FIBER OPTIC COMMUNICATIONS: TECHNO-ECONOMICS

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Summary

Communications using optical fiber are at the forefront of a bandwidth revolution over the past decade. This chapter attempts to unfurl the wide landscape of optical fiber communications through the introduction of fundamental issues related to wave propagation in optical fibers, the evolution of optical fiber communication systems, and the latest technologies that have enabled Wavelength Division Multiplexing (WDM) – a key technique that promises to unleash the bandwidth potential of an optical fiber.

The latter part of this chapter is aimed towards describing the techno-economics aspect of optical fiber communications, particularly in India. This discussion reviews the growth of the optical fiber industry in India, while pointing out the scale of deployment of optical fiber communication systems/networks. Finally, the worldwide demand for optical equipment is presented and a projection of the specific demand from India is discussed.

1. Introduction

We are living in an era that is seeing tremendous demand for bandwidth, at the center of which are optical communications using fine strands of glass fibers. The birth of the optical fiber has literally revolutionized the field of communications over the past few decades. However, the concept of optical communications is not new by itself. Early communication systems employed by man constituted mirrors reflecting sunlight and smoke signals. Visible light in free space acted as the carrier, the mirrors or smoke signals were the information being transmitted on the carrier while the human eye acted as detector. These primitive communication systems consisted of manual modulation schemes and their bandwidth was severely limited e.g. the rate at which one could transmit information was limited by man's ability to turn on and off the smoke signal.

Modern day communications were shaped by the invention of the telephone in the 19th century which enabled the transmission of voice and data over copper lines. Man learnt how to communicate over long distances through electronic modulation of a carrier frequency accompanied by improvements in our mathematical understanding of signal processing. However, the modulation bandwidth or the information carrying capacity continues to be limited by the carrier frequency and we progressively aspire to use higher carrier frequencies. With the advent of radio waves, the world has seen the birth of radio, television, cellular phones, radar, microwave links, and satellite communications using carrier frequencies spanning from a few kHz to tens of GHz.

From the above perspective, the use of optical frequencies (few THz) is a natural extension. However, this was not an option until the invention of the laser in the 1960s due to the lack of access to a controlled coherent light source as a carrier. Even after the invention of the laser, its use for communication purposes was limited by its bulkiness. Moreover, optical communications using such lasers had to be carried out over free space, which meant that they were susceptible to losses due to fog and rain, are limited to line of sight operations and pose serious eye safety issues.

The drawback related to the bulkiness of the laser was alleviated by the invention of compact, efficient semiconductor lasers in the 1970s. Almost concurrently, optical fibers were demonstrated with <20 dB/km loss by scientists at Corning Incorporated. These events marked the birth of fiber optic communications. Apart from being a transmission medium that could be easily routed along a desired path, it was unaffected by atmospheric conditions, had a low transmission loss (0.2 dB/km at 1550 nm), a large bandwidth (few THz), negligible electromagnetic interference (EMI), and very low cross-talk (< -30dB) from neighboring fibers.

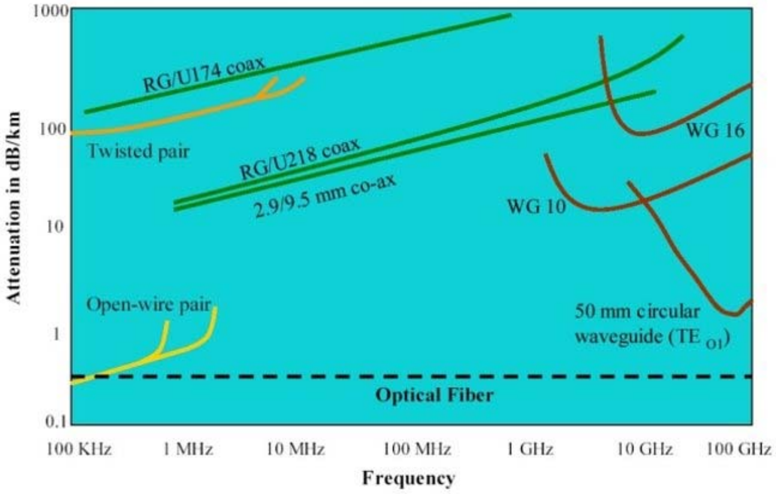

Figure 1. Attenuation as a function of frequency for different waveguides. Optical fibers have the lowest attenuation and largest bandwidth.

