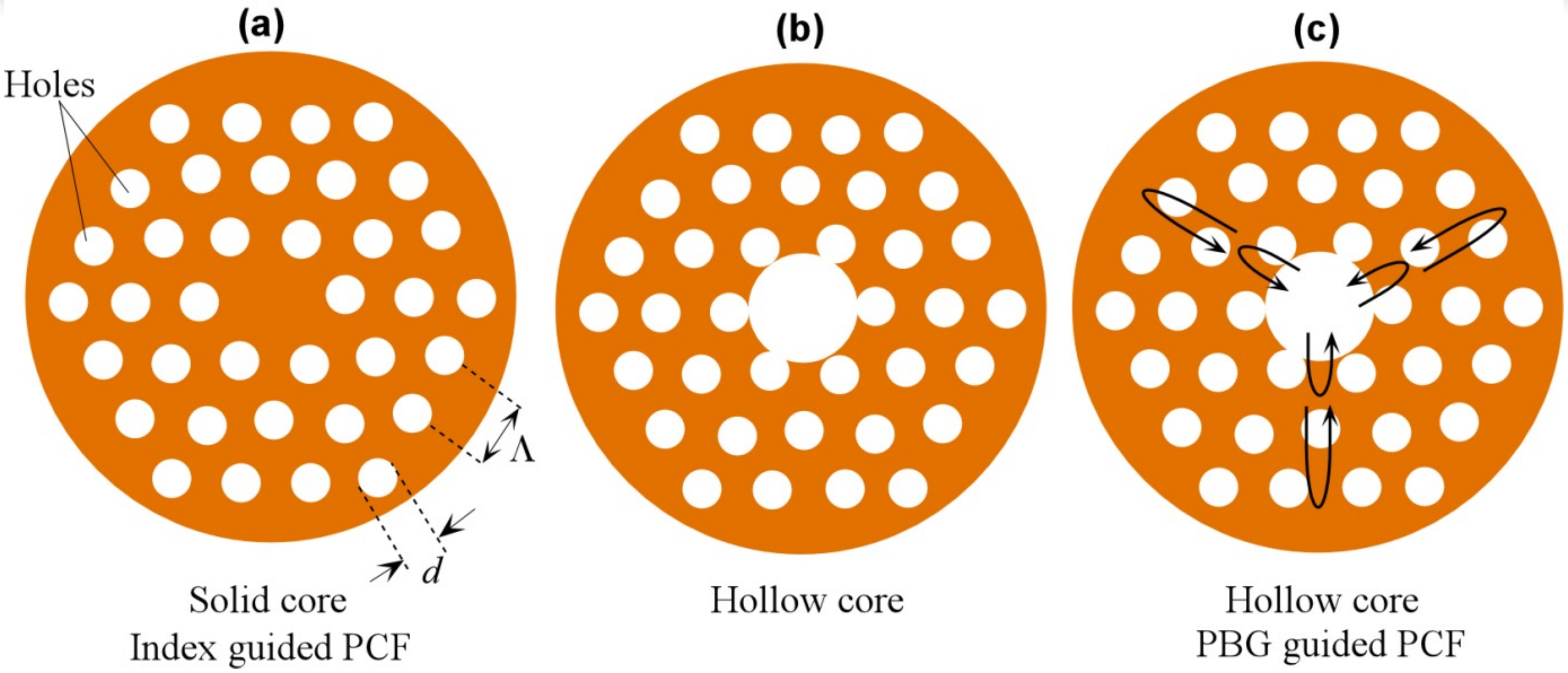


Dispersion D vs. wavelength characteristics involved in dispersion compensation. Inverse dispersion fiber enables the dispersion to be reduced and maintained flat over the communication wavelengths.

Dispersion Compensation and Management

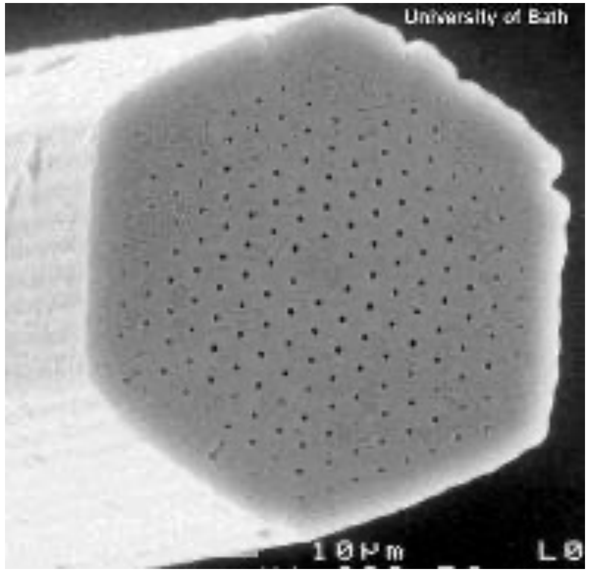
- Compensating fiber has higher attenuation.
  Doped core. Need shorter length
- More susceptible to nonlinear effects.
  Use at the receiver end.
- Different cross sections. Splicing/coupling losses.
- Compensation depends on the temperature.
- Manufacturers provide transmission fiber spliced to inverse dispersion fiber for a well defined D vs. λ

Photonic Crystal Fibers: Holey Fibers

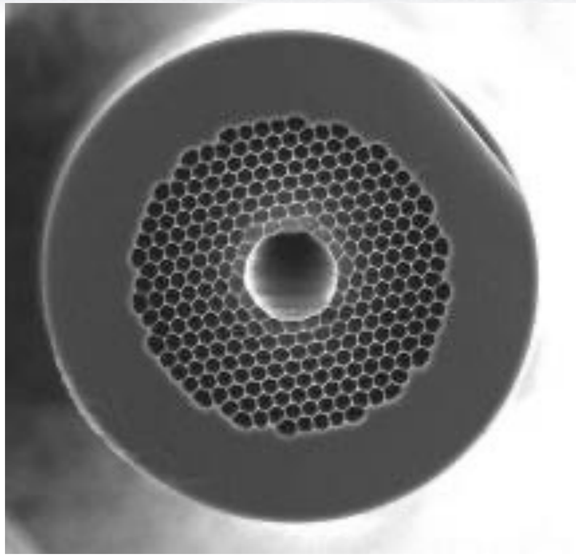


(a) A solid core PCF. Light is index guided. The cladding has a hexagonal array of holes. *d* is the hole diameter and Λ is the array pitch, spacing between the holes (b) and (c) A hollow core PCF. Light is photonic bandgap (PBG) guided.

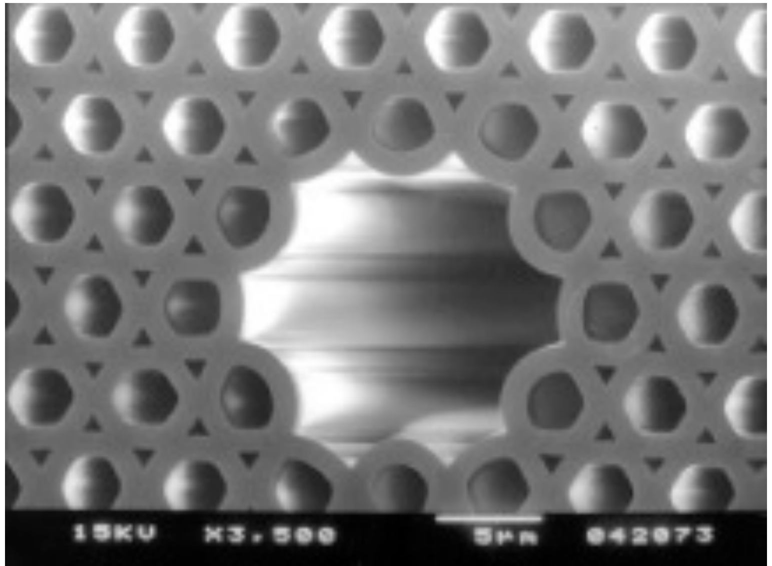
Photonic Crystal Fibers: Holey Fibers



Left: The first solid core photonic crystal fiber prepared by Philip Russell and coworkers at the University of Bath in 1996; an endlessly single mode fiber. (Courtesy of Philip Russell)

