

Field Guide to

Optical Fiber Technology

Rüdiger Paschotta

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Field Guide to Optical Fiber Technology

Fiber optics have become one of the essential elements of modern optical technology. Early work has mostly focused on the transmission of light over long distances, particularly for use in optical fiber communications. Further work has greatly expanded the application areas of optical fibers, which now also include fields like fiber amplifiers, fiber lasers, supercontinuum generation, pulse compression, and fiber-optic sensors. This diversity of applications has been enabled by a variety of types of optical fibers, which can greatly differ in many respects.

This Field Guide provides an overview of optical fiber technology. It not only describes many different types of fibers and their properties, but also presents in a compact form the relevant physical foundations. Sophisticated mathematics, e.g., concerning fiber modes, are not included, as such issues are covered in detail by several textbooks. Both passive and active (amplifying) fibers are discussed, and an overview on fiber nonlinearities and the application of active fibers in amplifiers and lasers is included. The large bibliography contains many useful references, covering both pioneering work and later seminal articles and books. This Guide should be very useful for a wide audience, including practitioners in industry as well as researchers.

I am greatly indebted to my wife, Christine, who strongly supported the creation of this Field Guide by improving most of the figures.

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Glossary of Symbols

a	core radius
$A(z,t)$	complex envelope function
A_{eff}	effective mode area
c	velocity of light in vacuum
D_2	group delay dispersion
D_λ	dispersion parameter
E	electric field strength
E_p	pulse energy
E_{sat}	saturation energy
$F_{lm}(r)$	mode field function
g	gain coefficient
g_R	Raman gain coefficient
g_{ss}	small-signal gain coefficient
h	Planck's constant
k	wavenumber
I	optical intensity (power per unit area)
I_p	pump intensity
I_s	intensity of Stokes or signal wave
L_b	polarization beat length
n	refractive index
n_2	nonlinear index
n_{core}	refractive index of the fiber core
n_{eff}	effective refractive index of a mode
n_{cladding}	refractive index of the fiber cladding
NA	numerical aperture
P	optical power
P_p	peak power of a pulse
P_{sat}	saturation power
V	V number
w	Gaussian beam radius

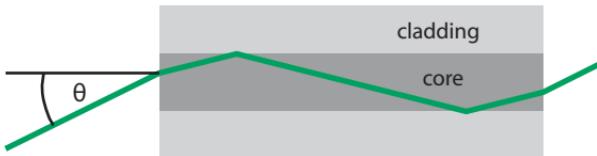
Glossary of Symbols (cont.)

α	power loss coefficient
β	propagation constant
β_2	group velocity dispersion
β_3	third-order dispersion
γ	nonlinear coefficient
η	efficiency (various types of efficiency, see the context)
λ	wavelength
Λ	grating period
ν	optical frequency
σ_{abs}	absorption cross section
σ_{em}	emission cross section
τ	pulse duration
$\phi_{v\lambda}$	nonlinear phase shift
$\chi^{(3)}$	tensor for third-order nonlinearity
$\Psi(r, \phi)$	transverse field function
ω	angular optical frequency

Principle of Waveguiding

Optical fibers represent a special kind of optical waveguide. A waveguide is a material structure that can “guide” light, i.e., let it propagate while preventing its expansion in one or two dimensions. Fibers are waveguides that guide in two dimensions and can effectively be used as flexible pipes for light.

In the simplest and most common case, the waveguide effect is achieved by using a **fiber core** with a refractive index that is slightly higher than that of the surrounding **cladding**. We initially consider **step-index** fibers, where the refractive index is constant within the fiber core (p. 8).



For a step-index fiber, the waveguide effect is often explained as resulting from total internal reflection of light rays at the core–cladding interface (see the figure). One easily comes to the conclusion that total internal reflection at the interface occurs if the external beam angle θ (in air) fulfills the condition

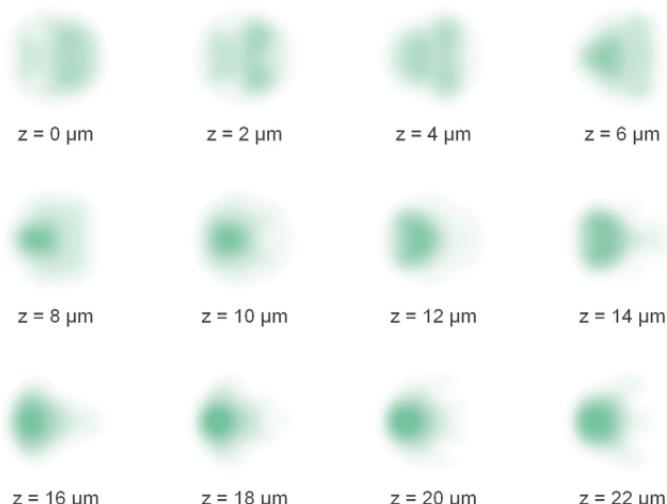
$$\sin \theta < NA \equiv \sqrt{n_{\text{core}}^2 - n_{\text{cladding}}^2},$$

where NA is called the **numerical aperture** of the fiber (see p. 11). The fiber can then guide all light impinging the input face with angles fulfilling this condition, which does not depend on the core size.

This purely geometric picture gives reasonable results for large cores (strongly multimode fibers, see p. 14), but is invalid for small single-mode cores (p. 9), where the wave nature of light cannot be ignored.

Wave Propagation in Fibers

A precise description of light propagation in fibers requires the treatment of light as a wave phenomenon. A common method for numerical calculations is the **beam propagation method**. Starting with a certain electric field distribution at an input face, one calculates how the field propagates a small distance into the fiber. By applying further propagation steps, one can calculate the field distribution (and intensity distribution) everywhere in the fiber. In general, the field distribution can undergo sophisticated changes during propagation. The figure below shows an example for a multimode fiber (p. 14).



A very useful concept is that of **modes**. These represent field distributions with the special property that their shape in the transverse direction remains constant during propagation. These field distributions have only a phase change (which is the **propagation constant** β times the propagation distance z), and a change of power proportional to $\exp(-\alpha z)$ where α is the loss coefficient. (Note: the effective loss coefficient may be negative in an amplifying fiber—see p. 74.) In general, each mode can have its own values of α and β . The number of modes, their field distributions, and their α and β values depend on the optical frequency ν or the wavelength λ .

Calculation of Fiber Modes

Here we briefly consider how fiber modes are calculated in cases where two simplifying assumptions apply: the index contrast is small, and the refractive index depends only on the radius r (the distance to the fiber axis), but not the azimuthal angle φ . This excludes, e.g., fibers with an elliptical core.

If a field distribution $E(r, \varphi, z)$ corresponds to a mode, it must have a simple z dependence, leaving the shape of the intensity profile constant:

$$E(r, \varphi, z) = \Psi(r, \varphi) \exp(i\beta z)$$

with the **propagation constant** β . Absorption losses have been ignored here. The transverse field function $\Psi(r, \varphi)$ is further decomposed:

$$\Psi(r, \varphi) = F_{lm}(r) \cos(l\varphi),$$

where l describes the azimuthal dependence and must be an integer, as the field must stay unchanged for an increase of φ by 2π . Another solution contains $\sin(l\varphi)$ instead of $\cos(l\varphi)$. The second integer index m is necessary, as multiple solutions can exist for a given value of l .

By inserting the latter equation into the wave equation, one obtains the equation

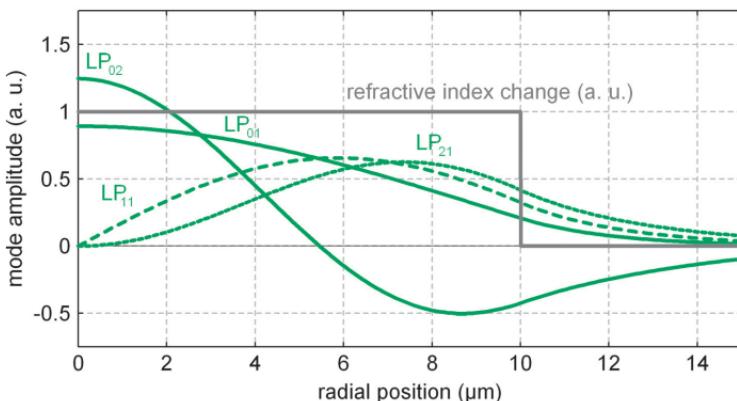
$$F_{lm}''(r) + \frac{F_{lm}'(r)}{r} + \left(n^2(r) k^2 - \frac{l^2}{r^2} - \beta_{lm}^2 \right) F_{lm}(r) = 0,$$

where $k = 2\pi/\lambda$ and the primes indicate derivatives with respect to r . This differential equation combined with suitable boundary conditions (e.g., $F \rightarrow 0$ for $r \rightarrow \infty$ in the case of guided modes, see p. 6) must be solved with analytical or numerical means.

Calculation of Fiber Modes (cont.)

For arbitrary values of β , the solutions for F will usually diverge for $r \rightarrow \infty$ and thus cannot represent guided-fiber modes. For some given (not too high) non-negative integer value of l and suitably chosen β values, however, one may find solutions that asymptotically go to zero for increasing r . The one with the highest value of β can be labeled with $m = 1$, and solutions with lower β obtain higher integer values of m . Numerical methods may be used for fibers with arbitrary index profiles.

As an example, the figure below shows the radial amplitude distributions of all of the solutions for a step-index fiber at a given wavelength.



For example, LP_{02} means that $l = 0$ (i.e., there is no φ dependence) and $m = 2$. The fundamental mode LP_{01} is closest to a simple Gaussian profile, extending somewhat beyond the core.

More sophisticated calculations are required for fibers with high index contrast or with an azimuthal dependence of the refractive index.¹⁸ Particularly difficult to calculate are modes of photonic crystal fibers (page 55), containing air holes.

Decomposition into Modes

Once all modes of a fiber are known, the propagation of a monochromatic beam with arbitrary field distribution along the fiber can be calculated in an efficient way:

- Decompose the initial field distribution $E_0(x,y)$ into fiber modes, i.e., consider it as a linear combination of modes:

$$E_0(x,y) = \sum_{l,m} a_{lm}(0) E_{lm}(x,y)$$

where $E_{lm}(x,y)$ is the field distribution for mode indices l and m . Calculate the initial complex amplitude coefficient $a_{lm}(0)$ of each mode using an overlap integral. Assuming normalized mode functions, this reads:

$$a_{lm}(0) = \int E_{lm}^*(x,y) E_0(x,y) dx dy.$$

It is often sufficient to consider only guided modes (p. 6), since cladding modes (p. 7) are usually fairly lossy and thus do not contribute to the output.

- For all considered modes, calculate the change of amplitude and phase during propagation using the known α and β values:

$$a_j(z) = a_j(0) \exp\left(-\frac{\alpha_j}{2} z + i\beta_j z\right).$$

- Calculate the final field distribution based on the final mode coefficients and the mode fields:

$$E(x,y,z) = \sum_{l,m} a_{lm}(z) E_{lm}(x,y).$$

For polychromatic beams, the different frequency components must be propagated separately.

Types of Fiber Modes

Fibers can support different types of modes:

- **Guided modes** are those with intensity distributions limited to the core and its immediate vicinity. Their field distributions decay exponentially in the cladding. Guided modes normally exhibit rather small propagation losses.
- In some situations, so-called **leaky modes** occur, which are concentrated around the core but lose some power into the cladding.
- **Cladding modes** (p. 7) have intensity distributions that essentially fill the full cladding region, thus also reaching the outer surface of the cladding, where they often experience large power losses. The intensity in the fiber core is substantial for some cladding modes, but very small for others.

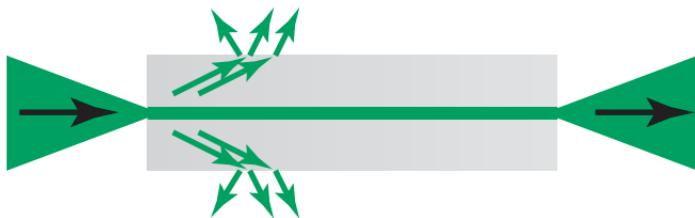
The number of guided modes depends strongly on the fiber design:

- Fibers with only a single guided mode per polarization direction are called **single-mode fibers** (p. 9). Single-mode guidance is usually restricted to some wavelength range. Typically, there is multimode guidance for wavelengths below some cut-off wavelength, whereas the propagation losses increase for longer wavelengths.
- Fibers with more than one guided mode are **multimode fibers** (p. 14). Some support just a few guided modes, others may support a very large number.

In general, the number of guided modes increases with decreasing wavelength.

Cladding Modes

Cladding modes are propagation modes of a fiber (or other waveguide) that are not confined to the surroundings of the core. When trying to launch light into the fiber core, one may inject some part of the power into cladding modes, if the input light is not well matched to the guided mode(s).



The fiber cladding is often surrounded by a polymer coating, which not only mechanically protects the fiber, but also causes high propagation losses for cladding modes. Any power in cladding modes may then quickly decay and will not get to the fiber end (except when the fiber is rather short). The light launched into the core has much lower propagation losses, so that its power remains nearly constant, unless the fiber is very long.

The high loss for cladding modes is convenient, e.g., when checking how efficiently light is launched into the fiber core, or when measuring the propagation losses of the fiber core.

Residual light in cladding modes can be disturbing, e.g., when one tries to measure strong absorption in a short, highly doped rare-earth-doped fiber. Here, light in cladding modes evades the absorption (because the cladding is undoped) and thus simulates a weaker degree of core absorption. Elimination of light in cladding modes may then be accomplished by splicing a longer undoped single-mode fiber to the test fiber. Another possibility is to use a droplet of index-matching fluid on the fiber where its coating is stripped off.

Step-Index Fibers

Step-index fibers are optical fibers with the simplest possible refractive index profile: a constant refractive index n_{core} in the core with some radius a , and another constant value n_{cladding} in the cladding. We always have $n_{\text{core}} > n_{\text{cladding}}$, as otherwise no guided modes exist.

Some important parameters of step-index fibers are:

- The **numerical aperture**

$$NA \equiv \sqrt{n_{\text{core}}^2 - n_{\text{cladding}}^2}$$

(as already defined on p. 1) is related to the refractive index contrast. If the index difference $\delta n = n_{\text{core}} - n_{\text{cladding}}$ is small (which is usually the case), we can approximate

$$NA \approx \sqrt{2 n_{\text{cladding}} \delta n} .$$

- The **V number** (p. 10) is

$$V = \frac{2\pi}{\lambda} a NA = \frac{2\pi}{\lambda} a \sqrt{n_{\text{core}}^2 - n_{\text{cladding}}^2} .$$

The V number determines the number of guided modes. For example, single-mode propagation is obtained for V smaller than ≈ 2.405 . Also, the V number determines the fraction of the power of a mode that is propagating within the core. Obviously, the V number depends on the wavelength, whereas that dependence is very weak for the numerical aperture.

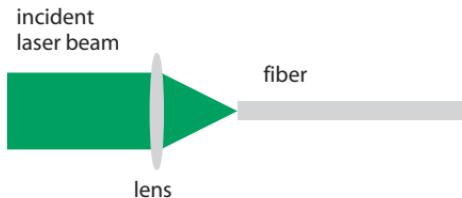
Note that these parameters are not universally defined for fibers with other than step-index profiles.

Single-Mode Fibers

In some wavelength regions, a fiber with a small core may have only a single guided mode per polarization direction. In that regime, the intensity profile at the fiber output has a fixed shape, independent of the launch conditions and the spatial properties of the injected light, provided that no cladding modes (p. 7) can carry significant power to the fiber end. The launch conditions do, however, influence the efficiency with which light can be coupled into the guided mode. Efficient launching requires that the light on the input fiber end has a complex amplitude profile similar to that of the guided mode. That implies

- that the injected light must have a high beam quality;
- that this light is focused on the input fiber end in such a way that a spot with the proper size and position is obtained on the fiber end, and that the beam direction is aligned correctly.

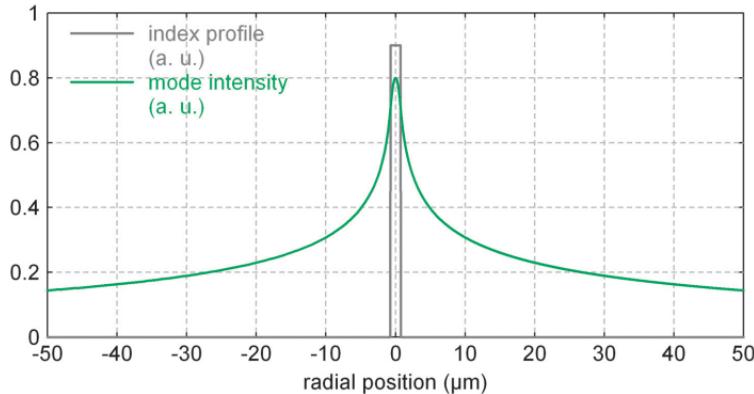
If these conditions are not fulfilled, a large fraction of the power of incident light gets into cladding modes.



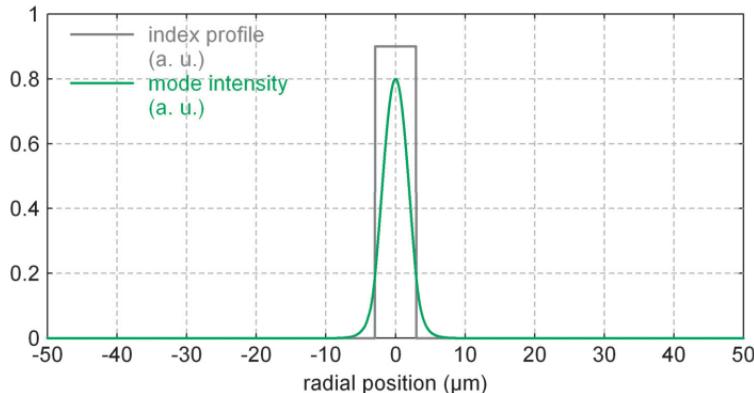
A long-term, stable, efficient launch of a free-space laser beam into a single-mode fiber requires a stable opto-mechanical setup containing a focusing lens with appropriate focal length (depending on the fiber's mode size and the initial beam size) and a holder for the fiber end. These parts need to be aligned precisely, and stably fixed without excessive thermally induced drifts.

V Number of Single-Mode Fiber

For fiber designs with a small V number of, e.g., 0.5, much of the optical power propagates outside the fiber core:



For designs with large V number of, e.g., 2, most of the power is confined in the fiber core, and the mode shape is approximately Gaussian:



Designs with large V provide more robust guidance.

For V numbers between ≈ 0.8 and 2.5 , the mode radius can be estimated with Marcuse's formula:⁴

$$\frac{w}{a} \approx 0.65 + \frac{1.619}{V^{3/2}} + \frac{2.879}{V^6}.$$

Numerical Aperture of a Single-Mode Fiber

The **numerical aperture** (as defined on p. 8) is also an important design parameter:

- Single-mode fibers with a moderate NA of, e.g., 0.1 or 0.15 (corresponding to index contrasts <1%) can have rather low propagation losses. Standard passive single-mode fibers usually operate in this regime.
- Higher values of the NA, such as 0.3, combined with a reduced core size, may be used to decrease the effective mode area, e.g., for active fibers with high gain efficiency, or for maximizing nonlinear effects (p. 32). The propagation losses, however, may increase, because scattering in the core or at the core–cladding interface becomes stronger.
- Very low values of the NA (0.05 or smaller) are used for large mode area fibers (p. 60), as needed, e.g., when nonlinear effects need to be minimized. This, however, leads to less robust guidance. The fiber may then be sensitive to bend loss (p. 23), and a high precision of refractive index control is required for avoiding extra losses resulting from index inhomogeneities.

