Light propagation in fibers, fiber lasers

Prof. Tobias J. Kippenberg

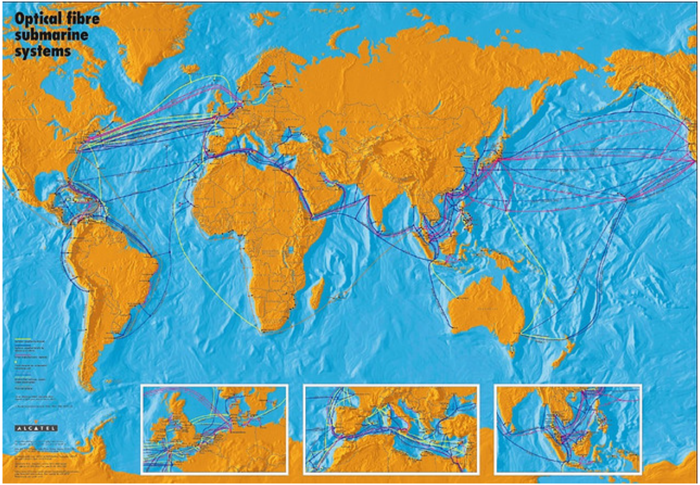
Modules of the 2024 Course

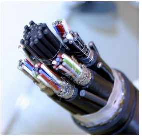
Topics covered	No	Lecture/Date
Introductory presentation; Basic of laser operation I: dispersion theory, atoms	1	11. 09. 2024
Basic of laser operation II: dispersion theory, atoms	2	18. 09. 2024
Laser systems I: 3 and 4 level lasers, gas lasers, solid state lasers, applications	3	25. 09. 2024
Laser systems II: semi-conductor lasers, external cavity lasers, applications	4	02. 10. 2024
Noise characteristics of lasers: linewidth, coherence, phase and amplitude noise, OSA (1)	5	09. 10. 2024
Noise characteristics of lasers: linewidth, coherence, phase and amplitude noise, OSA (2)	6	16. 10. 2024
Optical detection	7	30. 10. 2024
Optical fibers: light propagation in fibers, specialty fibers and dispersion (GVD)	8	06. 11. 2024
Ultrafast lasers I.: Passive mode locking and ultrafast lasers	9	13. 11. 2024
Ultrafast lasers II: mode locking, optical frequency combs / frequency metrology	10	20. 11. 2024
Ultrafast lasers III: pulse characterization, applications	11	27. 11. 2024
Nonlinear frequency conversion I: theory, frequency doubling, applications	12	04. 12. 2024
Nonlinear frequency conversion II: optical parametric amplification (OPA)	13	11. 12. 2024
Laboratory visits (lasers demo)	14	20. 12. 2024

Light propagation in fibers, fiber lasers

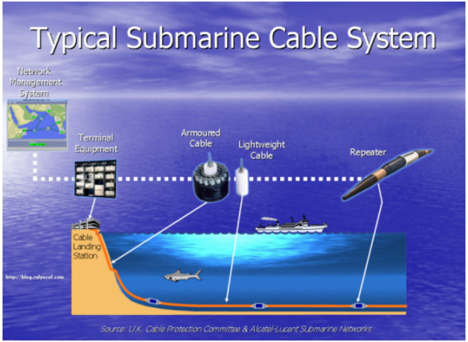
- Modes in planar waveguide
- Fiber: circular waveguide
- Fiber types
- Fiber lasers

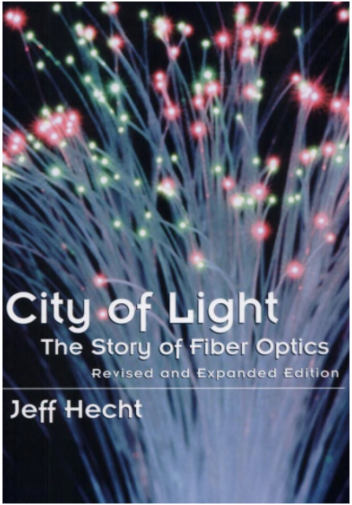
Fiber optics for communication

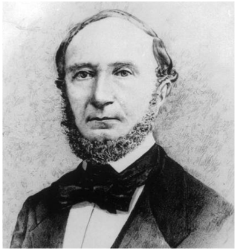




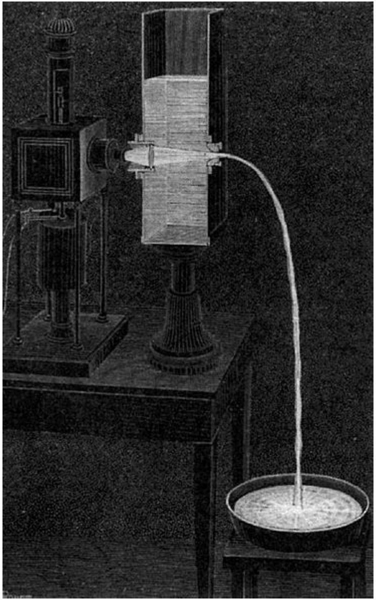
1984: British Telecom lays first submarine fiber to carry regular traffic to the Isle of Wright



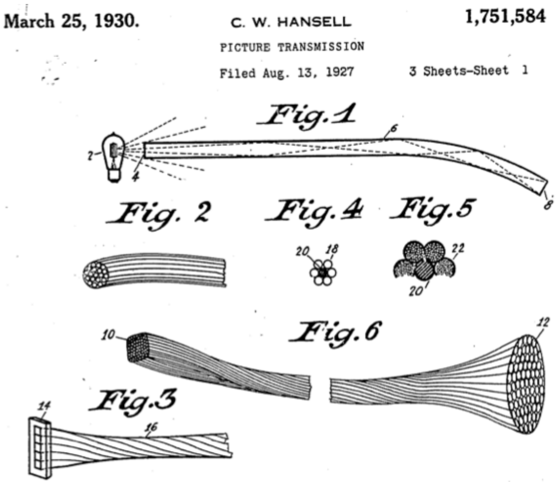




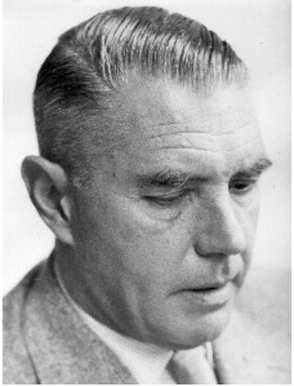
Daniel Colladon
1841



The first proposed application for fibers is not for communication but imaging!



April 11, 1951: Holger Moller Hansen files for Danish patent of “Fibrescope”
Proposes for the first time “cladding” the glass fiber in the bundle with a material with lower index.



A. Van Heel

B. O’Brien

Send letter to Nature in May 21, 1953

Imaging Fiber Bundle

H.H Hopkins

Submit letter to Nature on Nov 22, 1953

H. H. Hopkins
N. S. Kapany
Department of Physics,
Imperial College of Science and Technology,
London, S.W.7.
Nov. 22.

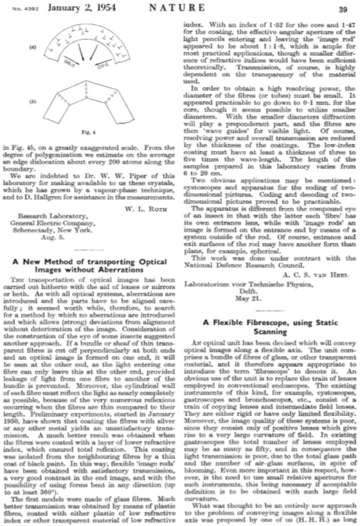


Fig. 4

in Fig. 4*b*, on a greatly exaggerated scale. From the degree of polygonization we estimate on the average an edge dislocation about every 200 atoms along the boundary.