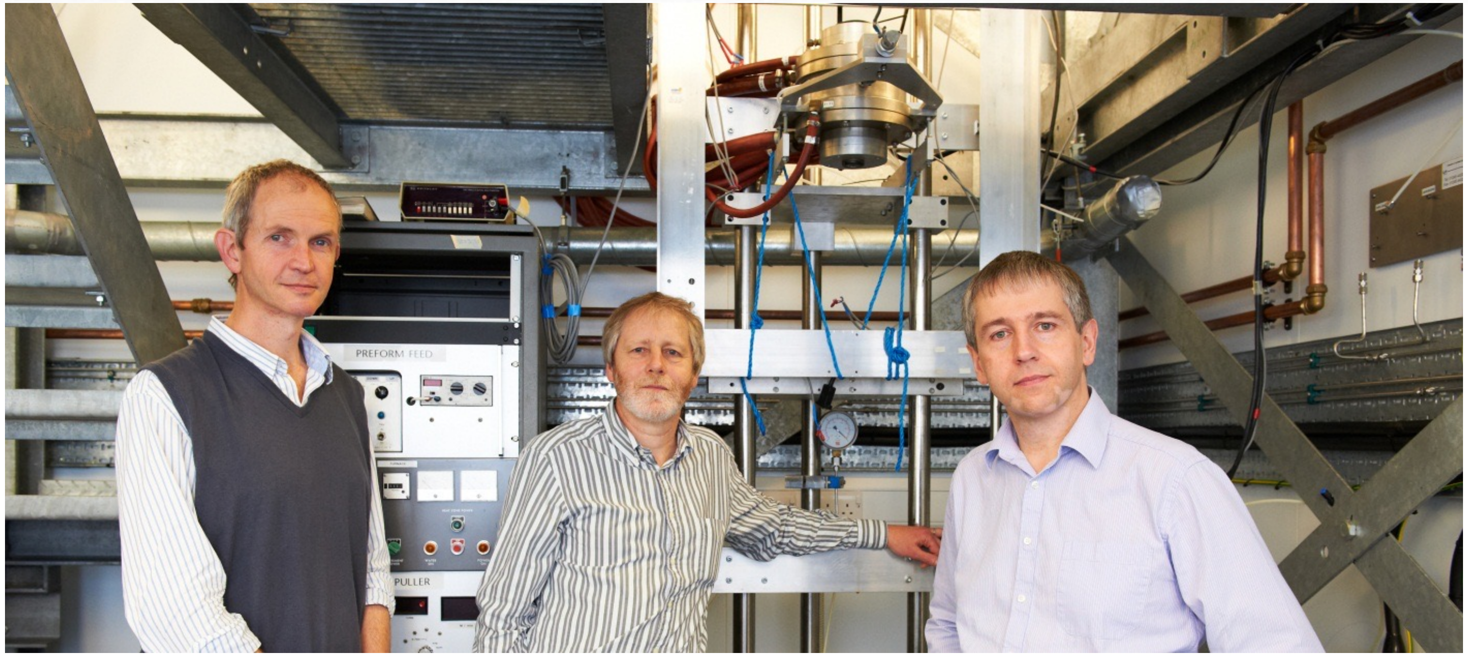


Above: A commercially available hollow core photonic crystal fiber from Blaze Photonics. (Courtesy of Philip Russell)



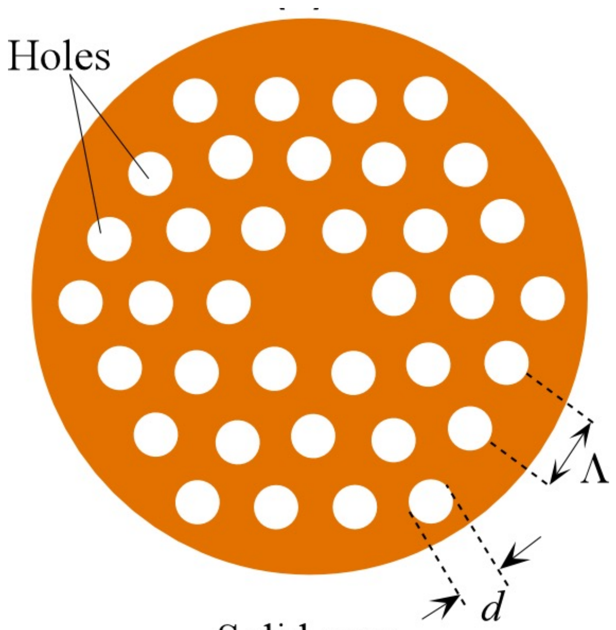
Left: One of the first hollow core photonic crystal fibers, guiding light by the photonic bandgap effect (1998) (Courtesy of Philip Russell)

Photonic Crystal Fibers: Holey Fibers



Philip Russell (center), currently at the Max Planck Institute for the Science of Light in Erlangen, Germany, led the team of two postdoctoral research fellows, Jonathan Knight (left) and Tim Birks (right) (both currently professors at the University of Bath in England) that carried out the initial pioneering research on photonic crystal fibers in the 1990s. (See reviews by P.St.J. Russell, *Science*, **299**, 358, 2003, J. C. Knight, *Nature*, **424**, 847, 2003) (Courtesy of Philip Russell)

Solid Core Photonic Crystal Fibers



Solid core
Index guided PCF

Both the core and cladding use the same material, usually silica, but the air holes in the cladding result in an effective refractive index that is lower than the solid core region.

The cladding has a lower effective refractive index than the core, and the whole structure then is like a *step index fiber*.

Total internal reflection then allows the light to be propagated just as in a step index standard silica fiber. Light is **index guided**.

Linear vs Nonlinear optics

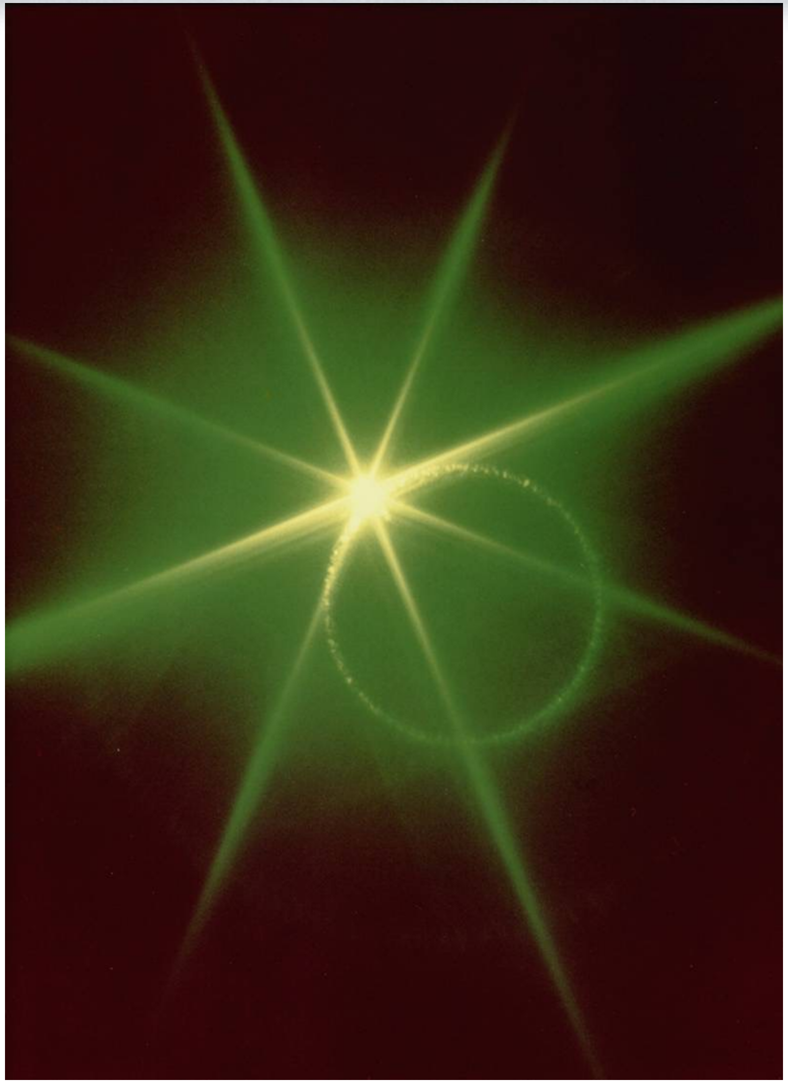
- ✓ Linear optical phenomenon are characterized by interactions of materials with a single photon
- ✓ All of the phenomenon discussed so far are linear optic effects
- ✓ Pulses sent through linear materials may be am plified and phase distorted, but the output frequency is equal to the input frequency
- ✓ Linear optical phenomenon are independent of the intensity of the field
- ✓ Lenses, mirrors, prisms, gratings, optical fibers, and cavities can all be described by the theory of linear optics.

