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Study of Optical Fiber Light Transmission

Laboratory Guide
to the Lab Work No 1

2017

The aim of the work:

To get acquainted with the principle of action and design of optical fiber and to carry out by means of it the transmission of laser radiation. To observe the principle of operation of co-axial multi-fiber light guide.

Preleminary task

1. Study the principle of transmission of radiation (information) through opto-fiber, the methods used to encode information, the types of fibers used, and their parameters.
2. Determine the transmittance T for optical fiber of 2 m long with attenuation of 10 dB/km (50 dB/km).
3. The laser beam is transmitted along a fiber line with a damping of 0.03 m^{-1}. How will the intensity of light change after 10 m, 100 m?
4. Determine the numerical aperture, the critical angle and the specific refractive index difference for the fibers with $n_1 = 1.47$ and $n_2 = 1.46$.

Theory

The progress in the field of telecommunications, which occurs in recent years, is primarily due to the development and intensive implementation of fiber-optic communication lines (FOCLs) and intensive introduction of endoscopic instruments in medical practice.

The birth of fiber optics dates back to the first demonstration of guiding light by refraction by Daniel Colladon and Jacques Babinet in early 1840s France. The first practical applications of optical fiber appeared early last century when it was used for internal illumination during dentistry procedures. It was not until 1965 though that fiber finally hit its potential when Charles K. Kao (Nobel Prize recipient in Physics 2009) and George A. Hockham, of the firm Standard Telephones and Cables, proposed that optical fiber could be effectively used for telecommunications by removing impurities within the optical glass to reduce the signal attenuation to below the threshold of 20 dB/km. The first optical fiber with losses of 20 dB / km (at a wavelength of 0.633 μm) was manufactured by Corning Glass Works in 1970. In 1972, the losses in OM were reduced to 4 dB / km, and modern fibers have losses of less than 0.2 DB / km (at a wavelength of 1.55 μm). Initially, the fiber was exceptionally brittle. For its functioning as a reliable high-quality component of the system, the fiber should not have flaws and be protected from mechanical impact. Modern fiber can be tied into a knot with a diameter of 5 mm and does not crumble. Typical wavelengths of modern FOCLs are 1.3 and 1.55 μm; Single-mode fiber (also dispersion-shifted fiber), InGaAsP / InP laser transmitter, InGaAsP / InP detector are used.

The fiber optic systems are widely used due to a number of advantages that are absent in the transmission of signals via copper cables (coaxial, twisted pair) or radio, as the transmission medium:

- wide bandwidth;
- low attenuation of signals;
- no electromagnetic interference;
- transmission range for tens of kilometers;
- service life is more than 25 years;
- galvanic isolation.

Fig. 1 shows the structure of the optical fiber. Usually, light-water includes an inner region-a core, with a high refractive index (n_1), homogeneous in the direction of propagation of radiation, as well as an outer shell with a smaller refractive index ($n_2 < n_1$). At the core and spreading radiation. The cross-sections of light guides are different, the most common type of section is round. Light propagating through an optical fiber is an electromagnetic wave; therefore, in order to carry out rigorous analysis, it is necessary to solve the wave equation that follows from the Maxwell equations. We will confine ourselves to representations of geometric optics.