We are indebted to Dr. W. W. Piper of this laboratory for making available to us these crystals, which he has grown by a vapour-phase technique, and to D. Hallgren for assistance in the measurements.

W. L. Roth
Research Laboratory,
General Electric Company,
Schenectady, New York.
Aug. 5.

A New Method of transporting Optical Images without Aberrations

The transportation of optical images has been carried out hitherto with the aid of lenses or mirrors or both. As with all optical systems, aberrations are introduced and the parts have to be aligned carefully; it seemed worth while, therefore, to search for a method by which no aberrations are introduced and which allows (strong) deviations from alignment without deterioration of the image. Consideration of the construction of the eye of some insects suggested another approach. If a bundle or sheaf of thin transparent fibres is cut off perpendicularly at both ends and an optical image is formed on one end, it will be seen at the other end, as the light entering one fibre can only leave this at the other end, provided leakage of light from one fibre to another of the bundle is prevented. Moreover, the cylindrical wall of each fibre must reflect the light as nearly completely as possible, because of the very numerous reflexions occurring when the fibres are thin compared to their length. Preliminary experiments, started in January 1950, have shown that coating the fibres with silver or any other metal yields an unsatisfactory transmission. A much better result was obtained when the fibres were coated with a layer of lower refractive index, which ensured total reflexion. This coating was isolated from the neighbouring fibres by a thin coat of black paint. In this way, flexible 'image rods' have been obtained with satisfactory transmission, a very good contrast in the end image, and with the possibility of using forms bent in any direction (up to at least 360°).

The first models were made of glass fibres. Much better transmission was obtained by means of plastic fibres, coated with either plastic of low refractive index or other transparent material of low refractive index. With an index of 1·52 for the core and 1·47 for the coating, the effective angular aperture of the light pencils entering and leaving the 'image rod' appeared to be about 1 : 1·8, which is ample for most practical applications, though a smaller difference of refractive indices would have been sufficient theoretically. Transmission, of course, is highly dependent on the transparency of the material used.

In order to obtain a high resolving power, the diameter of the fibres (or tubes) must be small. It appeared practicable to go down to 0·1 mm. for the core, though it seems possible to utilize smaller diameters. With the smaller diameters diffraction will play a preponderant part, and the fibres are then 'wave guides' for visible light. Of course, resolving power and overall transmission are reduced by the thickness of the coatings. The low-index coating must have at least a thickness of three to five times the wave-length. The length of the samples prepared in this laboratory varies from 6 to 20 cm.

Two obvious applications may be mentioned: cystoscopes and apparatus for the coding of two-dimensional pictures. Coding and decoding of two-dimensional pictures proved to be practicable.

The apparatus is different from the compound eye of an insect in that with the latter each 'fibre' has its own entrance lens, while with 'image rods' an image is formed on the entrance end by means of a system outside of the rod. Of course, entrance and exit surfaces of the rod may have another form than plane, for example, spherical.

This work was done under contract with the National Defence Research Council.

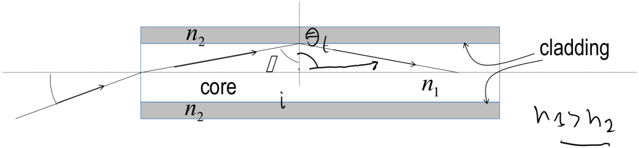
A. C. S. van Heel
Laboratorium voor Technische Physica,
Delft.
May 21.

A Flexible Fibrescope, using Static Scanning

An optical unit has been devised which will convey optical images along a flexible axis. The unit comprises a bundle of fibres of glass, or other transparent material, and it therefore appears appropriate to introduce the term 'fibrescope' to denote it. An obvious use of the unit is to replace the train of lenses employed in conventional endoscopes. The existing instruments of this kind, for example, cystoscopes, gastroscopes and bronchoscopes, etc., consist of a train of copying lenses and intermediate field lenses. They are either rigid or have only limited flexibility. Moreover, the image quality of these systems is poor, since they consist only of positive lenses which give rise to a very large curvature of field. In existing gastroscopes the total number of lenses employed may be as many as fifty, and in consequence the light transmission is poor, due to the total glass path and the number of air–glass surfaces, in spite of blooming. Even more important in this respect, however, is the need to use small relative apertures for such instruments, this being necessary if acceptable definition is to be obtained with such large field curvature.

What was thought to be an entirely new approach to the problem of conveying images along a flexible axis was proposed by one of us (H. H. H.) as long

Light guiding principle

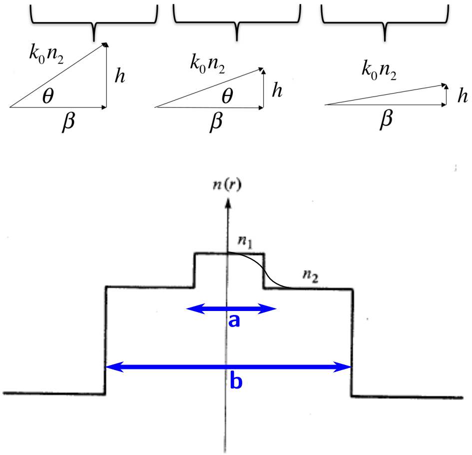


Light is guided in the waveguide by **total internal reflection** (TIR). The condition for guiding is:

$$n_1 \sin\theta_i = n_2 \sin\theta_t$$

$$\theta_c = \text{asin}\left(\frac{n2}{n1}\right)$$

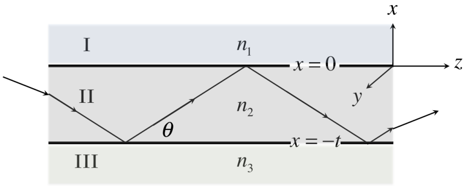
Fiber



A fiber consists of a core and cladding.
The index contrast is made by doping
the SiO_2 (silica core) with e.g Germanium.

Example of step index fiber
a: core diameter
b: cladding diameter

Slab waveguide



Slab waveguide infinite in y direction and $n_2 > n_3 > n_1$

$$\nabla^2 E(r) + k_0^2 n^2(r) E(r) = 0$$

$$E(r,t) = E(x,y) \cdot e^{i(\omega t - \beta z)}$$

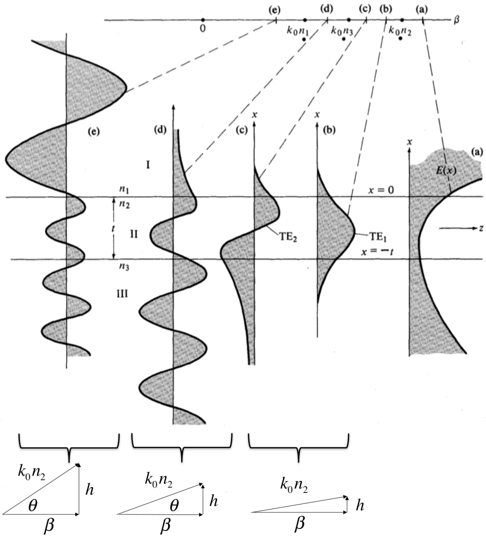
$$\left(\frac{\partial}{\partial x^2} + \frac{\partial}{\partial y^2}\right) E(x,y) + (k_0^2 n^2 - \beta^2) E(x,y) = 0$$

Region I
$$\frac{\partial^2}{\partial x^2} E(x,y) + \left(k_0^2 n_1^2 - \beta^2\right) E(x,y) = 0$$

Region II
$$\frac{\partial^2}{\partial x^2} E(x,y) + \left(k_0^2 n_2^2 - \beta^2\right) E(x,y) = 0$$

Region III
$$\frac{\partial^2}{\partial x^2} E(x,y) + \left(k_0^2 n_3^2 - \beta^2\right) E(x,y) = 0$$

