FIBER OPTIC DEVICES AND SYSTEMS

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Contents

Summary

The working principle and the basic parameters of an optical fiber are introduced in this chapter. The various types of optical fibers are then described, in particular, non-communication types are discussed in detail. This is then followed by the treatment of applications of fibers with particular emphasis on medical sensing, diagnostics and surgery. Most of the fiber optic sensors are based on the simple optic lever principle, i.e. the variation of the received optical intensity is recorded. This variation is caused by the deformation or displacement of the object under examination. Consequently, many sensors can be constructed such as blood flow sensor, humidity sensor, cataract sensor, radiation sensor, bile concentration sensor, blood pH sensor and oximetry sensor. The fiber optic confocal scanning microscope is then described. Fiber bundles can be used as

image transmission such as in endoscopy and also for DNA identification. Finally, applications of fiber in surgery are described such as laser thrombolysis and laser soldering.

1. Introduction

Modern optical fiber consists of two coaxial glass cylinders with the inner one having a larger refractive index than the outer one. This structure was already proposed in the late 19th century but its practical application started with the development of endoscopy in medical technology in the early 1950s when the then Indian PhD student, Narinder S. Kapany, was asked by his supervisor, Professor H.H. Hopkins, to fabricate a meter-length cladded glass fiber for image transmission. At that time, the fiber attenuation was about 1000dB/km but this did not impede its application as an endoscope because the fiber length required was only 1 meter. However, the popularity of optical fiber did not start until 1970 when scientists in Corning Glass Co., USA manufactured the first low loss fiber with attenuation less than 20dB/km.
The applications of optical fiber at the present moment may be classified into four categories: (1) telecommunication, (2) sensing, (3) medical, and (4) illumination. Among these, the telecommunication industry uses most of the fiber and it is this industry, in fact, that stimulated the rapid development of fiber technology. However, medical industry is also building up a strong demand for fiber. This is especially true in diagnostic applications.

The properties of optical fiber required for diagnostic applications are very different from those for telecommunication. For latter applications, the fiber has to transmit information over a very long distance and to transmit as much information as possible. To satisfy these requirements, the fiber loss should be a minimum and its information-carrying capacity, i.e. bandwidth, a maximum. Special fiber design, particularly in the variation of its refractive index in the core, is important. On the other hand, fiber for medical diagnostics has to carry as much optical power as possible so as to deliver a large signal-to-noise to the receiver which may be human eye or a photodetector. The wavelength of light traveling in the fiber is usually different for medical application from that for telecommunication.

The purpose of the present chapter is to describe the construction of optical fibers and their various applications in medical diagnostics.

2. Basic Construction of Optical Fiber

If a beam of light is launched into a length of glass rod at certain launching angle as shown in Figure 1, it will be trapped.

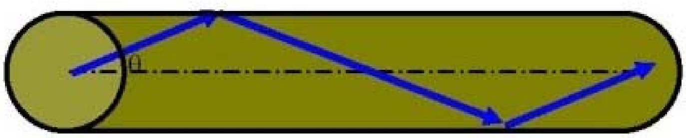

Figure 1: Light ray trapped in a glass rod

The glass has a nominal refractive index n_1=1.5 and it is surrounded by air with a refractive index n_2=1. It can be shown that as long as a ray passes with launching angle θ less than

$$\theta_c = \cos^{-1}\left(\frac{1}{n_1}\right) = \cos^{-1}\left(\frac{1}{1.5}\right) = 48^0 \tag{1}$$

it will be trapped by the fiber. This means that any ray with a launching angle larger than θ_c will not be trapped by the fiber. Hence θ_c is called the critical launching angle of the fiber. Obviously we would like to have θ_c as large as possible because this means that more optical power can be launched into the fiber. However, in practical situations, θ_c is much smaller than 48° because the glass rod is not directly exposed to air as is the case shown in Figure 1. A protective glass cladding is put over the rod as shown in Figure 2.