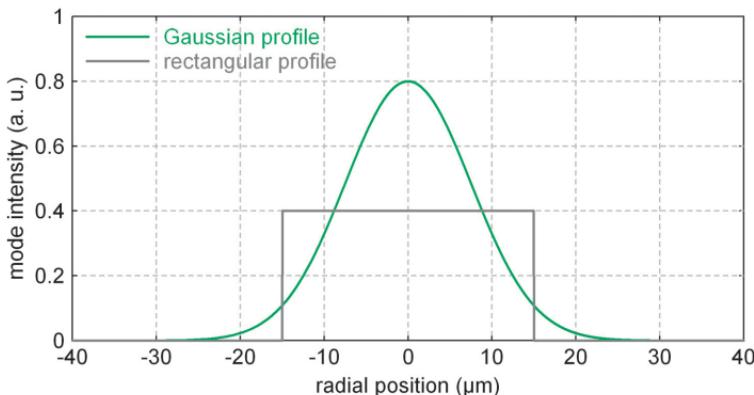
Single-mode fibers often have refractive index profiles that significantly deviate from a step-index design, i.e., that are not rectangular. For example, a refractive index dip may occur at the center as an unintended consequence of the preform fabrication process. In other cases, non-rectangular index profiles (e.g., multi-step or triangular profiles) are intentionally used, e.g., for modifying the dispersion properties (p. 24). A numerical aperture may still be defined for such fibers, but there appears to be no universally accepted definition. One possibility is to use the maximum refractive index within the core for n_{core} in the definition of the NA. Various equations derived for step-index fibers are no longer applicable, however.

Effective Mode Area

If a fiber mode were to have a rectangular transverse profile with some radius w , its mode area would simply be $A = \pi w^2$. However, modes normally do not have rectangular profiles, so we need to work with some kind of **effective mode area**. The common definition can be based on the complex electric field profile $E(r)$ or the intensity profile $I(r)$:

$$A_{\text{eff}} = \frac{\left(\int |E|^2 dA \right)^2}{\int |E|^4 dA} = \frac{\left(\int I dA \right)^2}{\int I^2 dA}.$$

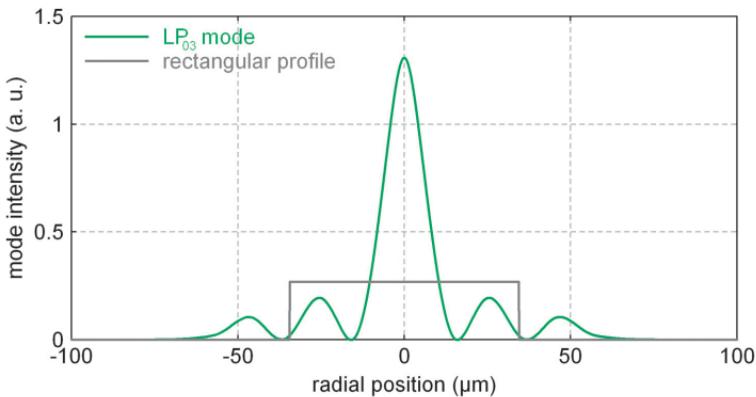
The integration is done over the full area where the mode intensity is not negligible. For a rectangular shape with radius w , or for a Gaussian shape with the Gaussian mode radius w (the $1/e$ E-field radius), one obtains the result $A_{\text{eff}} = \pi w^2$.



The diagram shows a Gaussian mode profile and a rectangular profile with the same effective mode area for comparison. The intensities are in arbitrary units, but both curves have the same intensity scaling for a given power. The Gaussian mode has twice the intensity at the center.

Effective Mode Area (cont.)

As another example, the diagram below shows the situation for a higher-order mode. Here, the peak intensity is far above that of the rectangular profile with the same effective mode area.



For any profile, the calculated effective area will be such that the nonlinear Kerr phase shift (p. 34) in a fiber with length L and nonlinear index n_2 (see p. 33) is

$$\phi_{\text{nl}} = n_2 \frac{P}{A_{\text{eff}}} \frac{2\pi}{\lambda} L$$

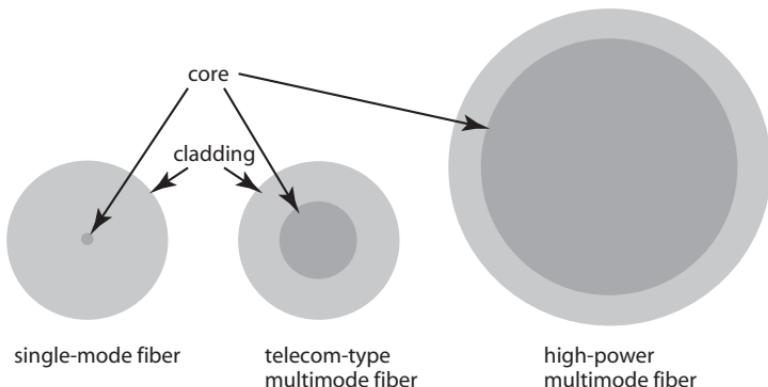
if P is the optical power in the guided mode. The larger the effective area, the smaller is the average intensity, and the weaker are nonlinear effects. The higher contributions of the intensity peaks to the nonlinear phase shift are compensated by the lower phase shifts in the low-intensity regions, and the mode-shaping mechanism equalizes the phase shifts within the profile.

Typical single-mode telecom fibers (p. 49) have effective mode areas of the order of 50–100 μm^2 , corresponding to mode diameters of $\approx 8\text{--}11 \mu\text{m}$. Some highly nonlinear photonic crystal fibers (p. 55) can have values of only a few μm^2 , whereas large mode area fibers can exhibit values of hundreds or even thousands of μm^2 .

Multimode Fibers

Multimode fibers are fibers supporting more than one guided mode per polarization direction. Typically, they have a larger core.

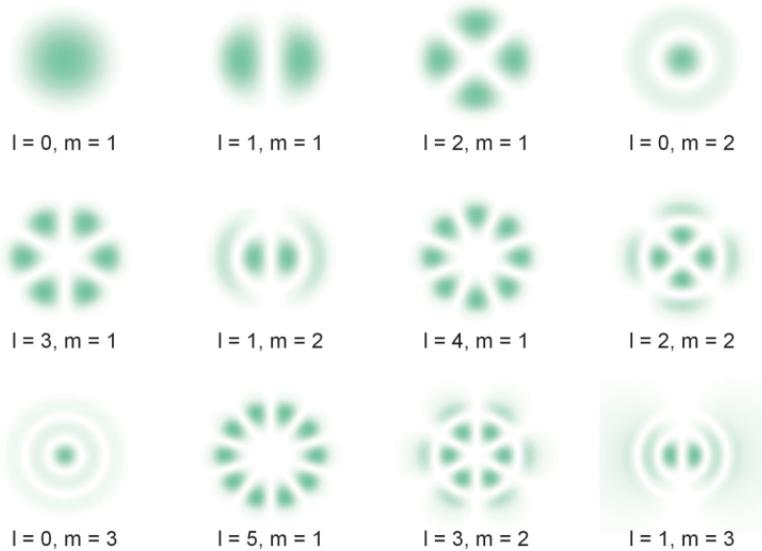
The figure below first shows a single-mode fiber (for comparison) and a typical multimode fiber as used, e.g., for short-range optical fiber communications. Both fibers have a cladding diameter of 125 µm. The multimode fiber has a step-index profile with a core diameter of 50 µm or 62.5 µm and a numerical aperture of, e.g., 0.3 (index contrast: $\approx 2\%$). It supports hundreds of guided modes.



The right side shows a high-power multimode fiber, where the core is only slightly smaller than the cladding. Such a fiber supports many thousands of modes and can be used for transporting several tens of watts or more from a fiber-coupled high-power laser diode, having a relatively poor beam quality. Typically, step-index designs with core diameters of 50, 100, 200, 400, 600 or 800 µm are used. The larger values require fibers with large outer diameter, thereby limiting the mechanical flexibility. The core often consists of pure silica and is surrounded by an index-depressed cladding, which is doped with fluorine, for example. In addition, there will usually be some buffer around the glass fiber (not shown in the figure).

Multimode Fibers (cont.)

The figure below shows all mode profiles for a step-index fiber with smaller core and $V \approx 8.8$. (Additional modes with the same shape, but rotated by 90°, for example, are not shown.)



The modes of such fibers are usually described as LP_{lm} modes with indices l and m (see p. 3). The index l determines the number of zero lines in the azimuthal direction, whereas m is related to the zeros of the radial function.

If the V number is large, the number of guided modes can be approximated as

$$M \approx \frac{4}{\pi^2} V^2.$$

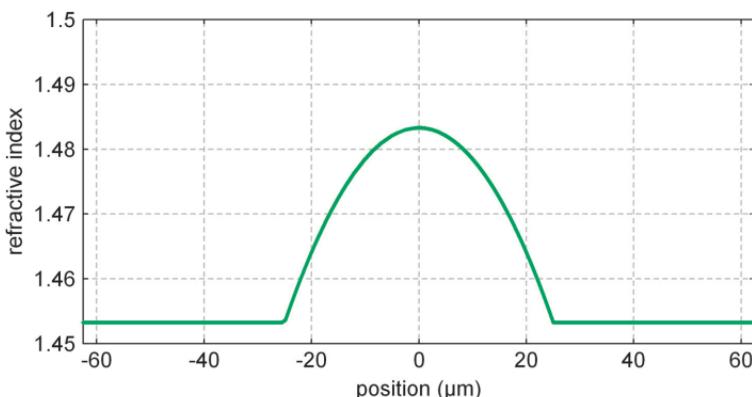
Launching light into multimode fibers or splicing such fibers is much simpler than for single-mode fibers: the core is much larger, while the often higher NA somewhat relaxes the angular tolerance.

Multimode Fibers (cont.)

The output profile of light from a multimode fiber is sensitive to the launch conditions, since these determine the exact distribution of power over the fiber modes and the relative phases of light in these modes. As the modes have different propagation constants, the relative phases change rapidly during propagation, so that the intensity profile within the fiber undergoes rapid and complicated changes, as shown on p. 2. The exact propagation conditions are also sensitive to variations of the temperature and to mechanical stress. For broadband light, the total intensity profile may be smooth, because it contains contributions from different wavelengths.

The propagation losses of multimode fibers are generally higher than those for single-mode fibers. This results from the generally higher numerical aperture, i.e., the increased index contrast, which increases the tendency for scattering light at the core–cladding interface.

For telecom applications, step-index designs are not ideal, because different modes then exhibit significantly different group velocities. (This is called **intermodal dispersion**.) As a result, short pulses (representing transmitted bits) are rapidly washed out in the temporal domain. This effect can be greatly reduced by using parabolic index profiles as shown below.



Glass Fibers

Glass fibers can be made of a variety of glasses, out of which **silica glass** (quartz glass, amorphous SiO_2) is most often used due to its outstanding properties and relatively low cost. It is well suited for fiber drawing from a preform and can exhibit extremely small propagation losses (p. 21).

The core and/or the cladding glass may be modified with certain dopants, which can have different functions:

- The refractive index of the core can be raised by doping with germania (GeO_2), phosphorus pentoxide (P_2O_5), or alumina (Al_2O_3). This leads to germanosilicate, phosphosilicate, or aluminosilicate glasses.
- The refractive index of the core or the cladding may be reduced by doping with fluorine or boron oxide (B_2O_3). For example, one can make fibers with a pure silica core and fluorine-doped (index-depressed) cladding.
- Rare-earth dopants (p. 74) are mostly used for active (amplifying) fibers as those used in fiber amplifiers and lasers.
- Alumina and some other dopants can be used to increase the solubility of the glass for rare-earth ions. Such dopants can also affect the emission and absorption spectra and the strength of energy transfer processes between laser-active ions.

Furthermore, dopants can influence the tendency for photodarkening and radiation damage, the sensitivity to UV light (used for fabricating fiber Bragg gratings, p. 70), the strength of optical nonlinearities (p. 32), and the phonon properties. The latter influence the mid-infrared transmission losses and the rate of multi-phonon transitions in rare-earth-doped fibers (p. 74).

Non-Silica Glass Fibers

Various non-silica glasses are also often used for optical fibers:

- **Phosphate glasses** are sometimes used for fiber amplifiers and lasers, because phosphates lead to a low tendency for quenching processes (i.e., processes reducing metastable level lifetimes), even for high rare-earth doping concentrations. That applies particularly to erbium-doped fibers.
- **Chalcogenide glasses** include sulphide, telluride, and selenide glasses. These have relatively small phonon energies, which makes them suitable for mid-infrared applications: the transmission window can include the wavelength region of several microns, and rare-earth dopants in such glasses can have unquenched laser transitions, even for small energy gaps as needed for mid-infrared emission.
- **Fluoride glasses** containing heavy metals such as zirconium also exhibit relatively small phonon energies and are used for mid-infrared and upconversion lasers. Particularly important are ZBLAN (fluoro-zirconate) glasses and variants thereof.

Non-silica glasses often require specialized fabrication techniques, such as the double crucible method, where core and cladding are simultaneously drawn from a crucible having reservoirs for glasses with different compositions. Not all glasses are suited for drawing from a preform, and fusion splicing may not be possible. Partly as a result of modified fabrication processes, the cost and the propagation losses of non-silica fibers are often much higher than for silica fibers. Also, chalcogenide and fluoride glasses tend to be more brittle than silica, which makes them more difficult to handle.

Nanofibers

Optical nanofibers, also called **photonic nanowires**, are optical fibers with diameters in the range from tens to a few hundreds of nanometers. The alternative term **subwavelength fibers** emphasizes that the diameter is well below the optical wavelength. Nanofibers, often made of silica, have rather peculiar properties:

- The numerical aperture is very high, which leads to a very small mode area. For precise calculations of the mode properties, full vectorial models are required, as the paraxial approximation is not valid.
- For fiber diameters below ≈ 600 nm (in the case of silica fibers), the mode radius of guided light *increases* as the fiber diameter is further decreased. This is essentially because the “guiding power” of a thinner fiber becomes weaker. Most of the optical power then propagates in the evanescent field outside the fiber.
- Due to their exceptional mechanical strength, silica nanowires can be bent with radii of a few micrometers. The bend losses still remain small because of the high numerical aperture. Tightly coiled fibers can be used for miniature fiber resonators, acting as notch filters or couplers.
- The small effective mode area leads to strong nonlinear interactions with the fiber material, allowing for very compact and low-power nonlinear devices. For example, supercontinuum generation is possible with rather low power levels. In addition, the significant evanescent fields just outside the fiber surface can interact, e.g., with gases. That may be useful for optical sensors.

Nanofibers are often fabricated by tapering large fibers while heating them. The non-tapered fiber part can serve for launching light into the nanofiber.

Plastic Optical Fibers

Plastic optical fibers (POF) are optical fibers made of polymer materials. While their performance is inferior to that of glass fibers, they allow for mechanically more robust and cost-effective solutions due to the simpler handling and installation. A major application is short-range data transmission, e.g., within industrial settings, homes, and cars, but POF are also used for illumination purposes.

For cheap mass applications, PMMA (acrylic), polystyrene, and polycarbonates are often used. For example, a PMMA core can be surrounded by a fluorinated cladding, having a lower refractive index. For high data rates, certain perfluorinated polymers such as poly-perfluorobutenevinylether are preferred, since they have lower propagation losses and can be operated at longer wavelengths, where transmitters and receivers developed for glass fibers can be used.

Comparing POF with glass fibers, the major differences are:

- POF often have their loss minimum at visible wavelengths, or in the near infrared (at $<1.3\text{ }\mu\text{m}$) in the case of perfluorinated polymers, whereas silica fibers have the loss minimum at $>1.5\text{ }\mu\text{m}$, and some other glasses have theirs at much longer wavelengths.
 - A typical POF has high propagation losses of, e.g., 50–100 dB/km, whereas silica fibers can achieve a few dB/m or well below 1 dB/km.
 - POF are usually multimode fibers with a large core and a high numerical aperture, implying a large number of guided modes.
 - POF are mechanically more robust and flexible and are thus easier to handle and install. They also have a lower weight.
-

Origins of Propagation Losses

When propagating in the fiber, light loses some of its optical power. The (linear) power losses are usually quantified in decibels per kilometer (dB/km). They strongly depend on the type of fiber, various fabrication details, the optical wavelength, and the bend radius.

Intrinsic losses are those losses with fundamental origins, which cannot be removed without using an entirely different material:

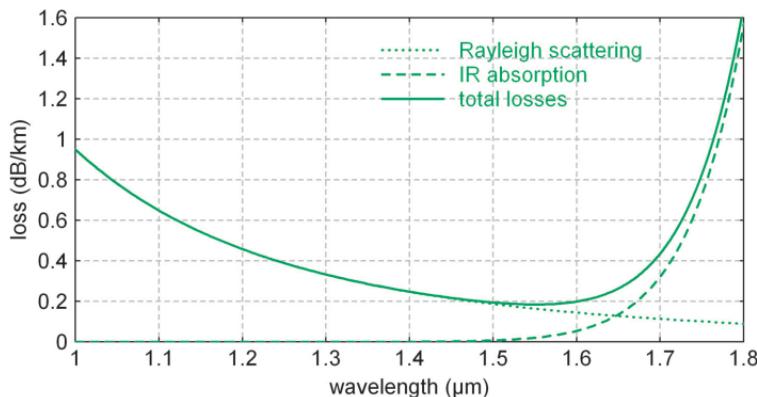
- Intrinsic light absorption can occur both because of electronic transitions (particularly for ultraviolet light) and vibrational resonances (in the mid infrared) and their overtones (extending into the near infrared). At visible and near-infrared wavelengths—well away from the corresponding resonances—intrinsic absorption is weak.
- The irregular microscopic structure of a glass implies density fluctuations, which cause Rayleigh scattering. That loss is proportional to the inverse 4th power of the wavelength. It usually dominates the loss at visible and near-infrared wavelengths, apart from possible extrinsic loss peaks (see below).

Extrinsic losses are additional losses due to imperfections that could in principle be avoided:

- Extrinsic absorption can be caused by unwanted impurities. For example, hydroxyl (OH^-) ions in silica glass can create loss peaks around $1.39\ \mu\text{m}$ and $1.24\ \mu\text{m}$. These can be essentially eliminated by fabrication methods avoiding any influence of water vapor.
- Extrinsic scattering can result, e.g., from irregularities of the core–cladding interface, including variations of the core diameter and microbends.

Losses of Silica Fibers

Specifically for silica-based single-mode fibers, it has become possible to virtually eliminate all extrinsic losses by using very pure raw materials, avoiding any contamination during preform production, and carefully controlling the fiber drawing process. The measured losses are then close to the intrinsic losses as shown in the graph below.



The IR absorption associated with vibrational resonances increases at wavelengths above $1.6 \mu\text{m}$, whereas Rayleigh scattering dominates at shorter wavelengths. UV absorption is not important in the considered wavelength range. The loss minimum occurs in the region of $1.5\text{--}1.6 \mu\text{m}$, with losses of only $\approx 0.2 \text{ dB/km}$.

If the silica is not water-free, additional loss peaks around $1.39 \mu\text{m}$ and $1.24 \mu\text{m}$ (not shown) can be observed.

The losses also become higher for high doping of the core, e.g., with germania. Multimode fibers also have higher losses. They typically have higher numerical apertures, which increase the tendency for scattering at the core–cladding interface. Such fibers are still used for shorter transmission distances, since their losses are less critical.

Bend Losses

When an optical fiber is bent, this can lead to increased propagation losses, called **bend losses**. Typically, such losses are very small for weak bending, but increase rapidly when the bend radius gets below some critical value. Generally, bend losses get stronger for fibers with a low numerical aperture and at longer wavelengths, although the wavelength dependence is often strongly oscillatory.

For multimode fibers, the critical radius depends on the propagation mode. Typically, bend losses get larger for modes of higher order. This effect is sometimes exploited for suppressing higher-order modes while causing only moderate losses for the fundamental mode.

Even if there is no macroscopic bending, there can be losses due to **microbends** caused in the fiber production process. Such microbends must be minimized for low-loss telecom fibers.

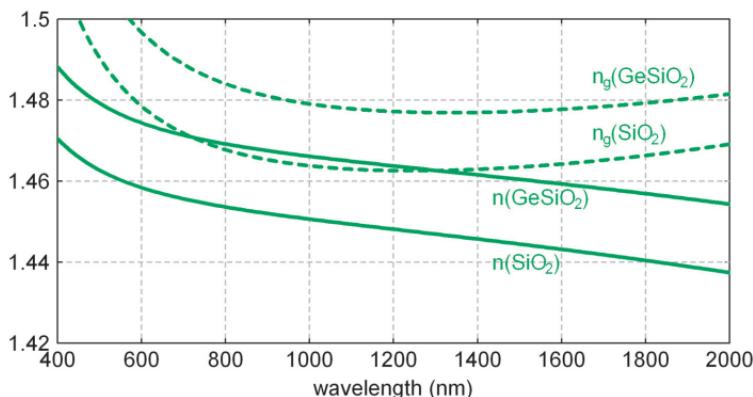
A common method for estimating bend losses is the **equivalent index method**. Here, the effect of bending is described as an increase of refractive index in the radial direction, and modified mode fields can be calculated on that basis. Note, however, that various neglected effects such as stress-induced index changes and reflections from the outer surface of the cladding can be significant, so that the precision of such estimates is not always high. More precise methods exist but are relatively complicated to use.