Slab waveguide: insights in the mode types



Assume plane wave propagation at angle θ

$$E(r) = E(x)e^{-i\beta z} = C\sin(hx+\alpha)e^{-i\beta z}$$

$$-C\sin(hx+\alpha)h^2e^{-i\beta z}+$$
$$+(k_0^2n_2^2-\beta^2)C\sin(hx+\alpha)e^{-i\beta z}=0$$

$$h^2+\beta^2 = k_0^2n_2^2$$

guiding condition $\beta > k_0n_3$ leads, using
$\beta = k_0n_2\cos\theta$, to $\theta < \cos^{-1}(n_3/n_2) = \theta_c$

Symmetric slab waveguide: rigorous solution (1/2)

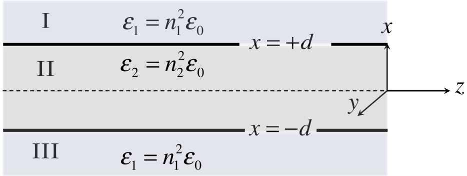
$$\left.\begin{aligned} \frac{\partial E_y}{\partial z} &= i\omega\mu H_x \\ \frac{\partial E_x}{\partial z} - \frac{\partial E_z}{\partial x} &= -i\omega\mu H_y \\ \frac{\partial E_y}{\partial x} &= -i\omega\mu H_z \end{aligned}\right\} \qquad \left.\begin{aligned} &\boxed{E_y = -\frac{\omega\mu}{\beta} H_x} \\ &-i\beta E_x - \frac{\partial E_z}{\partial x} = -i\omega\mu H_y \\ &\boxed{\frac{\partial E_y}{\partial x} = -i\omega\mu H_z} \end{aligned}\right\}$$

E_y, H_x, H_z
Transverse Electric (TE) modes

$$\left.\begin{aligned} \frac{\partial H_y}{\partial z} &= -i\omega\varepsilon E_x \\ \frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x} &= -i\omega\varepsilon E_y \\ \frac{\partial H_y}{\partial x} &= i\omega\varepsilon E_z \end{aligned}\right\} \qquad \left.\begin{aligned} &H_y = -\frac{\omega\varepsilon}{\beta} E_x \\ &\boxed{-i\beta H_x - \frac{\partial H_z}{\partial x} = i\omega\varepsilon E_y} \\ &\frac{\partial H_y}{\partial x} = i\omega\varepsilon E_z \end{aligned}\right\}$$

H_y, E_x, E_z
Transverse Magnetic (TM) modes

Symmetric slab waveguide: rigorous solution (2/2)



Symmetric infinite Slab waveguide $\frac{\partial}{\partial y} = 0$

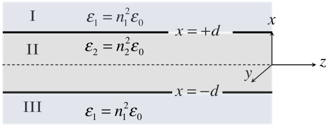
$\nabla \times E = -\frac{\partial \beta}{\partial t}, \quad B = \mu H$

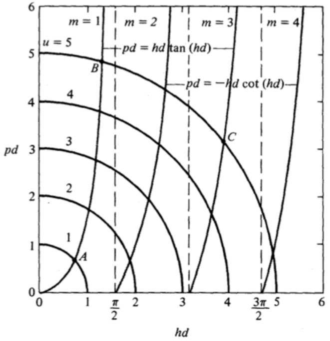
$\nabla \times H = i + \frac{\partial D}{\partial t}, \quad D = \varepsilon E \quad (\varepsilon = n^2)$

H and E with time behavior in the form $e^{i\omega t}$

H and E propagate in the z direction: $e^{-i\beta z}$

Symmetric slab waveguide: rigorous solution





Symmetric waveguid w.r.t. $x = 0 \rightarrow$ try solution

$$\text{even modes } E_y(x, z, t) = E_y(-x, z, t)$$

$$\text{odd modes } L_y^2(x, z, t) = -L_y^2(-x, z, t)$$

$$\frac{\partial E_y}{\partial x} = -i\omega\mu H_z$$

Even modes

$$\left.\begin{aligned} E_y &= A e^{-p(|x|-d)} e^{-i\beta z} \quad & |x| \geq d \\ E_y &= \beta \cos(hx) e^{-i\beta z} \quad & |x| \geq d \end{aligned}\right\}$$

$$H_z = -i\frac{pA}{\omega\mu} e^{-p(|x|-d)} e^{-i\beta z} = -\frac{ih\beta}{\omega\mu}\sin(hx)e^{-i\beta z}$$

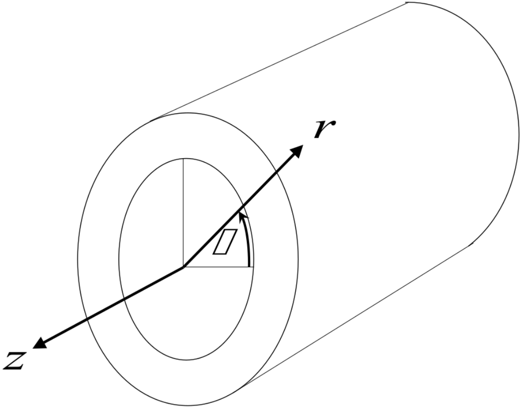
Continuity of tangential field components, E_y, H_z at interface

$$\left.\begin{aligned} &E_y: \quad A e^{-p(d-d)} e^{-i\beta z} = \beta \cdot \cos(hd) \cdot e^{-i\beta z} \\ &\rightarrow \quad A = \beta \cdot \cos(hd) \\ &H_z: \quad \frac{ipA}{\omega\mu} = \frac{ih\beta}{\omega\mu} \cdot \sin(hd) \quad \rightarrow \quad pA = h\beta \cdot \sin(hd) \end{aligned}\right\} pd = hd \cdot \tan(hd)$$

Satisfy wave equation

$$\left.\begin{aligned} h^2 + \beta^2 &= k_0^2 n_2^2 \quad |x| \geq d \\ \beta^2 - p^2 &= k_0^2 n_1^2 \quad |x| \leq d \end{aligned}\right\} (hd)^2 + (pd)^2 = (n_2^2 - n_1^2)k_0^2 d^2$$

Solutions for a fiber geometry (cylindrical)



Laplacian in cylindrical coordinates:

$$\nabla^2 = \frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r} + \frac{1}{r^2}\frac{\partial^2}{\partial \phi^2} + \frac{\partial^2}{\partial z^2}$$

Methodology: solve for:

$$\left(\nabla^2 + k^2\right)\left\{\begin{array}{c} E_z \\ H_z \end{array}\right\} = 0$$

Express the other field components as functions of E_z, H_z:

$$\begin{aligned} E_r &= f_1\left(E_z, H_z\right) \\ E_\phi &= f_2\left(E_z, H_z\right) \\ H_r &= f_3\left(E_z, H_z\right) \\ H_\phi &= f_4\left(E_z, H_z\right) \end{aligned}$$

$$E(r,\phi,z) = F(r)e^{im\phi}e^{i\beta z}$$

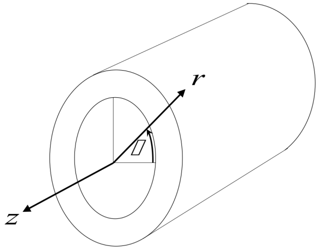
$$\frac{d^2F}{dr^2} + \frac{1}{r}\frac{dF}{dr} + \left(n^2\frac{\omega^2}{c^2} - \beta^2 - \frac{m^2}{r^2}\right)F = 0$$

Bessel differential equation:

$$F(r) = AJ_m(\kappa r) \qquad \text{in the core,}$$
$$F(r) = BK_m(\gamma r) \qquad \text{in the cladding.}$$

Solutions for a fiber geometry (cylindrical)

EPFL



Core
$$E_z(r,\phi,z) = AJ_m(\kappa r)e^{im\phi}e^{i\beta z}$$
$$H_z(r,\phi,z) = BJ_m(\kappa r)e^{im\phi}e^{i\beta z}$$

