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Introduction: Faster, Further, More Information

The realization of these three features has motivated the development of communication systems since the dawn of history. Optical communication systems in the broad sense date back to ancient times. One of the earliest optical communication systems was fire and smoke. Although atmospheric conditions, such as rain, snow, fog, and dust, strongly affect the transmission reliability, this type of optical communication was used for a long time worldwide. In addition to the sensitivity to the environmental conditions, the signal receiver was the human eye; thus, the transmission system had poor reliability. More stable and dependable communication systems were developed; for instance, a courier or pigeon carried messages and letters.

The era of electrical communication started in 1837 with the invention of the telegraph by Samuel F. B. Morse. The telegraph system used the Morse code, which represents letters and numbers by a coded combination of dots and dashes. The encoded symbols were conveyed by sending short and long pulses of electricity over a copper wire at a rate of tens of pulses per second. The telegraph and Morse code dramatically improved the speed, quality, and information capacity of transmission, although well-trained and skilled operators were required.

Another giant leap in the history of communication systems was brought about by Alexander Graham Bell in 1876. Bell developed a fundamentally different and user-friendly device that could transmit the entire voice as is, in an analog signal. The device is the telephone, which rapidly increased the speed and quality of communication. Subsequently, the invention of the facsimile machine enabled the transmission of figures and drawings. The development of electrical communication systems shifted to use progressively higher frequencies, which offered increases in bandwidth or information capacity. Optical communication was gradually becoming attractive because optical frequencies are several orders of magnitude higher than those used by electrical communication systems. Therefore, the optical carrier frequencies yield a far greater potential transmission bandwidth than electrical systems with metallic cables.

No significant advance in optical communication appeared until the invention of the laser in the early 1960s because no practical transmitter existed, and all communication systems must include the fundamental elements of a transmitter, the transmission medium, and a receiver. The invention of the laser aroused

curiosity about the possibility of using the optical wavelength region of the electromagnetic spectrum for transmission systems. The optical frequencies generated by such a coherent optical source are on the order of 10^{14} Hz, and the laser theoretically has an information capacity exceeding that of microwave systems by a factor of 10^5 . Experimental investigations using atmospheric optical channels were conducted in the early 1960s with the potential of such broadband transmission capacities in mind. However, the transmission quality was unstable, again depending on the atmospheric conditions. At the same time, it was recognized that an optical fiber can provide a more reliable transmission channel because it is immune to environmental conditions [1]. The initial optical fibers appeared impractical because of their extremely large optical losses of more than 1000 dB/km. The situation changed in 1966, when Kao and Hockham speculated that the high losses were a result of impurities in the fiber material, and that the losses could potentially be reduced significantly in order to make optical fibers a functional transmission medium [2]. The technical breakthrough for optical communication occurred in 1970, only 4 years after this prediction; an optical fiber was demonstrated with a purified silica glass having an optical power loss low enough for a practical transmission link [3]. Charles K. C. Kao won the Nobel Prize in physics in 2009 for his pioneering insight and his enthusiastic further development of low-loss optical fibers. Ultimately, these efforts resulted in practical optical communication systems widely used across the earth. Optical fiber systems commonly provide great advantages such as longer distance, greater information capacity, immunity to electromagnetic interference, information security, smaller size, and lighter weight. Applications for these sophisticated networks include web browsing, e-mail exchange, telemedical care, remote education, and grid and cloud computing.

The telecommunication industries seriously considered standardizing on multimode fibers (MMFs) before deciding to adopt single-mode fibers (SMFs; see the next section). MMFs are very attractive because the mechanical tolerances of link components, such as connectors, splices, and coupling optics, are remarkably relaxed compared to those of SMFs. However, MMFs were considered unsuitable for telecommunication systems in the final analysis because of two critical technical problems: modal noise, and unstable bandwidth performance. Modal noise is attributed to fluctuation in time of the speckle pattern resulting from interference between the propagating modes, and bandwidth instability arises from the central dip in the refractive index. In contrast, plastic optical fibers (POFs) have an enormous number of propagating modes, and hence speckle patterns, which practically cancel the modal noise effect by averaging the fluctuations. POFs have essentially no central dip because of fabrication processes. Thus, serious modal noise and unstable bandwidth have not been observed, even though POFs are MMFs. Therefore, because the large mechanical tolerance provides easy and cost-effective installation, MMFs, particularly POFs, have become attractive again and have gradually been installed in short-reach networks such as local area networks (LANs) in homes, offices, hospitals, and vehicles, and even very short-reach networks such as interconnects inside computers which contain many connections.