Linear vs Nonlinear optics

- ✓ Nonlinear optical phenomenon are characterized by interactions of materials with multiple photons
- ✓ Nonlinear optical phenomenon are in general a strong function of the intensity
- ✓ When any system is driven hard enough, it will exhibit nonlinear behavior.
- ✓ With ordinary light intensities, nonlinear optic effects are too small to be noticed

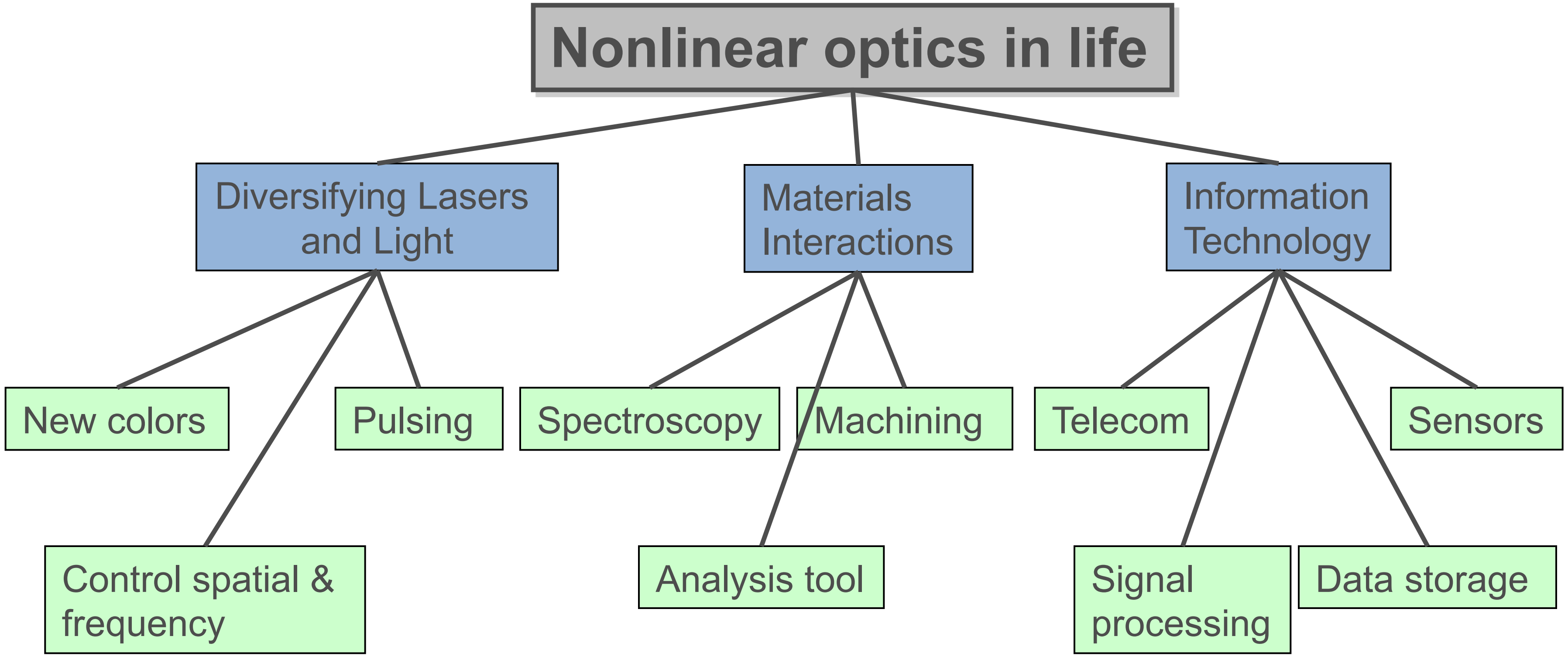
Nonlinear Optics produces many exotic effects

Sending high-intensity infrared laser light into a crystal yielded this display of green light:



Nonlinear optics allows us to change the color of a light beam, to change its shape in space and time, and to test the fundamental principles of quantum mechanics.

