The Adam Hilger Series on Optics and Optoelectronics

Infrared Optical Fibers

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To our wives

Mitsuko Matsumura and Tomoko Katsuyama

Series Editors' Preface

Optics has been a major field of pure and applied physics since the mid 1960s. Lasers have transformed the work of, for example, spectroscopists, metrologists, communication engineers and instrument designers in addition to leading to many detailed developments in the quantum theory of light. Computers have revolutionised the subject of optical design and at the same time new requirements such as laser scanners, very large telescopes and diffractive optical systems have stimulated developments in aberration theory. The increasing use of what were previously not very familiar regions of the spectrum, e.g. the thermal infrared band, has led to the development of new optical materials as well as new optical designs. New detectors have led to better methods of extracting the information from the available signals. These are only some of the reasons for having an *Adam Hilger Series on Optics and Optoelectronics*.

The name Adam Hilger, in fact, is that of one of the most famous precision optical instrument companies in the UK; the company existed as a separate entity until the mid 1940s. As an optical instrument firm Adam Hilger had always published books on optics, perhaps the most notable being Frank Twyman's *Prism and Lens Making*.

Since the purchase of the book publishing company by The Institute of Physics in 1976 their list has been expanded into all areas of physics and related subjects. Books on optics and quantum optics have continued to comprise a significant part of Adam Hilger's output, however, and the present series has some twenty titles in print or to be published shortly. These constitute an essential library for all who work in the optical field.

Preface

Since Pinnow, Van Uitert, Goodman *et al* discussed in 1978 the possibility of an ultra-low loss optical fiber with a loss of less than 0.01 dB km^{-1}, non-silica-based infrared fibers have become a center of interest in optical fiber research. The number of articles appearing in the technical journals has increased significantly, although to our knowledge there have as yet been no books describing infrared optical fibers systematically.

This may be the first book on infrared optical fibers. It is intended as a state-of-the-art review for use by researchers and engineers engaged in these research fields, and also as an introductory textbook for readers wanting to begin research on infrared optical fibers. It is assumed therefore that readers have a basic, but not necessarily extensive, background knowledge of physics and chemistry. Chapters 2 and 3 give the basic concepts of optical fibers for infrared transmission, including the theory of light guiding and of transmission loss. Readers do not therefore need any particular knowledge of optical fibers.

The book is largely influenced by many excellent review papers on the infrared material and fiber technology; particularly I W Donald and P W McMillan, *Review of Infra-red Transmitting Materials* (1978 *J. Mater. Sci.* **13** 1151–76), T Miyashita and T Manabe, *Infrared Optical Fibers* (1982 *IEEE J. Quantum Electron.* **QE-18** 1432–50), and D C Tran, G H Sigel Jr and B Bendow, *Heavy Metal Fluoride Glasses and Fibers: A Review* (1984 *J. Lightwave Technol.* **LT-2** 566–586). In addition, the description of the concepts of optical fibers (§§2.1 and 2.2) is based on the book written by Y Suematsu and K Iga: *Introduction to Optical Fiber Communications* (1982 John Wiley and Sons, New York, translated into English by H Matsumura and W A Gambling). We would like to thank the authors for giving us some ideas on book preparation.

We also thank the editors and authors of some technical journals for allowing us to use figures which appear in this book. The cited journals include *Applied Optics*, *Optics Letters*, the *Journal of Applied Physics*,

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Applied Physics Letters, the *IEEE Journal of Quantum Electronics*, the *Journal of Lightwave Technology*, *IEEE Transactions: Microwave Theory and Techniques*, the *Journal of Non-Crystalline Solids*, *Electronics Letters*, the *Materials Research Bulletin*, the *Japanese Journal of Applied Physics*, the *Physics and Chemistry of Glasses*, *Infrared Physics*, the *Journal of Materials Science*, the *Bell System Technical Journal*, *Kougakugijitsu contact* (the *Journal of the Association of Optical and Electro-optical Technology)*, *Tsuuken kenkyuu jitsuyouka houkoku (Electrical Communication Laboratories Technical Journal)*, *Denki gakkai zasshi (Journal of Institute of Electrical Engineers of Japan)*, *Ouyou butsuri (Journal of the Japan Society of Applied Physics)* and *Laser kennkyuu (Journal of Laser engineering)*. Figures are also cited from the materials issued by the Institute of Electrical Communication, Tohoku University, Le Verre Fluore and John Wiley and Sons, Inc.

The authors wish to extend their appreciation for the encouragement given by Drs Y Takeda and M Kudo of the Central Research Laboratory of Hitachi Ltd. Thanks are also due to Drs B Yoda, H Nagano and K Mikoshiba of Hitachi Cable Co. for their encouragement throughout infrared fiber research.