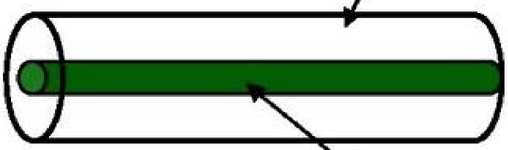

Figure 2: Cladded fiber

Since the purpose of the cladding is to isolate the core from the atmosphere, it is not necessary to be made of glass. Some fibers have plastic cladding and they are called plastic-clad step (PCS) index fiber. For that matter, even the core does not have to be glass. It can also be plastic as long as it is transparent enough. This is called plastic or polymer fiber. However, it is important to have the refractive index n_2 of the cladding to be smaller than n_1 of the core, otherwise no light will be trapped. We note that if there is no cladding as shown in Figure 1, the surrounding air will act as cladding. In this case, n_2=1. On the other hand, if there is a cladding, the critical angle θ_c can be modified from Eq.(1):

$$\theta_c = \cos^{-1}\left(\frac{n_2}{n_1}\right) \tag{2}$$

We are now in a position to examine the realistic magnitude of the critical angle θ_c of standard fibers. In the case of both core and cladding being made of glass, their respective refractive indices are close to each other. For example, if the fiber is made for communication applications, the basic glass material is pure silica SiO_2 which has a fixed index value of 1.457. This is normally the material for cladding, i.e. n_2=1.457. Since the core has to have a larger refractive index, it is achieved by doping the silica with germanium dioxide, GeO_2, i.e. we now have a compound glass SiO_2+GeO_2. In fact, the more GeO_2 is doped, the larger is the resulting refractive index. It may have a value

n_1=1.479. With these two known core (n_1=1.479) and cladding (n_2=1.457) indices, we can calculate the critical launching angle θ_c by means of Eq.(2) and found θ_c =9.8°. This angle is quite small and it implies that not much light can be launched into the fiber. For example, if we have a source emitting light in the forward direction with a radiation pattern as shown in Figure 3 and it is butt-joined directly to the fiber, most of the light from the source will be missed by the fiber, only the light cone with an angle $2\theta_c$ will go into the fiber.

Therefore it is important to choose a light source with a narrow radiation pattern so that most of its light is launched into the fiber. The pattern shown in Figure 3 comes from a Lambertian source such as Light Emitting Diode (LED) and mathematically it is represented by:

$$I(\theta) = I_0 \cos\theta \tag{3}$$

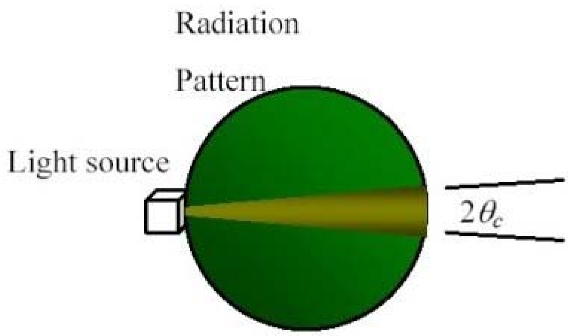

Figure 3: Radiation pattern of light source

where I_0 is the light intensity directly opposite to the light emitting area of the source. An example of light source that delivers a narrow radiation pattern to the fiber is a laser. Its radiation pattern can be represented by

$$I(\theta) = I_0 \cos^{20}\theta \tag{4}$$

where the exponent 20 is quoted as an example to show the narrowness of the radiation pattern generated by the laser. Returning to the consideration of the cladded optical fiber, since only light within the launching angle θ_c is trapped by the fiber, we can represent the light acceptance by a triangle as shown in Figure 4:

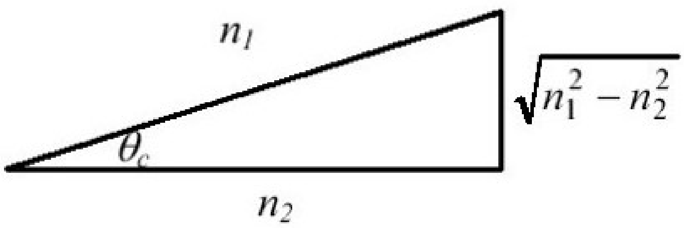

Figure 4: Triangle depicting critical launching angle

The sides enclosing the angle θ_c have respective lengths n_1 and n_2 according to Eq.(2).