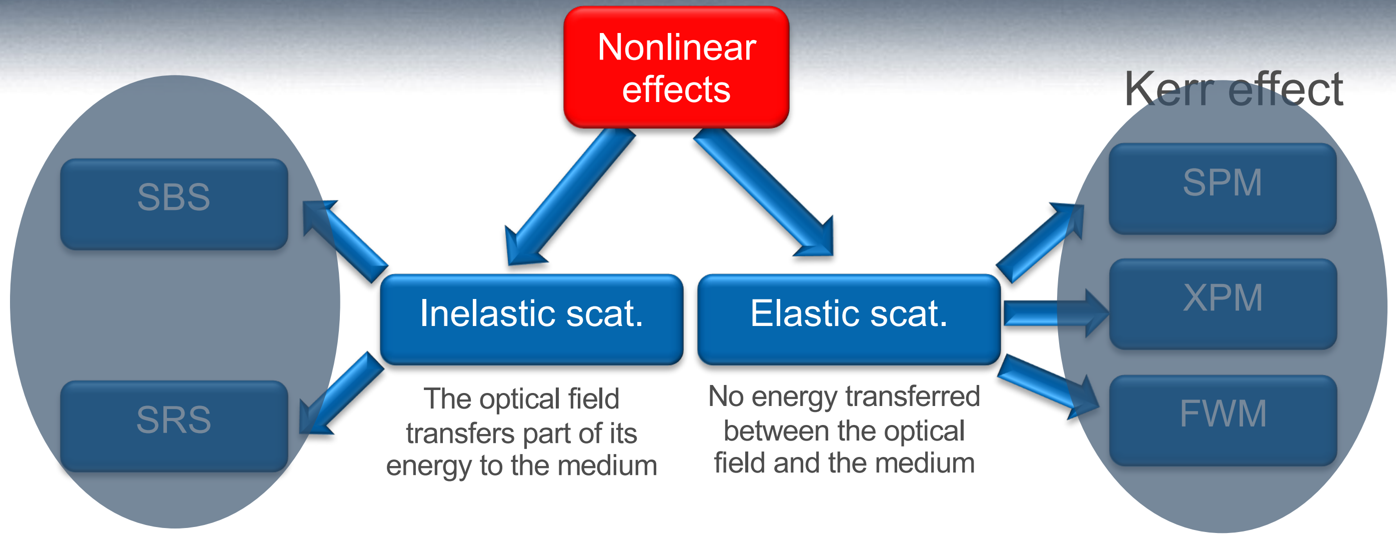
Scope



9 nobel prizes in Physics and Chemistry

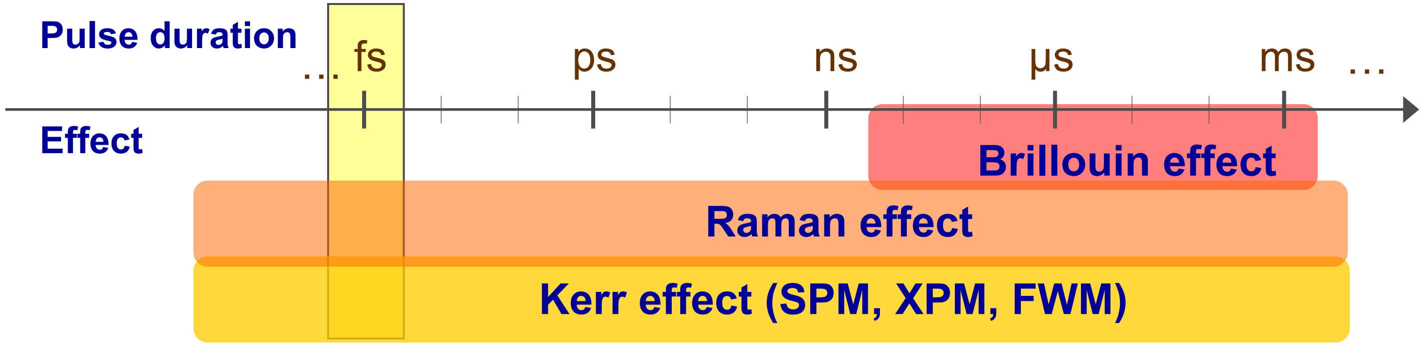
Elsa Garmire, “Nonlinear optics in daily life,” Optics express, pp. 30532-30544 (2013)

Origin of nonlinear effects



Helmoltz equation: $$\nabla^2\vec{E}(x,y,z,t) - \frac{1}{c^2}\frac{\partial^2 \vec{E}(x,y,z,t)}{\partial t^2} = \mu_0 \frac{\partial^2 \vec{P}_L(x,y,z,t)}{\partial t^2} + \mu_0 \frac{\partial^2 \vec{P}_{NL}(x,y,z,t)}{\partial t^2}$$

$$P_{NL} = P_{NL}^{Kerr} + P_{NL}^{Raman}$$



FWM: Four Wave Mixing, XPM: Cross Phase Modulation, SPM: Self Phase Modulation, SRS: Stimulated Raman Scattering, SBS: Stimulated Brillouin Scattering

Why the use of fibers for nonlinear optics?

Raman Oscillation in Glass Optical Waveguide

R.H. Stolen, E.P. Ippen, and A.R. Tynes
Bell Telephone Laboratories, Holmdel, New Jersey 07733
(Received 20 September 1971)

AppJ. Phys. Lett., Vol. 20, No.2, 1972

Stimulated Brillouin scattering in optical fibers

E.P. Ippen and R.H. Stolen
Bell Telephone Laboratories, Holmdel, New Jersey 07733
(Received 16 August 1972)

Appl. Phys. Lett., Vol. 21, No. II, I 1972

Optical Kerr effect in glass waveguide

R.H. Stolen and A. Ashkin
Bell Telephone Laboratories, Holmdel, New Jersey 07733
(Received 5 December 1972)

Appl. Phys. Lett., Vol. 22, No.6, 1973

− Cons	Pros +
− No second-order susceptibility	+ Long lengths over which fibers can maintain high optical intensities
− Third-order susceptibility 100 times smatter compared to many crystals and liquids	+ Nonlinear effects in optical fibers can be observed at relatively low power levels: - a small spot size (mode diameter) - extremely low losses

Let us compare the efficiency of NL process in bulk media and silica fiber:

$$(I_0 L_{eff})_{bulk} = \left(\frac{P_0}{\pi\omega_0^2}\right)\frac{\pi\omega_0^2}{\lambda} = \frac{P_0}{\lambda}$$

$$(I_0 L_{eff})_{fiber} = \int_0^L I_0 e^{-\alpha z} dz = \frac{P_0}{\pi\alpha\omega_0^2}(1 - e^{-\alpha L})$$

$$\frac{(I_0 L_{eff})_{fiber}}{(I_0 L_{eff})_{bulk}} = \frac{\lambda}{\pi\alpha\omega_0^2}$$

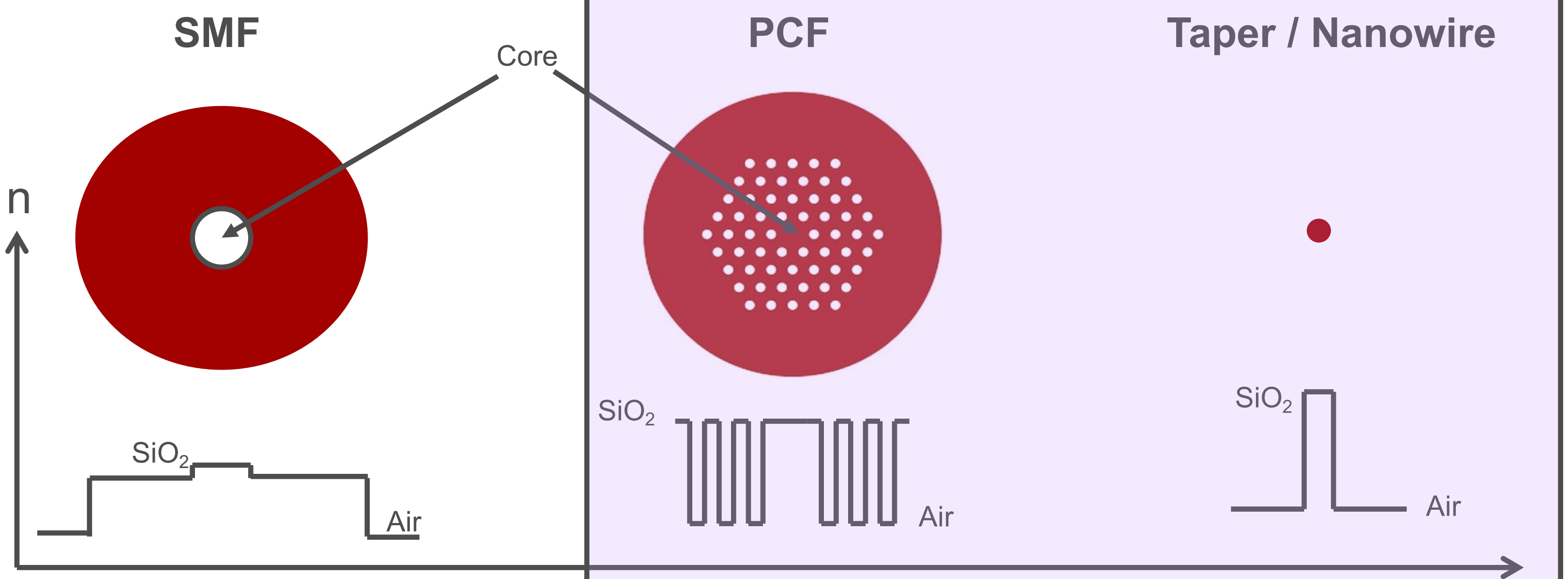
Ex: at 1550 nm, enhancement factor of 10^9 with ω_0=0.2 µm and α=0.2 dB/km

Nonlinearity in fiber optics

- How to generate and enhance nonlinearities in optical fibers?

$$\boxed{\gamma = \frac{2\pi n_2}{\lambda A_{eff}}[W^{-1}km^{-1}]}$$

- Playing with: material and/or fiber geometry:



$A_{eff} \sim 80\ \mu m^2$

$\gamma_{1550} \sim 1\ W^{-1}\ km^{-1}$

Specialty fibers

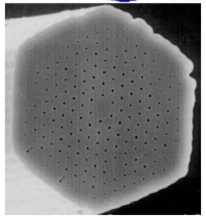
What about γ ?