Note that the bending of a fiber can not only increase the propagation losses, but can also induce birefringence (p. 25) as well as modify (often reduce) the effective mode area. This is an important issue in the context of large mode area fibers (p. 60). The strength of such effects can strongly depend on the fiber design.

Chromatic Dispersion

Chromatic dispersion is the phenomenon where the phase velocity and group velocity of light in a medium depend on the optical frequency. In a fiber, such a frequency dependence arises from two factors:

- **Material dispersion** is related mainly to the properties of the core glass and to some extent by the cladding glass. Material dispersion alone can be measured on bulk samples of the glass.

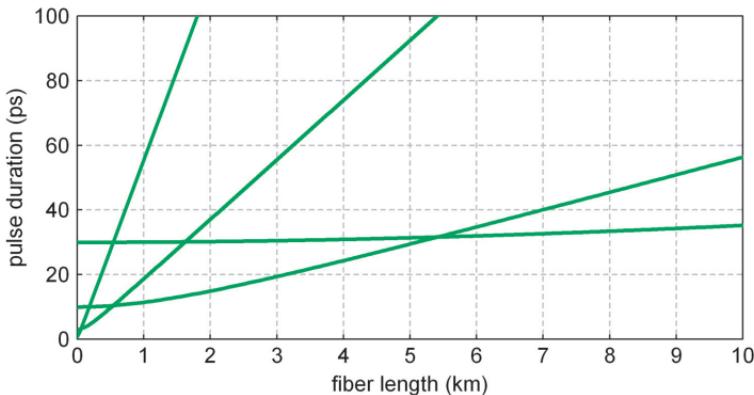


The above graph shows the wavelength-dependent refractive indices and group indices of pure SiO_2 (fused silica) and of germanosilicate glass with 10% GeO_2 . If the latter material is used for the fiber core, surrounded by pure fused silica, a numerical aperture of 0.25 results.

- The waveguide effect further modifies chromatic dispersion. That contribution is called **waveguide dispersion**. Essentially, the phase delay per unit length is influenced by the optical confinement of the modes, and that effect depends both on the propagation mode and the wavelength. It is generally stronger for waveguides with small mode areas, and it can be influenced via the details of the refractive index profile of the fiber core.

Chromatic Dispersion (cont.)

Chromatic dispersion is particularly important in situations where ultrashort optical pulses, or other kinds of signals with a temporally fast variation, are transmitted through a fiber. Ultrashort pulses can be dispersively broadened. The diagram below shows how pulses with initial durations of 1 ps, 3 ps, 10 ps and 30 ps, respectively, become broadened within a few kilometers of a fiber with a group velocity dispersion of $20,000 \text{ fs}^2/\text{m}$.



Pulses may be compressed again when encountering dispersion of the opposite sign.

Higher-order dispersion (p. 26) can lead to the distortion of pulse shapes. Fast signals, as used, e.g., in the context of optical fiber communications, can be distorted, making it difficult to detect the information content.

Chromatic dispersion also affects the phase matching of nonlinear interactions such as four-wave mixing (p. 44).

Dispersion compensation (p. 52) is the introduction of additional chromatic dispersion into a system (e.g., a fiber transmission line) with the purpose of compensating dispersive effects. More generally, **dispersion management** is the use of tailored dispersion properties for optimizing fiber-optic (and other) systems.

Chromatic Dispersion (cont.)

The phase delay per unit length in a fiber for monochromatic light with a given wavelength is called the **propagation constant** β , which, however, is not constant but rather depends on the mode and the wavelength. It can be calculated by solving the mode equation (p. 3) for different optical frequencies. Subsequently, the total chromatic dispersion (including both material and waveguide dispersion) can be calculated from the dependence of β on the angular frequency $\omega = 2\pi v$: For a given center frequency ω_0 , $\beta(\omega)$ can be expressed with a Taylor expansion:

$$\beta(\omega) = \beta_0 + \frac{\partial \beta}{\partial \omega} (\omega - \omega_0) + \frac{1}{2} \frac{\partial^2 \beta}{\partial \omega^2} (\omega - \omega_0)^2 + \frac{1}{6} \frac{\partial^3 \beta}{\partial \omega^3} (\omega - \omega_0)^3 + \dots$$

where all derivatives are taken at the center frequency. The meaning of these terms is:

- The first derivative ($\partial \beta / \partial \omega$) is the **inverse group velocity**, i.e., the temporal delay of a pulse maximum per unit length of fiber (assuming a pulse spectrum that is not too broad).
- The second derivative ($\beta_2 \equiv \partial^2 \beta / \partial \omega^2$) is the **group velocity dispersion (GVD)** (or **second-order dispersion**) per unit length, measured in units of fs^2/m or ps^2/km , for example. It determines to first order the frequency dependence of the inverse group velocity.
- The third derivative quantifies **third-order dispersion (TOD)**, and is measured, e.g., in units of fs^3/m .

Higher orders of dispersion can be defined, but are relevant only when rather broad frequency regions are considered. An alternative to the Taylor expansion is to consider $\partial \beta / \partial \omega$ or $\partial^2 \beta / \partial \omega^2$ as a function of frequency (the expansion point ω_0).

Chromatic Dispersion (cont.)

In the context of optical fiber communications, it is common to use the dispersion parameter $D_\lambda(\lambda)$ defined as

$$D_\lambda(\lambda) = \frac{\partial}{\partial \lambda} \left(\frac{1}{v_g} \right),$$

and typically quantified with units of ps/(nm·km). It can be related to β_2 via

$$D_\lambda = -\frac{2\pi c}{\lambda^2} \cdot \beta_2,$$

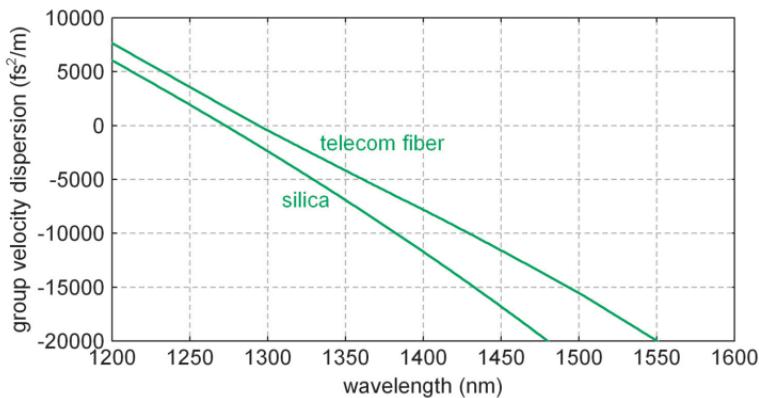
and has the opposite sign, since an increase of frequency implies a decrease of wavelength. Therefore, one should not use the terms *positive* and *negative* dispersion, but rather *normal* and *anomalous* dispersion:

- **Normal dispersion** means $\beta_2 > 0$ and $D_\lambda < 0$. This regime is usually (but not always) encountered for shorter (e.g., visible) wavelengths. Here, an initially unchirped (transform-limited) pulse will acquire an increasingly strong up-chirp, i.e., develop an instantaneous frequency that increases with time. Pulses with a longer center wavelength propagate faster.
- **Anomalous dispersion** means $\beta_2 < 0$ and $D_\lambda > 0$. This regime is often encountered for longer wavelengths. Here, an initially unchirped pulse will acquire a down-chirp, and pulses with shorter center wavelengths propagate faster. In conjunction with self-phase modulation (p. 34) with positive n_2 , anomalous dispersion leads to **soliton** effects (p. 37).

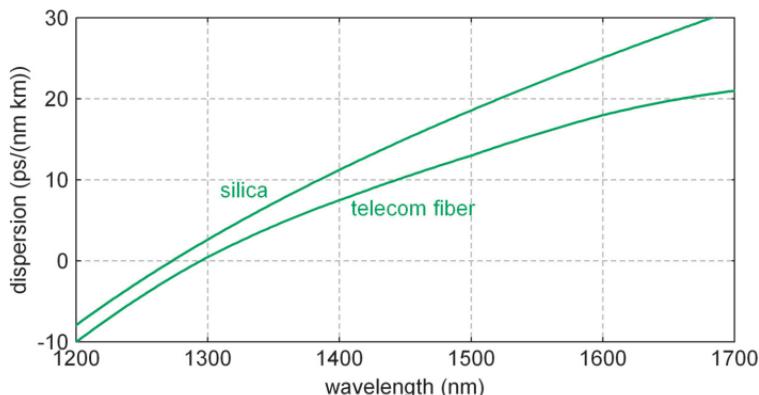
Wavelength regions with normal and anomalous dispersion, respectively, join at a **zero-dispersion wavelength**. A fiber often has one such wavelength, but in some cases more than one or none at all.

Chromatic Dispersion (cont.)

Typical values for the group velocity dispersion of single-mode fibers are of the order of $\pm 10,000 \text{ fs}^2/\text{m}$. The graph below shows that the GVD of silica becomes negative for wavelengths longer than $\approx 1.27 \mu\text{m}$. The GVD for a silica-based single-mode telecom fiber is somewhat shifted due to the influence of waveguide dispersion and the modified core material.



In terms of the dispersion parameter D_λ , the fiber dispersion is of the order of $\pm 10 \text{ ps} / (\text{nm} \cdot \text{km})$:



With modified fiber designs, significantly different dispersion curves can be obtained, as shown on p. 51.

Birefringence and Polarization Effects

If an optical fiber has an elliptical core, or some other feature breaking the rotational symmetry, this can lead to **birefringence**, meaning that the propagation constant β has different values for the two polarization eigenstates. For an elliptical-core fiber, these eigenstates have linear polarization directions along the principal axes of the elliptical cross-section. Any other input polarization state will change during propagation (and can thus not belong to a mode), but will periodically reappear after integer multiples of the **polarization beat length**

$$L_b = \frac{2\pi}{|\Delta\beta|}.$$

Similar effects can occur if the fiber has a design that in some other way breaks the rotational symmetry, or if the fiber is bent, which causes asymmetric strain.

Apart from such well-defined asymmetries, some level of birefringence (typically with a long beat length of, e.g., several meters) can arise from random imperfections of the fiber, even if the fiber design is symmetric and the fiber is not significantly bent. As a result of this, the polarization of an input beam may be modified in a complicated way during propagation. These polarization changes can depend on the wavelength, the fiber temperature, and on the exact way in which it is bent. Such a fiber is not polarization-maintaining.

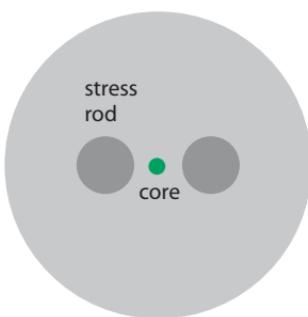
Fiber-based communication systems are normally made from such non-polarization-maintaining fibers, and designed such that the polarization changes have hardly any impact on the performance. It is necessary for that purpose to avoid the use of any optical elements (e.g., modulators or couplers) that are polarizing or in other ways polarization dependent.

Polarization-Maintaining Fibers

For various applications, such as interferometric sensors or polarized fiber lasers, it is essential to have fibers that preserve a given linear polarization direction independent of temperature and bending effects. The usual way to achieve this is not to avoid any birefringence (which would be very difficult), but to use a fiber design with some built-in asymmetry that leads to strong birefringence. Such fibers are called **polarization-maintaining fibers**.

There are different ways of introducing strong birefringence into a fiber:

- **Shape birefringence** is obtained simply by making the fiber core elliptical.
- **Stress birefringence** is obtained in designs with built-in mechanical stress, which influences the refractive indices (photo-elastic effect). Typically, two stress rods made of a modified glass are inserted into the fiber preform (see the figure). Due to different thermal expansion coefficients, a built-in stress arises during fiber fabrication, when the fiber is cooled down. That stress remains permanently in the fiber.
- **Photonic crystal fiber** designs (p. 55) can have asymmetric arrangements of air holes that also lead to birefringence. In addition, stress elements consisting of a different glass can also be used.



The polarization beat length achieved with these methods varies, but can be of the order of a few millimeters or even less.

Polarization-Maintaining Fibers (cont.)

It is essential to launch the linearly polarized input light into a polarization-maintaining fiber such that the polarization direction is aligned precisely along one of the fiber's birefringence axes. The polarization direction will then follow this axis, even if the fiber is somewhat bent or twisted. If the polarization beat length is sufficiently short, and excessive mechanical stress (e.g., in fiber connectors) is avoided, external disturbances cannot significantly couple the two polarization states in the fiber.

If the input polarization is not properly aligned, the output polarization will in general not be linear and will be sensitive to environmental disturbances.

Disadvantages of polarization-maintaining fibers are

- the higher price
- the need to precisely align the polarization axes, e.g., when fibers are spliced
- the somewhat higher propagation losses

For such reasons, polarization-maintaining fibers are usually only used at the device level, e.g., within interferometers or fiber lasers but not for optical data transmission.

There are also **single-polarization fibers**, which guide only light with a certain linear polarization, or at least exhibit very high losses for the other polarization directions. Such fibers can be realized with different design principles. For example, one may use an elliptical core in a design, making the waveguide leaky for one of the polarization directions. Other techniques can be applied in photonic crystal fibers (p. 55).

Overview on Fiber Nonlinearities

At sufficiently low optical intensities, light propagation is linear. In this regime, doubling the input power into a fiber will simply double the output power and not change anything else. More generally, the combination of different inputs leads to outputs where the complex amplitudes of all input contributions are simply added. The same holds for the electric polarization of the medium.

At higher optical intensities, nonlinearities of various kinds can occur, due to a nonlinear dependence of the electric polarization on the electric field:

- **Parametric nonlinearities** are associated with the instantaneous third-order nonlinearity, as described with the $\chi^{(3)}$ tensor of the medium. Here, the material's electric polarization contains a component that is proportional to the third power of the electric field. This leads to phenomena like **self-phase modulation**, **cross-phase modulation**, **four-wave mixing**, **self-focusing**, and **parametric amplification**.
- The imaginary part of the $\chi^{(3)}$ tensor is related to **two-photon absorption**, but this effect is usually not relevant in fibers.
- The delayed (non-instantaneous) nonlinear polarization related to the imaginary part of the $\chi^{(3)}$ tensor leads to **spontaneous and stimulated Raman scattering** and **Brillouin scattering**.
- When glass fibers are “poled” with a strong electric field, they can also develop a $\chi^{(2)}$ nonlinearity, which allows for **frequency doubling**, for example.

Some other effects can also lead to a kind of nonlinear response: saturation phenomena in active fibers (p. 74) and mode deformations via heating effects.

Effects of the Kerr Nonlinearity

The simplest kind of nonlinearity in fibers is the instantaneous third-order nonlinearity, acting on a single light field. Here, the third-order polarization effectively modifies the phase delay per unit length in proportion to the optical power (**Kerr effect**). For not-too-short optical pulses, this can be described simply as a nonlinear change of the refractive index:

$$\Delta n = n_2 I$$

where n_2 is the nonlinear index of the material and I is the optical intensity. For silica, $n_2 \approx 2.7 \times 10^{-20} \text{ m}^2/\text{W}$, which is a relatively small value compared with those of other glasses or crystalline materials.

The consequences of the Kerr effect in a fiber are:

- The phase delay for the light depends on its intensity. This is called **self-phase modulation (SPM)**. Its effects are discussed on the following page.
- The transverse refractive index profile is modified. This can affect the shape of the transverse intensity distribution. Such effects are usually rather weak in fibers. For very high intensities, however, they can lead to critical **self-focusing** (p. 85) and subsequently to damage of the fiber.

For very short and broadband pulses, the above description of the Kerr effect as a simple change of refractive index is not accurate. A more complete description includes the additional effect of **self-steepening**. This effect reduces the velocity with which the peak of the pulse propagates, and thus leads to an increasing slope of the trailing part of the pulse. This effect is relevant, e.g., for supercontinuum generation.

Self-Phase Modulation

Self-phase modulation (SPM) means that the phase delay for an optical beam, propagating through a fiber, for example, depends on the optical power of the same beam. If different beams (or different spectral portions of one beam) interact with each other based on that non-linearity, it is called cross-phase modulation (p. 43).

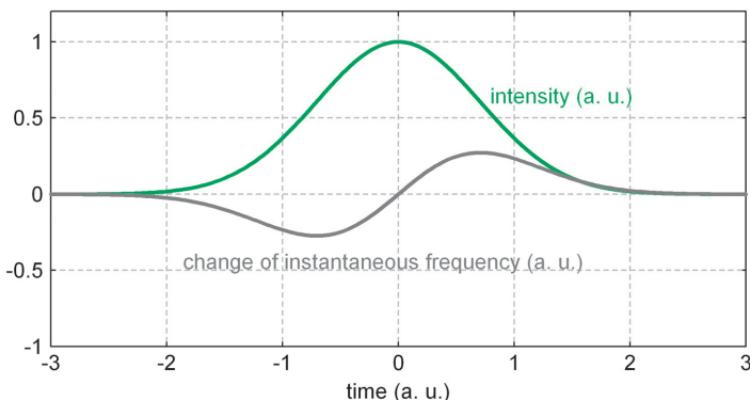
For calculating the phase shift due to SPM in some length L of fiber, one can use the equation

$$\varphi_{\text{nl}} = n_2 \frac{P}{A_{\text{eff}}} \frac{2\pi}{\lambda} L .$$

An effective n_2 can be used, including contributions from the core and the cladding.

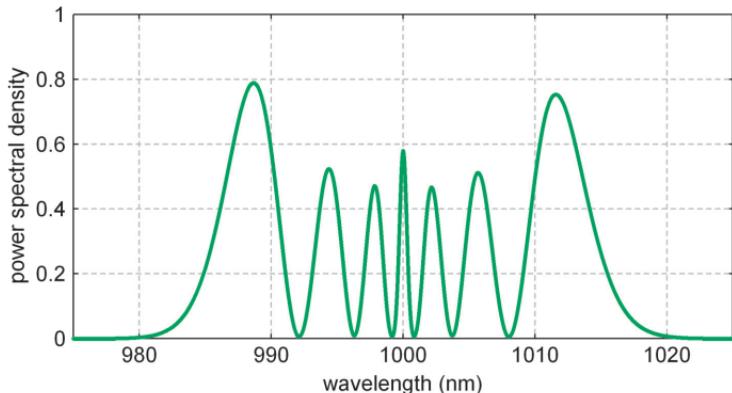
Typical consequences of SPM are:

- If SPM is dominating over other effects, an initially unchirped pulse will develop some chirp (temporally varying instantaneous frequency). The graph below illustrates the shape of such a frequency chirp. The frequency change is highest where the intensity changes most rapidly.



Self-Phase Modulation (cont.)

- If SPM effects are strong, a pulse will be spectrally broadened. Typically, if SPM is the dominating effect, the spectrum develops strong wiggles as shown in the figure below.



The spectral broadening effect may be used for nonlinear pulse compression (p. 40).

- Additional chromatic dispersion or an initial pulse chirp can strongly modify that behavior. For example, SPM in combination with anomalous dispersion can lead to soliton effects (p. 37), and SPM acting on a down-chirped pulse may reduce its spectral bandwidth. SPM in fibers with normal dispersion can lead to **self-similar parabolic pulse propagation (similariton pulses)**, where the approximately parabolic pulse shape remains, but the temporal and spectral width increases. See also p. 40 for the application in pulse compression.
- In a mode-locked fiber laser (p. 94), SPM can strongly influence the pulse formation process. It may be useful in the context of soliton pulse shaping, but it often effectively limits the achievable pulse energy and pulse duration.

Numbers on Fiber Nonlinearities

The phase shift due to SPM in a fiber can be written as

$$\varphi_{\text{nl}} = \gamma PL \quad \text{with} \quad \gamma = \frac{2\pi n_2}{\lambda A_{\text{eff}}}.$$

when the effective mode area is defined as on p. 12.

