Optical Fiber Technology

Physical Principles and Applications of Different Types of Optical Fibers

Optical fibers have a very broad range of applications, where they serve many purposes, such as simply transporting light from a source to some other device, transmitting optically encoded data, sensing temperature or strain in some environment, or generating and amplifying laser light. This article gives an introduction into both the basic physical principles and different types of fibers.

Guiding Light

The most basic function of a fiber is to guide light, i.e., to keep light concentrated over longer propagation distances – despite the natural tendency of light beams to diverge, and possibly even under conditions of strong bending. In the simple case of a step-index fiber, this guidance is achieved by creating a region with increased refractive index around the fiber axis, called the *fiber core*, which is surrounded by the *cladding*. The cladding is usually protected with a polymer coating, and in fiber-optical cables with additional thicker layers.

It is common to explain the guiding effect as a result of total internal reflection: a light beam approaching the core-cladding interface from the core region is reflected (see Fig. 1), provided that the incidence angle (measured against the normal direction) is sufficiently large. That criterion limits the angle of incidence of a ray which hits the fiber core from outside: guidance is obtained only if the angle between the beam and fiber axis is below a certain maximum, the sine of which is called the *numerical aperture* (NA). That value is determined by the refractive indices of core and cladding:

$$NA = \sqrt{n^2_{core} - n^2_{cladding}}$$

Any beam with an incidence angle larger than arcsin NA is not guided and will thus experience high losses at the outer interface of the cladding.

The used ray picture cannot be applied to fibers with a small core and/or a small refractive index contrast between core and cladding. The reason is that wave effects occur: a real beam has some finite width, and the incident and reflected wave interfere with each other. Furthermore, the optical field somewhat extends beyond the core/cladding interface. Therefore, the ray picture is only a rough approximation for strongly guiding large core fibers, while a wave analysis is required for the more general case.

Waveguide Modes

A very important concept in fiber optics is that of *waveguide modes*. These are field configurations which maintain their intensity profile during propagation, apart from possible power losses. Of highest interest are usually the *guided modes*, i.e., those modes which have significant intensity only in or near the core. Depending on the fiber design and the optical wavelength, some number of guided modes may exist, or only a single one, or even no guided mode at all. A fiber with only one guided mode is called a *single-mode fiber*, and *multimode fibers* support several or even many guided modes. Fig. 2 shows the intensity patterns of the guided modes of a step-index fiber.

In any case, a fiber also has a multitude of *cladding modes*, which reach to the outer boundary of the cladding, and are usually very lossy. That loss is essentially determined by the coating around the cladding.

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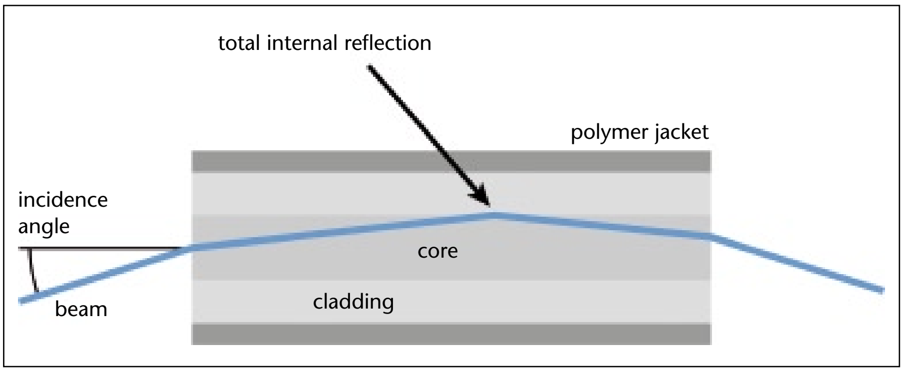

FIGURE 1: **Guidance of a light beam in a multimode fiber via total internal reflection at the core-cladding interface.**