Figure 1 compares the loss of several waveguides as a function of frequency. It clearly illustrates the fact that the optical fiber is one of the lowest loss transmission media available for communications.

2. Propagation through Optical Fibers

An optical fiber consists of three regions namely, the core, the cladding and a protective buffer region. The first two are made of fused silica glass with ultra-high purity, whereas the buffer is typically made of acrylate and is used for mechanical protection. The principle of light propagation in optical fibers may be roughly described to be due to total internal reflection at the core-cladding interface.

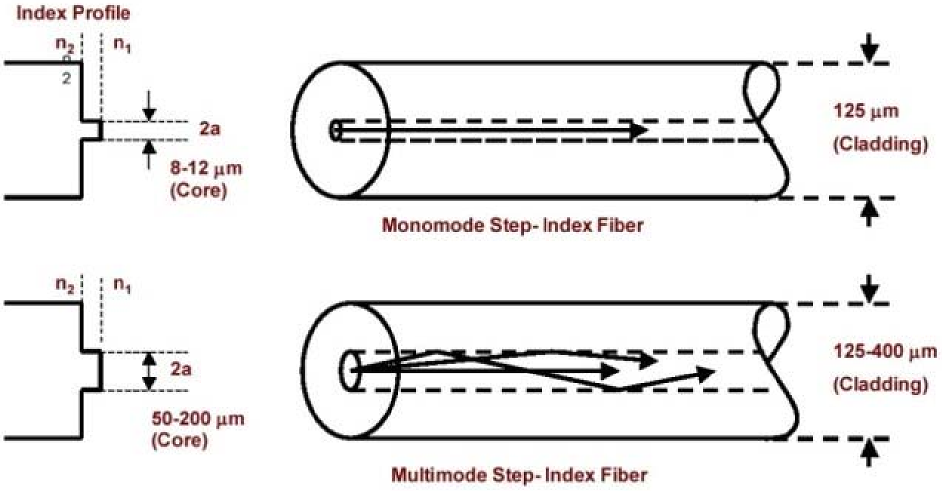

Figure 2. Structure and types of optical fibers. Multimode fibers typically have much larger core diameter compared to single mode fibers.

Optical fibers may be broadly classified as single-mode and multi-mode fibers. The modes of an optical fiber refer to the electromagnetic field configurations supported by the optical fiber. Loosely speaking, the modes may be viewed as unique paths of wave propagation. Multimode fibers capable of supporting several modes typically have 50-100 μm core diameter. Such a large core diameter facilitates efficient coupling of light from even incoherent sources of radiation such as semiconductor light emitting diodes (LEDs). However, such fibers suffer from significant inter-modal dispersion, which limits the bandwidth supported by the fiber.

Inter-modal dispersion in multimode fibers is due to the fact that different modes travel different effective distances in the fiber. For example, the fundamental mode traverses a near-parallel path with respect to the fiber axis, whereas a higher order mode traverses a much steeper angle. Thus the higher order mode arrives at a much later time. This is shown pictorially through the ray diagram in Figure 2 for the multi-mode fiber. Since energy coupled into the fiber is distributed over several modes each having different arrival times at the destination, the resultant pulse looks broadened. Such broadening is averted if only the fundamental mode is supported by the fiber as shown in the single mode fiber in Figure 2. However, this means that the fiber core diameter is in the order of a few microns and hence coupling light into fiber is challenging. Moreover, the bandwidth of single-mode fibers is limited by a more subtle intra-modal dispersion effect viz. chromatic dispersion, which will be elaborated in the following section

3. Challenges in Fiber Optic Communications

As in any communication system, the key challenges in fiber optics are: (i) Attenuation and (ii) Dispersion. Nonlinear effects in optical fibers are also becoming increasingly important and will be discussed later in this section.