This chapter briefly describes the fundamentals of optical fibers and provides an introductory review of the development of POFs.

1.1

Principle of Optical Fiber

The principle of light propagation through optical fibers is simply explained as follows [4, 5]. An optical fiber generally consists of two coaxial layers in cylindrical form: a core in the central part of the fiber and a cladding in the peripheral part that completely surrounds the core. Although the cladding is not required for light propagation in principle, it plays important roles in practical use, such as protecting the core surface from imperfections and refractive index changes caused by physical contact or contaminant absorption, and enhancement of the mechanical strength. The core has a slightly higher refractive index than the cladding. Therefore, when the incident angle of the light input to the core is greater than the critical angle determined by Snell's law, the input light is confined to the core region and propagates a long distance through the fiber because the light is repeatedly reflected back into the core region by total internal reflection at the core–cladding interface. The propagation of light along the fiber can be described in terms of electromagnetic waves called *modes*, which are patterns of electromagnetic field distributions. The fiber can guide a certain discrete number of modes that must satisfy the electric and magnetic field boundary conditions at the core–cladding interface according to its material and structure and the light wavelength.

Optical fibers can be commonly classified into two types: SMFs and MMFs [6]. As the names suggest, SMF allows only one propagating mode, whereas MMF can guide a large number of modes. Both SMFs and MMFs are again divided into two classes: step-index (SI) and graded-index (GI) fibers. The SI fiber has a constant refractive index in the entire core. The refractive index changes abruptly stepwise at the core–cladding boundary. The GI fiber has a nearly parabolic refractive index distribution. The refractive index decreases gradually as a function of the radial distance from the core center. Figure 1.1 conceptually illustrates the refractive index profiles and ray trajectories in SMF and in SI and GI MMFs, and shows the measured input and output pulse waveforms. The most significant difference among these types of fibers is modal dispersion. Because modal dispersion is described in detail in Chapter 3, the difference due to modal dispersion is only briefly explained here.

When an optical pulse is input into an MMF, the optical power of the pulse is generally distributed to a huge number of the modes of the fiber. Different modes travel at different propagation speeds along the fiber, which means that different modes launched at the same time reach the output end of the fiber at different times. Therefore, the input pulse broadens in time as it travels along the MMF. This pulse broadening effect, well known as *modal dispersion*, is significantly observed in SI MMFs. As shown in Figure 1.1, different rays travel along paths with different lengths; here each distinct ray can be thought of as a mode in a