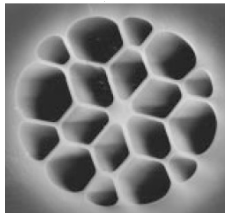
Specialty fibers

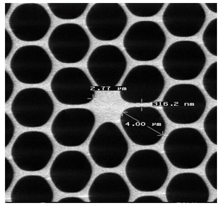
Photonic Crystal Fiber (PCF)

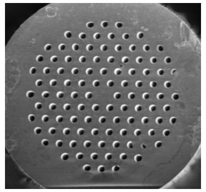
UNIVERSITY OF BATH

CRYSTAL FIBRE



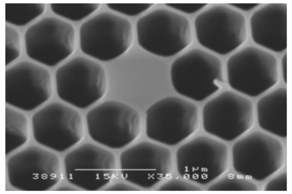






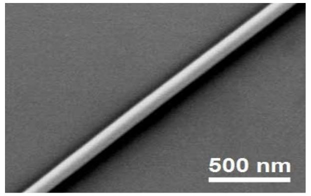
Nanowire → Tapering SMF or PCF:

Tapered photonic crystal fiber

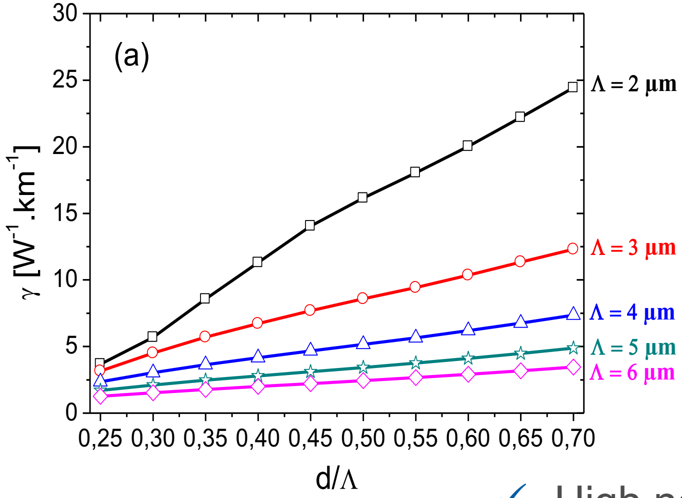


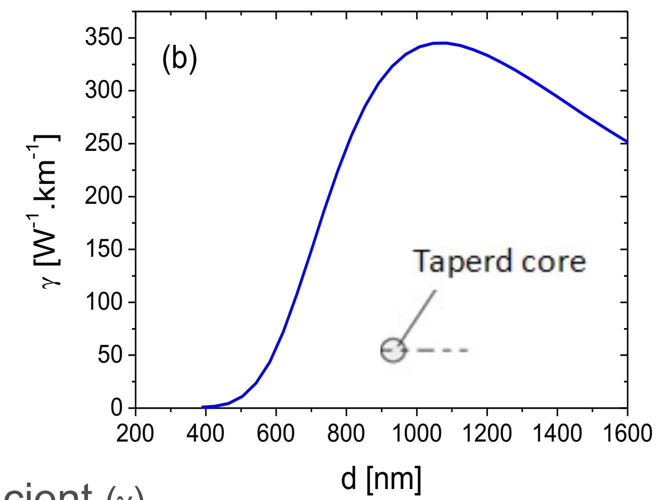
S. Leon-Saval et al., Opt. Exp. 12, 2864-2869 (2004)

Drawn directly from bulk glass



L.M. Tong et al., Opt. Exp. 14, 82-87 (2006)



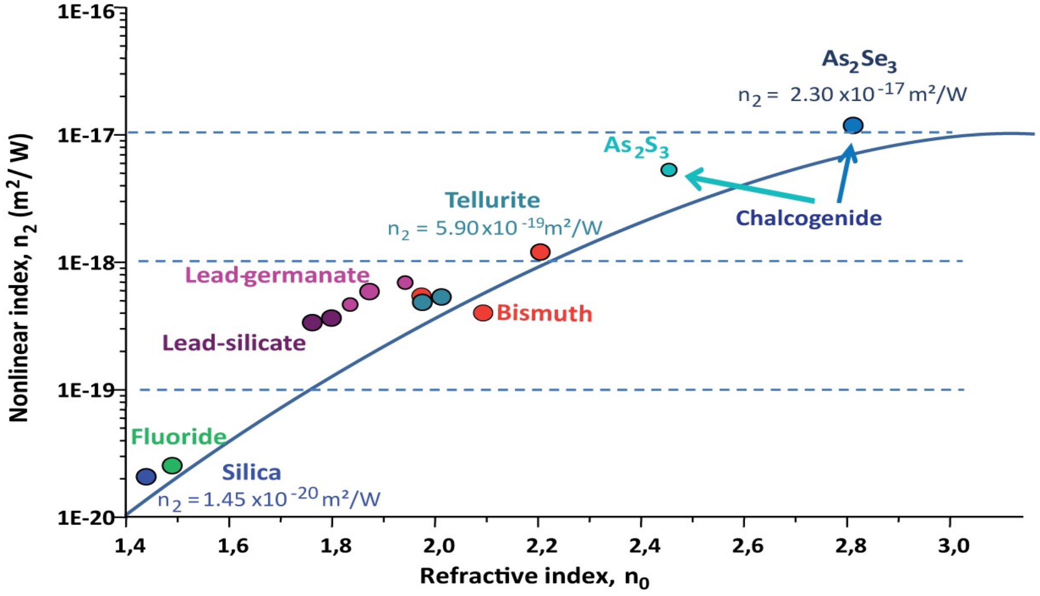


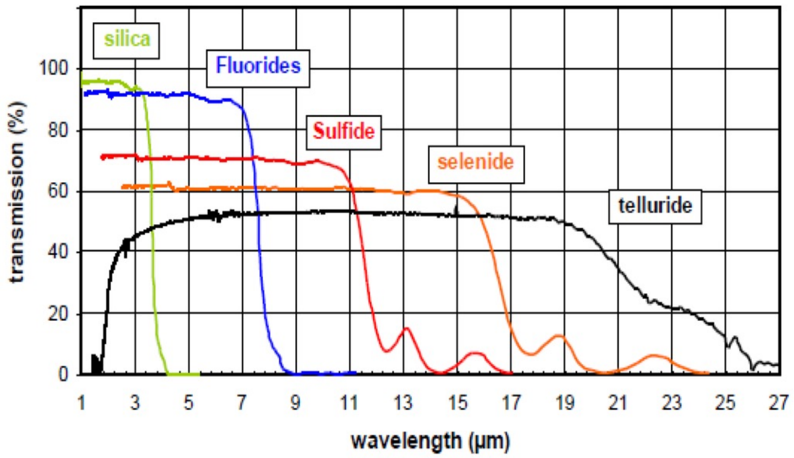
- ✓ High nonlinear coefficient (γ)
- ✓ High confinement of light (high Δn)
- ✓ High birefringence (> 10^{-3} @ 1540 nm)
- ✓ Dispersion control (λ_{ZD}, slope)

Non-silica glasses

- Highly nonlinear fibers can be drawn using a variety of non-silica glasses.