The nonlinear coefficient γ mostly depends on the fiber properties and less on the wavelength. Some example cases are:

- A standard single-mode fiber with a mode area of $85 \mu\text{m}^2$ at 1550 nm has a γ value of $\approx 1.3 \text{ mrad/W}\cdot\text{m}$. This means that a power level of 1 kW over 1 m of fiber generates a significant nonlinear phase shift of 1.3 rad. Because ultrashort pulse fiber amplifiers easily generate peak powers of many kilowatts and can be several meters long, strong nonlinear phase shifts can occur. Therefore, chirped-pulse amplification (with strongly stretched pulses) is required for high pulse energies.
- Some photonic crystal fibers (p. 55) have small mode areas of the order of $10 \mu\text{m}^2$, leading to γ values of $> 10 \text{ mrad/W}\cdot\text{m}$ in the visible or near-infrared spectral range. Strong self-phase modulation occurs even for sub-kW peak powers in less than a meter of fiber. Further increased nonlinearities occur in soft-glass fibers, where the material nonlinearity can be an order of magnitude larger.
- Large mode area fibers with mode areas of thousands of μm^2 can have γ values well below $0.1 \text{ mrad/W}\cdot\text{m}$. Even much smaller values than that are obtained for hollow-core fibers, where the light has little overlap with the glass.

Soliton Pulses

Under certain conditions, the effects of chromatic dispersion and the Kerr nonlinearity in a fiber can exactly cancel each other, such that the pulses stay unchanged during propagation. This situation can arise when the following conditions are fulfilled:

- The chromatic dispersion is anomalous (assuming a positive nonlinear index) and there is not much higher-order dispersion.
- The pulse is an unchirped sech²-shaped pulse:

$$P(t) = P_p \operatorname{sech}^2(t / \tau) = \frac{P_p}{\cosh^2(t / \tau)},$$

where τ is the FWHM pulse duration divided by 1.76. The graph on the next page shows the shape of such a pulse.

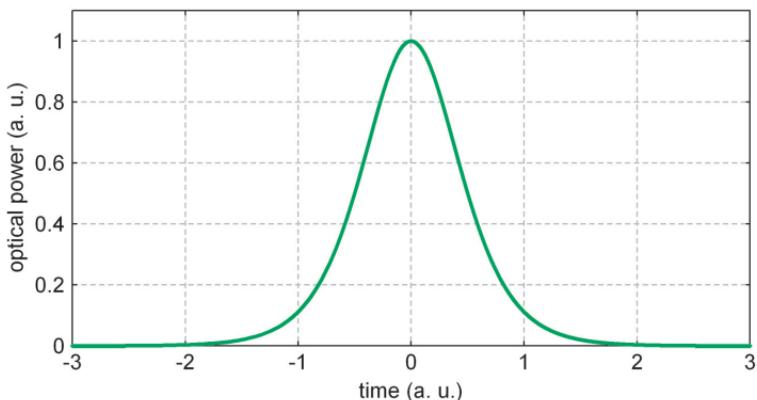
- The pulse duration and the pulse energy E_p are related to each other via

$$E_p = \frac{2|\beta_2|}{|\gamma|\tau},$$

where β_2 is the group delay dispersion per unit length and γ is the nonlinear phase change per unit length and per watt of optical power.

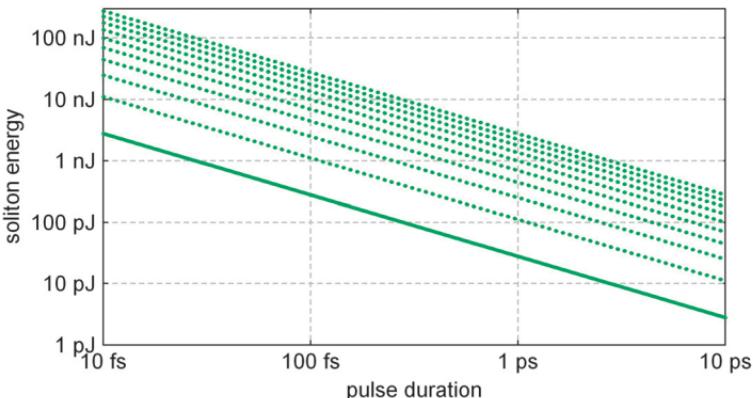
Such solitons are remarkably stable. If a pulse with approximately the soliton energy but a different (e.g., Gaussian) temporal shape is launched into a fiber, much of its energy is transferred into a perfect soliton, and some of the energy is lost in the form of a weak background, which is broadened more and more by the chromatic dispersion. Solitons also reconstitute themselves after disturbances such as sudden energy losses.

Soliton Pulses (cont.)



Apart from such **fundamental solitons**, there are higher-order solitons, starting with a j^2 times higher energy (where j is an integer). Here, the pulse shape is not constant, but is periodically reproduced. **Higher-order solitons** are not always stable to perturbation; they may, e.g., decay into several fundamental solitons.

The graph below shows pulse energies for fundamental and higher-order solitons as a function of pulse duration for some single-mode silica fiber with $80 \mu\text{m}^2$ mode area.



Fundamental solitons are important for soliton fiber lasers (p. 94) and for long-range optical fiber communications.

Linear Pulse Compression

Optical fibers can be used in various ways for **pulse compression**, i.e., for reducing the duration of pulses.

Linear compression techniques are based purely on the chromatic dispersion of fibers. They are applied to pulses that are initially chirped, i.e., not bandwidth-limited. A reduction of pulse duration results from the removal of the chirp, whereas the pulse bandwidth stays more or less unchanged. Normal chromatic dispersion can compensate a down-chirp, whereas anomalous dispersion may remove an up-chirp, but note that higher-order dispersion may also have to be considered.

There are different fiber-based implementations of this technique:

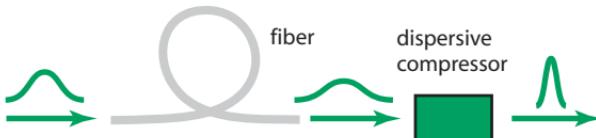
- For a wide range of wavelengths, fibers with either normal or anomalous chromatic dispersion are available. (For anomalous dispersion at relatively short wavelengths, for example, in the visible spectral region, photonic crystal designs are required.) One may, however, require relatively long lengths of fibers. Strong nonlinear effects, pulse distortion or prohibition of compression may then be avoided only for rather low peak power levels. Large mode area fibers can somewhat mitigate this problem, but their chromatic dispersion can hardly be tailored via the fiber design.
- Much stronger group delay dispersion within a short length can be obtained with **fiber Bragg gratings** (p. 70). Accordingly, shorter fibers can be used, and higher peak powers are possible, although nonlinear self-focusing may set a limit to that. Additionally, the grating design gives more freedom for tailoring the higher-order dispersion.

Nonlinear Pulse Compression

There are also **nonlinear compression techniques**, where typically the Kerr nonlinearity is used for increasing the spectral width, and a suitable amount of chromatic dispersion (inside or outside the nonlinear device) removes the pulse chirp, thus minimizing the pulse duration.

Various variants of this technique can be implemented with fibers:

- Pulses that are originally unchirped can be spectrally broadened in a normally dispersive optical fiber and then dispersively compressed in a fiber with anomalous dispersion or in some other optical element, such as a pair of diffraction gratings.



The useful fiber length is limited by the temporal pulse broadening, which leads to a reduction in peak power. Substantial pulse compression requires a sufficiently high peak power of the input pulses.

Although the amount of anomalous dispersion of the pulse compressor needs to be chosen correctly, the pulse parameters are not particularly critical for that technique.

- A variant of that technique for high-intensity femtosecond pulses is based on spectral broadening in a **gas-filled hollow fiber**. Here, most of the optical power propagates in the gas, where self-phase modulation occurs. Despite the low nonlinearity of gases, a moderate length of hollow fiber is sufficient due to the very high peak intensity.

Nonlinear Pulse Compression (cont.)

- Pulse compression is also possible with a single fiber with anomalous dispersion. The most common variant is **higher-order soliton compression**, where a pulse with an energy far above the fundamental soliton energy is injected into the fiber. After a certain propagation distance, a strongly compressed pulse can be obtained, but the choice of propagation distance can be critical.



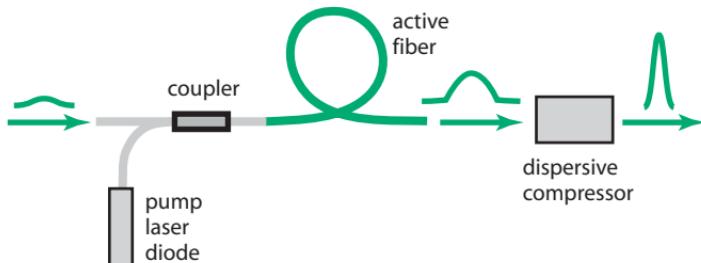
For deviations from the optimal fiber length or pulse energy, strong pulse distortions can result. The pulse energy can be roughly one to two orders of magnitude above that of a fundamental soliton. Higher compression ratios imply a more critical adjustment of parameters.

- Another variant requiring only a fiber is **adiabatic soliton compression**. Here, a soliton pulse is compressed during propagation in a fiber where the anomalous dispersion becomes weaker and weaker along the propagation direction. Alternatively, the pulse energy can be increased by amplification in a doped fiber with constant dispersion properties. If the dispersion (or pulse energy) varies sufficiently slowly, the soliton will adiabatically adapt to the changing conditions by continuously reducing its duration.

The pulse quality can be very high with adiabatic soliton compression. The pulse energy, however, is fairly limited due to the small soliton pulse energies of typical fibers. Also, a very long length of fiber may be required if the input pulses are not rather short already. Therefore, initial pulse durations below 1 ps are desirable.

Nonlinear Pulse Compression (cont.)

- In a fiber amplifier with normal dispersion, one may exploit **self-similar parabolic pulse evolution**. Here, the nonlinearity, dispersion, and laser gain act together such that the pulse duration and spectral width increase together with the pulse energy, but the parabolic pulse shape is preserved. The input pulses do not need to be parabolic pulses, as the parabolic shape is automatically more and more approximated during propagation.



The parameters of the input pulses are fairly uncritical, as the pulses automatically evolve towards the asymptotic solution. High pulse energies (far above typical soliton pulse energies) are possible. The resulting chirp is linear, which makes it relatively easy to obtain strong temporal compression in a subsequent dispersive optical element, such as a pair of diffraction gratings.

Which of the described techniques is most appropriate depends very much on the circumstances. The most important aspects are the initial and final pulse duration and the pulse energy. Other aspects to consider are the wavelength regime and the required pulse quality, including possible pedestals in the temporal pulse shape.

In many cases, numerical pulse propagation modeling is very useful for understanding the limitations and optimizing the parameters of a pulse compressor setup.

Cross-Phase Modulation

If two beams at different wavelengths are sent simultaneously through a fiber, the third-order nonlinearity can create a nonlinear phase delay for beam 1 in proportion to the intensity of beam 1, and vice versa. This is called **cross-phase modulation (XPM)**. If both beams are linearly polarized in the same direction, the phase change for beam 2 is twice as large as expected by a naïve use of the equation on page 34:

$$\Delta n^{(1)} = 2n_2 I^{(2)}.$$

For cross-polarized beams, the factor 2 must be replaced by 2/3.

Both self-phase modulation and cross-phase modulation are correctly described with a propagation equation for the complex amplitude of the form

$$\frac{\partial}{\partial z} A(z, t) = i\gamma A(z, t) |A(z, t)|^2,$$

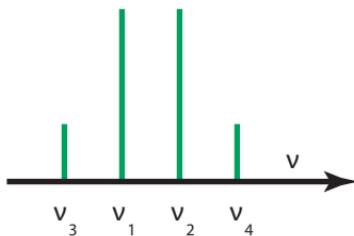
assuming that z is the coordinate for the propagation direction, $A(z, t)$ describes all of the propagating light, and the coefficient γ depends on n_2 and the normalization of the amplitudes. Dispersive (and other) effects could also be introduced in the equation, leading to a so-called **nonlinear Schrödinger equation**.

For broadband optical fields with complicated structures, the distinction between self-phase modulation and cross-phase modulation breaks down, but the propagation equation as shown above can be used.

Cross-phase modulation can have various effects, e.g., enabling a nonlinear interaction between soliton pulses with different center wavelengths when they cross in a fiber. In optical fiber communications, XPM can introduce unwanted channel cross-talk.

Four-Wave Mixing

Four-wave mixing (FWM) can arise from the third-order optical nonlinearity when light components with different optical frequencies overlap in a fiber. Assuming just two optical frequencies v_1 and v_2 (with $v_2 > v_1$), four-wave mixing generates new frequency components at $v_3 = v_1 - (v_2 - v_1) = 2v_1 - v_2$ and $v_4 = v_2 + (v_2 - v_1) = 2v_2 - v_1$, as shown in the figure. If a wave at frequency v_3 or v_4 is already present, it can experience parametric amplification (p. 45). Such processes are also possible in a situation with partial degeneracy, where $v_2 = v_1$.



Four-wave mixing is a phase-sensitive process. Its effect can coherently accumulate over large distances in the fiber only if it is phase-matched, i.e., if the following condition is fulfilled:

$$k_1 + k_2 = k_3 + k_4.$$

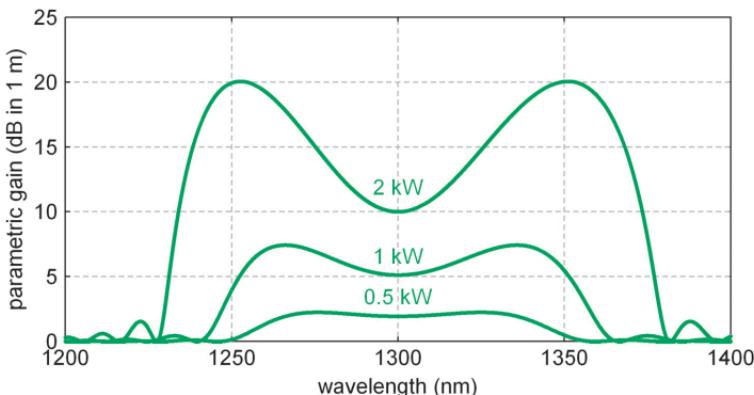
Therefore, the effect of FWM processes can strongly depend on the chromatic dispersion properties of the fiber (p. 24) and the involved wavelengths. Dispersion engineering can be used to maximize or suppress such effects.

Four-wave mixing in fibers is relevant in many situations. An example is supercontinuum generation, where four-wave mixing contributes to the spectral broadening, particularly in the regime of picosecond pulse durations. Detrimental FWM processes can occur in optical fiber communications with wavelength division multiplexing, where FWM leads to channel cross-talk.

Parametric Amplification

Parametric amplification can occur, e.g., when a strong pump wave at the frequency v_1 propagates in a fiber together with a signal input at the frequency v_3 . (We consider the degenerate case with $v_2 = v_1$.) The signal is then amplified, and simultaneously an “idler” wave at the frequency $v_4 = v_1 + (v_1 - v_3) = 2v_1 - v_3$ is generated. The signal frequency can be above or below the pump frequency v_1 .

The interaction is somewhat complicated because the optical phases of signal and idler are influenced both via cross-phase modulation (XPM) and the chromatic dispersion of the fiber. (For strong signals, self-phase modulation also occurs.) Amplification is obtained only within some wavelength range around the pump wavelength, which can be fairly wide when the chromatic dispersion is weak. The highest gain occurs for a signal wavelength where phase matching is obtained by mutual cancelation of XPM and dispersion effects. This is possible only for anomalous dispersion. The graph below shows the gain spectra in 1 m of a fiber with a group velocity dispersion of $-2000 \text{ fs}^2/\text{m}$ for different pump powers.



Parametric amplification can be used for low-noise parametric amplifiers or for parametric oscillators emitting nanosecond or even ultrashort pulses.

Raman Scattering

Raman scattering is a nonlinear process that involves optical phonons, i.e., high-frequency lattice vibrations (sound waves) in the glass.

For some monochromatic pump input, **spontaneous Raman scattering** can occur, where some of the pump photons are converted into lower-energy (Raman-shifted) photons, and the corresponding part of the optical input energy is transferred to the lattice vibrations. The possible energy (or frequency) offsets are determined by the vibration spectrum of the material.

If some longer-wavelength signal is injected together with the pump, and the frequency difference fits some part of the vibration spectrum, the signal can be amplified via **stimulated Raman scattering**. Here, the growth rate of the signal intensity I_s is proportional to the existing signal intensity and to the pump intensity I_p :

$$\frac{\partial}{\partial z} I_s = g_R I_p I_s$$

where g_R is the Raman gain coefficient (dependent on the material and the frequency offset) and z is the coordinate along the beam direction. As each added signal photon implies the loss of one pump photon, the pump intensity is reduced:

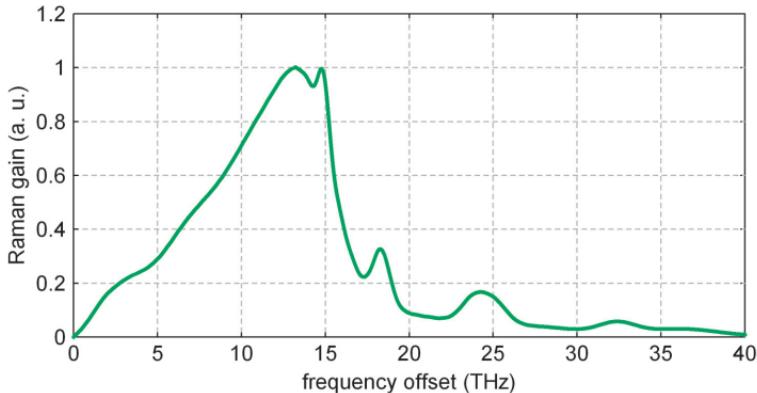
$$\frac{\partial}{\partial z} I_p = -g_R \frac{\lambda_s}{\lambda_p} I_p I_s$$

where the ratio of wavelengths takes into account the difference of photon energies.

Raman amplification works in essentially the same way with a counter-propagating pump wave as it does with a co-propagating pump, with the exception that the minus sign must be removed in the equation for the pump intensity.

Raman Scattering (cont.)

For silica glass, the Raman gain coefficient is $\approx 10^{-13}$ m/W for a frequency offset of ≈ 13 THz, and smaller for other offsets (see the figure). The gain bandwidth amounts to several THz. Certain core dopants such as germania (GeO_2) affect both the peak gain and the shape of the gain spectrum.



For ultrashort pulses and broadband signals, the simple equations of the previous page are not appropriate. Instead, one can set up a more complicated differential equation involving a Raman response function.

Stimulated Raman scattering in fibers is mainly used in low-noise Raman amplifiers for telecom signals and in Raman fiber lasers, allowing conversion of optical power to somewhat longer wavelengths. The transmission fiber itself may be used for a **distributed Raman amplifier**, where amplification occurs over a length of tens of kilometers.

Unwanted Raman gain can occur in fiber amplifiers for short and ultrashort pulses. If the Raman gain exceeds roughly 70 dB, it can shift a significant part of the signal power to wavelengths outside the amplification bandwidth. That situation arises, for example, when a beam with 16 W propagates through a 1-km-long low-loss single-mode fiber with a mode area of $100 \mu\text{m}^2$.

Brillouin Scattering

Brillouin scattering is in principle very similar to Raman scattering, but it involves acoustic rather than optical phonons of the material in which light propagates. There are important differences to Raman scattering:

- The involved optical frequency shifts are much smaller—typically, of the order of 10–20 GHz for silica fibers, which is three orders of magnitude less than for Raman scattering.
- The bandwidth of the gain resulting from stimulated Brillouin scattering is much smaller—of the order of 50–100 MHz for silica fiber, as compared to many THz for Raman scattering.
- The corresponding gain coefficient is much larger than for Raman scattering: for silica, it is $\approx 5 \cdot 10^{-11} \text{ m/W}$ at the optimum frequency shift.
- Due to phase-matching details, a pump wave can generate Brillouin gain only for a counterpropagating signal.

Due to the much higher gain coefficient, **stimulated Brillouin scattering** (SBS) dominates for narrowband pump waves. The small gain bandwidth, however, implies that the Brillouin gain is reduced for larger optical bandwidths, where gain contributions from different pump wavelength components appear at different wavelengths. In such cases, Raman scattering can dominate.

Stimulated Brillouin scattering (SBS) is applied in Brillouin fiber lasers, which can have an emission linewidth well below that of the (single-frequency) pump laser. In other situations, SBS can be a strongly detrimental effect. For example, it tends to limit the performance of high-power fiber amplifiers for single-frequency lasers.