3.1. Attenuation in Fused Silica Optical Fibers

Attenuation refers to the loss of signal during transmission, which limits the capability of the receiver to distinguish the signal from noise and thereby the transmission distance. Suppose optical power of 0 dBm is coupled into an optical fiber, which has an attenuation of 1 dB/km at the transmission wavelength and the signal is collected at the receiver having a noise floor corresponding to –60 dBm. If we ignore the effects of dispersion and assume that a signal-to-noise ratio of 20 dB is to be achieved for reliable detection, then the total length of the link is limited to 40 km.

Note that the optical fiber attenuation in the above example was mentioned for a particular wavelength. This is due to the fact that as in all waveguides, the optical fiber attenuation is a function of frequency/wavelength. In an optical fiber, the attenuation is primarily due to the glass material although the construction of the optical fiber can also play a role through bending losses, specifically in single-mode fibers. The bending losses become relevant at wavelengths much longer than the design wavelength, where a significant portion of the fundamental mode travels in the cladding and is susceptible to losses at the cladding-buffer boundary. On the other hand, if the transmission wavelength is much shorter than the design wavelength the optical fiber allows more than one mode to propagate in the fiber core.

So, what is the basis of material attenuation for the fiber at optical frequencies? To understand this, let us refer the attenuation spectrum of a typical fused silica optical fiber illustrated in Figure 3. Note that the attenuation values mentioned in Figure 3 are only rough estimates provided to give a general feel for the reader. At the higher frequencies corresponding to shorter wavelengths, the fundamental limitation is due to Rayleigh scattering. As we all know, Rayleigh scattering is the reason why the sky appears blue on a clear, sunny day. Sunlight incident on fine particles that are of sizes comparable to the wavelength of light (λ) suspended in air gets scattered at a rate of $1/\lambda^4$. Thus blue color, which is of shorter wavelength compared to other visible colors is scattered much more strongly and results in the sky appearing blue. Similarly, Rayleigh scattering in glass optical fibers is due to structural inhomogeneities and defects formed during fiber fabrication.

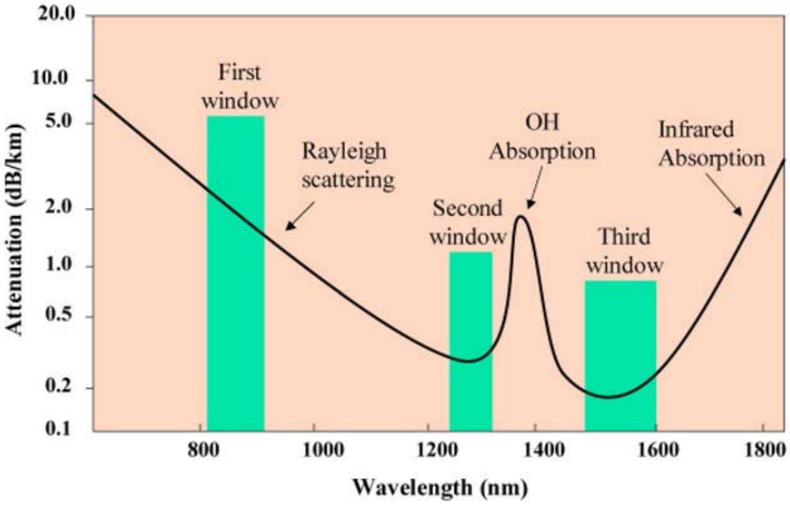

Figure 3. Attenuation spectrum of a fused silica optical fiber illustrating the dominant attenuation mechanisms in the different spectral regions and the spectral windows used for communication.