Cladding
$$E_z(r,\phi,z) = CK_m(\gamma r)e^{im\phi}e^{i\beta z}$$
$$H_z(r,\phi,z) = DK_m(\gamma r)e^{im\phi}e^{i\beta z}$$

Boundary conditions: tangential components of the E and H continuous at interface core-cladding

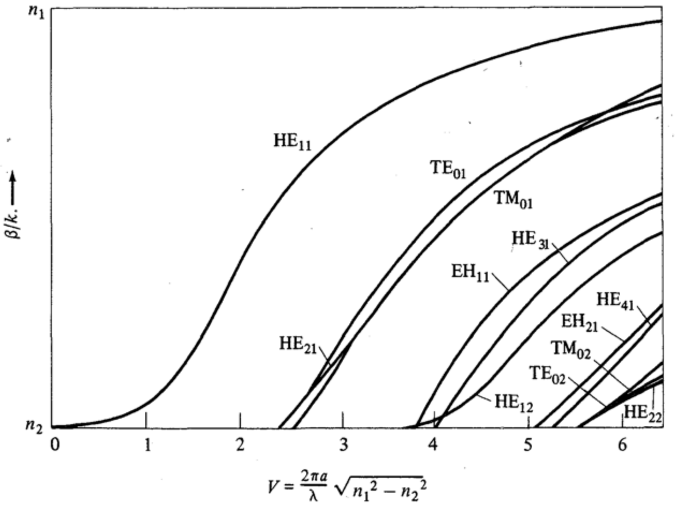
4 fields: H_z, H_ϕ, E_z, E_ϕ

4 linear equations for 4 unknowns (A, B, C, D)

Numerical solutions give the propagation constant

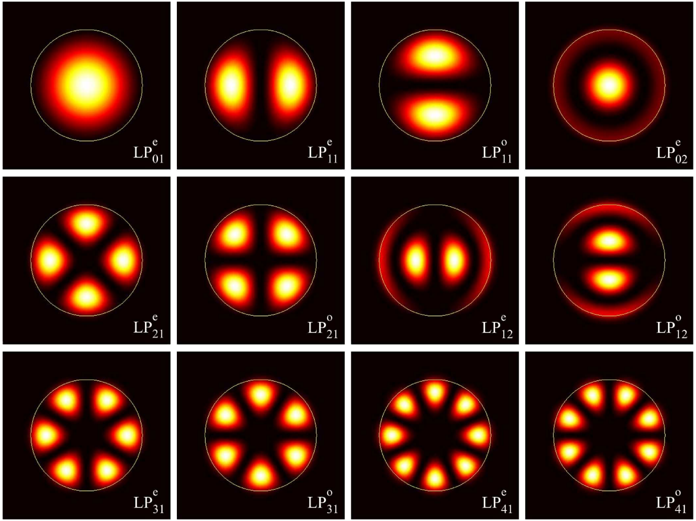
$$\beta_{mj}, \quad m,j = 1,2,3,\ldots$$

Fiber modes



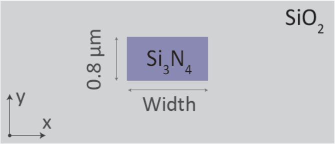
$V = 2.405 =$ cutoff for TE01 (LP11)

Intensity of a few LP modes

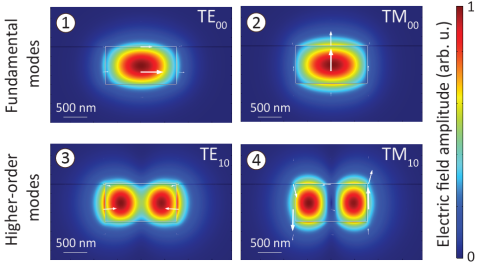


Integrated optical waveguides

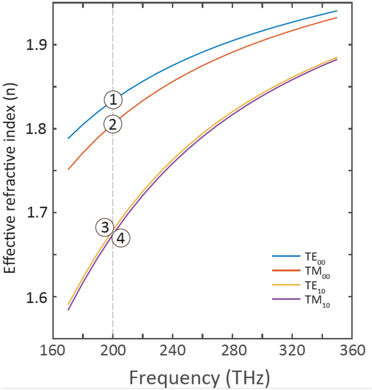
Buried photonic waveguides



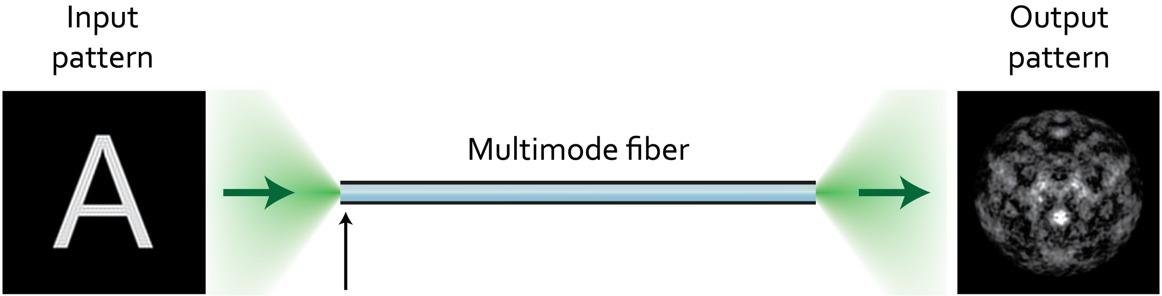
Quasi-TE mode: in-plane electric field × Quasi-TM mode: out-of-plane electric field