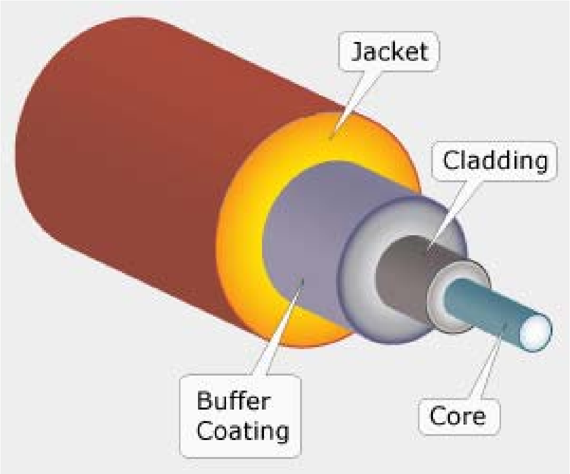


Fig. 1. Fiber structure

It is known that in different media the beam of light propagates at different rates. Getting to the boundary of two transparent media, the ray of light is partially reflected, partially refracted (Fig. 2). The angle of the reflected beam is equal to the angle of the incident ray, and the angle of the refracted ray depends on the ratio of the refractive indices of the media. According to the Snellius law: the product of the sine of the angle of the incident and refracted rays by the corresponding refractive indices of the media is equal.

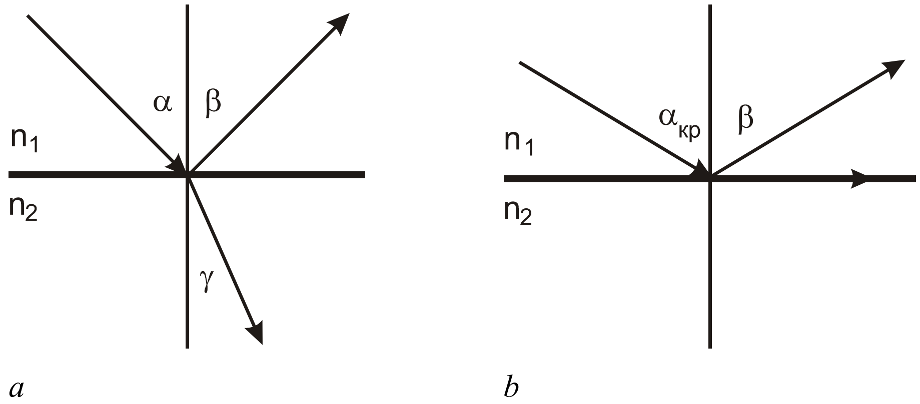


Fig. 2. Passage of light through the interface between two media

Let us set the condition that the refracted beam does not penetrate into the second medium (Fig. 2b), but move along the interface. Since $\gamma = 90$, it is not difficult to calculate the so-called critical angle:

$$\theta_c = \sin^{-1}\frac{n_2}{n_1}$$

Light is transmitted through the core of a fiber optical cable by bouncing off the walls of the cladding by the principle of total internal reflection allowing the fiber to act as a light waveguide. Because the cladding does not absorb light from the core, signals can travel great distances with only slight losses occurring from impurities in the glass. Fiber cable can be made to support a single propagation path (single-mode fiber) or multiple propagation paths (multi-mode fiber).

Let us consider the passage of radiation along a plane lightguide (Fig. 3). Optical ray, passing through the light pipe, experiences full multiple reflections from the interface "core-shell". However, if the angle of incidence Q becomes greater than the critical value, complete reflection does not occur and the radiation penetrates the envelope.