Wavelength Regions for Data Transmission

Various spectral regions (called **telecom windows**) can be employed for optical data transmission via glass fibers:

- The **first telecom window** at 800–900 nm offers the advantage that common GaAs/AlGaAs-based laser diodes, light-emitting diodes (LEDs), and silicon photodiodes can be used in transmitters and receivers. However, fibers exhibit relatively high losses in this region, and good fiber amplifiers are not available. Therefore, the first telecom window is suitable only for short-distance transmission.
- In the **second telecom window**, with wavelengths around 1.3 μm, the losses of silica fibers are much lower, and the chromatic dispersion is very weak, resulting in low signal distortion. Early long-haul transmission systems used that window, but the performance of fiber amplifiers for 1.3 μm is not as good as that of 1.5-μm amplifiers.
- The **third telecom window**, with wavelengths around 1.5 μm, is now preferred for long-haul transmission. The losses of silica fibers are lowest in this region, and high-performance erbium-doped fiber amplifiers are available. Fiber dispersion is usually anomalous but can be tailored with great flexibility.

The third telecom window consists of these bands:

Band	Description	Wavelength range
O	original	1260–1360 nm
E	extended	1360–1460 nm
S	short wavelengths	1460–1530 nm
C	conventional	1530–1565 nm
L	long wavelengths	1565–1625 nm
U	ultralong wavelengths	1625–1675 nm

Optimization of Telecom Fibers

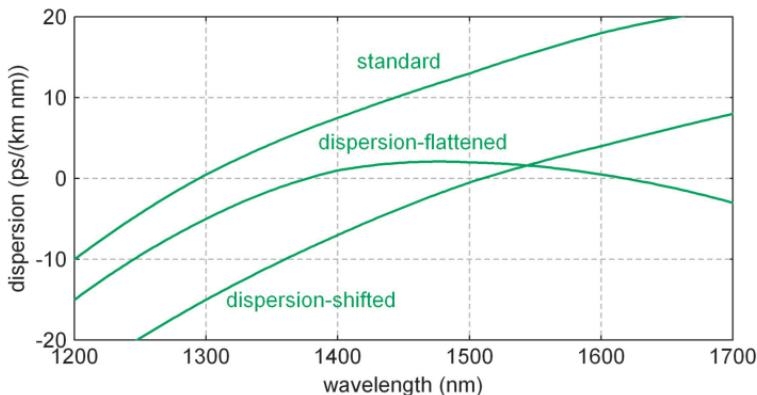
Fibers for data transmission are optimized in various respects, but the optimization criteria depend very much on the application:

- **Single-mode fibers** are useful for medium to long distances, whereas **multimode fibers** have practical advantages for short distances. In particular, it is easier to launch light into multimode fibers, and the alignment tolerances are much less critical. Plastic optical fibers (p. 20) typically offer a lower performance, but allow for cheaper installations.
- Minimizing **propagation losses** (p. 21) is essential for long-haul transmission, which can, in that case, reach the level of 0.2 dB/km, at least in the C band (around 1550 nm). When optimized, even 100 km-long fiber spans then exhibit only moderate power losses.
- For single-mode fibers, an **effective mode area** close to that of common fibers helps to avoid excessive splice losses in connections with other fibers. Somewhat larger mode areas can help to reduce nonlinear effects. For multimode fibers, the **core sizes** of different fibers must be matched to each other.
- For fiber-to-the-home (FFTH) applications, fibers should have a high **tolerance for tight bending**.
- **Chromatic dispersion** in the wavelength region of interest can be an important issue, and is discussed on the following page.
- For very high data rates, weak **polarization mode dispersion** (variations of group velocity with the polarization) can be another criterion (see p. 54).

Apart from the fiber itself, the protective material around it also must be optimized corresponding to the conditions of use.

Considerations on Chromatic Dispersion

Standard single-mode fibers exhibit rather weak chromatic dispersion in the 1.3- μm region, but significant anomalous dispersion in the 1.5- μm region. By modifying the refractive index profile, one can obtain **dispersion-shifted fibers**, where the zero dispersion wavelength is shifted to the 1.5- μm region.



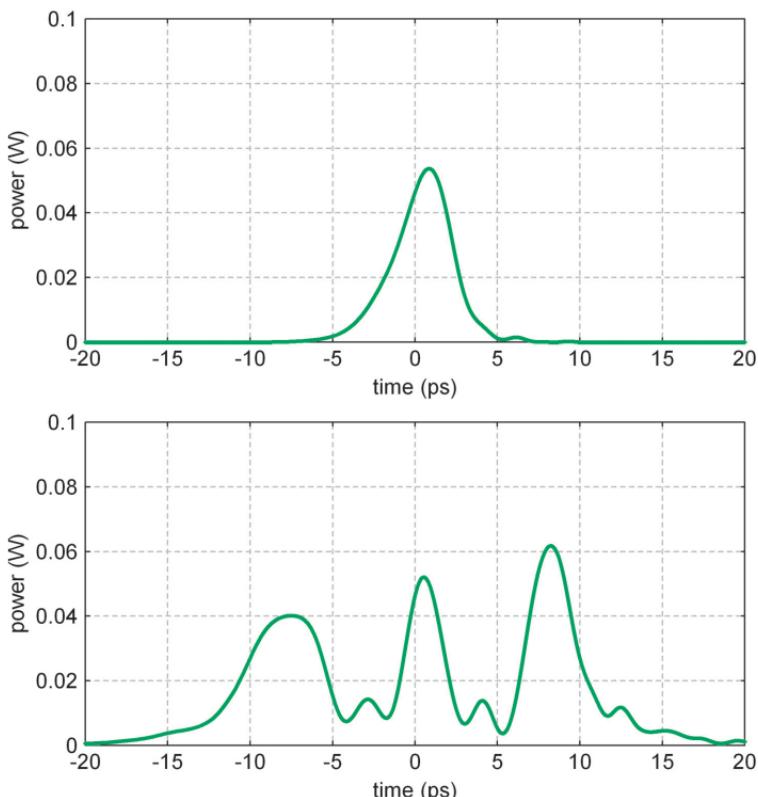
Close-to-zero dispersion is not necessarily the optimum. Anomalous dispersion allows the use of soliton pulse propagation (p. 37). Even when soliton effects are not exploited, nonlinear effects can be better suppressed with a somewhat dispersive fiber, leading to longer signal pulses, plus some short length of dispersion-compensating fiber for recompression before photodetection. Particularly for multi-channel data transmission systems (using wavelength division multiplexing), some amount of chromatic dispersion for reducing channel cross-talk can be vital.

In many cases, it is desirable to minimize the **dispersion slope**, i.e., essentially to obtain small dispersion of third and higher order. This means that the group delay dispersion does not vary much within the wavelength region of interest. Fibers with substantially reduced dispersion slope, called **dispersion-flattened fibers**, can be realized by optimizing the refractive index profile.

Dispersion Compensation

In principle, any distortions of a pulse or a telecom signal arising from chromatic dispersion can be undone by applying dispersion of the opposite sign. This is called **dispersion compensation**.

For longer pulses (or slowly modulated signals), only second-order dispersion is important. For shorter pulses, however, dispersion of higher order should be addressed. Problems can arise, for example, when dispersion-shifted fibers (p. 51) with a substantial dispersion slope are used, and only dispersion of second order is compensated. The following diagrams show this effect for single and triple 2-ps pulses, respectively, after 50 km of a fiber. Significant signal distortions can arise from effects that have only a moderate influence on a single pulse.



Important Standards for Telecom Fibers

The table below gives an overview on important **standards for telecom fibers** as developed by the International Telecommunications Union (ITU) (see <http://www.itu.int/>):

Name	Title
G.650.1 (06/04)	Definitions and test methods for linear, deterministic attributes of single-mode fiber and cable
G.651 (02/98)	Characteristics of a 50/125 µm multimode graded-index optical fiber cable
G.651.1 (07/07)	Characteristics of a 50/125 µm multimode graded-index optical fiber cable for the optical access network (pre-published)
G.652 (06/05)	Characteristics of a single-mode optical fiber and cable
G.653 (12/06)	Characteristics of a dispersion-shifted single-mode optical fiber and cable
G.654 (12/06)	Characteristics of a cut-off shifted single-mode optical fiber and cable
G.655 (03/06)	Characteristics of a non-zero dispersion-shifted single-mode optical fiber and cable
G.656 (12/06)	Characteristics of a fiber and cable with non-zero dispersion for wideband optical transport
G.657 (12/06)	Characteristics of a bending loss insensitive single-mode optical fiber and cable for the access network

Polarization Mode Dispersion

Even fibers with rotationally symmetric design exhibit some random birefringence due to imperfections and bending. This **polarization mode dispersion (PMD)** leads not only to random changes of the polarization state of light, but also to pulse broadening. Even complete temporal separation of polarization components can occur, and such effects can limit the data rate of a telecom system.

The broadening (or splitting) occurs because the group delay of some fiber span depends on the input polarization. The difference of group delay between the two principal states of polarization is called the **differential group delay (DGD)**. It would be difficult to ensure that the input corresponds to a principal state of polarization, because the principal states and the polarization changes are generally wavelength-dependent, and they can also change with time, e.g., as a result of temperature changes. For broadband signals, PMD can introduce a pulse chirp similar to that which occurs due to chromatic dispersion. In that way, complicated pulse shape distortions can arise.

For fiber sections with a length of at most a few meters, the DGD evolves in proportion to the fiber length. For much longer lengths, the birefringence axis of the fiber changes randomly, and the r.m.s. value of the DGD scales only with the square root of the fiber length. Note, however, that the actual DGD can be strongly wavelength-dependent, and for some wavelengths, it can be well above the r.m.s. value. For such reasons, the average degree of pulse broadening in a telecom system by PMD should usually not be more than a few percent of the signal pulse duration.

The full description of PMD and its effects requires rather sophisticated mathematics, involving frequency-dependent Jones matrices and statistical methods.

Introduction to Photonic Crystal Fibers

Photonic crystal fibers (PCFs)⁴⁴ are optical fibers containing some kind of microstructure, typically an array of tiny air holes extending along the fiber axis. Such fibers are also called **microstructure fibers** or **holey fibers**.

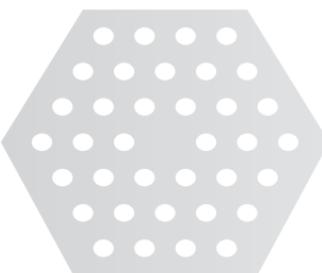
PCFs are typically glass fibers, in most cases consisting of undoped fused silica, and are fabricated by pulling from a structured preform in a furnace. Such preforms are usually made by stacking capillary tubes and/or solid tubes that are inserted into a larger tube. A preform may first be drawn into a cane with a diameter of, e.g., 1 mm, and subsequently to a fiber with a diameter of 125 μm . As an alternative, some PCFs (particularly those consisting of soft glasses or polymers) are fabricated with extrusion techniques.

Optical guidance (the waveguide effect) in a PCF typically results not from using doped materials with a higher refractive index for the core, but rather from the effect of air holes. Different guiding mechanisms can be used, as described on the following pages. Depending on the design, very different optical properties can be achieved:

- Single-mode guidance can be achieved in very wide wavelength regions, and with extremely large or small values of the numerical aperture and the effective mode area. In other cases, guidance occurs only in fairly limited wavelength regions.
 - PCFs can exhibit very strong birefringence or single-polarization guidance.
 - The chromatic dispersion properties can be tailored in wide ranges.
 - Some designs allow for guiding light into a hollow core, so that most of the power propagates in air rather than in glass. The air holes may also be filled with other gases or with liquids.
-

Guidance According to Average Refractive Index

A frequently used PCF design contains a triangular lattice of air holes, with one missing hole at the center. (The figure shows only the core region.) Here, the guidance can be understood by considering that the core is solid, while the cladding has a reduced average refractive index due to the air holes. The larger phase delay in the center can compensate the natural tendency of light to diverge, and thus stabilizes one or several guided modes, depending on the hole size and spacing, and also on the wavelength.



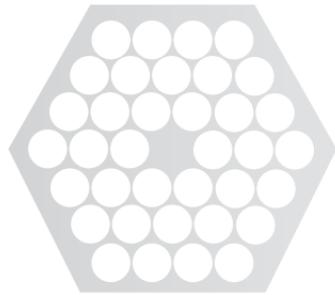
For long wavelengths, the fiber modes simply “see” some average cladding index, whereas modes at shorter wavelengths can adjust their shape such that the intensity distribution somewhat avoids the holes. Therefore, the effective index difference (thus the effective numerical aperture) can be smaller for shorter wavelengths, reducing the number of guided modes at short wavelengths. If the air holes are sufficiently small, such fibers can be **endlessly single-mode**: they exhibit single-mode guidance in a wide wavelength range.

The triangular lattice is often used, but not essential for this type of guidance. It is possible to use other types of lattices, even random hole arrangements, and of course to vary parameters like the hole size and spacing. Such modifications can affect the number of guided modes, the effective mode area, the minimum bend radius and the chromatic dispersion. One can also obtain birefringence.

For active fibers (p. 74), the central region can be made from rare-earth-doped glass. The dopant can be pumped with pump light injected into the fiber core. Alternatively, a pump cladding around the core can be obtained with additional structures (See **double-clad fibers**, p. 77).

Fibers with Large Air Holes

If the air holes in the triangular lattice (see the previous page) are enlarged, this leads to a structure where the core is suspended only by narrow silica strands. Due to the high index contrast between silica and air, the guided mode is strongly confined in the silica, even if the core is made rather small. For the calculation of the modes, it is essential to use a full vectorial model, as a scalar approximation (considering only the electric and magnetic field in a single direction) fails. The guiding properties of such fibers are not too different from those of a cylindrical piece of silica with a diameter approximating that of the core structure.



Particularly for small core sizes, the chromatic dispersion is strongly influenced by the contribution of waveguide dispersion. Depending on the hole size and spacing, unusual chromatic dispersion profiles can be obtained. For example, it is possible to obtain a broad wavelength region (possibly extending well into the visible spectral region) where the chromatic dispersion is anomalous. This allows, e.g., soliton propagation at visible wavelengths. Also, such fibers can be used to introduce tailored amounts of dispersion (including higher-order dispersion) into optical systems.

Such fibers are also often used for **supercontinuum generation**. Strong nonlinear broadening of optical spectra can be obtained, particularly when the injected light has a wavelength not far from a zero-dispersion wavelength. Here, different spectral components can have similar group velocities and therefore propagate over longer distances without losing the temporal overlap. The nonlinear interaction is also enhanced by the small mode area.

Photonic Bandgap Fibers

Photonic crystal fibers can also be designed such that guidance is based on a 2D photonic bandgap. Here, the cladding is made such that there are no propagating modes in the wavelength region of interest, i.e., the transverse wavevector component must have an imaginary component, so that the amplitude decays exponentially. As a result, light in the core structure cannot escape into the cladding, even though its intensity distribution may somewhat penetrate the cladding. The core can even be hollow, as in the example shown with seven missing tubes.



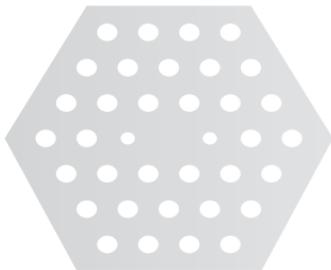
Such **hollow-core photonic bandgap fibers** (also called **air-guiding fibers**) are interesting for applications where a minimum overlap of the light with the glass structure is wanted, as this minimizes any nonlinearities and may allow the propagation of high optical powers. Since chromatic dispersion can be obtained despite a small overlap with the glass, such fibers may become useful for pulse compressors.

Typically, photonic bandgap fibers exhibit guidance only in some isolated spectral regions, between which no guided modes are supported. This can be advantageous, if some nonlinear mixing products (resulting from Raman scattering, for example) should be suppressed.

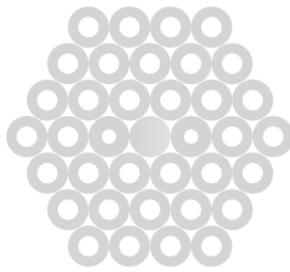
The details of the cladding structure are essential for the guidance properties of such fibers. Increased propagation losses can result from surface modes being located around the core-cladding interface. Rather low-loss photonic bandgap fibers have been obtained by making the silica parts rather thin.

Birefringent PCFs

It is easy to design PCF structures that exhibit strong birefringence. The figures to the right show examples where two smaller holes are used on the left and right side of the core. Alternatively, one may use larger holes or missing holes. Similar possibilities exist for photonic bandgap fibers.



It is also possible to integrate stress rods made of a different glass, as in conventional-type polarization-maintaining fibers (PANDA fibers).



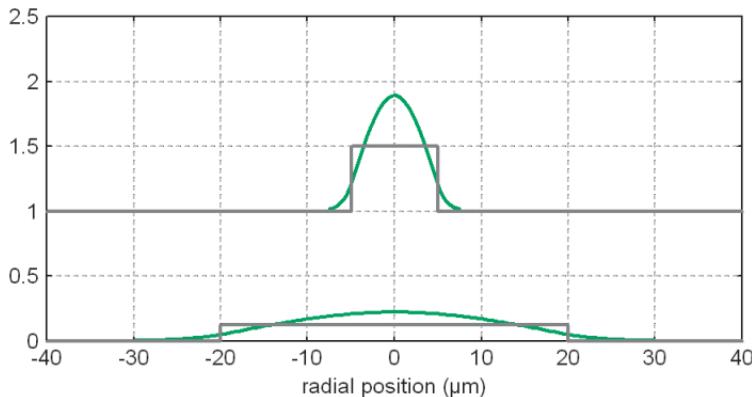
The degree of birefringence achievable with PCF designs is much larger than for standard solid fibers: the polarization beat length can be a few millimeters or even less. Therefore, one can strongly suppress the coupling between different polarization modes. This is useful particularly for **polarization-maintaining fibers** (p. 30). Of course, such features can also be integrated into double-clad fibers (p. 77) for high-power amplifiers and lasers.

Strong design asymmetries can even lead to strongly polarization-dependent guidance properties. This allows the design of **single-polarization fibers**, which guide only light with one polarization direction. One way to achieve this is to use a photonic bandgap fiber (p. 58) with a broken symmetry, so that the wavelength regions with guidance only partly overlap for the two polarization directions. Other designs do not rely on photonic bandgaps.

Large Mode Area Fibers

For various applications, it is important to have fibers that exhibit single-mode guidance but at the same time have a rather large effective mode area. For example, single-mode guidance is often needed for high-power fiber amplifiers (p. 85), because this helps to obtain a high beam quality of the output, but standard single-mode fibers would have a mode area that is too small, leading to strong nonlinear effects or even damage. A larger mode area (p. 12) helps to reduce optical intensities and thus nonlinear effects. In double-clad fibers (p. 77), it also helps to limit the area ratio of pump cladding and core, and thus to improve pump absorption and/or to reduce the fiber length.

Conceptually, the simplest design of a **large mode area fiber** is a step-index design with a rather large fiber core. For single-mode guidance, the refractive index difference and thus the numerical aperture must be very small. The figure below shows two index profiles (gray, with arbitrary units) for different mode sizes, but both with single-mode guidance.



For rather large mode areas ($>1000 \mu\text{m}^2$, for example), small refractive index inhomogeneities may have disturbing effects. Furthermore, the mode becomes very sensitive to bending the fiber as the guidance becomes very weak.

Other Solid-Core Fiber Designs

Several techniques have been developed for realizing fibers with larger mode areas than possible with a simple step-index design:

- One may use a fiber with a large core that supports a few guided modes, but avoid the excitation of higher-order modes.⁴⁶ This requires (a) launching primarily into the fundamental mode and (b) avoiding excessive mode coupling. Unfortunately, larger cores imply smaller differences in the propagation constant and thus stronger coupling to higher-order modes. To a limited extent, higher-order modes can be attenuated by strong bending of the fiber. For that purpose, one may also use a tapered region in the fiber.
- One may use a fiber supporting a larger number of modes and a high-order mode for propagation.⁵³ Conversion into that mode and back again to a nearly Gaussian mode can be done with a long-period fiber Bragg grating. The mode area can be rather large, but the intensity profile is strongly structured, with an intense peak at the center.
- There are **chirally coupled core fibers** where an additional core is helically wound around the central core.⁵⁵ The coupling to the helical core can be stronger for higher-order modes of a multimode central core, thus supporting single-mode operation of a multimode core.
- Another novel concept is that of the **gain-guided, index-antiguided single-mode fiber**.⁵⁰ Here, an active fiber becomes guiding only via the effect of gain guiding. Very large mode areas are possible, but a severe difficulty is that the pump light is not guided.