Quasi-TE and TM modes of integrated waveguides usually have different dispersion



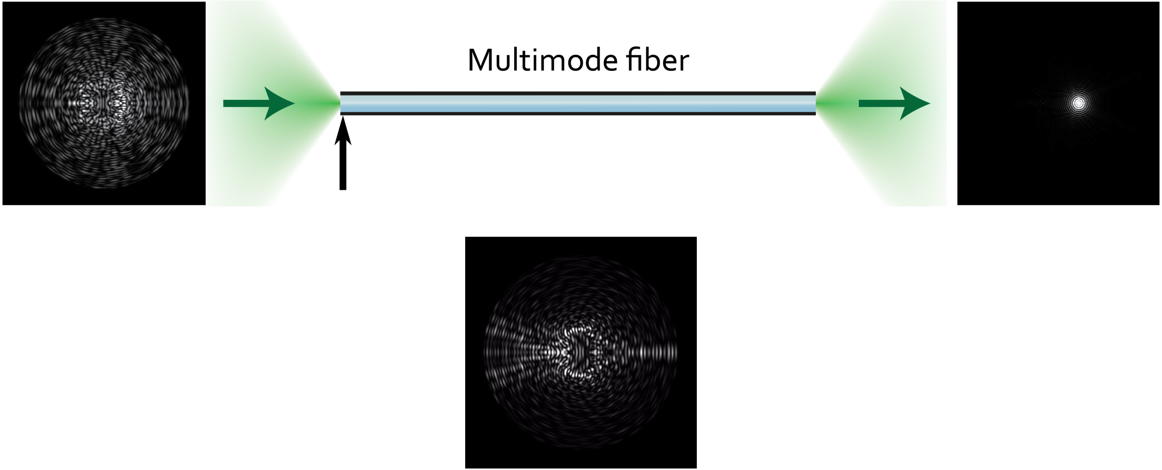
Modal scrambling distorts images



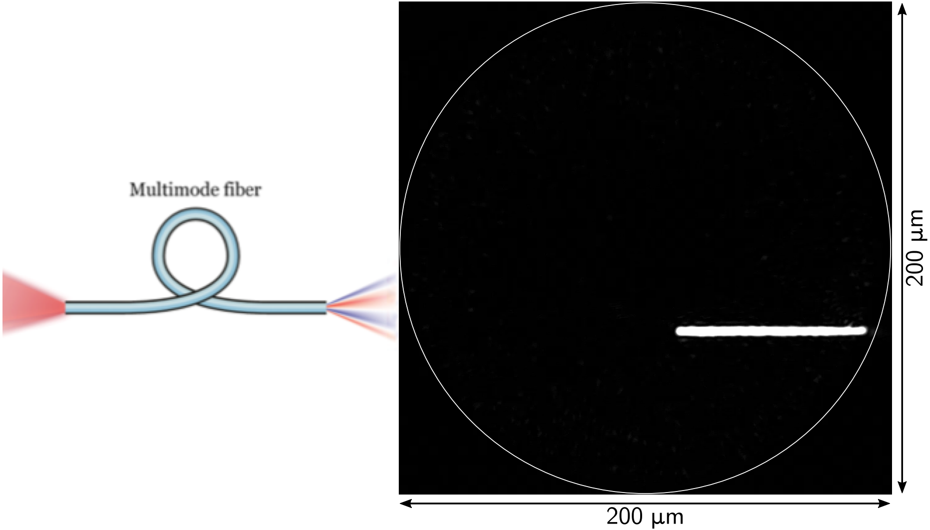
However, modal scrambling can be compensated

Shaped wavefront

Focused output

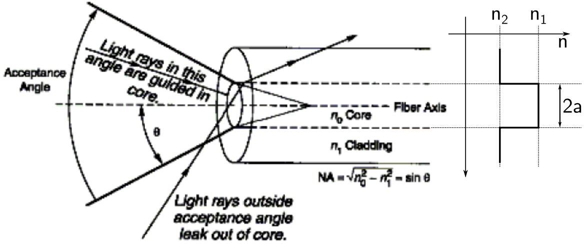


Modal scrambling



SPIE Organic Photonics + Electronics San Diego 2015

Fiber parameters



The acceptance angle is characterized by the **numerical aperture** of the fiber:

$$NA = \sin\theta \cdot n \overset{\text{air}}{=} \sin\theta = \sqrt{n_1^2 - n_2^2}$$

The **number of modes** in a fiber is approximately given by:

$$M \approx \frac{4}{\pi^2}\left(2 \cdot \pi \cdot \frac{a}{\lambda_0} \cdot NA\right)^2$$

Condition for single mode propagation:

$$V = 2 \cdot \pi \cdot \frac{a}{\lambda_0} \cdot NA < 2.405$$

a is the fiber core radius,
λ is the wavelength in vacuum,
NA is the numerical aperture

Fiber absorption

Dielectric-fibre surface waveguides for optical frequencies

K.C. Kao and G.A. Hockham

Indexing terms: *Optical fibres, Waveguides*

Abstract: A dielectric fibre with a refractive index higher than its surrounding region is a form of dielectric waveguide which represents a possible medium for the guided transmission of energy at optical frequencies. The particular type of dielectric-fibre waveguide discussed is one with a circular cross-section. The choice of the mode of propagation for a fibre waveguide used for communication purposes is governed by consideration of loss characteristics and information capacity. Dielectric loss, bending loss and radiation loss are discussed, and mode stability, dispersion and power handling are examined with respect to information capacity. Physical-realisation aspects are also discussed. Experimental investigations at both optical and microwave wavelengths are included.

3.1.2 Absorption: Absorption bands in solids are usually broad, owing to the close packing of the molecules. They arise from the natural-vibration frequencies of the molecular and electronic systems. Near such frequencies, the energy of the external electromagnetic field couples energy into the vibration of the molecules and electrons. In the wavelength region between 100 and 1 μm, many longitudinal and rotational resonances of molecules are present in almost all substances, especially the long-chain polymers. Strong absorption takes place throughout most of the region. In the 0.3–0.1 μm region, electronic-resonance absorption bands are present. In the intermediate region (i.e. 1–0.3 μm), resonance-absorption phenomena are relatively absent. This represents a region for the material to have low loss.

In inorganic glasses, it is known that absorption can occur owing to the presence of impurity ions. It is known that, in high-quality optical glasses, the main contribution to absorption loss in the 1–3 μm region is due to the Fe^{++} and Fe^{+++} ions. The ferrous ion has an absorption band centred at about 1 μm, while the ferric ion has one at about 0.4 μm. At band centre, the absorption due to 1 part per million of Fe^{+2} in certain glass systems[3] is estimated to result in an absorption coefficient of less than 20 dB/km.

Fiber absorption

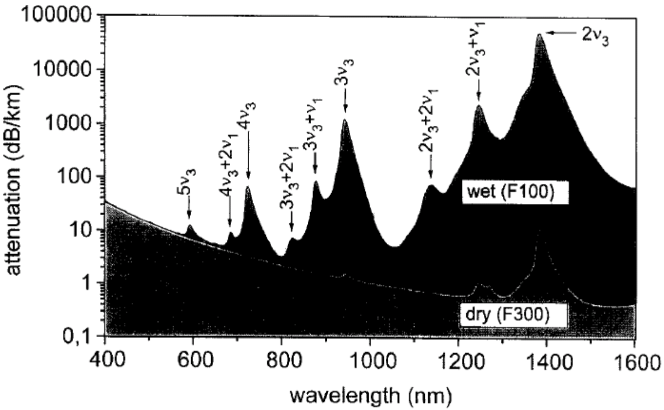
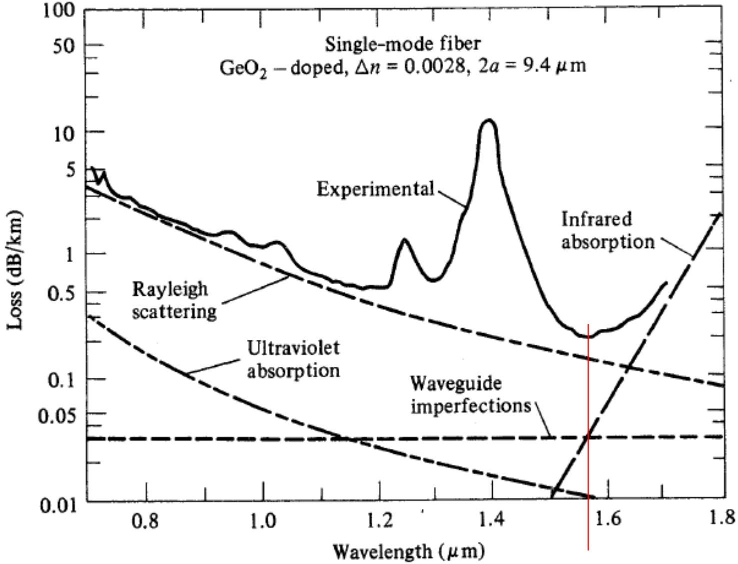


Fig. 2. Attenuation spectra of wet (100) and dry (F300) silica core fibers.

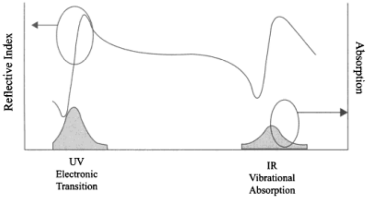
1966: Key for using silica in fibers was to reduce the OH concentration. This allows to have 95% transmission after 1 km.