$\boxed{n = n_0 + n_2 I}$





✓Strong nonlinear refractive index : $n_2 \gg n_2$ silica

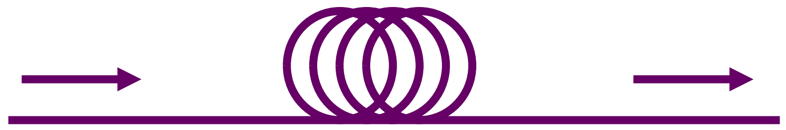
✓Large transparency windows

✓Potential applications : fiber lasers sources, lenses for IR camera, sensors, optical functions, IR signal transmission, …

Feng et al. Nonsilica Glasses for Holey Fibers, J. Lightwave Tech. 23, 2046 (2005)

Fibers for nonlinear optics

- ✓ Pulse propagation in optical fibers
  - No diffraction, long interaction length



- ✓ Nonlinearity/chromatic dispersion can be controlled

"Specialty" FIBERS

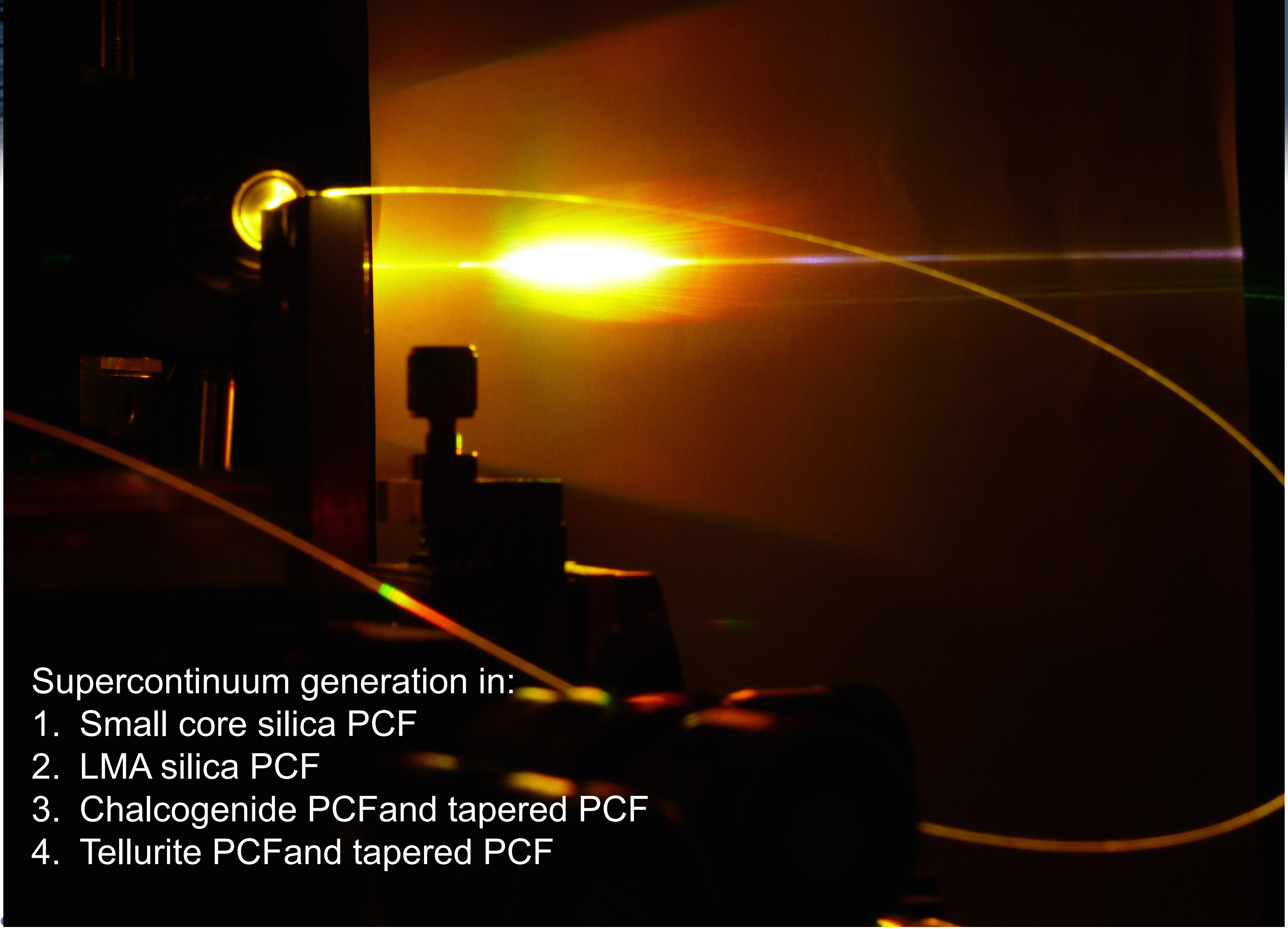
Small core, high doping
Photonic crystal fibers
Tapered fibers
Non-silica materials

PARAMETER CONTROL

Dispersion
nonlinearity
Confinement

APPLICATIONS

Supercontinuum
Frequency conversion
Pulse compression
Amplification

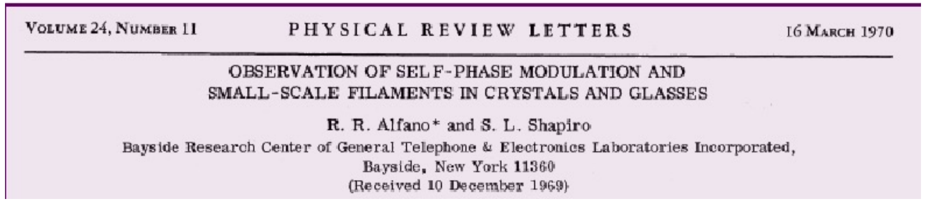


Supercontinuum generation in:

1. Small core silica PCF
2. LMA silica PCF
3. Chalcogenide PCFand tapered PCF
4. Tellurite PCFand tapered PCF

What is supercontinuum?

Supercontinuum= spectral broadening of pump pulses in nonlinear media.


VOLUME 24, NUMBER 11 PHYSICAL REVIEW LETTERS 16 MARCH 1970

OBSERVATION OF SELF-PHASE MODULATION AND SMALL-SCALE FILAMENTS IN CRYSTALS AND GLASSES

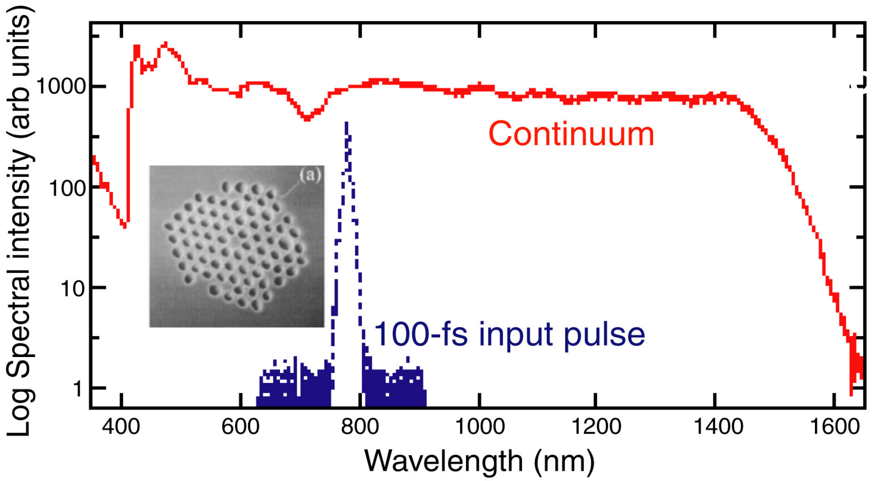
R. R. Alfano* and S. L. Shapiro

Bayside Research Center of General Telephone & Electronics Laboratories Incorporated, Bayside, New York 11360

(Received 10 December 1969)

SCG is 49 years old!