Another attenuation mechanism in an optical fiber that provides the basis for the fundamental limitation in the longer wavelength side is the absorption due to vibrational resonance associated with silicon-oxygen bonds in the fused silica glass. This absorption edge meets the Rayleigh scattering curve at 1.55 μm, thereby providing the lowest attenuation at that wavelength for fused silica glass fibers. Using ultra-pure material processing techniques, the commercial optical fibers provide only 0.2 dB/km loss at 1.55 μm. The other important attenuation feature that is present in most optical fibers buried in the ground today is the hydroxyl (OH) absorption peak at around 1.4 μm. The process of fiber fabrication will invariably introduce moisture in the glass, which has a fundamental overtone peaking at 2.8 μm. The first overtone of this OH absorption peak occurs at 1.4 μm. This peak defines two spectral windows on either side of it viz. the 1.3 μm window and the 1.55 μm window for optical communications using fused silica fiber.

Although the above argument points to communications at either the 1.3 μm or the 1.55 μm window, early optical fiber communication systems were based at around 0.85 μm since it coincided with the availability of GaAs-based semiconductor lasers and Silicon PIN photodiodes at that time. For reasons that will become obvious in the following section, second generation systems utilized the 1.3 μm window. As such, it was not until the 1990s that third generation systems based on the 1.55 μm window became popular. Recent advances in the fiber fabrication processes have helped to reduce the OH absorption, resulting in the development of the Zero Water Peak (ZWP) optical fiber. This development has opened up the possibility of utilizing the entire spectral window spanning 1280-1620nm for fiber optic communications.

3.2. Dispersion in Optical Fibers

As mentioned earlier in this section, the other serious challenge in optical fiber communications is dispersion. Dispersion refers to the broadening of pulses used to convey information. This is a problem in digital transmission as it may cause inter-symbol interference (ISI). Dispersion in optical fibers manifests as Inter-modal dispersion, Intra-modal or Chromatic Dispersion, and Polarization Mode Dispersion. We already discussed the origin of inter-modal dispersion, which is the major bandwidth limitation in multi-mode fibers. As pointed out in that section, such a dispersion mechanism is eliminated in single-mode fibers.

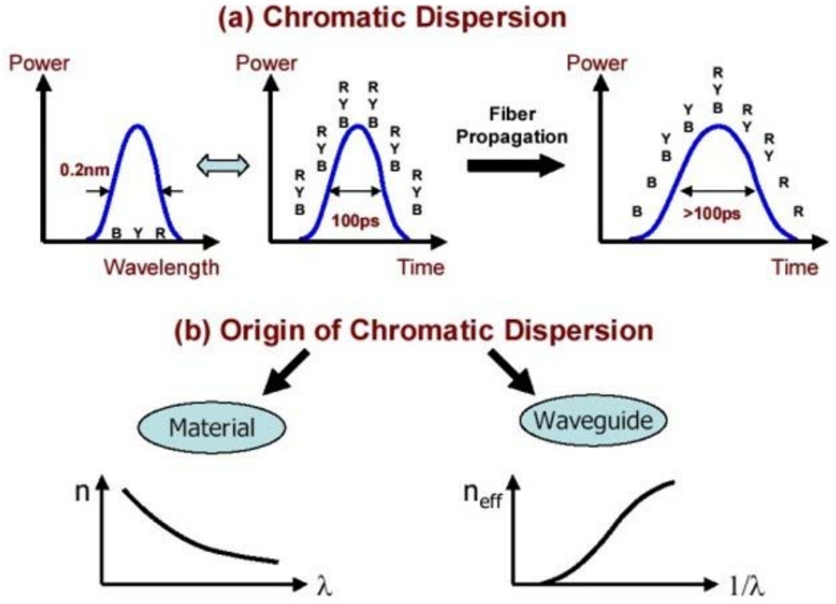

Figure 4. Illustration of (a) the effect of chromatic dispersion due to propagation in an optical fiber and (b) the origin of chromatic dispersion in optical fibers.