Toshio Katsuyama
Hiroyoshi Matsumura
Tokyo, January 1988

Contents

1 Introduction

Recently, optical fibers have become a center of interest as transmission lines for such diverse applications as communication links and sensing systems. In particular, optical fiber communications offer an exciting alternative to traditional wire communications. These are mainly based on the successful fabrication of low loss silica-based optical fibers whose transmission losses are reduced to as low as 0.2 dB km^{-1}. Thus, the low loss quality of silica-based optical fibers has enabled us to construct high bit-rate and long haul communication systems. For example, in Japan optical communication links spanning the Japanese islands have already been established and the telecommunication services using these systems have become commercially available. However, the demand for further improvements in transmission capacity is still increasing. These high capacity optical communication systems essentially require the realization of ultra-low loss optical fibers with losses far below those of the silica-based optical fibers.

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Historically Pinnow *et al* (1978), Van Uitert and Wemple (1978) and Goodman (1978) first discussed the possibility of an ultra-low loss, less than 10^{-2} dB km^{-1}, for infrared materials, and these discussions motivated the research efforts on the non-silica-based infrared optical fibers. Furthermore, there have been increasing demands on laser power transmission through flexible optical fibers in the fields of laser surgery and machining. Since CO_2 laser power transmission is particularly useful in these fields, studies on low loss infrared fibers at a 10.6 μm wavelength have been extensively performed.

Optical materials studied to date for infrared optical fibers are heavy-metal oxides, halides and chalcogenides. In the heavy-metal oxides, GeO_2-based glasses have been extensively studied since Olshansky and Scherer (1979) predicted a low loss reaching below 0.2 dB km^{-1}. On the other hand, polycrystalline and single-crystalline halide materials such as TlBr–TlI mixed crystal (which is called KRS-5), AgCl, AgBr, KCl and CsBr have mainly been studied. These crystalline materials are particularly advantageous for laser power transmission because the losses are sufficiently low at a CO_2 laser wavelength of 10.6 μm. Chalcogenides so far studied are basically divided into sulfides, selenides and tellurides whose states are vitreous or glassy. Among them, sulfide glass fibers can transmit light of wavelength between 2 and 5 μm. On the other hand, selenide and telluride glass fibers have a wide transparency range which covers around 10 μm in wavelength. These selenide and telluride glass fibers are therefore being studied for CO_2 (10.6 μm) and CO (5.3 μm) laser power transmissions.

It should be noted that the infrared fiber research has been accelerated by the discovery of ZrF_4-based fluoride glasses by Poulain *et al* (1975). This discovery and the subsequent researches on the ZrF_4-based glasses have made it possible to fabricate low loss infrared fibers. The progress of the loss reduction is so fast that a loss of less than 1 dB km^{-1} has been obtained (Tran 1986, Kanamori and Sakaguchi 1986). These fluoride glasses are therefore thought to be the most promising candidates for the ultra-low loss optical fibers in long distance optical communications. The loss value predicted is less than 0.01 dB km^{-1} at 2–4 μm wavelengths.

On the other hand, various hollow waveguides have been studied mainly for infrared light power transmission, particularly CO_2 laser power transmission at a 10.6 μm wavelength. The transmission characteristics of various metallic hollow waveguides, such as parallel-plate metallic waveguides and dielectric-coated metallic hollow waveguides, have been improved. Hollow core fibers utilizing total reflections between the hollow cores and dielectric claddings have also been proposed. This light guiding is possible only in the wavelength regions of abnormal dispersion where the refractive indices become lower than unity.

Applications of infrared optical fibers can be classified into two categories: long distance optical communications and short haul light transmissions, as shown in the above description. Among them, long distance optical communications require infrared fibers which have ultra-low losses and low dispersions. On the other hand, short haul light transmissions require them with wide band transparency and/or high power light transmission. The applications in short haul transmissions are, for example, optical transmissions in a nuclear radiation environment, infrared remote sensing such as temperature measurement by thermal radiations, and laser surgery and machining.

This book is divided into eight chapters. Following this introductory chapter, basic concepts of optical fibers including the mechanism of light guiding, refractive index and dispersion properties, and transmission loss characteristics are described in chapter 2. These concepts are fundamental to the understanding of optical fibers. In chapter 3, introductory remarks on infrared optical fibers are presented. The historical sketch, materials for infrared transmission, classifications and applications of the infrared optical fibers studied to date, and some measurement techniques of transmission properties are briefly described. Thus one can obtain an overview of the infrared optical fiber researches and their applications.