Since rays with launching angle less than θ_c will be accepted by the fiber, the length of the vertical side of the triangle in Figure 4 then represents the amount of optical power accepted by the fiber. This is obviously an important quantity and is given a name: the numerical aperture (NA) of the fiber, i.e.

$$NA = \sqrt{n_1^2 - n_2^2} \quad (5)$$

Therefore NA can be interpreted as representing the amount of optical power acceptable by the fiber. It is of interest to note from Eq.(5) that this power is independent of the diameter of the fiber core. This is quite contrary to our common sense. We would have thought that the larger is the diameter, the more optical power it can carry. Eq.(5) indicates that the amount of power accepted by the fiber increases with the difference between of the core index and the cladding index. If both the core and cladding are made of glass, the NA of the fiber is rarely larger than 0.3. This is because it is technologically difficult to dope too much GeO_2 into the core since the thermal expansion coefficient of the core increases linearly with the GeO_2 content. This results in an expanding thermal stress in the core. Too much of this stress may shatter the fiber.

On the other hand, if the cladding is made of polymer (plastic) and the core is still glass, the thermal stress problem is less severe because the polymer is more elastic (much smaller Young's Modulus) and the fiber is less prone to fracture. As a matter of fact, there exist many kinds of polymers with different refractive indices. It is possible to construct the fiber with pure silica (SiO_2) core and a polymer cladding with refractive index less than 1.457. In this way, we do not have to introduce GeO_2 into the glass.

A further modification of the optical fiber is to replace the glass core by a polymer core in addition to the polymer cladding. This becomes a fully plastic optical fiber. The stress problem is further relieved and a numerical aperture as large 0.7 can be obtained.

3. Multimode and Single mode Fibers

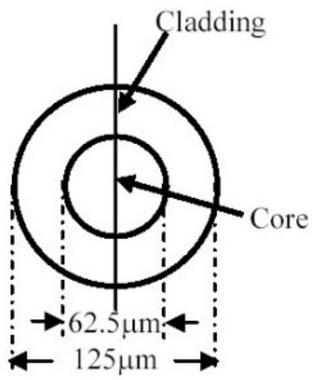

Figure 5: Telecommunication type multimode fiber

Many of us heard of two types of optical fibers: Multimode and single mode. Not only that their constructions are different, they also find different applications. In general, multimode fibers are used to carry large amount of optical power and hence large numerical aperture is important. On the other hand, single mode fibers are mainly concerned with the transmission of information. Its power-carrying capacity is less important than its information-carrying capacity, i.e. its bandwidth. Another important application of single mode fiber is in optical sensing where the interferometric principle is utilized.

As it was pointed out in Section 2, an optical fiber consists of two concentric cylinders of transparent materials such as glass or polymer. In the case of multimode fiber, the core diameter is usually very large. For example, when the fiber is used for telecommunication, both the outer diameter and the core diameter have standard values as shown in Figure 5, i.e. the core diameter is 62.5μm and the overall diameter (core + cladding) is 125μm.

Fibers for medical applications usually have larger core and overall diameters than telecommunication type. Its core may be as large as 400μm and the overall diameter 600μm.

Polymer fiber (both core and cladding are made of polymer) have 900μm core and 1mm overall diameter.

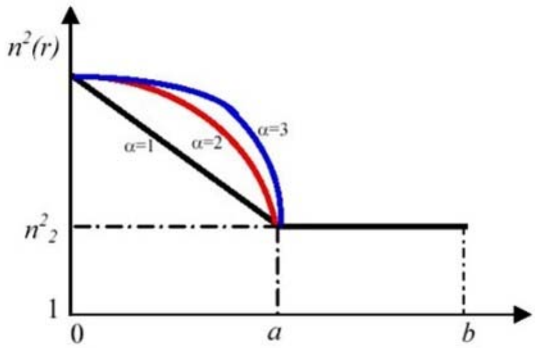

Figure 6: Refractive index profile of multimode optical fiber

Multimode fibers can also be divided into two categories: step index and graded-index. In step index fiber, the refractive index of the core is a constant value, say n_1, which is slightly larger than the cladding index n_2. However, in graded-index fiber, the refractive index n of the core decreases monotonically with the radial distance from the center as shown in Figure 6 where a is the core radius and b is the overall radius of the core and cladding combination.