Fiber absorption

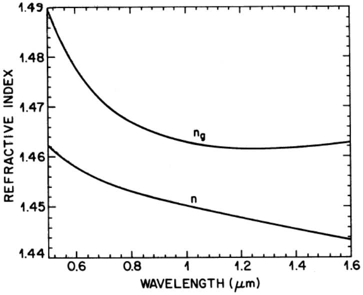


Minimum absorption occurs at 1550 nm

Chromatic dispersion in fibers



Fused silica fiber:



$$\beta(\omega) = n(\omega)\frac{\omega}{c} =$$
$$= \beta_0 + \beta_1(\omega - \omega_0) + \tfrac{1}{2}\beta_2(\omega - \omega_0)^2 + \dots$$

$$\beta_m = \left(\frac{d^m\beta}{d\omega^m}\right)_{\omega=\omega_0} \qquad (m = 0, 1, 2, \dots)$$

$$\beta_1 = \frac{1}{v_g} = \frac{n_g}{c} = \frac{1}{c}\left(n + \omega\frac{dn}{d\omega}\right)$$
$$\beta_2 = \frac{1}{c}\left(2\frac{dn}{d\omega} + \omega\frac{d^2n}{d\omega^2}\right)$$

Group Velocity Dispersion

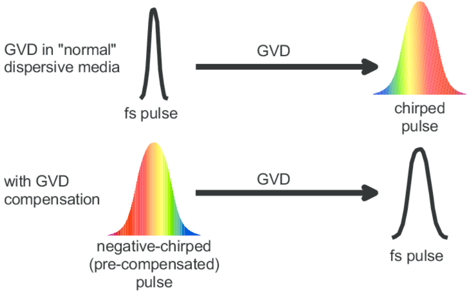
GVD – the frequency dependence of the group velocity in a medium, or (quantitatively) the derivative of the inverse group velocity with respect to angular frequency

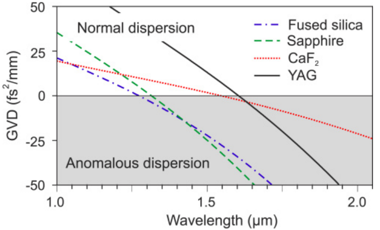
$$\beta(\omega) = n(\omega)\frac{\omega}{c} = \beta_0 + \beta_1(\omega-\omega_0) + \frac{1}{2}\beta_2(\omega-\omega_0)^2 + \dots$$

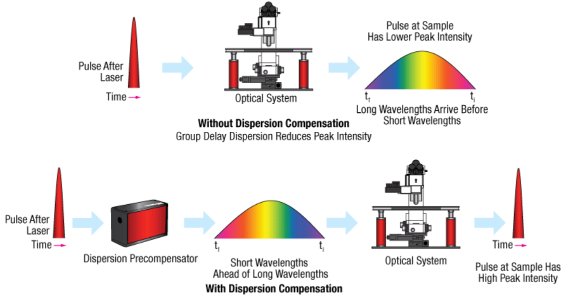
$$\beta_m = \left(\frac{d^m\beta}{d\omega^m}\right) \qquad (m = 0, 1, 2, \dots)$$

$$\beta_1 = \frac{1}{v_g} = \frac{n_g}{c} = \frac{1}{c}\left(n + \omega\frac{dn}{d\omega}\right)$$

$$\beta_2 = \frac{1}{c}\left(2\frac{dn}{d\omega} + \omega\frac{d^2n}{d\omega^2}\right)$$





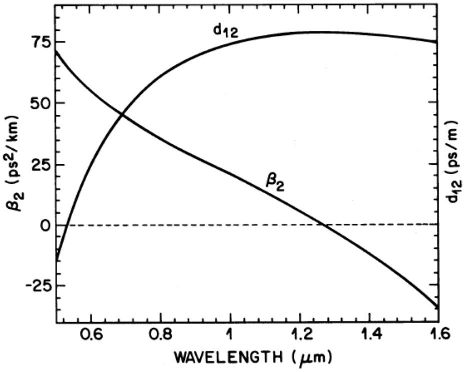


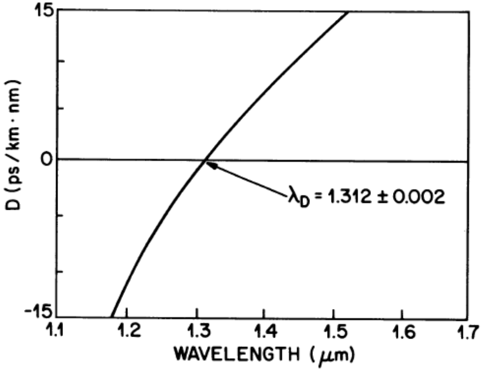
Chromatic dispersion in fibers

Walk-off parameter

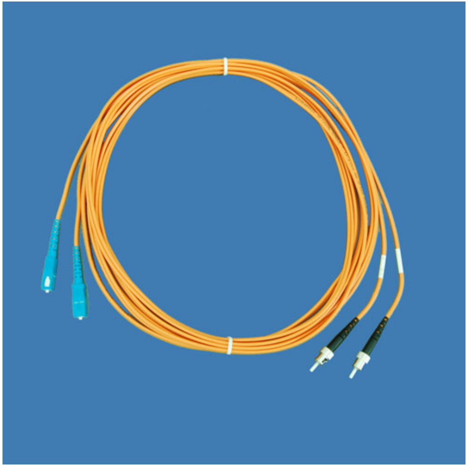
$$d_{12} = \beta_1(\lambda_1) - \beta_1(\lambda_2) = v_g^{-1}(\lambda_1) - v_g^{-1}(\lambda_2)$$

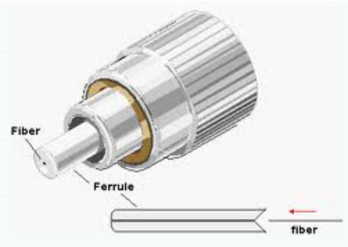
$$D = \frac{d\beta_1}{d\lambda} = -\frac{2\pi c}{\lambda^2}\beta_2 \approx \frac{\lambda}{c}\frac{d^2 n}{d\lambda^2}$$



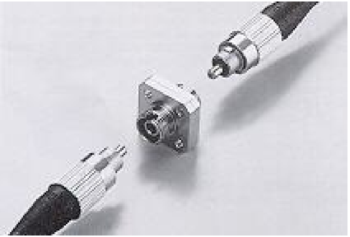


Connectors

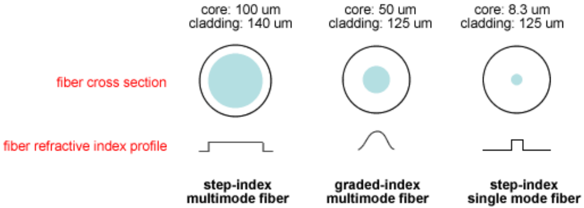




Fiber connector types:
FC
APC



Fiber types



Wavelength range (single mode cutoff)

Absorption

Polarization maintaining / non maintaining

Core diameter

Cladding diameter

Jacket

Connectorized (or bare fiber)

Fiber examples: communication

Corning Fiber	Fiber Type	Core Diameter [mm]	Cladding Diameter [mm]	Attenuation [dB/km]		Mode Field Diameter (MFD) [mm]		Applications / Market
				at 1.31 mm	at 1.55 mm	at 1.31 mm	at 1.55 mm	
SMF-28e	Standard single mode fiber	8.2	125	0.35	0.20	9.2 $\pm$ 0.4	10.4 $\pm$ 0.5	The traditional standard single mode fiber. For metropolitan and access networks.
MetroCor	Negative nonzero dispersion shifted fiber	9?	125	0.5	0.25		$7.6 \leq \text{MFD} \leq 8.6$	A negative non-zero dispersion shifted fiber. For metropolitan and access networks.
LEAF	Large effective area, positive non-zero dispersion shifted fiber	9?	125		0.22		9.6 $\pm$ 0.4	A positive non-zero dispersion shifted fiber. For long-haul and high data-rate metropolitan networks.

1st: $\sim$€ 0.6/m

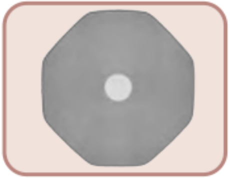
Fiber examples: doped fibers (lasers)

EPFL

Highly Doped Er Fibers, 1.53 - 1.61 µm (Page 1 of 2)

Thorlabs offers a wide range of highly doped erbium fibers suitable for fiber lasers and amplifiers operating in the 1.53 to 1.61 µm wavelength region. These fibers are utilized in a broad range of applications including telecommunication amplifiers (EDFAs), high-power PON/CATV boosters, and ultra-short pulse amplifiers used in instrumentation, industrial, and medical applications.