Chapters 4 and 5 are devoted to the detailed descriptions of the glass fibers and crystalline fibers for infrared transmission. Materials, fabrication techniques and properties of these fibers are described. A hollow waveguide whose light guiding mechanism is slightly different from the conventional optical fibers is presented in chapter 6. Furthermore, chapter 7 describes in detail the applications of infrared optical fibers, including ultra-long repeaterless links, nuclear radiation resistant links, measurement systems of thermal radiation, and laser power transmission systems. Finally, concluding remarks and prospects for future work are added in chapter 8.

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2 Basic Concepts of Optical Fibers

In this chapter the fundamental properties of optical fibers are described. The mechanism of light guiding, refractive index and dispersion properties, and transmission loss characteristics are the most important concepts for understanding optical fibers, including infrared optical fibers.

2.1 The mechanism of light guiding

2.1.1 The basic structure of an optical fiber

An optical fiber consists of a central part called the 'core', surrounded by a material called the 'cladding', as shown in figure 2.1. The core has a refractive index n_1, which is higher than that of the cladding n_2. Therefore, electromagnetic waves can be confined in the core region and are transmitted by total internal reflections at the boundary between the core and cladding. In the low loss silica glass fiber which is used for optical fiber communications the typical core diameter is usually in the range from a few micrometers to tens of micrometers, and the outer cladding diameter is fixed at 125 μm. Also optical fibers are normally given a plastic primary coating and then a nylon coating, because fibers without coating are very weak mechanically and are subject to chemical attacks by moisture. An optical fiber cable may contain several coated optical fibers.

2.1.2 Refraction and reflection of a light ray

Since the light is described as an electromagnetic wave, its propagation property must be explained in terms of Maxwell's equations. However, it is often convenient to use geometrical optics when the wavelength of light is considerably shorter than the core dimension.

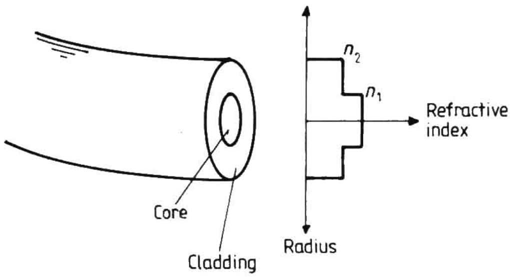

Figure 2.1 The structure of an optical fiber.

First let us consider the refraction and reflection of light at the boundary of two dielectric media with different refractive indices. These are most important basic concepts in light guiding.

In figure 2.2, n_1 and n_2 are the refractive indices of media I and II respectively. In the case of $n_1 < n_2$ (figure 2.2(*a*)), the light ray, which is projected obliquely onto the boundary from the upper left, changes direction at the boundary. The refraction angle follows from Snell's law, that is

$$\frac{\sin \alpha_1}{\sin \alpha_2} = \frac{n_2}{n_1}, \tag{2.1}$$

where α_1 and α_2 are the angles made by the input and refracted rays, respectively, with the normal to the interface. For the complementary angles θ_1 and θ_2, equation (2.1) can be expressed as

$$\frac{\cos \theta_1}{\cos \theta_2} = \frac{n_2}{n_1}. \tag{2.2}$$

On the other hand, when $n_1 > n_2$ (figure 2.2(*b*)), then θ_2 decreases with decreasing θ_1, until finally we find $\theta_2 = 0$ at a certain finite value of θ_1, because $\theta_1 > \theta_2$ from equation (2.2). At this point, transmission of the light wave into medium II ceases completely, and all the energy is totally reflected at the boundary. The angle $\theta_1 = \theta_c$ at which this total reflection occurs is given, from equation (2.2), by

$$\theta_c = \cos^{-1}\left(\frac{n_2}{n_1}\right). \tag{2.3}$$

θ_c is called the 'critical (complementary) angle' or the 'total reflection complementary angle'.

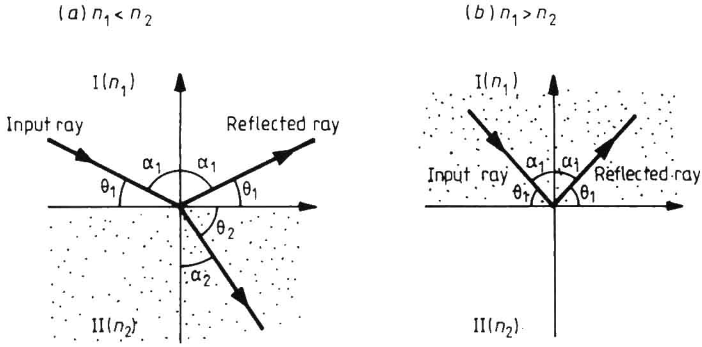

Figure 2.2 Refraction and reflection of a light ray, for (*a*) $n_1 < n_2$, and (*b*) $n_1 > n_2$ (total reflection).