1st SC in a PCF by Ranka *et al.* in 2000, 3000 citations



Visible continuum generation in air–silica microstructure optical fibers with anomalous dispersion at 800 nm, Optics letters, Vol. 25, No. 1, 2000

1.7-μm diameter silica core PCF

Applications:

- Fiber sensing
- IR spectroscopy
- Fiber laser
- WDM sources
- Optical tomography coherence

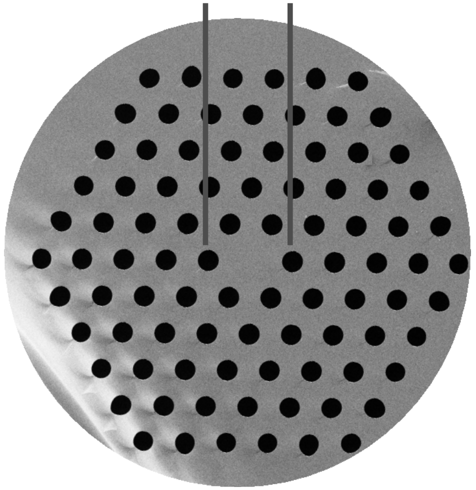
Our motivations?

Use large mode area PCF

- Facilitate the coupling into the PCF
- Allow better control during the fabrication process,
- Eliminate the birefringence.

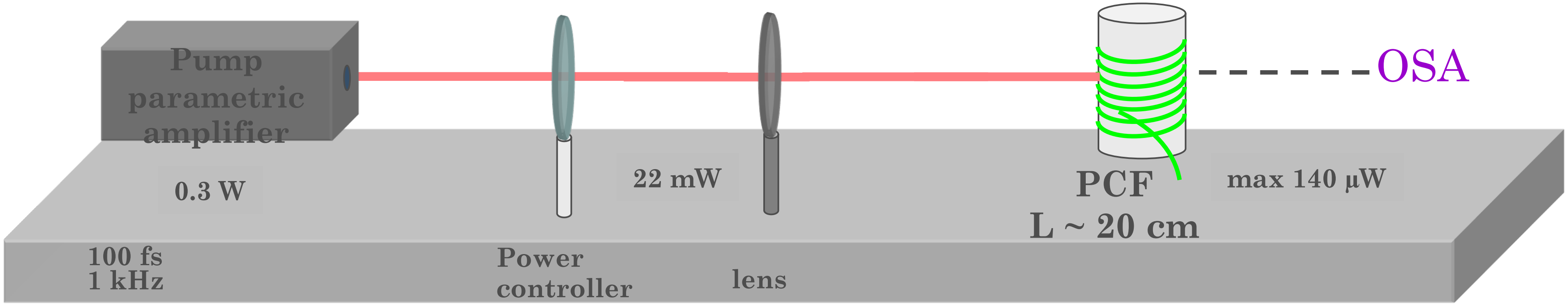
⇩

Core diameter=36 μm



The special properties of these fibers open the way to:
1. High power,
2. Single-mode,
3. Compact

Supercontinuum sources with a low divergence of the output beam.