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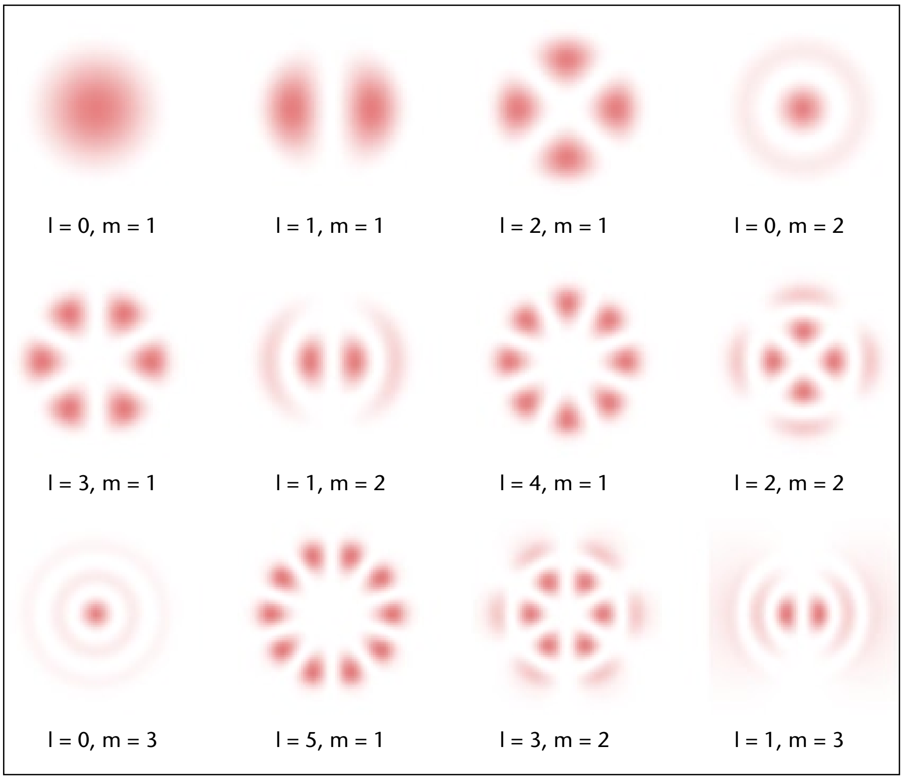


FIGURE 2: **Intensity profiles of the modes of a step-index fiber. In any case, a fiber also has a multitude of cladding modes, which reach to the outer boundary of the cladding, and are usually very lossy. That loss is essentially determined by the coating around the cladding.**

Any light propagating in a fiber can be considered as a superposition of light in different waveguide modes. For example, when light is injected into a single-mode fiber (Fig. 3), at the fiber entrance this creates a superposition of the guided moder and a number of cladding modes. The power in the latter is lost through the coating during a short distance of propagation, and essentially only light in the guided mode is obtained at the end. Interestingly, the intensity profile at the output is then entirely determined by the fiber properties only, not by the launch conditions. The latter only influence the efficiency with which light is coupled into the guided mode.

When light is launched into a multimode fiber, multiple guided modes can be excited, and at the fiber exit there is an intensity profile (Fig. 4) which arises from the interference of light in all these modes (assuming again that light in cladding modes has been lost). It is now important that this intensity pattern changes all the time during propagation, because each mode experiences a different phase shift, which is the so-called propagation constant β (dependent on the mode and the wavelength) times the propagation distance. The more modes are involved, the more complicated can the resulting intensity pattern be. However, the intensity pattern can effectively be smeared out, when the light has a finite optical bandwidth and only the total intensity is detected. The reason is that the propagation constants are wavelength-dependent, so that the interference pattern looks different for each wavelength component.

Properties and Applications of Single-Mode and Multimode Fibers

Single-mode guidance in a fiber is achieved with a combination of relatively small core radius and NA. For example, a single-mode fiber for operation in the 1.5 μm wavelength region may have a core radius of 5 μm and an NA of 0.1. Increasing the core radius to 10 μm would lead to multiple guided modes, but single-mode guidance may be restored by reducing the NA to 0.05. Generally, robust single-mode guidance requires a not too large mode area, since otherwise the NA and thus the refractive index contrast has to be very small, and this causes very weak guidance: substantial losses may then e.g. result even from only slight bending of the fiber. Also, random index fluctuations due to imperfections can then have a stronger effect.