2.1.3 The mechanism of light guiding

Let us consider the principle of the guiding mechanism of the optical fiber. The refractive index n_1 in the central region (called the core) in figure 2.3 is higher than n_2, that of the surrounding region (called the cladding). Furthermore, the refractive index in the core is uniform, forming the 'step-index optical fiber'. Consider a ray 1 in air at an angle θ' to the fiber axis, as in figure 2.3, striking the core. Due to refraction at the air/fiber surface, the angle of the ray to the axis changes to θ as it enters the core, where, from equation (2.1),

$$\frac{\sin \theta'}{\sin \theta} = n_1, \tag{2.4}$$

since the refractive index of air is 1.

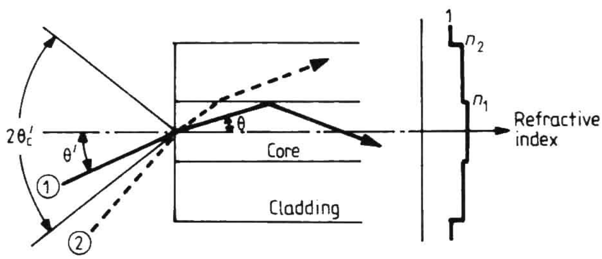

Figure 2.3 Light transmission in an optical fiber.

If the angle θ of the ray to the axis inside the core is smaller than the total reflection complementary angle $\theta_c = 90° - \alpha_c = \cos^{-1}(n_2/n_1)$

(where α_c is the critical angle), then complete reflection occurs and the ray continues to propagate along the core, since all subsequent reflections occur at the same angle and therefore with no loss of energy. On the other hand, if a ray 2 enters at such a wide angle that inside the core it strikes the core/cladding boundary at an angle greater than θ_c, then only partial reflection takes place and some of the energy is lost by refraction into the cladding. After several successive reflections, very little energy is left in the core and the guidance is lost. Thus only those rays up to an angle θ'_c in air are accepted and guided by the core.

In most practical situations, and especially with optical fibers, the difference between n_1 and n_2 is small, that is $n_1 - n_2 \ll n_1$, so that the 'relative refractive index difference' Δ can be defined by

$$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2} \simeq \frac{n_1 - n_2}{n_1}. \tag{2.5}$$

Δ is usually expressed as a percentage.

The total reflection complementary angle in the core from equation (2.3) can be written in terms of Δ as follows:

$$\begin{aligned} \theta_c &= \cos^{-1}(n_2/n_1) = \cos^{-1}(1 - \Delta) = 2\sin^{-1}(\tfrac{1}{2}\Delta)^{1/2} \\ &\simeq (2\Delta)^{1/2} \qquad \Delta \ll 1. \end{aligned} \tag{2.6}$$

Thus, when $\Delta = 1\%$ we have $\theta_c = 0.14$ rad $= 8.0°$.

The maximum acceptance angle (figure 2.3) is given by $2\theta'_c$, where $\theta'_c = \sin^{-1}(n_1 \sin\theta_c)$, so that

$$2\theta'_c = 2\sin^{-1}(n_1 \sin\theta_c) \simeq 2\sin^{-1}(n_1^2 - n_2^2)^{1/2}. \tag{2.7}$$

Another important definition is that of 'numerical aperture', often abbreviated to *NA*, which is given by

$$NA = \sin\theta'_c = n_1 \sin\theta_c = (n_1^2 - n_2^2)^{1/2} \simeq n_1(2\Delta)^{1/2}. \tag{2.8}$$

Thus if $\Delta = 1\%$ and $n_1 = 1.5$, then $NA = 0.21$ and $2\theta'_c = 24°$.

The parameters such as the relative refractive index difference Δ, the acceptance angle $2\theta'_c$ and the numerical aperture *NA* are the fundamental values describing the characteristics of optical fibers.

2.1.4 The concept of modes

An optical wave guided by successive total internal reflections may be represented by bundles of rays called the 'modes'. By using the idea of the mode, the phenomenon of light guidance, so far expressed by the total internal reflections of rays, can also be treated as a wave, which is the other characteristic of light. In order to provide a basic explanation of the modes, we consider for simplicity a two-dimensional slab of uniform material. Figure 2.4 shows the rays which make an angle $\pm\theta$

with the core/cladding interface of the slab waveguide. Each ray represents a plane wave from the wave point of view and is drawn perpendicularly to the wavefront.