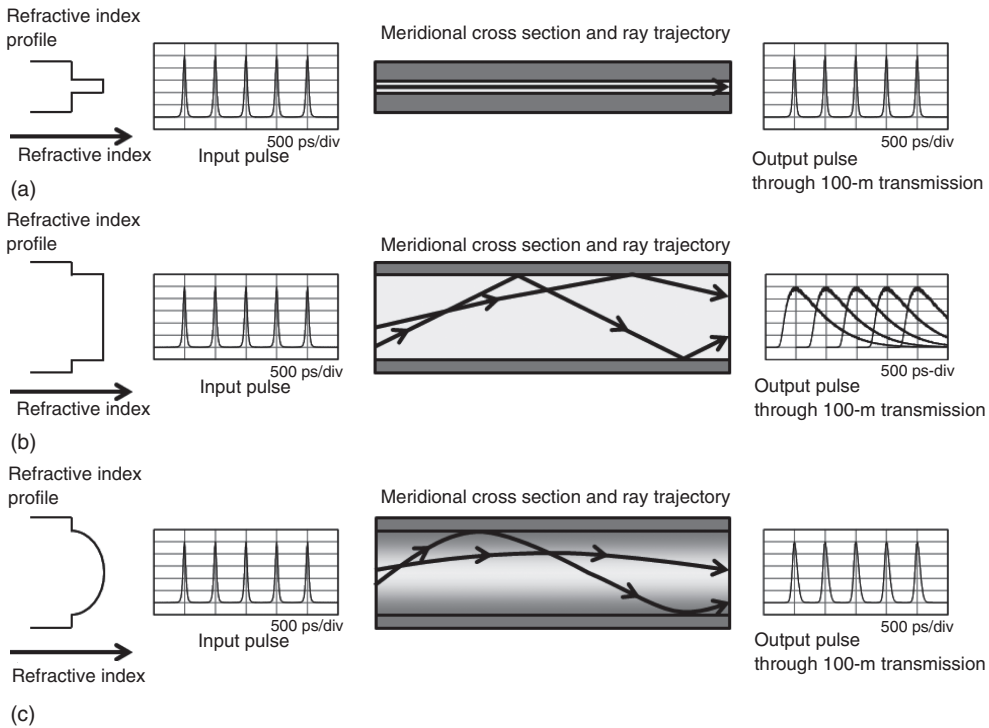


Figure 1.1 Refractive index profiles and ray trajectories in (a) SI SMF, (b) SI, and (c) GI MMFs.

simple interpretation. The rays travel at the same velocity along their optical paths because of the constant refractive index throughout the core region in an SI MME. Consequently, the same velocity and different path lengths result in different propagation speeds along the fiber, which causes a wide pulse spread in time. The pulse broadening caused by modal dispersion seriously limits the transmission capacity of MMFs because overlapping of the broadened pulses induces intersymbol interference and disrupts correct signal detection, thereby increasing the bit error rate (see Chapter 7) [7].

Modal dispersion is generally a dominant factor in pulse broadening in MMFs. However, modal dispersion can be dramatically reduced by forming a nearly parabolic refractive index profile in the core region of a GI MME, which allows a much higher bandwidth and hence higher speed data transmission [8]. The optical ray is confined to near the core axis, corresponding to a lower order mode, and travels a shorter geometrical length at a slower light velocity along the path because of the higher refractive index. The sinusoidal ray passing through near the core-cladding boundary, which is considered as a higher order mode, travels a longer geometrical length at a faster velocity along the path, particularly in the lower refractive index region far from the core axis. As a result, the output times from the fiber end of rays through the shorter geometrical length at the

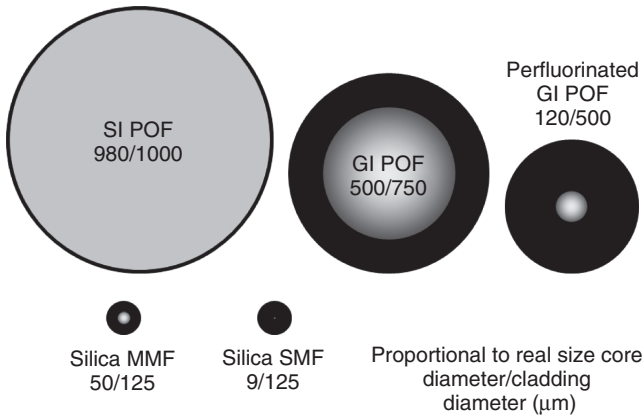


Figure 1.2 Cross sections of typical optical fibers.

slower velocity and of those through the longer geometrical length at the faster velocity can be almost the same because of the optimum refractive index profile. Therefore, GI MMF can realize high-speed data transmission. On the other hand, SMF has no modal dispersion in principle because only one mode is contained in it owing to its extremely small core. Thus, SMFs provide even higher bandwidth. Cross sections of typical optical fibers are shown in Figure 1.2.

Moreover, optical fibers can be categorized according to their base materials: silica glass and polymer. Silica SMFs are widely used in long-haul communication systems such as undersea networks because of the extremely low attenuation and high bandwidth [9]. On the other hand, optical fibers are currently required for data communication in LANs in homes, offices, hospitals, vehicles, and aircraft, as well as in long-haul telecommunication. As optical signal processing and transmission speeds have increased with developments in information and communication technologies, metal wiring has become a bottleneck for high-speed data transmission systems and large parallel processing computer systems. This is because electrical wiring causes significant problems, including electromagnetic interference, high signal reflection, high power consumption, and heat generation [10]. Thus, optical networking is expected to be used even in very short-reach networks. However, the connection of SMFs requires accurate alignment using expensive and precise connectors because of the extremely small core diameters of less than $10\ \mu\text{m}$, which is almost $1/10$ of the diameter of a human hair. The connection requirements of SMFs result in high installation costs, especially in LANs where many connections are expected [11]. Silica MMFs have larger core diameters (50 or $62.5\ \mu\text{m}$) than SMFs. However, in addition to the modal noise and unstable bandwidth performance mentioned above, the core diameters of MMFs cannot be enlarged sufficiently for rough connections. Silica MMFs with larger core diameters are easily broken, because silica glass is inherently brittle. On the other hand, POFs can have much larger core diameters, from hundreds of micrometers to nearly $1000\ \mu\text{m}$. SI POFs with core diameters of almost $1000\ \mu\text{m}$