On the other hand, a multimode fiber with an NA of 0.3 guides robustly even when it is strongly bent. This holds also for large core areas, which then imply a large number of guided modes.

Single-mode fibers have the essential advantage of a well-defined, clean amplitude profile of the guided light, leading to high beam quality of the output beam. Therefore, single-mode guidance is usually preferred for active fibers as used in fiber lasers and amplifiers (see below), and for light transport in applications requiring a high spatial coherence, such as interferometers. Limitations arise from the small mode areas, which make e.g. launching into a single-mode fiber significantly more difficult and can lead to excessive nonlinear effects in high power fiber devices. Also, efficient launching into a single-mode fiber requires an input beam with a high beam quality, allowing to match the complex amplitude profile (and not only the intensity profile) of the guided mode at the fiber input.

Strongly multimode fibers are required when light from a source with poor spatial coherence has to be transported. For example, the output of a high power diode bar contains thousands of modes, and requires a correspondingly large number of fiber modes. When that number of guided modes is made larger than strictly required, efficient launching becomes easier, but the launched light will usually spread over more modes and thus obtain a reduced beam quality and brightness at the output. Therefore, it is often preferable e.g. to have a fiber-coupled diode laser with 100 W of optical power in a fiber with 200 μm rather than 400 μm for a given NA of 0.22.

Other Propagation Properties

The most frequently used optical fibers are made of silica glass, usually with some additional dopants (e.g. germania) in the fiber core for controlling the refractive index profile. When made from very pure materials in a carefully controlled process, single-mode silica fibers can have extremely low propagation losses of below 0.2 dB/km (≈4.5% per km) in the 1.5-μm spectral region, as used for optical fiber communications. For shorter wavelengths, scattering losses due to

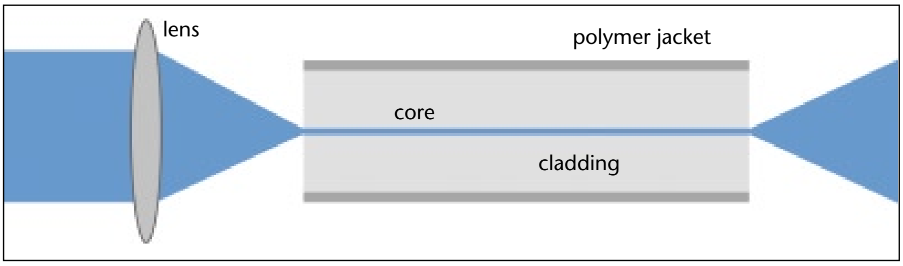
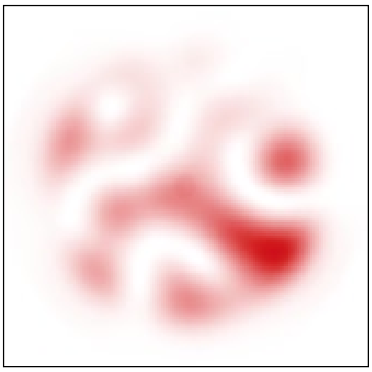


FIGURE 3: **Guidance of light in a single-mode fiber. The intensity profile within the core is determined by the fiber design only.**

FIGURE 5: **Different designs of double-clad fibers.**



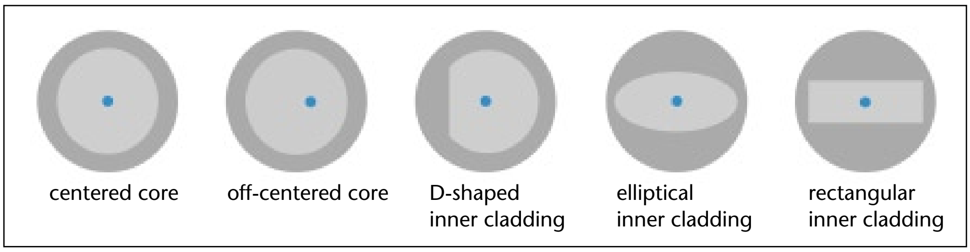


FIGURE 4: **Typical intensity pattern at the output of a multimode fiber for an input of monochromatic light with random phases of the excited modes.**

refractive index inhomogeneities and fluctuations of the core diameter increase, while multiphonon absorption occurs at longer wavelengths and blocks light transmission approximately above 2 µm. Scattering losses are usually higher for fibers with higher NA, and when special dopants (e.g. rare-earth ions, see below) are incorporated.