The quantity

$$k_0 = \frac{2\pi}{\lambda} \tag{2.9}$$

denotes the 'phase constant' and λ the wavelength of the plane wave in a vacuum. Within the core, where the refractive index is n_1, the wavelength becomes smaller ($= \lambda/n_1$) while the phase constant is larger ($= k_0 n_1$).

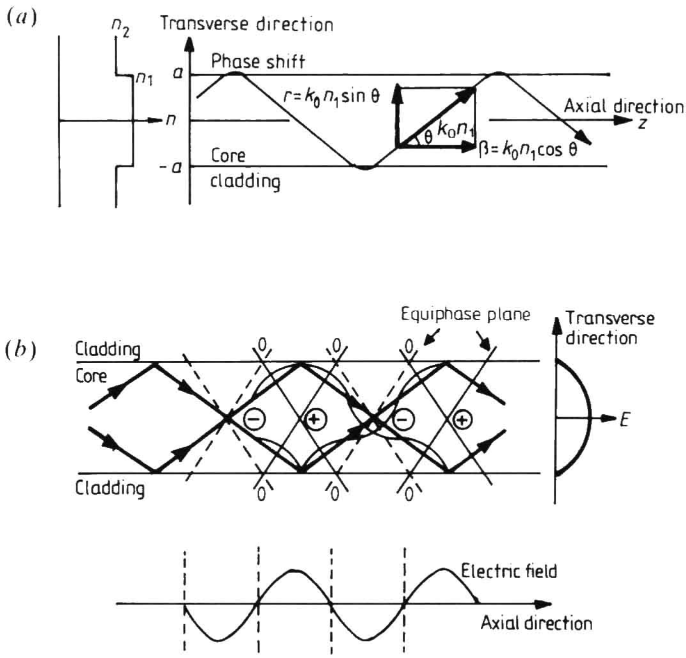

Figure 2.4 Formation of a mode in a dielectric waveguide. (*a*) Decomposition of the propagation direction. (*b*) Interference of the incident and reflected waves (after Suematsu and Iga 1982).

This plane wave can be resolved into two component plane waves propagating in the axial and transverse directions, as shown in figure 2.4(*a*). The plane wave, or equivalent ray, travels along its path with a phase constant $k_0 n_1$ and at a constant angle $\pm\theta$ to the axial direction by successive reflections along the complete length of the waveguide. The component of the phase constant in the axial direction is $k_0 n_1 \cos\theta$, and this is also, therefore, the axial propagation constant β. That is

$$\beta = k_0 n_1 \cos\theta. \tag{2.10}$$

On the other hand, if γ denotes the transverse component of the propagation constant, it is similarly given by

$$\gamma = \pm k_0 n_1 \sin\theta. \tag{2.11}$$

The transverse component of the plane wave is reflected at the core/cladding interfaces, so that when the total phase change after two successive reflections at the upper and lower interfaces becomes $2m\pi$ (where m is any integer), a standing wave is established in the transverse direction. Figure 2.4(b) shows this self-consistent field in terms of the interference of the two light rays, where a positive electric field direction along the phase plane vertical to the ray is expressed by the faint solid lines and the negative field by the faint dashed lines.

Near the boundary between the core and the cladding, the positive and negative phase planes always coincide, so that the electric field becomes zero. On the other hand, in the central region the fields sum and the combined electric field on the axis becomes large. This behaviour is equivalent to the confinement of the optical wave.

In the case just described, the field distribution in the transverse direction does not change as the wave propagates in the axial direction. This kind of stable field distribution is called the mode and is obtained only when the angle between the ray and the interface has a particular value.

Figure 2.5 shows the field distribution for each mode. The mode is characterized by the mode number, which is equal to the number of zeros of the intensity distribution in the transverse direction. This property of the mode is, of course, applicable to the slab waveguide. However, the propagation characteristics of a circular cylindrical fiber can be easily predicted by using a certain correspondence between the slab and the cylindrical fiber.

So far we have considered the so-called multimode optical fiber. The multimode optical fiber can support a large number of modes. In describing the characteristics of the circular fiber, it is convenient to introduce the normalized frequency V:

$$V = \frac{2\pi}{\lambda} n_1 a (2\Delta)^{1/2} = (n_1^2 - n_2^2)^{1/2} k_0 a, \tag{2.12}$$

where λ is the free-space wavelength and a is the core radius. The multimode operation results when $V > 2.4$. In contrast, the optical fiber with a normalized frequency of less than 2.4 is called the 'single-mode

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