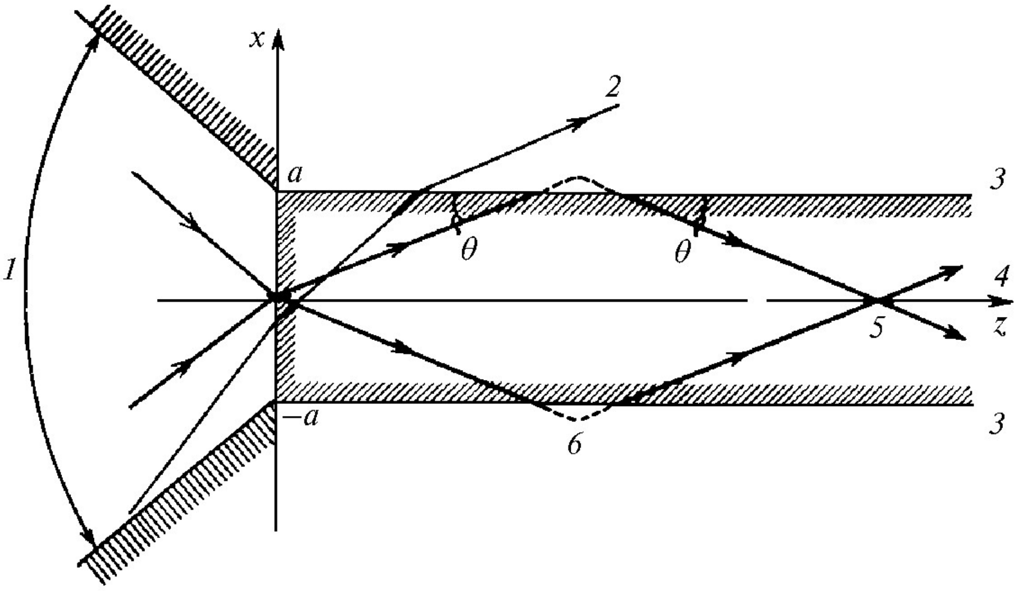


Fig. 3. The propagation of light incident on the optical fiber by optical fiber: 1 - angle of entrance of rays 2Qmax., 2 - light that is not transmitted along the optical fiber ($\Theta > \Theta_c$), 3 - shell with n2, 4 - core with n1, 5 - propagating radiation, 6 - phase shift in reflection

The maximum (critical) angle of entrance at which the total reflection occurs is determined by the formula:

$$Q_c = \arccos\frac{n_2}{n_1} = \arcsin\sqrt{\frac{n_1^2 - n_2^2}{n_1^2}} = \arcsin\sqrt{2\Delta}$$

The parameter Δ is called the specific refractive index difference and is determined by the refractive indices of the core and the shell

$$\Delta = \frac{n_1^2 - n_2^2}{2 \cdot n_1^2} \approx \frac{n_1 - n_2}{n_1} .$$

The ray of light that propagates in the light guide, reflected from the interface at the maximum angle Qc, upon entering the light guide, according to the laws of refraction, falls on its end at an even larger angle $Q_{max} > Q_c$:

$$Q_{max} = \arcsin(n_1^2 \cdot \sin^2 Q_c) = \arcsin\sqrt{(n_1^2 - n_2^2)} .$$

This angle is the maximum angle at which it is possible to draw and output radiation from the light guide. The quantity $NA = n_1 \cdot \sqrt{2\Delta} = n_1 \cdot \sin Q_c$ is called the numerical aperture of the fiber.

Attenuation and distortion of signals in the transmission over optical fiber

The important parameters of an optical fiber are attenuation and dispersion. Fig. 4 shows the spectral characteristics of losses in a quartz fiber. The lowest propagation losses associated with absorption of radiation are from the region 1.3-1.6 µm. Obviously, the main losses are due to the absorption of radiation by impurities, which can not be completely avoided. The minimum losses realized today are less than 0.2 dB / km. That is, on the hundred-kilometer section of the fiber optic cable, the initial radiation will weaken 100 times. Typical for a fiber of length L, the transmission T can be described on the basis of an exponential function:

$$T = \frac{P}{P_0} = e^{-\alpha L}$$

Where P_0 is the input power, P is the output power, and α is the attenuation coefficient. The fiber technique uses a scale in decibels. Therefore, losses are found by the following formula:

$$D = 10\log\frac{P_0}{P} = \bar{\alpha}L$$

Then the attenuation D in the fiber will look like this:

$$T = 10^{\frac{-D}{10}} = 10^{\frac{-\bar{\alpha}L}{10}}$$

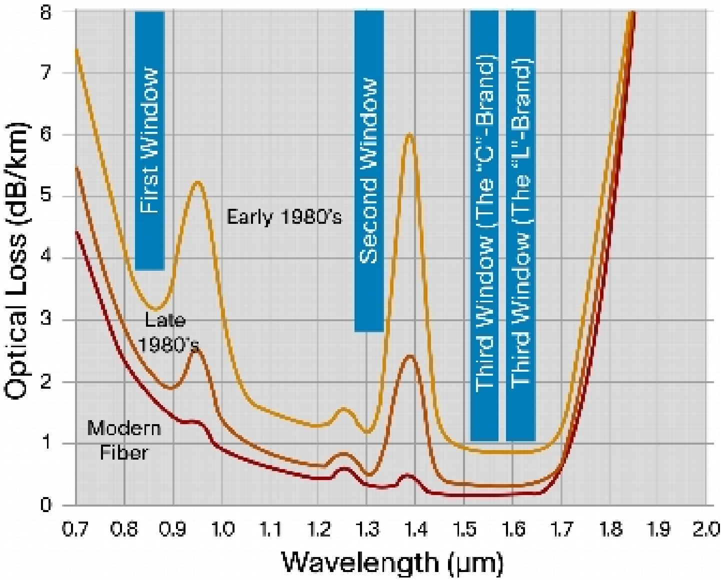


Fig. 4. Losses in optical fiber

Dispersion is the scattering in time of the spectral and mode components of an optical signal. There are three types of dispersion:

- The dispersion of modes is characteristic of multimode fiber and is due to the presence of a large number of modes, the propagation time of which is different.
- The dispersion of the material is due to the dependence of the refractive index on the wavelength.
- Waveguide dispersion - is due to processes inside the mode and is characterized by a dependence of the propagation velocity of the mode on the wavelength.

The attenuation and dispersion of different types of optical fibers are different. For the transmission of signals, two types of fiber are used: one-mode and multimode. The name of the fiber was obtained from the method of propagation of radiation in them.

Multimode optical fiber allows transmitting simultaneously several hundreds of allowed light modes introduced into optical fibers from different angles (Fig. 5a). All allowed modes have different propagation paths and, accordingly, a different propagation time along the optical fiber. Therefore, the main disadvantage of multimode fiber is the large size of the modal dispersion that limits the bandwidth, and accordingly, the range of signal transmission. Bandwidth of multimode fibers reaches 800 MHz·km, which is acceptable for local communication networks. Such fiber is used in FOCL for transmission to a distance of 4 to 5 km. Multimode fibers are convenient for installation, because in them the size of the fiber-conductor is several times larger than in single-mode fibers. Fiber cable is easier to terminate with optical connectors with low losses (up to 0.3 dB) in the joint. Multimode fibers are designed radiators at a wavelength of 0.85 microns - the most affordable and cheap radiators produced in a very wide assortment.

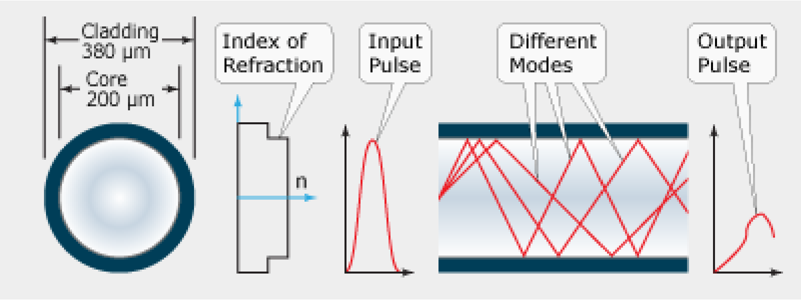


Fig. 5a. Step-Index Multi-mode Fiber

To reduce the modal dispersion and maintain high poles by skipping, in practice, optical fibers with graded index are used. Unlike standard multimode optical fibers having a constant refractive index of the core material, such an optical fiber has a refractive index, which smoothly decreases from the center to the shell (Fig. 5b).