Experimental results

↗ P at λ=1260 nm

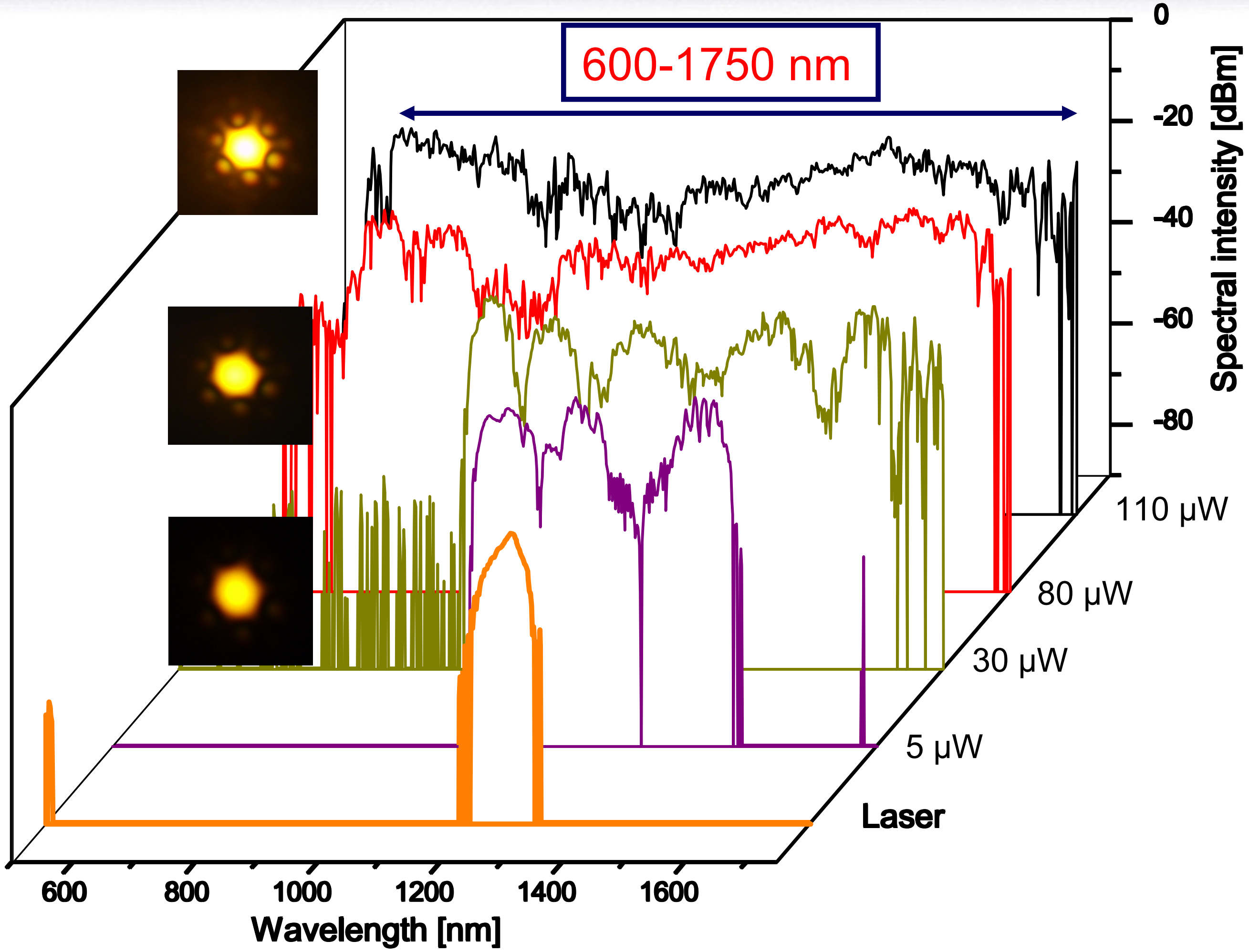
Anomalous dispersion regime

⬇

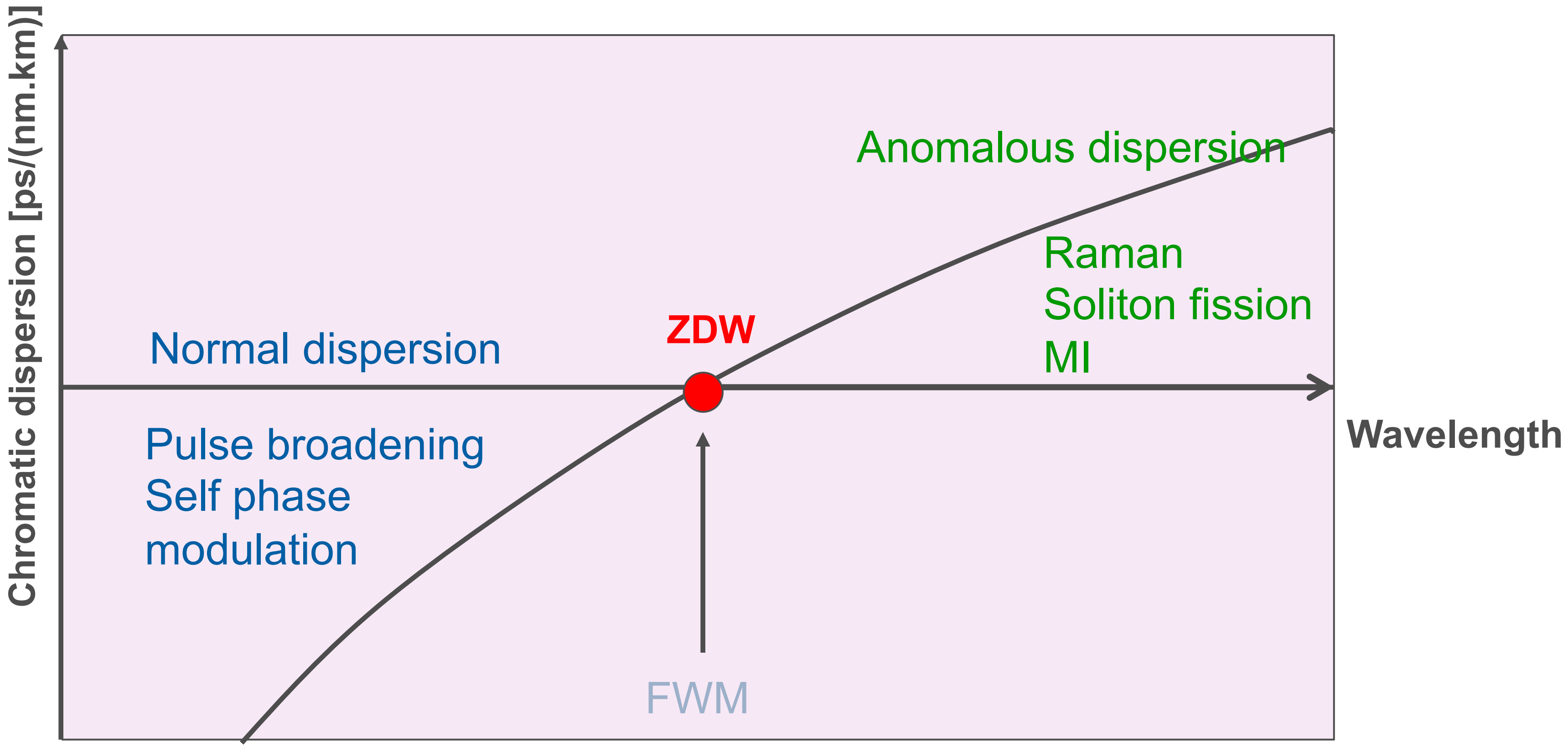
Kerr effect → spectral broadening

⬇

Raman → Raman soliton

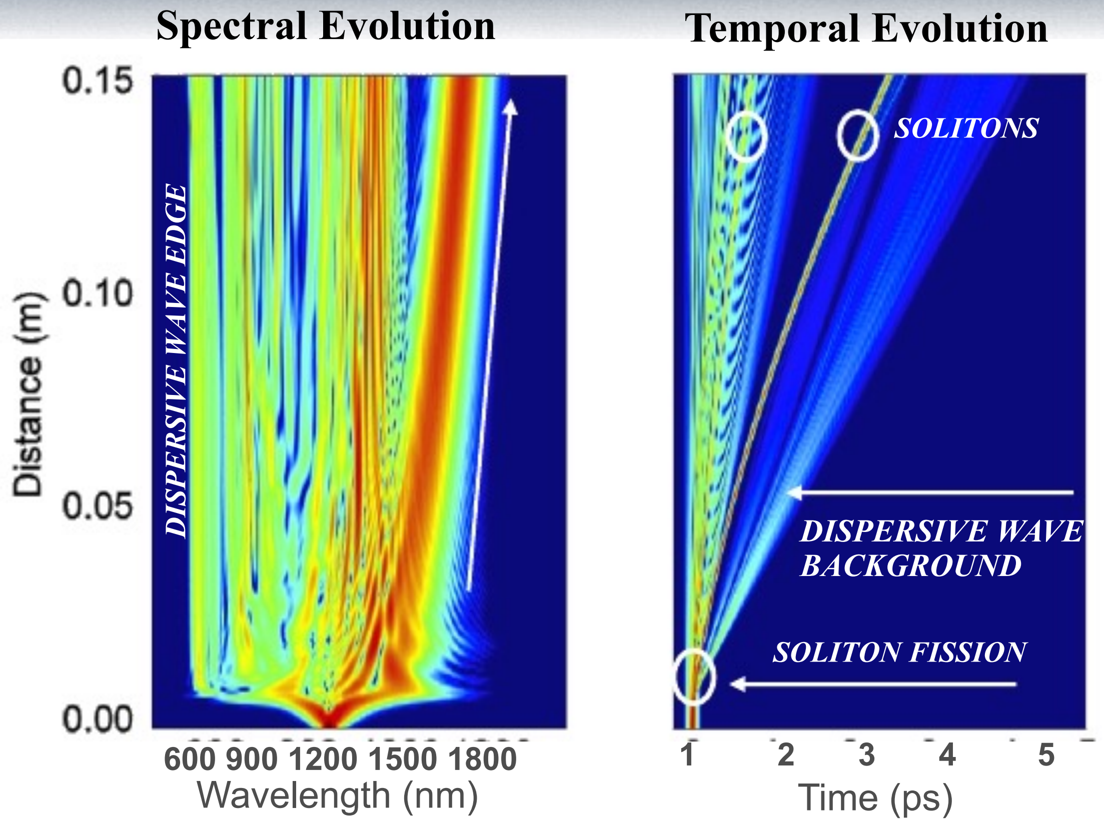


Pump wavelength is crucial



Propagation dynamics depend on pump wavelength relative to fiber zero dispersion wavelength (ZDW)

Better in color

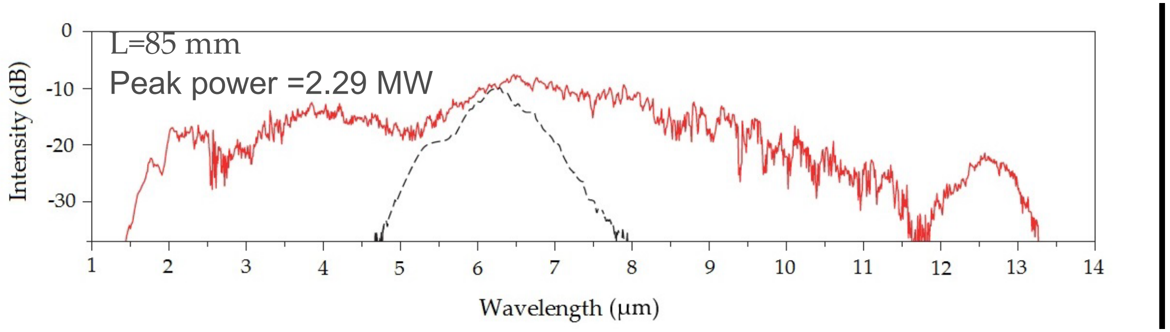


Evolution can be divided in 3 stages

- Symmetric spectral broadening due to SPM,
- Soliton fission and dispersive wave generation
- Raman self-frequency shift

Broadband mid-IR sources

- ✓ Design novel structures of specialty fibers for mid-IR SCG
- ✓ Determine the optimal structure dimension in which nonlinear interactions are highly exhibited with strong soliton dynamics aiming to generate efficient ultra-broad broadband SC in the mid-IR region.



Petersen, C.R et al. Mid-infrared supercontinuum covering the 1.4–13.3 m molecular fingerprint region using ultra-high NA chalcogenide step-index fibre. Nat. Photonics **2014**, 8, 830–834.

Summary