Photonic Crystal Fiber Designs

Photonic crystal fibers (p. 55) allow one to implement various techniques to obtain large mode areas:

- Simple PCF designs, as shown on p. 56, can also be used for larger mode areas. These, however, suffer from similar limitations as standard large mode area fibers.
- **Leakage channel fibers** may have only six air holes surrounding the core, i.e., strictly speaking, they do not contain a photonic “crystal” (a periodic structure).⁵⁴ The core does support a few higher-order modes, but these exhibit high losses due to leakage into the cladding, whereas the fundamental mode exhibits only very weak leakage. Mode areas well above $1000 \mu\text{m}^2$ are possible without excessive bend sensitivity. Further improved versions can contain an additional ring of air holes around the inner ring.
- Mechanical stress can be induced into a pattern like the one on p. 56 by using capillaries with different glass compositions, such that the stress leads to an approximately parabolic index region near the center. Guidance may occur by this index profile rather than by the presence of the holes.⁵⁷



Note also that hollow-core photonic bandgap fiber designs (p. 58) allow for reduction of the effective nonlinearity of a fiber without strongly increasing the mode area.

Tolerances for Low-Loss Fiber Joints

It is often necessary to connect two fibers so light can be transferred from one fiber to the other with low power losses. For that purpose, the fiber ends must be brought close together with good alignment of the fiber cores, and the fiber ends must be fixed in order to maintain that alignment. **Mechanical splices** are made with some stable holder and may be used for non-permanent connections. With **fiber connectors**, where each fiber end is embedded into a separate part, it is easier to make and release connections. The most stable (but permanent) connections, also exhibiting the smallest losses (on the order of 0.02 dB under good conditions), are made by **fusion splicing**, a process where the fiber ends are fused together, typically using an electric arc for heating.

While the optical power losses at the interface very much depend on the type and quality of the connection, they also depend on the type and other details of the fibers:

- For **multimode fibers**, low losses require that the core area and the numerical aperture of the output fiber be at least as large as those of the input fiber. If these parameters are not equal for the two fibers, the losses may depend on the direction of light propagation. Proper alignment of the cores is normally not difficult to achieve, since the core areas tend to be large.
 - For **single-mode fibers**, low losses require that the fiber modes have a high spatial overlap. This means that the shapes of the intensity profiles and the effective mode areas should be as similar as possible. Of course, the core positions need to be well matched, which can be difficult for small mode areas. The phase profiles of fiber modes are flat, so they are automatically matched, provided there is no angular misalignment. The larger the mode area, the more critical is the angular alignment. In any case, the losses do *not* depend on the propagation direction.
-

Tolerances for Low-Loss Fiber Joints (cont.)



If two single-mode fibers with approximately Gaussian mode profiles and different mode radii w_1 and w_2 are connected with a transverse offset Δx (see the figure) of the cores, the power transfer efficiency at the joint is

$$\eta = \frac{4w_1^2 w_2^2}{(w_1^2 + w_2^2)^2} \exp\left[-\frac{2(\Delta x)^2}{w_1^2 + w_2^2}\right].$$

The reduction in coupling efficiency for an **angular mismatch** $\Delta\theta$ can be estimated from

$$\eta = \exp\left[-\left(\frac{\pi \Delta\theta w}{\lambda\sqrt{2}}\right)^2\right],$$

assuming equal beam radii of both fibers and no additional air gap and transverse offset. This situation can occur, e.g., when the fiber ends are fused together after having been cut at slightly wrong angles.

For any fiber joint, an **air gap** between the fiber ends should be sufficiently narrow to avoid significant losses via Fresnel reflection. The width of such an air gap should be well below a quarter wavelength. The Fresnel reflections from both fiber ends then largely cancel each other by destructive interference. That can also occur for larger distances (integer multiples of $\lambda/2$), as long as the beam divergence is negligible, but such distances will be more difficult to stabilize, and the transmittivity becomes wavelength-dependent.

Launching Light into Single-Mode Fibers

In many applications, it is necessary to launch light from free space (often a laser beam) into a single-mode fiber. For a high coupling efficiency, one again requires a high overlap between the complex electric field distributions of the laser beam and the guided mode of the fiber. The wavefronts can be matched only if the fiber end is at the beam waist and the beam has a high beam quality (i.e., small wavefront distortions). Assuming that this condition is fulfilled, and both the laser beam and the fiber mode have nearly Gaussian profiles, we can use the equation

$$\eta = \frac{4w_0^2 w_f^2}{(w_0^2 + w_f^2)^2} \exp\left[-\frac{2(\Delta x)^2}{w_0^2 + w_f^2}\right] \left[1 - \left(\frac{n-1}{n+1}\right)^2\right].$$

Where w_0 is the beam waist radius of the laser beam, w_f is the mode radius of the fiber mode, Δx is the transverse offset, and n is the refractive index of the fiber core. The last factor accounts for the Fresnel reflection at the fiber end, assuming that it has no anti-reflection coating. It is also assumed that there is no angular mismatch. If there is an angular mismatch $\Delta\theta$ while the other errors are small, the efficiency can again be estimated from

$$\eta = \exp\left[-\left(\frac{\pi \Delta\theta w / \lambda}{\sqrt{2}}\right)^2\right] \left[1 - \left(\frac{n-1}{n+1}\right)^2\right].$$

Note that a larger mode area of the fiber makes it easier to minimize the effect of a transverse offset Δx , whereas the angular alignment becomes more critical.

For multimode fibers, the coupling is less critical. Essentially, most of the input light should correspond to some superposition of the guided modes of the fiber. It is not essential for the efficiency into which modes the light is launched.

Preparing Fiber Ends

Bare fiber ends can be obtained by **cleaving** (cutting) a fiber after removing any protective coating. Such coatings can normally be mechanically removed with certain tools. In some cases, one uses a solvent for that purpose. The cleaving process often works well when the fiber is bent after scratching its surface on one side with a diamond blade. There are fiber cleavers (cleaving machines) that allow for clamping the fiber into a well-defined position, to apply an adjustable amount of tension, and to trigger the cleaving process by touching the fiber end with a vibrating blade. For ordinary fiber materials (e.g., silica) and diameter, a cleaver with properly adjusted parameters should mostly produce fiber ends with a clean surface and an approximately normal cleave direction. The cleave quality should then typically be sufficient, e.g., for using the fiber in a connector, or for fusion splicing fibers. Some devices also allow to twist the fiber in order to obtain **angled cleaves**, where reflected light can leave the system rather than interfering with the main beams.



If the quality is critical, fiber ends must be inspected under a microscope and re-cleaved if the quality is not satisfactory. This is particularly important for non-standard fiber materials or fiber diameters.

In some cases, fiber ends must be **polished**. This is the case when a very flat surface and/or a well-defined (possibly non-normal) angular orientation is required, or for fibers where cleaving does not work well. Usually, the fiber is first fixed in a capillary tube to obtain a more stable part, and the whole tube is polished on a rotating plate with an abrasive.

It is also possible to apply **dielectric coatings** to fiber ends. These can be **anti-reflection coatings** or coatings for higher reflectivity in certain wavelength bands.

Fusion Splicing

The most stable and low-loss fiber joints can be obtained by **fusion splicing**. Essentially, the surfaces of two fiber ends are melted and joined (typically with a high-voltage electric discharge). Apart from equipment for removing fiber coatings, cleaving, and cleaning, a fusion-splicing apparatus is required. The typical steps to be performed are:

- Remove any coatings.
- Cleave the fibers with perpendicular angles and carefully clean the ends.
- Align the fiber ends precisely under a microscope, leaving only a small gap in between. In some cases, light throughput is monitored, using some light source and a photodetector.
- Fire the electric arc and push the fiber ends together.
- Check the quality of the obtained splice, ideally by measuring the transmission, since the process may not always work as expected.
- Protect the splice region through use of a heat shrink protector or a mechanical crimp protector.

Fairly low-loss splices with very small return loss may be reliably obtained under optimum conditions: standard fiber type, well chosen parameters of the splicer, and careful handling.

An alternative technique is to use mechanical splices. These need less expensive equipment, can be made in less time, and may be removed after use. The transition loss and return loss are higher, however, as is the cost per splice.

Fiber Connectors

Fiber connectors are mechanical parts that are attached to fiber ends in order to facilitate the process of making and releasing fiber connections. The ideal fiber connector would

- be cheap, compact, and easy to attach to the fiber end;
- guarantee a precise and stable attachment of fiber ends in order to achieve reliably low connection losses;
- effectively protect the fiber end while the connection is closed or released and when the fiber is handled while the connection is open;
- work with a wide range of fiber diameters and mode properties (single-mode or multimode), and possibly also with polarization-maintaining fibers (requiring an angular adjustment) and angle-polished fibers.

Note that there are also fiber cables that have protective layers with different diameters, requiring different techniques for preparing fiber ends.

Unfortunately, it is difficult to ideally fulfill all of these requirements. Therefore, there is a wide range of different fiber connector types with names such as FC, FC-APC, SC, ST and TOSLINK. Some are specifically designed for certain application areas, such as long-haul optical fiber communications or short-distance networks with plastic optical fibers.

Usually, the fiber is embedded in a **ferrule**, which may be made of ceramic material and can have a circular cross-section with a radius of, e.g., 2.5 mm, or a rectangular shape. A slightly curved top surface of the ferrule allows for obtaining a reliable physical contact point when the fibers are joined. Some designs contain additional features for angular orientation, strain relief, etc.

Fiber Couplers

Fiber couplers are devices for coupling light between different fibers. Typically, they are **directional couplers**, having one or more input fibers and one or more output fibers. Light injected into an input fiber will appear at one or several output fibers, but not (or only with a huge return loss) at other input fibers. The simplest device is a 2-by-2 coupler as shown below.



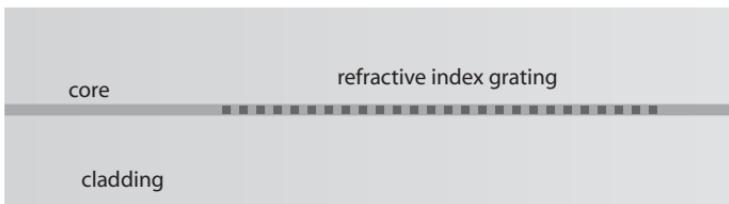
Typically, such couplers are made by fusing single-mode fibers together such that their cores are in close proximity over some length of fiber. Light guided in one fiber may then leak over to the other one. This is a coherent process, which is strongly wavelength-dependent, thus allowing to make **dichroic couplers** where two (or more) wavelengths are treated quite differently.

Some common cases are:

- A dichroic coupler may obtain light from two inputs with different wavelengths and feed it into the same output fiber. This is used, e.g., for injecting pump light into a single-mode fiber amplifier (p. 83).
- A coupler with a limited degree of coupling may serve as a **splitter** or **combiner** in an interferometer or as the output coupler of a fiber laser.
- There are **fiber splitters** with one input and many outputs, used, e.g., for distributing television signals.
- There are multimode pump couplers, combining two or more inputs at the same wavelength into one fiber. The output fiber must usually support a larger number of guided modes, e.g., by having a larger core.

Fiber Bragg Gratings

A **fiber Bragg grating (FBG)** is a piece of fiber with a refractive index modulation within its core.^{63, 64, 66, 72} The index modulation is typically periodic with a period well below 1 μm, or sometimes with a much longer period. The length of such a grating can vary between, e.g., 1 mm and several tens of centimeters.



An FBG with an index modulation period Λ can lead to strong back-reflection of light with a wavelength λ if the Bragg condition

$$\frac{2\pi}{\Lambda} = 2 \cdot \frac{2\pi n_{\text{eff}}}{\lambda} \Rightarrow \lambda = 2n_{\text{eff}}\Lambda$$

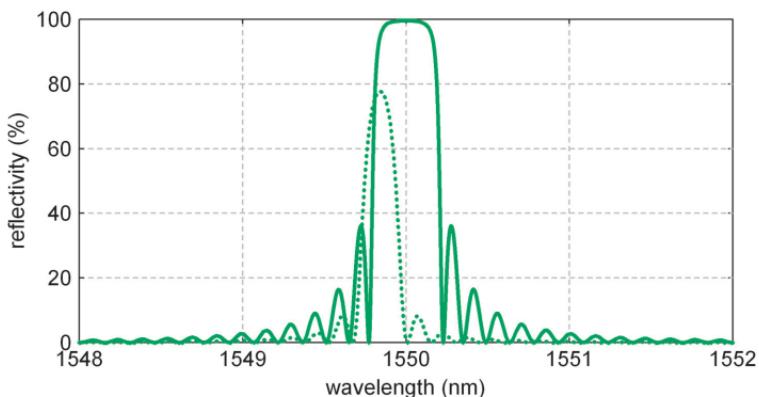
is fulfilled (at least approximately). Here, n_{eff} is the effective refractive index, which is related to the propagation constant β via

$$\beta = n_{\text{eff}} \frac{2\pi}{\lambda}.$$

Effectively, the FBG provides coupling between two counterpropagating optical modes with the same optical frequency. Similarly, an FBG may couple a guided mode to a cladding mode or a higher-order guided mode. If that mode propagates in approximately the same direction, there is only a small change of β value, so that the required modulation period Λ is much longer. One therefore requires a **long-period Bragg grating**. In some cases, short-period Bragg gratings cause unwanted losses by coupling to cladding modes.

Fiber Bragg Gratings (cont.)

The reflectivity of a fiber Bragg grating (or more generally, the coupling strength for a pair of modes) depends both on the amplitude of the refractive index modulation and on the length of the grating. The **reflection bandwidth** increases somewhat for increasing grating length, but is essentially limited by the refractive index contrast. Typical FBGs have a reflection bandwidth below 1 nm. The figure below shows an example of a 4.5 mm long FBG, where the index increase is $0.5 \cdot 10^{-3}$ (solid curve) or $0.2 \cdot 10^{-3}$ (dotted curve).



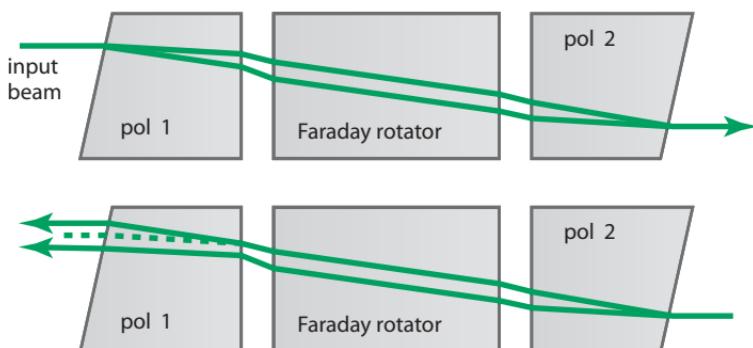
Such index gratings are usually written into a fiber by illuminating it with spatially structured ultraviolet light, obtained, e.g., by sending the output of an excimer laser into an interferometric arrangement.⁵⁹ The UV light causes a modification of the glass and thus a modification (typically an increase) of the refractive index depending on the local irradiation conditions. This process works best in photosensitive fiber—which has a suitable core composition—whereas some types of fiber are hardly suitable. It is also possible to write FBGs with strongly focused infrared beams consisting of ultrashort pulses.

Typical applications of FBGs are in optical filters (e.g., in telecom devices), end reflectors in fiber lasers, and fiber-optic sensors. In the latter case, the temperature and strain dependence of the Bragg condition is exploited.

Fiber-Coupled Faraday Isolators

A **Faraday isolator** is a device that acts like an optical diode: it transmits well in one direction while blocking light in the other direction. Such isolators are also available in fiber-coupled form, i.e., with input and output coupled to single-mode fibers.

In contrast to most bulk devices, fiber-coupled isolators are often polarization-insensitive, i.e., they work for any polarization direction of the input. (This is particularly important for telecom applications, which usually require polarization-independent components.) Input light is split into two polarization components, which travel through the isolator on different paths but are combined again at the end (see the upper part of the figure).



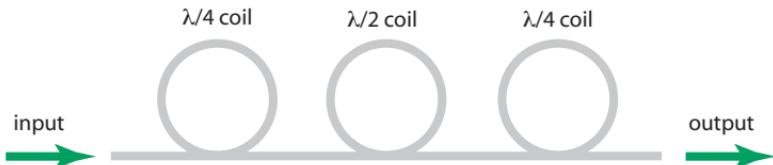
Light can also be transmitted in the other direction (lower part of the figure), but it comes back with a transverse offset such that it cannot be efficiently coupled back into the other fiber. It will thus be attenuated by, for example, 30 dB. Higher isolation is obtained with dual isolators.

Isolators are often used for protecting amplifiers against back-reflected light, but also in fiber interferometers or within fiber ring lasers to ensure unidirectional operation. There are also the somewhat more complicated **circulators**, having at least three optical ports. Light injected into port 1 will exit at port 2, while input at port 2 will be sent to port 3, and input at port 3 to port 1.

Fiber Polarization Controllers

A **fiber polarization controller** is a device that allows one to control the state of polarization of light within a fiber. This is required, for example, in fiber interferometers.

A popular type of fiber polarization controller exploits the birefringence that is induced by bending a fiber. With a simple holder, allowing one to arrange some variable number of loops of the fiber, one can realize an effective quarter or half waveplate. Frequently, one uses three such coils in a sequence, where the middle coil acts as a half waveplate and the outer ones as quarter waveplates. Each coil can be rotated around an axis in line with the input and output fibers. For a given wavelength and input state of polarization, any output state of polarization can be obtained by properly adjusting the orientations of the three coils. Note that the effect on the polarization has some wavelength dependence.



Alternatively, one may realize an effective variable waveplate with a device that allows one to squeeze some length of fiber with a variable amount of pressure. In addition, one can rotate the squeezed bit of fiber around its axis while keeping the fiber clamped a few centimeters away from the squeezed part. In this way, one can obtain an arbitrary polarization state at the output. Effectively, one can obtain the same result as with a Babinet-Soleil compensator (a bulk-optical device containing two birefringent wedges), although the operation principle is different.

As a variant of the latter approach, several squeezing sections can be used in a series. It is also possible to control the pressure with piezo-electric transducers.

Rare-Earth-Doped Fibers

For fiber lasers and fiber amplifiers, so-called **active fibers**, which can amplify light, are required. This is achieved by incorporating rare earth ions into the fiber core. When such ions are optically pumped into metastable excited levels, they can amplify light in certain wavelength regions. The following table shows the most important laser-active ions in fibers, the host glasses into which they are usually incorporated, and the typical wavelengths where they can amplify.

Ion	Hosts	Emission wavelengths
neodymium (Nd ³⁺)	silicate and phosphate glasses	1.03–1.1 μm, 0.9–0.95 μm, 1.32–1.35 μm
ytterbium (Yb ³⁺)	silicate glass	1.0–1.1 μm
erbium (Er ³⁺)	silicate and phosphate glasses, fluoride glasses	1.5–1.6 μm, 2.7 μm, 0.55 μm
thulium (Tm ³⁺)	silicate and germanate glasses, fluoride glasses	1.7–2.1 μm, 1.45–1.53 μm, 0.48 μm 0.8 μm
praseodymium (Pr ³⁺)	silicate and fluoride glasses	1.3 μm, 0.635 μm, 0.6 μm, 0.52 μm, 0.49 μm
holmium (Ho ³⁺)	silicate glasses, fluoro-zirconate glasses	2.1 μm, 2.9 μm

Importance of the Host Glass

The choice of host glass has many important influences on the possible performance and practical use of an active fiber:

- The limited **transparency range** may exclude the use of certain laser transitions.
 - The chemical composition determines the maximum **concentration of the dopant ions** that can be incorporated without excessive clustering.
 - It influences the **optical transitions** of the rare earth ions, i.e., their wavelengths, emission and absorption cross sections, absorption and emission bandwidth, total transition rates, degree of inhomogeneous gain saturation, etc.
 - The tendency for **energy transfers** between different ions is affected.
 - The maximum phonon energy of the host glass determines the rate of **multi-phonon emission** processes, thus the speed of nonradiative transfers between certain levels. This effect can be strong: certain levels may be long-lived (multiple milliseconds) in heavy-metal fluoride glasses, but very short-lived (few microseconds) in silicate glasses.
 - Some glasses (e.g., fluorides) tend to be difficult and expensive to fabricate and handle. Clean fiber cleaves are not always easy to obtain.
 - Some glasses are **photosensitive**, allowing the fabrication of fiber Bragg gratings with ultraviolet light. (This behavior can strongly depend on certain dopants.)
 - Glasses differ very much in their **optical nonlinearities** and **optical damage threshold**.
-

Common Host Glasses

Some important types of host glasses for rare-earth-doped fibers are:

Silicate glasses are essentially based on fused silica (SiO_2), but can contain additional materials for modifying various properties. For example, germanosilicates contain additional GeO_2 (which raises the refractive index and increases the Raman nonlinearity), aluminosilicates contain Al_2O_3 (which improves the solubility for rare-earth dopants), etc. Various dopants are used for tailoring the shape of emission spectra of rare earth ions, e.g., for gain flattening of erbium amplifiers. The phonon energies of silicate glasses are relatively high, so that long-lived metastable states of rare-earth dopants are obtained only where there is a sufficiently large energy gap below an excited level. (Multi-phonon transition rates become low when more than a few phonons are required to bridge the energy gap.)