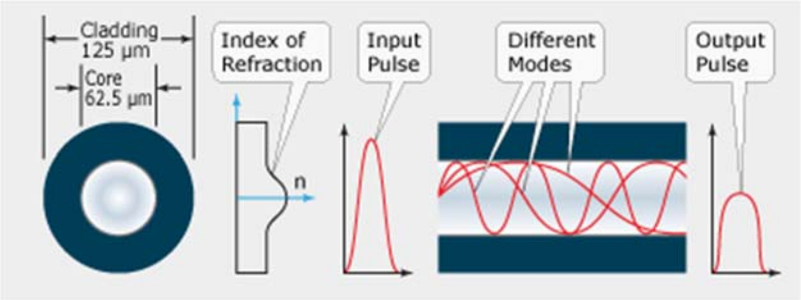


Fig. 5b. Graded-Index Multi-mode Fiber

Single-mode optical fiber (typical size 8/125 µm for wavelengths 1.3-1.55 µm) is designed in such a way that only one basic mode can propagate in the core of the optical fiber (Fig. 5c). If the propagation of light along a multimode fiber, as a rule, the mode dispersion predominates, then only the last two types of dispersion are inherent in a single-mode fiber. This ensures the highest throughput. Therefore, such optical fibers are used in the construction of trunk fiber-optic lines. The main advantages of single-mode optical fibers are a small attenuation of 0.25 dB/km, the minimum value of the mode dispersion and a wide bandwidth. However, single-mode radiation sources are several times more expensive than multimode radiation sources. In single-mode fiber it is more difficult to introduce radiation because of the small dimensions of the lightguide core, for this reason single-mode fibers are difficult to join with small losses.

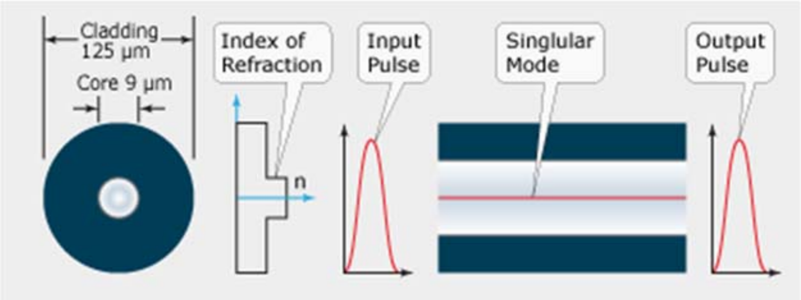


Fig. 5c. Step-Index Single-mode Fiber

Data Transmission

1. Fiber optics are used as a data transmission method whereby data is converted into modulated waves of light to be sent over optical fiber cable. Fiber optics are an alternative to traditional copper based data transmission cables over which they possess several advantages

such as extremely broad bandwidth, low losses even over great distances and inherent resistance to EMI.

Fiber optics offer a great many benefits over traditional copper based signal transmission which has in turn led to their popularity with the telecommunications industry. One main benefit of optical fiber is its massive bandwidth. In fact, fiber can often carry so much data that it would take thousands of metal-based wires to replace one single high-bandwidth fiber optic wire.

Another benefit of fiber cable is its very low signal loss, which allows for great distances between terminations or in-line signal repeaters. While copper cabling typically can run only about a mile before needing amplification, it is not uncommon for fiber optic cable to run 60 miles before signal boosting or processing. One reason for fiber's low losses stems from its lack of electrical conductivity which also means that it produces zero crosstalk between parallel runs of cable over great distances.

As fiber cables are all dielectric, they are effectively immune to RFI/EMI. This means that fiber cabling can be run in areas of high interference such near power lines, utility lines and transmission antennas. Furthermore, fiber cables are ideal for areas where lightning strikes are commonplace. In fact, fiber is even immune to nuclear electromagnetic pulses though it can be damaged by a blast's alpha and beta particle emission.

Because fiber cable is lighter than metal based wires, it is ideal for use on aircraft where weight is always a concern. Safety too is another hallmark of fiber as its inability to spark due to potential differences make it useful in flammable environments. Lastly, fiber is very difficult to signal tap without disrupting the original transmission which makes it a very secure data transmission method.