are commercially available. The large core diameters of SI POFs enable rough and easy connections, so SI POFs are expected to be used as the transmission media in LANs. However, as the required data rate increases, SI POFs cannot achieve reliable data transmission because of the low bandwidths induced by the large modal dispersion (see Chapter 3). In contrast, GI POFs have been investigated as the transmission media in high-speed and short-reach networks [12, 13]. This is because GI POFs can realize stable and reliable high-speed communication owing to the high bandwidth, and because GI POFs can have much larger core diameters owing to the inherent flexibility of polymers. Therefore, GI POFs allow rough connection and easy handling [14–19], which dramatically reduces the installation cost of networks, particularly LANs [20, 21]. Thus, GI POFs are attracting a great deal of attention in consumer use because of their user-friendly characteristics. Although several types of POFs, such as single mode, SI, multistep index, multicore, GI, and microstructured, have been reported [14, 22], this book explains mainly representative SI and GI POFs.

1.2

Plastic Optical Fiber

The peripheral component of communication networks, referred to as *the last mile*, is estimated to account for ~95% of the overall network. Electrical wiring such as unshielded twisted pair (UTP) and coaxial cables has most often been adopted in LANs. However, its bandwidth and transmission distance are severely limited, and it is difficult to realize high-speed data transmission on the order of gigabits per second at distances greater than 100 m using UTP. On the other hand, silica-based SMFs used in backbone systems can achieve extremely high data rates and long-distance communication. However, precise and time-consuming techniques are demanded for termination, connection, and branching because of their very small diameters of less than 10 μm , which induces high cost of installation of LAN systems with huge numbers of connections and junctions. In contrast, POFs, which consist of a polymer core and cladding, can have much larger core diameters (up to 1000 μm) than silica-based optical fibers because of their inherent flexibility, although POFs exhibit relatively high attenuation. POFs cannot penetrate human skin or be broken by bending and physical impact. Highly accurate alignment is not required for POF connections because of the large core. These characteristics enable easy and low-cost installation and safe handling.

The demand for high-speed communication over private intranets and the Internet is growing explosively as the available data volume in personal devices increases. In particular, a strong demand for more realistic video images, such as 8 K and/or 3D, and more realistic face-to-face communication requires higher resolution, more natural color, and higher frame rates. Thus, increasingly large bit rates for data transmission are required in high-resolution displays and cameras. Consequently, POFs are attracting a great deal of attention because electrical wiring causes critical problems as described above [11]. The commonly cited

advantages of optical fibers are their remarkably high bandwidth, immunity to electromagnetic interference, and immunity to crosstalk. With the demand for high-speed data processing and communication systems, GI POFs have become promising candidates for optical interconnects as well as optical networking in LANs because of their high bandwidth, in addition to their advantages for consumer use such as high tolerance to misalignment and bending, high mechanical strength, and long-term reliability [13, 16, 18, 19, 23].

The first SI POF was reported by DuPont in the mid-1960s, around the same time as the invention of the silica fiber. The SI POF was first commercialized by Mitsubishi Rayon in 1975. Asahi Chemical and Toray also entered the market. However, early POFs had quite high attenuation (for example, 1000 dB/km), and the transmission length was critically limited to only several meters. Thus, limited applications were considered, such as light guiding, illumination, and sensors, rather than data transmission. Analyses of attenuation in POFs clarified that the high attenuation was caused mainly by extrinsic factors such as contamination and imperfections introduced during fiber fabrication and were not intrinsic and inevitable (see Chapter 2). Indeed, POFs exhibited low attenuation near the theoretical prediction when the monomer was purified and contaminants were eliminated [24]. Thus, the attenuation of the SI POF became low enough for applications in premise networks. The achievements of low-loss POFs are shown in Figure 1.3.