Phosphate glasses allow for much higher doping concentrations, particularly for erbium ions, without leading to excessive quenching and upconversion processes; therefore, such glasses allow one to make much shorter active devices. This can be useful for various purposes, such as minimized nonlinear effects or large mode spacings.

Fluoride glasses, usually also containing heavy metals, have a high transparency in wavelength regions beyond $2 \mu\text{m}$, where many other glasses are strongly absorbing. They are thus useful for mid-infrared sources. In addition, the low phonon energies allow for long metastable level lifetimes, even when energy levels are closely spaced. This is important not only for mid-infrared lasers, but also for various visible upconversion lasers. Unfortunately, fluoride glasses tend to be difficult to handle. Special techniques are required for making low-loss fibers and clean fiber cleaves, and such glasses tend to be quite brittle.

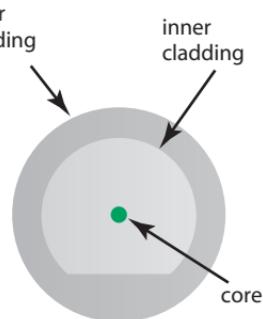
Double-Clad Fibers

For active fibers with an ordinary core–cladding structure, there is a dilemma concerning high-power operation:

- If the core exhibits single-mode guidance, one obtains a high beam quality, but also requires a pump source with high beam quality and brightness. High-power diode lasers tend to have a poor beam quality, such that their radiation cannot be efficiently launched into a single-mode core.
- A multimode core makes it easier to launch pump light, but it is then hard to obtain a high beam quality of the output. Even if signal light is launched only into the fundamental mode, it may later couple into higher-order modes.

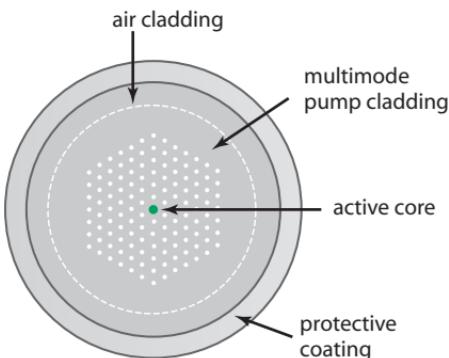
This dilemma can be resolved with a **double-clad fiber** design, allowing for **cladding pumping**:

- The laser light (or amplified light) is still guided by a single-mode core, ensuring highest beam quality. (Sometimes, the core supports several modes, since the core area can then be larger.)
- The pump light, however, is launched into a larger pump cladding, extending well beyond the core region up to an outer cladding (or polymer coating) with significantly lower refractive index. Due to the larger area and larger numerical aperture, the pump cladding supports many more modes than the core. Therefore, it is suitable for launching pump light with relatively poor beam quality.

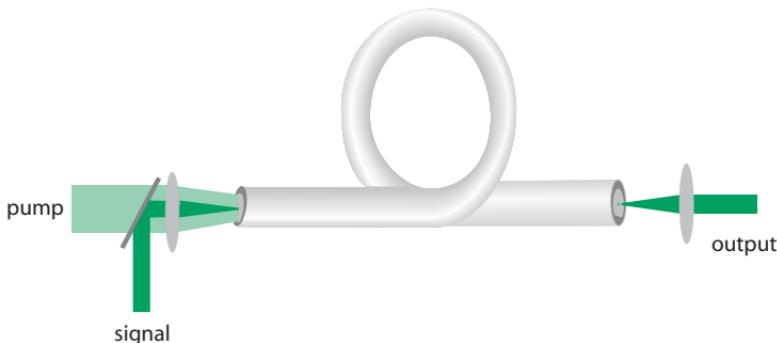


Double-Clad Fibers (cont.)

Double-clad fibers can also be realized as photonic crystal fibers (p. 55). Here, the core mode is stabilized by an array of air holes, whereas the pump cladding is surrounded by an air gap with tiny suspensions, too small to let pump light escape into the outer area. Such designs allow one to realize a very high numerical aperture of the pump cladding while avoiding the use of non-silica materials (polymers, e.g.), which could limit the power handling capability. Additional features can be incorporated into such designs, e.g., for polarization-maintaining signal propagation.



There are different ways of coupling pump light into the pump cladding. The simplest way is using free-space optics. As an example, the figure below shows an amplifier with free-space coupling of pump and signal.

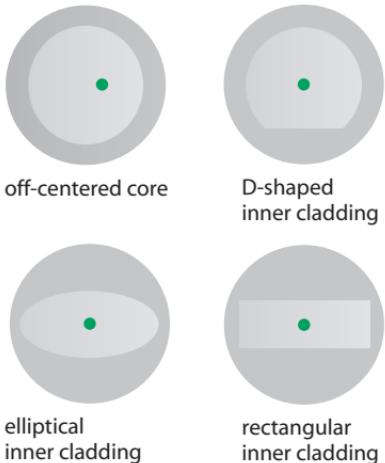


As alternative solutions, various types of fiber-based pump couplers allow one to avoid the disadvantages of free-space optics such as alignment issues, risk of contamination with dust, etc.

Pump Absorption in Double-Clad Fibers

Due to the limited overlap of pump light with the doped core, pump absorption in a double-clad fiber is reduced well below that of the core.

If the pump intensity profile were to stay rectangular during propagation, the pump absorption would simply be reduced by the ratio of the areas of pump cladding and core. However, as different modes of pump cladding have different overlap with the core, the pump intensity profile changes such that the absorption is reduced. Particularly for a simple symmetric fiber design, the pump cladding has many modes with a very low core overlap and thus very inefficient absorption. This problem can be mitigated by strongly coiling the fiber, which causes mode mixing. A more effective solution is to use one of the designs as shown in the figure. Here, the number of pump modes with poor absorption is reduced strongly.

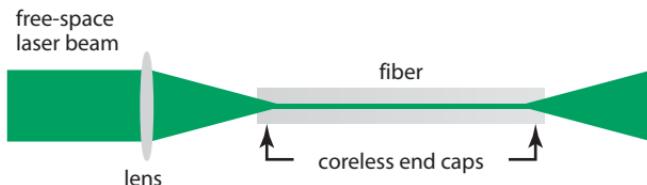


In any case, the reduced pump absorption implies that a correspondingly longer length of fiber is required. This can have detrimental consequences; for example, nonlinear effects become stronger. Another effect is that the pump intensity is reduced. Therefore, cladding-pumped devices tend to be operated at lower excitation densities.

For such reasons, the cladding-to-core area ratio is often kept as small as possible for the available pump source.

Coreless End Caps

Even for double-clad fibers with fairly large mode areas of the core, optical damage of the fiber ends can be a problem when extracting pulses with high peak powers. The air–glass interface can be significantly more sensitive to optical damage than the bulk material, and this depends strongly on the details of the surface preparation.



An effective solution against surface damage of fibers is the use of **coreless end caps**. These are end regions without any waveguiding, i.e., without a core structure. When light reaches such an end cap from within the fiber, it forms an expanding beam, which has a significantly increased beam area at the air–glass interface. Therefore, the fiber can tolerate higher optical powers, which are ultimately limited only by the tolerable intensity in the fiber core. A light beam launched from air into the fiber must follow exactly the same path, i.e., it must have its focus at the beginning of the waveguide structure and a correspondingly larger beam diameter at the air–glass interface.

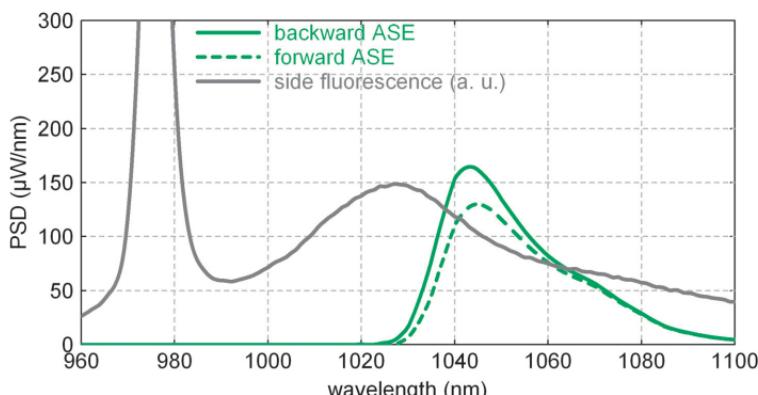
Note also that even for perpendicular ends, Fresnel reflections for light coming from within the fiber are less effectively coupled back into the fiber core, because reflected light would again expand before reaching the fiber core again.

Coreless end caps may be obtained by fusion splicing some homogeneous glass pieces to fiber ends, or in the case of photonic crystal fibers, by heating the fiber ends in a fusion splicer such that the air holes collapse.

Amplified Spontaneous Emission

Some of the excited laser-active ions spontaneously emit. The generated fluorescent light largely leaves the fiber in transverse directions. Some small part, however, of the fluorescence power propagates along the fiber and may be further amplified. This leads to **amplified spontaneous emission** (ASE). For wavelengths with a large gain (e.g., >30 dB), ASE can extract significant optical powers, which (in the same way as a signal) can also saturate the gain (p. 88). For that reason, even with hard pumping it is difficult to obtain well above 40 dB gain at any wavelength. A solution for higher gain can be to have several amplifier stages, between which ASE is filtered out.

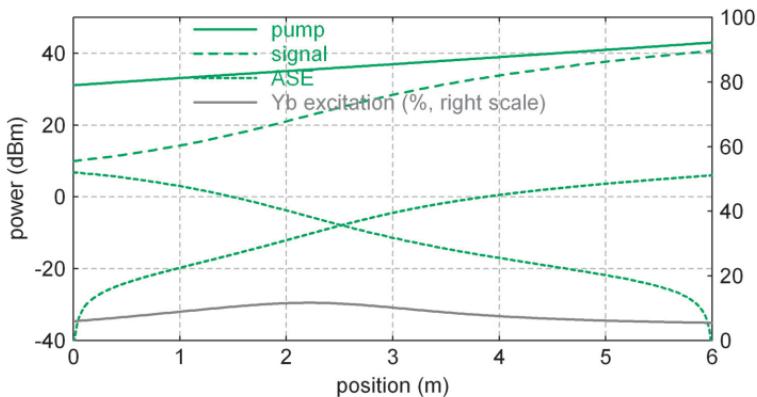
The generated ASE powers are not as directly linked to the gain for quasi-three-level amplifiers as they are for four-level systems. This is essentially because spontaneous emission depends on the emission cross sections only, whereas the gain also depends on the absorption cross sections. Even a weakly pumped region of fiber (with negative net gain due to reabsorption) may generate fluorescence that acts as a seed for ASE in a more strongly pumped (amplifying) region. The figure below shows a simulation for an ytterbium-doped fiber amplifier.



Amplified Spontaneous Emission (cont.)

When the excitation level of an amplifier is increased (e.g., via stronger pumping), ASE spectra tend to become narrower, and for quasi-three-level systems the peak wavelength can shift. The ASE power can then also be different in the forward and backward direction.

The figure below shows an example case with a backward-pumped ytterbium-doped amplifier. ASE powers grow in both directions and saturate the gain at both ends. With a weaker input signal power, the gain rises, and the ASE powers increase accordingly.



ASE that superimposes an amplified signal is also strongly related to amplifier noise. For quasi-three-level amplifiers, the quantum noise influence is stronger, particularly when the amplifier input is operated with a low level of excitation of the laser-active ions. Quantitatively, this can be described with a **noise figure** larger than 3 dB, which is the limit for a high-gain four-level amplifier without absorption losses.

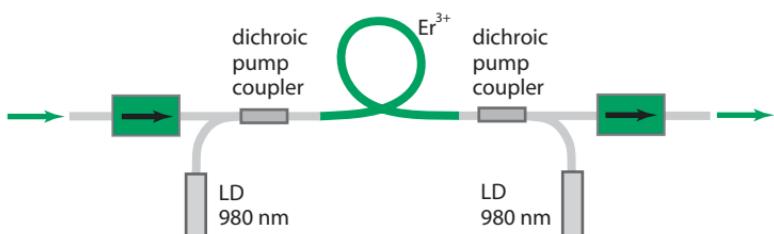
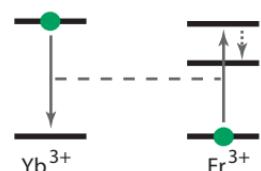
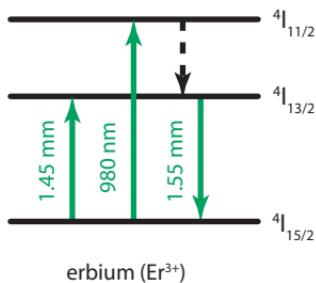
ASE may be used in superluminescent sources. Its broadband characteristics are interesting for applications such as white light interferometry (optical coherence tomography). The temporal coherence is very low compared with that of laser light, whereas the spatial coherence is high.

Erbium-Doped Fiber Amplifiers

For the 1.5- μm spectral region, erbium-doped fiber amplifiers are most important. They are usually pumped either at 980 nm (exploiting the fast nonradiative transfer from ${}^4\text{I}_{11/2}$ to ${}^4\text{I}_{13/2}$) or in-band (similar to Yb³⁺) around 1.45–1.48 μm . The latter option can be more power-efficient, but limits the degree of erbium excitation (due to stimulated emission by the pump), and thus has a lower gain per unit length and more amplifier noise.

Another possibility is to use Er-Yb-codoped fibers. Typically, the concentration of Yb³⁺ is made substantially higher than that of Er³⁺. One may then pump primarily the Yb³⁺ ions at 975 nm, and these can relatively efficiently transfer their energy to Er³⁺ ions, if the glass composition is optimized correspondingly. This is useful particularly for realizing very short amplifiers and lasers. There are trade-offs, however, that may compromise the spectral shape of the gain, for example.

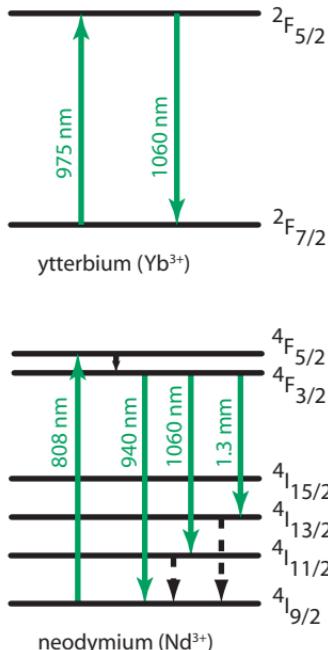
The figure below shows the setup of a low-power erbium amplifier as could be used, e.g., for telecommunications. The erbium-doped fiber is pumped with two laser diodes at 980 nm. Optical isolators prevent detrimental effects of back-reflected light. A gain of 30 or 40 dB can be achieved easily with a few hundred milliwatts of pump power.



Neodymium- and Ytterbium-Doped Amplifiers

For amplification in the spectral region just above 1 μm , amplifiers based on Nd^{3+} - or Yb^{3+} -doped silicate fibers are often used. There are various differences:

- Ytterbium supports a wider signal wavelength range: $\approx 1020\text{--}1100\text{ nm}$ (for silica glass). Neodymium is a bit more limited, but on the other hand, it has additional laser transitions in the 0.9- μm and 1.3- μm region.
- The 1- μm transition of Nd^{3+} has four-level characteristics, whereas Yb^{3+} has quasi-three-level behavior, particularly for short signal wavelengths. The latter means that there is signal reabsorption from the lower level; only above a certain pump intensity is positive net gain obtained. Also, the amplifier noise is higher.
- The roughly 3-times-longer upper-state lifetime of Yb^{3+} means that an Yb-doped amplifier can store more energy under conditions of continuous pumping.
- In silicate glasses, Nd^{3+} (but not Yb^{3+}) exhibits significantly inhomogeneous gain saturation.
- Ytterbium can be pumped at longer wavelengths. The smaller quantum defect (difference between pump and laser photon energy) implies a higher power conversion efficiency and a smaller heat load. Also, Yb^{3+} does not exhibit various detrimental upconversion effects that are possible for Nd^{3+} .



High-Power Fiber Amplifiers

Whereas core-pumped fiber amplifiers usually do not provide output powers well above 1 W, much higher power levels—even above 1 kW—are possible for amplifiers based on double-clad fibers (p. 77). Ytterbium-doped devices are most common, because they can have the highest power conversion efficiency (on the order of 80%). Some important technical issues are briefly discussed in the following:

- At least for commercial devices, suitable **fiber-based pump couplers** are needed. Various technologies are in use that differ in various details like power transfer efficiency, preservation of pump brightness, limitations for the fiber parameters (e.g., pump cladding size), and fabrication technologies.
- Due to the low pump brightness, the **pump intensity** and **Yb^{3+} excitation level** are often low. The quasi-three-level characteristics then lead to a relatively low net gain, which is peaked at long wavelengths (sometimes as long as 1.1 μm).
- High **heat loads** require active cooling of the fiber with a forced air flow or even with water.
- Particularly high-gain amplifiers are very sensitive to **optical feedback**. One must either carefully avoid the generation of any feedback or provide sufficient isolation with Faraday isolators. However, for high power levels these are bulky and expensive, and may reduce the output beam quality.
- **Optical damage** of the fiber (particularly at the output end) is a problem particularly for amplifying intense pulses. Nonlinear **self-focusing** above ≈ 4 MW sets a rather hard limit for the peak power.

Gain Efficiency

The **gain efficiency** of an amplifier is often defined for the steady state and in a situation with low signal intensities (negligible stimulated emission).

The gain (in dB) is usually fully determined by the energy stored in the amplifier. It may be negative for a quasi-three-level system (due to the reabsorption), and become positive only for sufficiently high pump powers. Normally, the gain rises in proportion to the pump power, until amplified spontaneous emission (ASE) (p. 81) becomes strong and reduces the further rise of gain. The differential gain efficiency in a simple case (without ASE) is given by

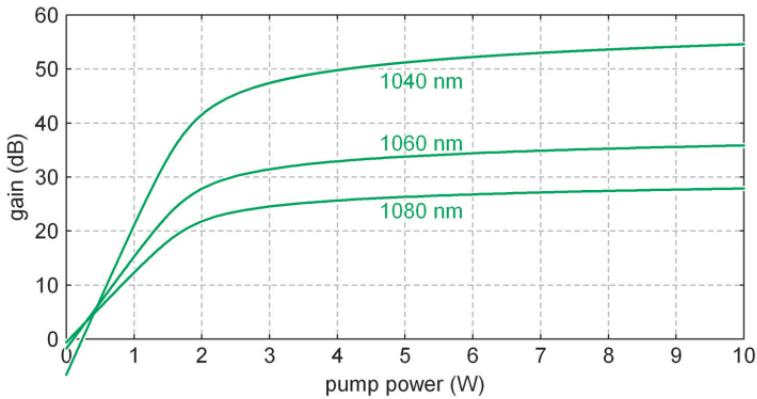
$$\frac{\partial g_{av}}{\partial P_p} L = \frac{\eta_p (\sigma_{em} + \sigma_{abs}) \tau_2}{h v_s A_{eff}},$$

where g_{av} is the average small-signal gain coefficient in units of m^{-1} , L is the length of the gain medium, so $\exp(g_{av}L)$ is the power amplification factor, and P_p is the incident pump power. On the right side, η_p is the pumping efficiency (including the pump absorption efficiency, the quantum defect and the pump quantum efficiency), σ_{em} and σ_{abs} are the signal emission and absorption cross sections, respectively, τ_2 is the upper-state lifetime, $h v_s$ is signal photon energy, and A_{eff} is the effective mode area. Note that an increased length L also increases η_p via the pump absorption efficiency.