The polarization of light in a fiber can be subject to sophisticated effects. Some weak birefringence, which can result from small imperfections and bending, often causes uncontrolled polarization changes. It can be disturbing that these changes are quite temperature-dependent. This problem may sometimes be eliminated by using *polarization-maintaining fibers*. These are *not* fibers with particularly low birefringence, but rather the opposite: strong birefringence is generated e.g. by incorporating stress rods, or by breaking the (nominally) circular symmetry of the fiber design e.g. with an elliptical core. If the input light is linearly polarized along one of the birefringent axes of the fiber, it will stay polarized along that axis, even if the fiber is somewhat bent or twisted. However, alignment of the input polarization is essential: if some of the light is propagating with a polarization along the other axis, the overall polarization state is elliptical and strongly oscillates. Unfortunately, the necessary alignment increases the fabrication cost of devices using polarization-maintaining fibers, and not all types of fibers are available in polarization-maintaining form.

FIGURE 6: **Design of the core region of the most common type of photonic crystal fiber. There is a triangular lattice of air holes, with the central hole missing.**

Light in a fiber also experiences *chromatic dispersion*, i.e., a frequency dependence of the group velocity. This can e.g. lead to dispersive broadening of ultrashort pulses, and to the distortion of data-carrying signals. Particularly for fibers with small mode areas, the dispersion is determined not only by the material properties, but also by the waveguide design, i.e., the refractive index profiles. This can be exploited. For example, special *dispersion-shifted fibers* have been developed which exhibit a strongly reduced dispersion in the telecom wavelength region around 1.5–1.6 µm, and particularly photonic crystal fibers (see below) can be made with very different dispersion properties.

Active Fibers

Optical glass fibers can also be doped with laser-active rare-earth ions such as Nd^{3+}, Yb^{3+}, Er^{3+}, or Tm^{3+}. If such ions are "pumped" with light at some wavelength, they can amplify light at some other wavelengths. For example, erbium-doped fiber amplifiers can be pumped around 980 nm or 1450 nm, and amplify light in the region around 1.53–1.6 µm. Neodymium- and ytterbium-doped fibers amplify at wavelengths somewhat longer than 1 µm, and particularly Yb-doped fibers are now widely used for high power fiber lasers and amplifiers. Attractive features of active glass fibers are a very high gain efficiency (due to the small mode area), a high power efficiency, high beam quality (for single-mode fibers), and a large gain bandwidth, which is suitable e.g. for broadly tunable lasers and for amplifying ultrashort laser pulses. On the other hand, the small mode areas and comparatively long length of fiber laser gain media lead to strong nonlinearities, which cause serious limitations e.g. in the field of ultrashort pulse generation and amplification.

Rather high average output powers are achievable with *double-clad fibers*, having an *inner cladding* around the core and an *outer cladding* with still lower refractive index further outside, so that the inner cladding can guide pump light over long distances. As the inner cladding is highly multimode and has a comparatively large area, it allows to launch pump light e.g. from high power diode bars with relatively poor beam quality. That light still has some overlap with the (typically single-mode) core, so that it can pump the rare earth ions in the core, even though the pump intensity is decreased and the absorption length is increased at least according to the area ratio of inner cladding and core. Different designs (Fig. 5) have been developed, which differ in terms of pump absorption and the ease of manufacturing.