Structure of Octagonal ER Fibers



Source: Thorlabs, Inc.

Highly Er-Doped Fiber Specifications

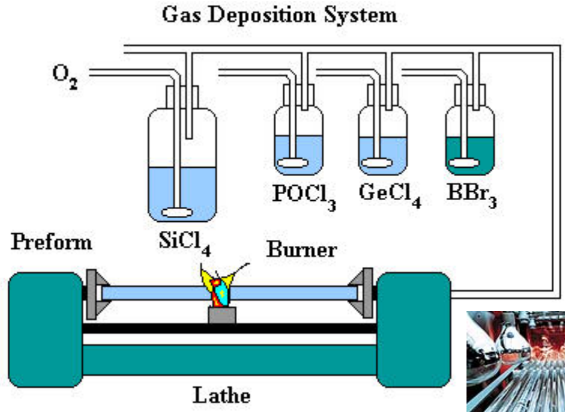
ITEM#	RECOMMENDED OPERATING λ	PEAK CORE ABSORPTION	MFD	CLADDING DIAMETER	COATING DIAMETER	CUTOFF WAVELENGTH	NA
ER16-8/125	C-Band	16 ± 2 dB/m	9.5 ± 0.8 µm	125 ± 2 µm	245 ± 15 µm	1100-1400 nm	0.13 ± 0.02
ER30-4/125	C- and L-Bands	30 ± 3 dB/m	6.5 ± 0.5 µm	125 ± 2 µm	245 ± 15 µm	800-980 nm	0.2 ± 0.02
ER60-40/140DC	C- and L-Bands	60 ± 6 dB/m	40 ± 3 µm*	140 ± 5 µm	245 ± 15 µm	—	0.09
ER80-4/125	C- and L-Bands	80 ± 8 dB/m	6.5 ± 0.5 µm	125 ± 2 µm	245 ± 15 µm	800-980 nm	0.2
ER80-8/125	C- and L-Bands	80 ± 8 dB/m	9.5 ± 0.5 µm	125 ± 2 µm	245 ± 15 µm	1100-1400 nm	0.13
ER110-4/125	C- and L-Bands	110 ± 10 dB/m	6.5 ± 0.5 µm	125 ± 2 µm	245 ± 15 µm	800-980 nm	0.2

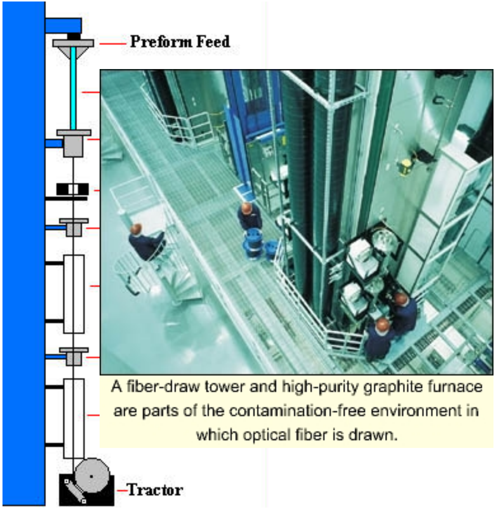
∼€ 60/m

Mode Field Diameter = diameter of the guided beam measured at the $\frac{1}{e^2}$ value

$$\lambda_{\mathrm{SM-cutoff}} > 2 \cdot \pi \cdot \frac{a}{2.405} \cdot NA$$

Optical fiber fabrication





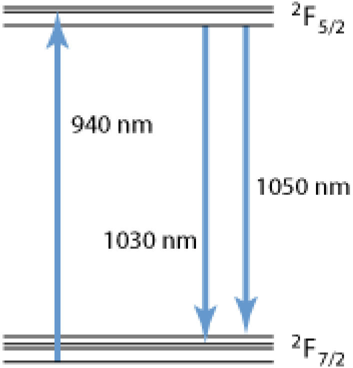
A fiber-draw tower and high-purity graphite furnace are parts of the contamination-free environment in which optical fiber is drawn.

Fiber fabrication

Optical fiber dopants

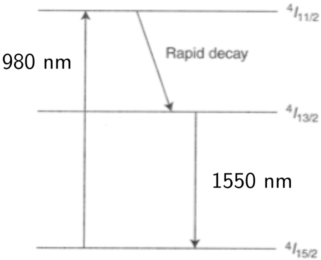
Host fiber: usually silica glass
Fiber dopants: **Yt, Er, Nd**

Ytterbium



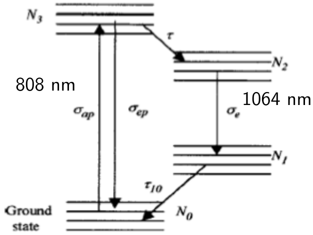
$A_{21}^{-1} = 1 - 2$ ms

Erbium



EDFA (Erbium Doped Fiber Amplifier)

Neodymium (Nd):
Mainly used in large glass slabs (LIF)



Thulium:
Less used.
Laser in the range 1900–2100 nm

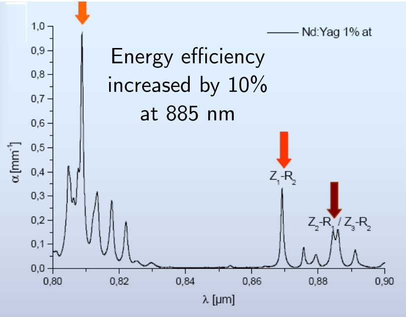
Quantum defect

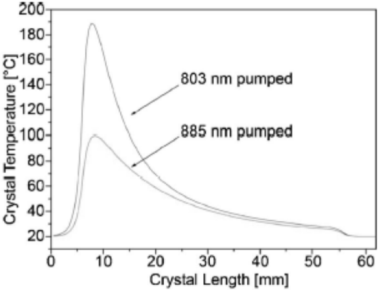
Active ion	Output band [mm]	Pump band [mm]	Energy conversion
Ytterbium	1030-1100	940/975	88 / 92
Erbium	1520-1580	980/1480	63 / 95
Neodymium	1064-1088	808/885	75 / 82
Thulium	1900-2100	793	40

Quantum defect is by definition a unitless number in percent:

$$1 - \frac{E_{\text{laser}}}{E_{\text{pump}}}$$

The lower this number, the **less heat deposited in the material**.





Fiber laser efficiency

Diode pumping
Converts electrical power into pump light
Pump wavelength matches absorption band

$$\eta_{\text{diode}} = 50\text{–}60\%(780\text{–}1000\text{nm})$$

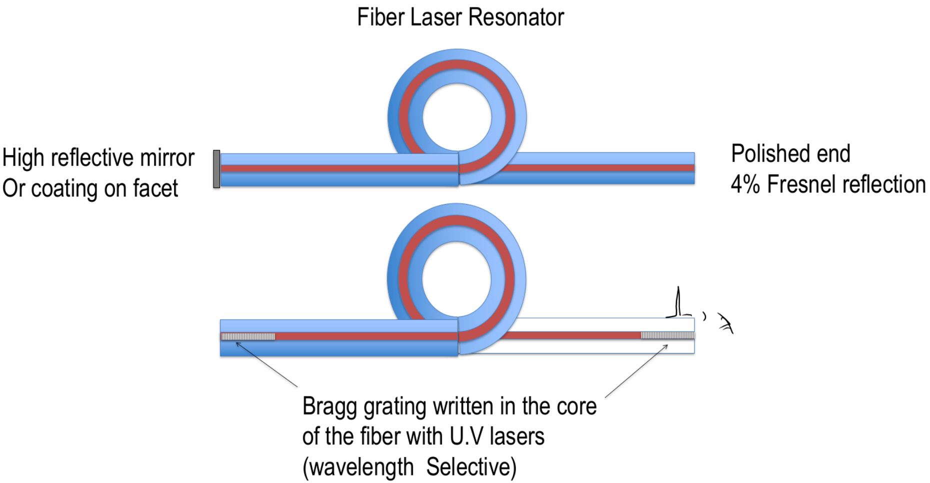
Optical pumping to Optical lasing
Quantum defect
extraction efficiency (incl. all other losses)