Chromatic dispersion is a major bandwidth limiting factor in single-mode fibers. Let us refer to Figure 4a for an illustration of the effect of chromatic dispersion. We know that information is transmitted in optical fibers as light pulses. If we observe the frequency content of the pulse, we find that it consists of a finite band of frequencies/wavelengths. For simplicity, let us assume that the pulse has blue (B), yellow (Y), and red (R) wavelengths. In the time domain, this manifests itself as a combination of these colors in any time slice of the pulse. As this pulse propagates through an optical fiber having finite amount of chromatic dispersion, the blue part of the pulse sees a higher refractive index and is slowed down with respect to the yellow and red parts. Similarly the yellow color is slowed down with respect to the red color of the pulse. Due to the different velocities at which each color travels, they arrive at different times at the destination thereby effectively broadening the pulse.

As shown in Figure 4b, the origin of chromatic dispersion may be traced to two distinct mechanisms: (1) variation of refractive index of silica glass with respect to optical wavelength/frequency and (2) variation of the fraction of energy propagating in the core versus cladding with respect to optical wavelength/frequency. The former is due to property of the material is hence termed as “Material Dispersion”, whereas the latter is a consequence of the waveguide design and hence is called “Waveguide Dispersion”. The left side of Figure 4b illustrates roughly the dependence of the refractive index of glass as a function of the wavelength. According to this, if the transmitted optical signal consists of a spread of frequencies, the different frequencies will travel at different speeds along the optical fiber.

Similarly, the right side of Figure 4b illustrates the dependence of the effective refractive index seen by the fundamental mode on the wavelength. The effective refractive index is a value between the refractive index of the core and the cladding, and is defined so due to the fact that a portion of the optical mode also travels in the cladding. The effective refractive index value tends towards the cladding refractive index for longer wavelengths and approaches the core refractive index for shorter wavelengths. Thus, different wavelengths in the optical mode travel with different velocities giving rise to pulse dispersion.

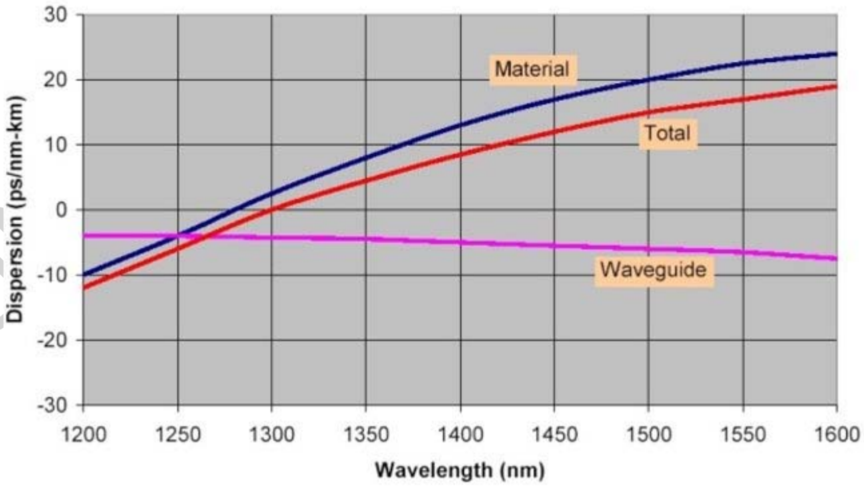

Figure 5. Wavelength dependence of dispersion in fused silica optical fibers.

The amount of pulse spreading is dependent on the material and waveguide dispersion as mentioned above through their respective dispersion coefficients, as well as the source linewidth (frequency spread) and the propagation length. The dispersion coefficients are, as such, expressed in ps/nm-km. Figure 5 illustrates the dependence of the material and waveguide dispersion coefficients on wavelength for fused silica single-mode optical fiber (SMF-28) fabricated by Corning Incorporated. The key aspect to note is that the material and waveguide dispersion coefficients have opposite slopes and tend to compensate each other. The total dispersion is the sum of the material and waveguide dispersion coefficients. As seen in Fig 5, the total dispersion is zero at 1310nm, which means that the pulse does not spread at all. This is one of the drivers for second-generation communication systems.