Special Materials

Not all fibers are based on silica glass, because other materials have advantages in various cases. Possible materials are e.g. various phosphate, chalcogenide and fluoride glasses. Phosphates are most similar to silicates, but often allow to incorporate higher concentrations of rare-earth ions, so that e. g. shorter laser and amplifier devices can be realized. Chalcogenide and fluoride (often fluorozirconate) glasses exhibit lower maximum phonon energies, which has important consequences. Such fibers exhibit good transmission in the mid-infrared spectral region, while silica absorbs beyond roughly 2 µm. Furthermore, the low phonon energies strongly reduce the tendency for multi-phonon decay processes in rare earth ions. This is of interest not only for mid-infrared lasers, but also for upconversion lasers. For example, thulium-doped fluorozirconate fibers can be used for infrared-pumped blue-emitting fiber lasers.

A quite different fiber type is based on polymers. Most importantly, *plastic optical fibers* (POFs) have a potential for cheap mass production, and may be widely used e. g. in cars, replacing the heavier copper wires for data transmission or transporting light from a compact semiconductor source to instruments. Substantially higher propagation losses can be tolerated where the required length is small.

Photonic Crystal Fibers

A novel huge playground for researchers, and certainly also an area with a substantial commercial future, is the field of *photonic crystal fibers* (PCFs), also called *microstructure fibers* or *holey fibers*. Here, many tiny air holes (with sub-micrometer diameters) go all along the fiber (see Fig. 6). Such holes are typically made by drawing the fiber from a structured preform, assembled from a stack of solid or hollow tubes. Guidance is achieved by exploiting the huge index contrast between glass (or polymers) and air, rather than the much smaller index differences between doped and undoped glass.

PCFs may be made e. g. of pure (undoped) silica or from polymers, and the huge index contrast leads to very unusual guiding properties in many respects, which can also be strongly influenced via the design, i. e., the arrangement of holes. Possible properties are e. g. very large or extremely small mode areas of single-mode fibers, single-mode guidance over huge spectral regions (→ endlessly single-mode fibers) or to the contrary guidance only in very limited regions, extremely strong birefringence, or anomalous dispersion in the visible spectral region. Also, double-clad fibers can be made with a very high NA of the inner cladding, which translates into important benefits for high power fiber devices. As the range of possible properties is much wider than for conventional solid glass fibers, PCFs are expected to find a very wide range of applications, of which probably only a small fraction has been explored so far.

Fiber Bragg Gratings

Another technologically very interesting area is that of *fiber Bragg gratings* (FBGs). Here, a weak refractive index modulation is typically written into a photosensitive fiber by exposure of some fiber section to ultraviolet laser light, which is spatially structured in the form of an interference pattern. The approximately periodic index modulation leads to reflection in some typically narrow wavelength region, while it has little effect on light at other wavelengths. Such a narrowband reflector can be used e. g. as the end mirror of a fiber laser, determining its emission wavelength and narrowing the emission spectrum. A short fiber laser may even consist only of a single fiber grating in a doped fiber (→ distributed feedback fiber lasers). Examples for other applications are adding and dropping data channels in wavelength division multiplexing telecom systems, and fiber-optic sensors exploiting the pressure or temperature dependence of the reflection feature.

Besides coupling counterpropagating core modes, fiber gratings can also couple light from the core into cladding modes. Long-period gratings based on the latter principle can be used e. g. for gain flattening of fiber amplifiers by introducing carefully controlled wavelength-dependent losses.

The photosensitivity of a fiber depends very much on the core material. This somewhat restricts the range of fibers in which gratings can be made with UV irradiation. However, an alternative method is the inscription of gratings with a femtosecond laser, exploiting two-photon absorption.

Conclusions

Although optical fibers have been used for many decades, the last 10 to 20 years have shown a lot of further development. The introduction of fiber Bragg gratings, photonic crystal fibers and new plastic optical fibers, to name only the most important new fields, has dramatically widened the range of possible applications. It is to be expected that fiber optics stays a very exciting area for many further years.

More details on many mentioned aspects can be found in the "Encyclopedia of Laser Physics and Technology", which is freely available in the internet (www.rp-photonics.com/encyclopedia.html) and will appear in print from Wiley-VCH in late 2008.