The variation of the refractive index profile within the core is usually represented mathematically by:

$$n^2(r) = n_1^2\left[1 - 2\Delta\left(\frac{r}{a}\right)^{\alpha}\right] \qquad (6)$$

where α is the profile index. When α=1, the profile is a straight line as shown in Figure 6. When α=2, it is a parabola etc. Δ is the relative index difference between the core and cladding and mathematically it is given by:

$$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2} \tag{7}$$

where n_1 is the index at the axis of the fiber and n_2 is the cladding index.

Since n_1 and n_2 are quite close to each other, Δ is usually very small, in the order of 1%. Of all the multimode graded index fibers, the one with parabolic index profile (α=2) is the most popular because it has nearly the maximum information-carrying capacity (bandwidth) and consequently finds widespread applications in local area communication networks. A nominal bandwidth of a parabolic index fiber is 1Gb/s-km, i.e. it can deliver 1000 million pulses in one second over a length of one kilometer.

Single mode optical fiber has a much smaller core diameter than that of multimode fiber. Unlike the multimode communication-type fiber in which the core diameter has a standard value of 62.5μm, there is no such a standard for single mode fiber. In general, its core diameter is about 10 times less than that of multimode fiber. In fact, for any given fiber, it can be single-mode or multimode depending on whether it satisfies the following equation:

$$\lambda_c = \frac{2\pi}{2.405} a \sqrt{n_1^2 - n_2^2} \tag{8}$$

where λ_c is called the cut-off wavelength of the fiber. If the operating wavelength of light is larger than λ_c , the fiber is single mode because there is only one wave pattern (mode) of light that can travel within the core.

This is called the fundamental mode of the light. On the other hand, if the operating wavelength is less than λ_c , the fiber is multimode because there exist more than one wave patterns (modes) in the fiber. The number of modes increases rapidly if the operating wavelength is reduced from λ_c . In this case, it can be shown that when the operating wavelength is less than half of λ_c , the number of modes in the fiber is given by:

$$N = \frac{V^2}{2} \tag{9}$$

where V is the normalized frequency of the fiber and is given by:

$$V = \frac{2\pi}{\lambda} a \sqrt{n_1^2 - n_2^2} \tag{10}$$

where λ is the operating wavelength.

For communication-type single mode fiber, the core diameter is about 8μm. Its overall diameter (core + cladding) is still 125μm.

4. Types of Non-communication Fiber

The development of communication fibers has dominated the industry in the past thirty years. However, there are many other areas of applications that require optical fibers and each of these areas, similar to communications, needs different type of fiber. These areas may include medicine, sensing, and illumination etc.

While the communication fiber is mainly concerned with its information-carrying capacity and its signal attenuation rate, i.e. dB/km, the non-communication fiber is mainly concerned with its power-carrying capacity while the fiber attenuation is only secondary consideration. The wavelength of light launched into the fiber can also vary from ultraviolet to far infrared depending on application whereas, in the case of communication, three main wavelengths are used, i.e. 850nm, 1300nm and 1550nm.

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Biographical Sketch

Pak L Chu was born in China and received his high school education in Hong Kong. He then entered the University of New South Wales, Sydney, Australia to pursue his BE(Hons), ME and PhD degrees in the School of Electrical Engineering. After graduation, he spent a year with AWA Pty Ltd, Sydney, working on microwave antenna research and development. A year later, he returned to the School of Electrical Engineering, University of New South Wales, as a tutor and then lecturer, senior lecturer, associate professor, and finally professor and head of the optical communications group. In July 2001, he returned to Hong Kong and took up the position as the Director of the Optoelectronics Research Centre and Chair Professor of the Department of Electronic Engineering, City University of Hong Kong. His research interests are in optical communication, optical fiber technology, optical sensing, optical waveguide technology, electromagnetic theory, plasma oscillations and wave propagation in nonlinear media. He has published more than 400 papers in international journals and conferences in these areas.

Dr. Chu is a Fellow of the Australian Academy of Technological Sciences and Engineering, a Fellow of the Optical Society of America (OSA), and a Fellow of the Institution of Engineers, Australia. He received the Centenary Medal from the Prime Minister’s Department of Australia in 2003 for his contributions in optical communications.