$$\eta_{\text{QD}} = 63\text{–}95\%$$
$$\eta_{\text{EXT}} = 90\%$$

Wall plug efficiency: electrical power input to optical lasing power output

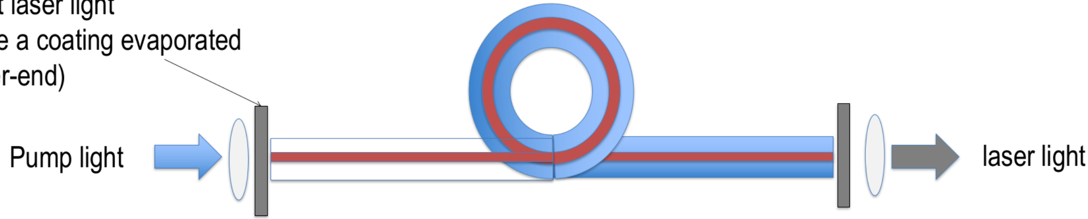
$$\eta_{\text{diode}} = 50\text{–}60\% \ (780\text{–}1000 \text{ nm})$$

Fiber laser resonator



Fiber laser: optical pumping

Dichroic mirror i.e
Pass pump light
Reflect laser light
(can be a coating evaporated on fiber-end)



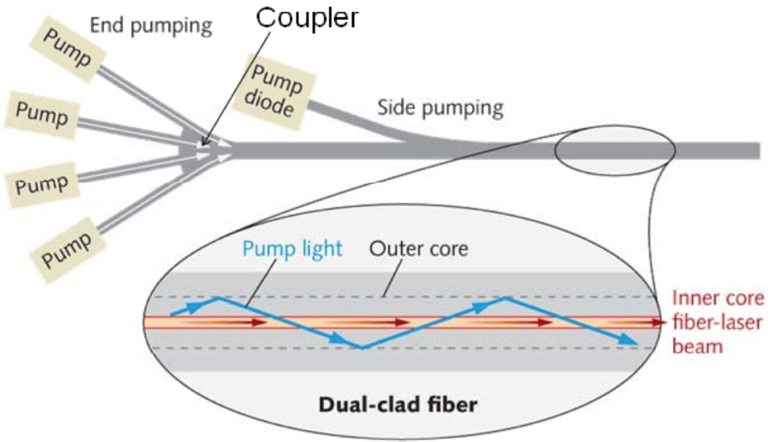
End pumping with pump light focused directly in the core.

↓

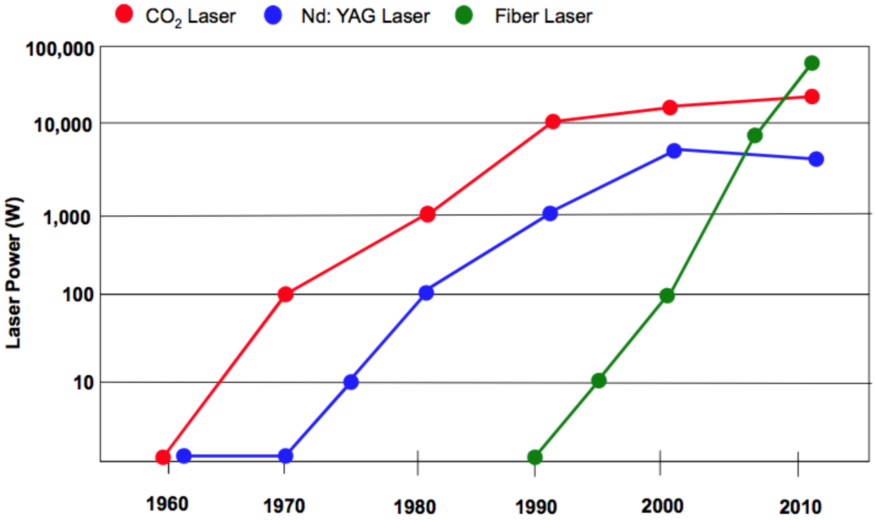
Limits the pump power to less than ~3 W due to the output of single mode laser diode

Fiber laser: double clad fiber

Invention of the double clad fiber (Snitzer, 1988)
enabled much more pumping power in the fiber core



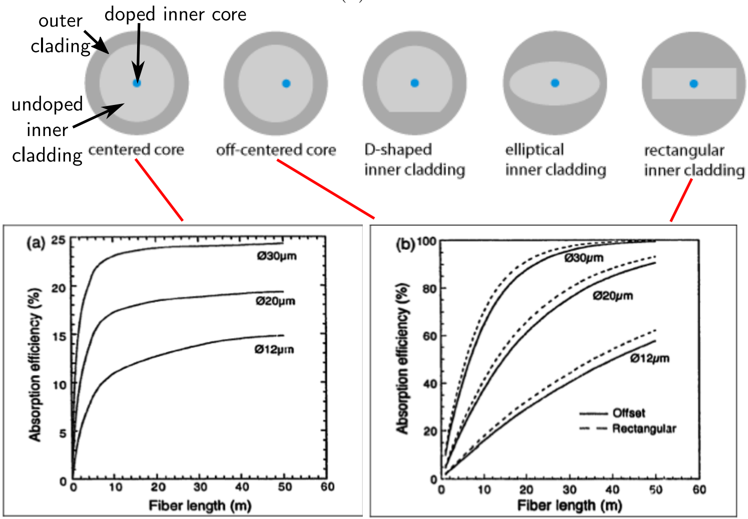
Fiber laser vs. gas & solid state laser



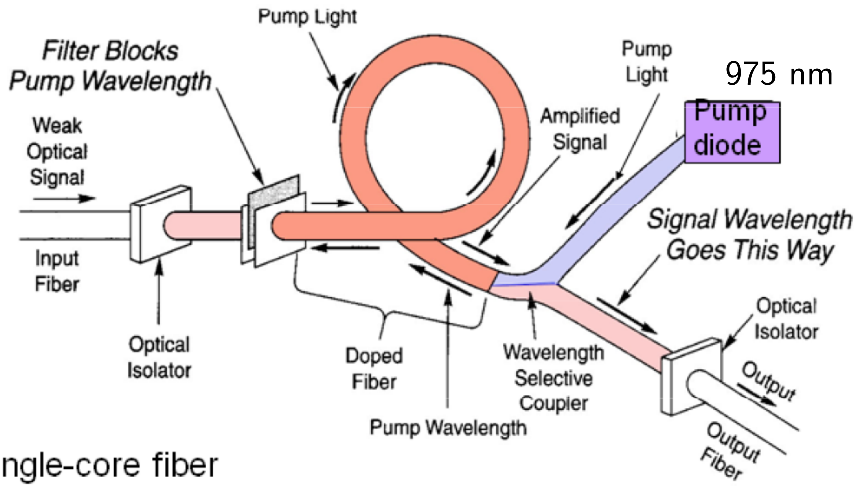
Source: EALA, Automatic Feed Co., ALAW 2009

Double clad designs

$$\eta = \frac{P(0)-P(L)}{P(0)} = 1 - e^{-F(S_{\text{core}}/S_{\text{total}})\alpha_p L}$$



Erbium doped fiber amplifier (EDFA)



Single-core fiber