Although the attenuation in SI POFs was dramatically reduced, their bandwidth, another important parameter, is severely limited by modal dispersion and is far from the requirements for high-speed data transmission. On the other hand, the first GI POF was reported in 1982 [25]. The GI POF theoretically has a high bandwidth (see Chapter 3); however, the attenuation was greater than 1000 dB/km. Thus, the development of POFs again encountered attenuation problems. The first GI POF was fabricated by copolymerization of more than two monomers with different refractive indices, and a graded refractive index profile was formed by controlling the composition distribution of the copolymer according to the

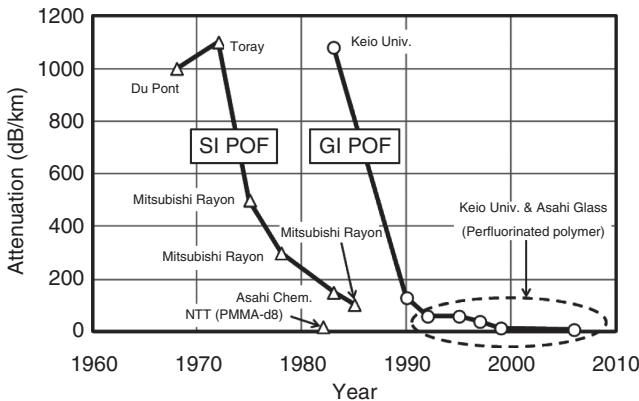


Figure 1.3 Reduction in attenuation of POFs.

monomer reactivity ratios. Impurities and contaminants were suspected to be a dominant factor in the high attenuation. However, microscopic heterogeneous structures caused by the composition distribution of the copolymer were found to cause high attenuation in GI POFs. Therefore, a GI POF with a low-molecular-weight dopant was invented in 1991 [12, 20]. The dopant had a higher refractive index than the base polymer of the GI POF, and a refractive index profile corresponding to the dopant concentration distribution was obtained in this GI POF by interfacial gel polymerization (see Chapter 5). The formation of GI POFs requires a dopant that has a higher refractive index than the host polymer. The addition of the dopant countered the trend toward purification to reduce attenuation because the dopant was considered a type of impurity. However, a low-loss, high-bandwidth GI POF with the dopant was developed. This was a breakthrough for high-speed POF networks. The attenuation was further reduced, and the bandwidth was further enhanced by fluorination of the polymer [26, 27]. After various reports of new high-bandwidth records, the GI POF realized 40 Gb/s data transmission over 100 m [28]. The achievements of high-speed data transmission in POF networks are plotted in Figure 1.4. The bit rate–distance product (vertical axis) indicates the data transmission performance, and higher values indicate that a higher bit rate and/or longer distance is available in the optical link. The transmission performance of the SI POF (diamonds) was limited to hundreds of megabits per second over 100 m because of the large modal dispersion. The bit rate of poly(methyl methacrylate)-based GI POFs (squares) increased to several gigabits per second over 100 m because of the graded refractive index profile. Both the transmission distance and bit rate of perfluorinated-polymer-based GI POFs (triangles) were dramatically improved because of the low attenuation and low material dispersion inherent to perfluorinated polymers (see Chapters 2 and 3). The bit rate of the perfluorinated GI POFs fabricated by coextrusion (circles) reached 40 Gb/s over 100 m, a breakthrough achievement.

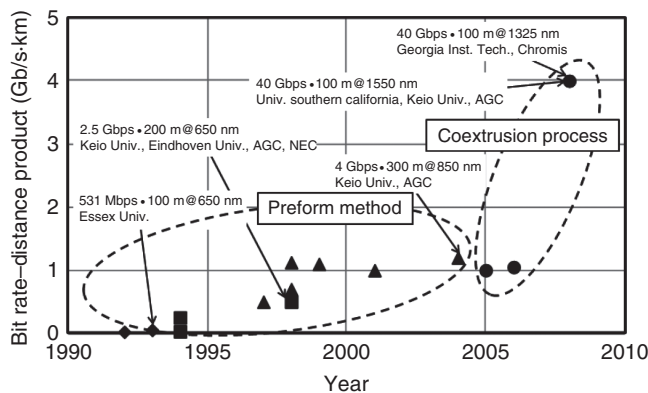


Figure 1.4 Enhancement in bit rate–distance product of POFs. ♦: PMMA (poly(methyl methacrylate))-based SI POF, ■: PMMA-based GI POF by preform method, ▲: perfluorinated GI POF by preform method, and ●: perfluorinated GI POF by coextrusion process.

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