Broadband doped fiber amplifiers are used as amplifiers for fiber-optic communication lines. They have a higher speed compared to electronic amplifiers and have practically no effect on the information transfer rate. The fiber amplifier consists of quartz fibers several meters long, doped with erbium (concentration 10^{-18}-10^{-19} cm^3). Pumping is carried out by laser diodes with a wavelength of 980 nm; The alternative pump wavelength is about 1.48 μm. The gain is at levels of 30 dB, which corresponds to a gain factor of 1000, with amplifiers saturated at approximately 10 mW output power.

In addition to the use in communication systems, optical fiber has a number of other applications:

2. Delivery of radiation to the working tool in technological and medical systems, as well as for lighting.
3. Observation and measurement by optical means in hard-to-reach zones or in an unfavorable environment.

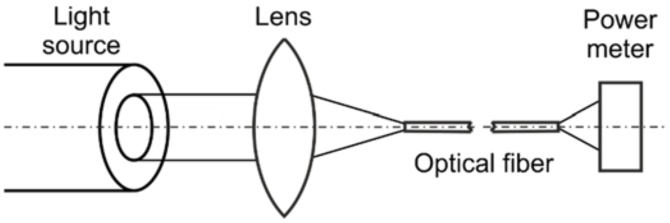
Here we can distinguish two areas of applications based on different effects. In the first case, the optical fiber is used directly to deliver the reflected (or emitted) object of light to the photodetector. In the simplest case, the eyepiece or camera lens. A typical example is the endoscope. Another area of application - fiber optic sensors - is based on a change in the characteristics of radiation (phase, polarization, attenuation, etc.) when passing through optical fibers under the influence of external factors. For this principle, for example, sensors for temperature, pressure, vibration, magnetic and electric fields are built. Fiber optic sensors are well suited for environments with temperatures too high for semiconductor sensors.

4. Generation of radiation by the fiber itself - fiber lasers.

In the fiber laser, the active medium is the core of the optical fiber optical fiber, activated by ions of rare-earth elements. As a rule, this is a single-mode quartz fiber. The pumping pump is transmitted longitudinally along the fiber length and directed either directly to the core itself, where the radiation propagates in the same way as the laser mode radiation, or through the inner shell surrounding this core (a double-clad fiber laser). Distinctive features of single-mode lasers are a very low pumping threshold and a very large gain coefficient, which can be obtained even with moderate pump power from diode lasers. Recently, there has been an increase in interest in fiber-optic lasers as lasers that are capable of operating at high power. This is due to the fact that the geometry of the fiber makes it possible to significantly reduce the role of thermal effects (in particular, the thermal lens) characteristic of such volume elements as laser rods. Today, in a single-mode mode, the continuous generation power exceeds 1 kW, and in multimode mode it reaches tens of kilowatts.

In-lab task

1. Measure the radiation power of the light source (He-Ne laser, solid-state laser).
2. Introduce the laser beam into the optical fiber.
3. Measure the output power of the optical fiber.
4. Calculate the attenuation and attenuation coefficient.
5. Repeat the paragraphs 2-4 for optical fibers of different lengths.
6. Introduce incoherent white light into outer branch of co-axial light-guide.
7. Using the objective obtain the image of the inner surface of the sample given by the teacher.



Scheme of coupling of light beam with optical fiber.

Control questions

1. Modern fiber consists of at least two components: the core and the shell. Which of these parts has a larger refractive index and why?

2. How and why does the pulse width change when passing through the fiber? A) - increases, b) decreases, c) does not change. Because of what is this happening?

3. How to make fiber single-mode?

4. What are the main causes of signal attenuation when transmitting over fiber?

5. Is it possible and why to transmit one fiber at the same time at the same time several signals?

6. Suggest a way to connect two optical fibers.

7. To increase the capacity of an optical channel, multiplexing of data transmission channels is used. How is this realized?

8. What tasks does optical fiber use?

9. Define the three main types of fiber.

10. What frequency band does each types of fiber have and where can it be used?

11. Explain the merits and demerits of single-mode fiber optics.