The equation shows that high gain efficiency results from a high $\sigma\tau$ product and a small mode area, apart from an efficient pumping scheme. A small effective mode area increases the gain efficiency, essentially because a smaller volume of active medium needs to be pumped for a given gain. Compared with amplifiers based on laser crystals, fiber amplifiers tend to have higher gain efficiencies due to their small mode areas, which are possible even for large amplifier lengths.

Gain Efficiency (cont.)

The figure shows how the small-signal gain of an ytterbium-doped fiber amplifier at three different wavelengths rises with increasing pump power. The slope is highest for 1040 nm, where the cross sections are highest, but the gain is negative for small pump powers due to signal reabsorption of unpumped ytterbium. For high pump powers, the gain saturates due to power extraction by amplified spontaneous emission (p. 81).



The small-signal gain efficiency can also be expressed as

$$\frac{\partial g_{av}}{\partial P_p} L = \frac{\eta_p}{P_{sat}},$$

where P_{sat} is the signal saturation power:

$$P_{sat} = \frac{hv_s A_{eff}}{(\sigma_{em} + \sigma_{abs})\tau_2}.$$

This shows that a high gain efficiency inevitably implies a low saturation power, so that low signal powers can cause significant saturation effects.

A low gain efficiency may be desirable for achieving good energy storage, particularly when it is limited by ASE.

Gain Saturation

When an intense signal is amplified, stimulated emission transfers ions from the excited state into a lower state, and this results in **gain saturation** or **gain compression**, i.e., the amplifier gain is reduced below the small-signal gain.

Under steady-state conditions, the local gain coefficient g in the amplifier (in units of m^{-1}) is reduced below the small-signal value g_{ss} according to

$$g(P_s) = \frac{g_{ss}}{1 + P_s / P_{\text{sat}}},$$

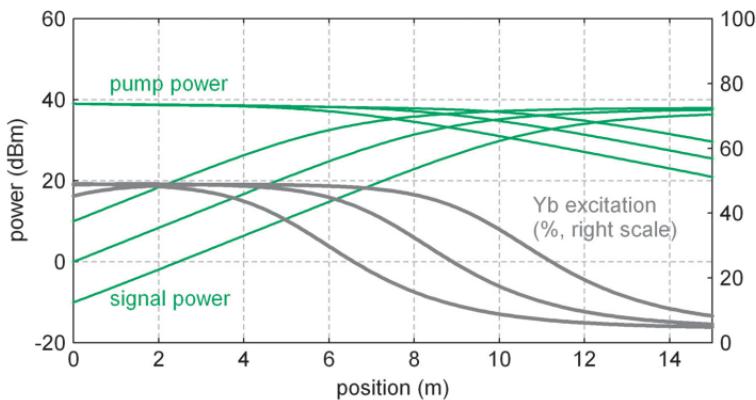
where P_s is the signal power and P_{sat} is the **saturation power**:

$$P_{\text{sat}} = \frac{h\nu_s A_{\text{eff}}}{(\sigma_{\text{em}} + \sigma_{\text{abs}})\tau_2}$$

(see the previous page). It is assumed that the pump rate remains constant. For high pump intensities, this may not be true, and the gain saturation effect is weaker, because de-excited ions can quickly be repumped into the upper laser level. That situation occurs frequently, particularly in core-pumped fiber amplifiers and lasers.

The figure on the next page shows with a logarithmic scale how the signal power at 1040 nm rises within an ytterbium-doped fiber amplifier. Curves for three different signal input powers (0.1 mW, 1 mW, 10 mW) are shown. After a few meters, the signal power becomes so high that the ytterbium excitation is reduced and the local gain is saturated. As this also increases the pump absorption, the decay of pump power is most rapid for the highest signal input power. For the weakest signal input, the ytterbium excitation at the left end is slightly reduced by backward-travelling ASE. The simulations have been done with the software RP Fiber Power.

Gain Saturation (cont.)



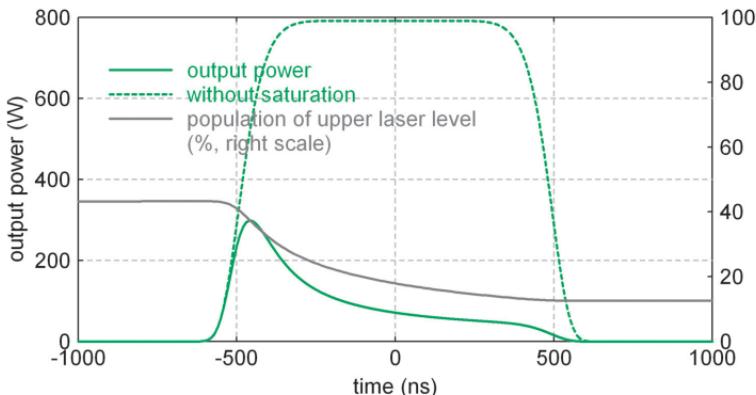
So far, gain saturation has been considered only for the steady state, i.e., with constant powers. If the gain is saturated by a short pulse, it is reduced by the factor

$$\exp(-E_p / E_{\text{sat}}),$$

where E_p is the pulse energy and E_{sat} is the **saturation energy**

$$E_{\text{sat}} = \frac{h\nu_s A_{\text{eff}}}{\sigma_{\text{em}} + \sigma_{\text{abs}}} = P_{\text{sat}} \tau_2 .$$

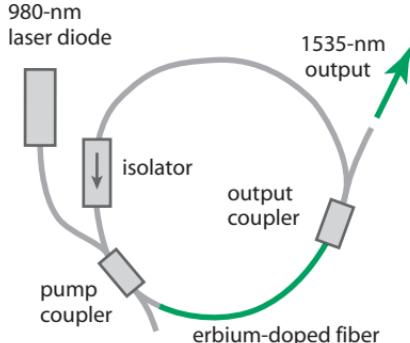
The diagram below shows how gain saturation can distort the shape of an amplified pulse.



Continuous-Wave Fiber Lasers

A continuously-emitting fiber laser consists of an optically pumped active fiber that is integrated into an optical resonator. The resonator provides optical feedback such that light can repeatedly pass the active fiber, either in a kind of ring or in a linear arrangement.

An all-fiber ring laser is shown at the right side. Pump light from a fiber-coupled 980-nm laser diode is injected into the fiber ring with a dichroic fiber coupler. A Faraday isolator ensures unidirectional operation. Additional components could be incorporated into the ring, for example, a polarization controller or a tunable bandpass filter for wavelength tuning.



The simplest linear fiber lasers have a resonator with reflecting elements at the two ends of an active fiber. As an example, the figure below shows a laser with two fiber Bragg gratings (p. 70).

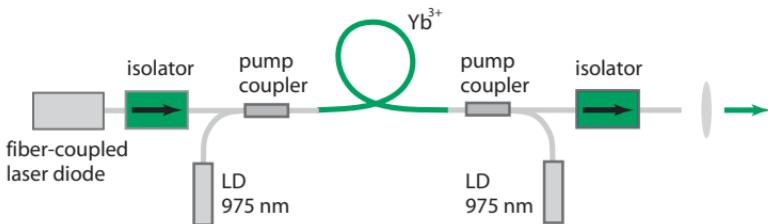


Alternative kinds of reflectors include fiber loop mirrors, bare fiber ends (using the 4% Fresnel reflection), dichroic mirror coatings on fiber ends, and separate dichroic mirrors used in free-space configurations.

With short resonators containing at least one narrow-band reflector (such as a fiber Bragg grating), one may achieve single-frequency operation with a very small linewidth.

High-Power Lasers vs MOPAs

It is possible to build fiber lasers that directly emit rather high output powers (hundreds of watts). Instead, however, one often uses a **MOPA (master oscillator power amplifier)** arrangement, sometimes also called **MOFA (master oscillator fiber amplifier)**, consisting of a low-power seed laser (continuous-wave or pulsed) and a high-power fiber amplifier.



Compared with a simple high-power fiber laser, this approach has various advantages:

- A MOPA often makes it easier to achieve the required performance, e.g., in terms of linewidth, wavelength tuning range, beam quality, or pulse duration. This is because various performance aspects are decoupled from the generation of high powers.
- A modulator for the power or optical phase may be inserted after the seed laser and then must perform only with a low-power beam.
- Combining an existing laser with an existing amplifier (or an amplifier chain) may be simpler than developing a new laser with higher output power.
- The optical intensities are lower in an amplifier, compared with the intracavity intensities in a laser. This helps to minimize nonlinear effects and optical damage problems.

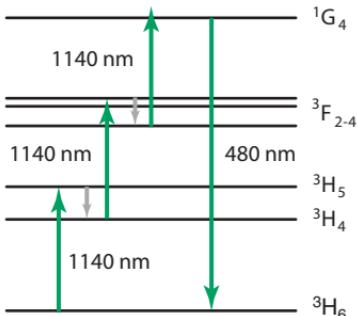
Despite these advantages, a MOPA setup is more complex and more sensitive to back-reflected light.

Upconversion Fiber Lasers

Upconversion lasers use more than one pump photon to excite a laser-active ion into a high-lying level, such that the radiation emitted has a higher photon energy (thus a shorter wavelength) than the pump photons. Fiber laser technology is particularly suitable for upconversion, because it conveniently allows one to realize the conditions required for upconversion pumping schemes: high pump intensities over a long interaction length.

Basically two types of upconversion pumping can be used:

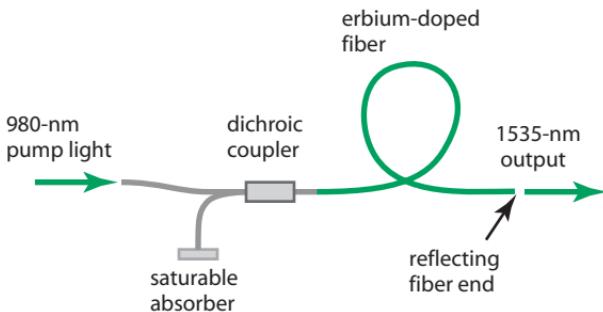
- Laser-active ions can be pumped into high-lying electronic levels by subsequent absorption of two or more pump photons. When the energy levels are conveniently located, a single pump laser can be sufficient. The figure shows an example of a thulium-doped fluoride fiber, where a 1140-nm pump beam can do an efficient three-step excitation process, followed by emission of blue light at 480 nm. Sufficiently long lifetimes of the involved metastable states $^3\text{H}_4$, $^3\text{F}_4$ and $^1\text{G}_4$ are obtained in heavy-metal fluoride glasses, which have suitable (fairly low) phonon energies. Such lasers can relatively efficiently generate hundreds of milliwatts of blue light.



- Alternatively, one may exploit energy transfers between ions to populate high-lying levels. For example, there are praseodymium/ytterbium-doped upconversion fiber lasers (again based on fluoride fibers), offering emission of red (635 nm), orange (605 nm), green (520 nm), or blue (491 nm) light. The pump light is absorbed by ytterbium, whereas praseodymium has the laser transitions.

Pulsed Fiber Lasers

It is possible to obtain short (nanosecond) pulses from fiber lasers. (Ultrashort pulse generation is discussed later.) A common technique is **Q switching**. Here, the resonator losses are initially kept high, so that lasing is prevented and energy can be stored in the active fiber. Then, a pulse is obtained by quickly reducing the losses, so that the laser is far above threshold and the laser power rises quickly. The resulting pulse can extract much of the stored energy. The loss switching may be accomplished actively (with an electrically controlled modulator, e.g., an acousto-optic modulator) or passively (with a saturable absorber device). An example for the latter approach is shown in the figure.



Compared with bulk lasers, Q-switched fiber lasers are fairly limited in terms of pulse energy, because their high gain efficiency limits the stored energy, and nonlinear effects limit the peak power (particularly when narrow-bandwidth emission is required).

An interesting alternative to a pulsed fiber laser is a pulsed MOPA (p. 91), consisting, e.g., of a pulsed seed laser diode and a high-power fiber amplifier. This approach is highly flexible. For example, it allows one to modify the pulse duration and pulse shape for a given pulse repetition rate, and to vary the repetition rate in a wide range. Also, a short pulse duration is possible without minimizing the fiber length, at least as long as nonlinear effects are not limiting the performance.

Mode-Locked Fiber Lasers

Ultrashort pulses, with durations measured in picoseconds or femtoseconds, can be generated with **mode-locked fiber lasers**. In such a laser, one or several ultrashort pulses circulate in the resonator, and each time such a pulse hits the output coupler, a pulse is emitted. Within each resonator round trip, a pulse is subject to various effects, but its parameters stay approximately unchanged after each round trip.

In contrast to typical solid-state bulk lasers, ultrashort pulses in a fiber laser resonator experience strong dispersive and nonlinear effects in each round trip, because such effects are much stronger in a fiber than in a short crystal and in air. To some extent, such effects can be used for pulse shaping; this holds in particular for soliton effects (p. 37). When very short pulses, high pulse energies, and high peak powers are wanted in particular, however, nonlinear and dispersive effects are often much stronger than desirable, and limit the achievable performance figures. A number of approaches have been developed for optimized pulse generation in different regimes of pulse duration and energy:

- **Soliton fiber lasers** avoid dispersive and nonlinear pulse distortions by using a balance of chromatic dispersion and Kerr nonlinearity, which is useful even for pulse shaping. Note that this method works well only in a limited range of pulse durations and pulse energies.
- **Stretched-pulse fiber lasers** contain fiber pieces with normal and anomalous dispersion, such that the pulses exhibit strong “breathing” in each round trip. As the pulses are significantly stretched at most locations in the resonator, the generated pulses can be shorter and more intense. The pulses often need to be dispersively compressed after leaving the laser.

Mode-Locked Fiber Lasers (cont.)

- **Similariton fiber lasers** exploit self-similar pulse propagation in the normal dispersion regime and recompression with a spectral filter. External pulse compression is required.
- Other **wavebreaking-free fiber lasers** are somewhat similar to similariton lasers, although no self-similar pulse evolution occurs. The performance figures are also similar.

For higher pulse energies, the use of MOPA architectures (p. 91) is common. Fiber amplifiers offer high gain, high efficiency, and a gain bandwidth that is sufficient for femtosecond pulses. It is necessary, however, to properly deal with the effects of chromatic dispersion and particularly the fiber nonlinearities. Some possible approaches are:

For high pulse repetition rates and correspondingly small pulse energies, it is sometimes sufficient to minimize the limited amplifier fiber length and choose a large mode area.

To some extent, dispersive and nonlinear effects in a fiber amplifier can be compensated with **dispersion compensation** before or after the amplifier.

In the normal dispersion regime, **similariton pulse propagation** with subsequent dispersive compression can be used.

The highest pulse energies are achieved with **chirped-pulse amplification**, where the pulses are dispersively stretched before the amplifier and compressed again after the amplifier.

More details on pulse generation are given in the Field Guide to Laser Pulse Generation (FG14 of this series).

Equation Summary

Numerical aperture:

$$NA = \sqrt{n_{\text{core}}^2 - n_{\text{cladding}}^2} \approx \sqrt{2 n_{\text{cladding}} (n_{\text{core}} - n_{\text{cladding}})}$$

V number:

$$V = \frac{2\pi}{\lambda} a \quad NA = \frac{2\pi}{\lambda} a \sqrt{n_{\text{core}}^2 - n_{\text{cladding}}^2}$$

Number of modes of a multimode fiber:

$$M \approx \frac{4}{\pi^2} V^2 \quad (\text{for } V > 10)$$

Marcuse formula for mode radius:

$$\frac{w}{a} \approx 0.65 + \frac{1.619}{V^{3/2}} + \frac{2.879}{V^6} \quad (\text{for } 0.8 < V < 2.5)$$

Effective mode area:

$$A_{\text{eff}} = \frac{\left(\int |E|^2 dA \right)^2}{\int |E|^4 dA} = \frac{\left(\int I dA \right)^2}{\int I^2 dA}$$

Electric field from transverse mode function and propagation constant:

$$E(r, \varphi, z) = \Psi(r, \varphi) \exp(i\beta z) = F_{lm}(r) \cos(l\varphi) \exp(i\beta z)$$

Radial part of wave equation:

$$F_{lm}''(r) + \frac{F_{lm}'(r)}{r} + \left(n^2(r) k^2 - \frac{l^2}{r^2} - \beta_{lm}^2 \right) F_{lm}(r) = 0$$

Equation Summary (cont.)

Evolution of mode amplitude:

$$a_j(z) = a_j(0) \exp\left(-\frac{\alpha_j}{2}z + i\beta_j z\right)$$

Taylor expansion of propagation constant:

$$\begin{aligned}\beta(\omega) &= \beta_0 + \frac{\partial\beta}{\partial\omega}(\omega - \omega_0) + \frac{1}{2} \frac{\partial^2\beta}{\partial\omega^2}(\omega - \omega_0)^2 \\ &\quad + \frac{1}{6} \frac{\partial^3\beta}{\partial\omega^3}(\omega - \omega_0)^3 + \dots\end{aligned}$$

Group velocity:

$$\frac{1}{v_g} = \frac{\partial\beta}{\partial\omega}$$

Dispersion parameter:

$$D_\lambda(\lambda) = \frac{\partial}{\partial\lambda}\left(\frac{1}{v_g}\right) = -\frac{2\pi c}{\lambda^2} \cdot \beta_2$$

Polarization beat length:

$$L_b = \frac{2\pi}{|\Delta\beta|}.$$

Nonlinear index change for self-phase modulation:

$$\Delta n = n_2 I$$



Equation Summary (cont.)

Nonlinear index change for cross-phase modulation:

$$\Delta n^{(1)} = 2n_2 I^{(2)}$$

Nonlinear phase shift due to self-phase modulation:

$$\varphi_{\text{nl}} = n_2 \frac{P}{A_{\text{eff}}} \frac{2\pi}{\lambda} L .$$

Temporal profile of a soliton pulse:

$$P(t) = P_p \operatorname{sech}^2(t / \tau) = \frac{P_p}{\cosh^2(t / \tau)}$$

Soliton relation:

$$E_p = \frac{2|\beta_2|}{|\gamma|\tau}$$

Power evolution with stimulated Raman scattering:

$$\begin{aligned} \frac{\partial}{\partial z} I_s &= g_R I_p I_s \\ \frac{\partial}{\partial z} I_p &= -g_R \frac{\lambda_s}{\lambda_p} I_p I_s \end{aligned}$$

Coupling efficiency for fibers:

$$\eta = \frac{4w_1^2 w_2^2}{(w_1^2 + w_2^2)^2} \exp\left(-\frac{-2(\Delta x)^2}{w_1^2 + w_2^2}\right)$$

where w_1, w_2 = mode radii, Δx = offset of fiber cores

Equation Summary (cont.)

With angular offset $\Delta\theta$:

$$\eta = \exp \left[- \left(\frac{\pi \Delta\theta w / \lambda}{\sqrt{2}} \right)^2 \right]$$

Reflection condition for fiber Bragg grating:

$$\lambda = 2n_{\text{eff}}\Lambda$$

or

$$\beta \Lambda = \pi$$

Differential gain efficiency:

$$\frac{\partial g_{\text{av}}}{\partial P_p} L = \frac{\eta_p}{P_{\text{sat}}}$$

Saturation energy:

$$E_{\text{sat}} = \frac{hv_s A_{\text{eff}}}{\sigma_{\text{em}} + \sigma_{\text{abs}}}$$

Saturation power:

$$P_{\text{sat}} = \frac{hv_s A_{\text{eff}}}{(\sigma_{\text{em}} + \sigma_{\text{abs}}) \tau_2} = \frac{E_{\text{sat}}}{\tau_2}$$

Saturated laser gain:

$$g(P_s) = \frac{g_{\text{ss}}}{1 + P_s / P_{\text{sat}}}$$



Equation Summary (cont.)

Gain saturation by a short pulse:

$$g \rightarrow \exp(-E_p / E_{\text{sat}}) g \quad (\text{for } g \ll 1)$$

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