The availability of optical amplifiers and the attractiveness of transmission with the lowest possible attenuation fueled the development of third-generation optical communication systems operating in the 1.55 μm band. However, a key question still remained – does one choose the 1.3 μm band for dispersion considerations or the 1.55 μm band for attenuation considerations? The answer to this lies in the careful observation of the dispersion plot above. The challenge was to move the zero dispersion point to 1.55 μm. This could possibly be achieved through two avenues: (1) move the material dispersion curve towards the right, or (2) push down the waveguide dispersion curve.

The material dispersion curve could be shifted to the right through careful use of dopants. Germania is one such dopant that is already used in fibers to increase the core refractive index. By increasing the germania content, the zero dispersion point was found to shift to the right by about 10 nm. But this was still well short of the desired range (> 200 nm). At this point, several scientists around the world came up with different waveguide designs that pushed down the waveguide dispersion curve as a function of wavelength. Examples for such design are the high delta fiber in which the core diameter is reduced and the refractive index increased, and the depressed cladding fiber in which a low refractive index ring surrounds the core area. Since such fibers produced a zero dispersion point at 1.55 μm, they were termed as “Dispersion Shifted Fibers” (DSF). By changing the slope of the waveguide dispersion through appropriate designs, one can also flatten the total dispersion over a range of wavelengths. Such fibers are called “Dispersion Flattened Fibers” (DFF).

An alternative approach to tackling the dispersion issue in regular single-mode fibers is by the use of a dispersion compensation technique. In this approach, the dispersion accumulated is carefully managed along the link by inserting elements which have a dispersion slope that counters that of the regular single mode fibers. A popular way of accomplishing the dispersion management is through the deployment of dispersion compensating (DC) fibers, which use high GeO_2 concentration in the fiber core to achieve the negative dispersion slope.

A serious drawback of such a scheme is that these fibers exhibit significant insertion losses and their relatively small mode field diameter results in their being more susceptible to nonlinear effects when compared with regular single-mode fibers. A more recent development is the use of chirped fiber Bragg gratings (FBGs) for dispersion compensation. The specific working principle of fiber Bragg gratings is explained in detail later. The idea is that the chirping of the grating period results in different wavelength channels being reflected from different parts of grating, thereby introducing a differential group delay that counters the dispersion accumulated in the incident pulse.

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Biographical Sketches

Dr. Balaji Srinivasan was born at Chennai, India in 1971. He obtained his Ph.D. in 2000 from the University of New Mexico, USA. Prior to that, he obtained his M.S. in Electrical Engineering and B.E. in Electronics and Communication Engineering from the University of New Mexico and the Thiagarajar College of Engineering, Madurai respectively.

After completing his Ph.D., he worked as a Senior Development Scientist at Corning Incorporated, USA, where he led technology development efforts related to 3D Optical Crossconnects and Channel Selectable Tunable Filters. Before joining the faculty position at IIT-Madras, Balaji served as a consultant for Midas Communications, Chennai for six months during which he was involved in the development of an Optical Time Domain Reflectometer (OTDR).

Dr. Srinivasan has authored or co-authored five journal publications and more than a dozen conference publications. He also has six patents to his credit. He is the winner of the prestigious Collegiate Inventor Award in 2000, and the New Focus Student Award in 1999. He is a member of the Optical Society of America and is a frequent reviewer for journals published by the Optical Society of America and IEEE.

Dr. Anil Prabhakar was awarded a Ph.D. in Applied Physics from Carnegie Mellon University, Pittsburgh in 1997 for his thesis on nonlinear interactions between magnetostatic and optical waves in thin ferrite films. He previously completed a M.S. in Electrical Engineering (Microwave and Fibre Optic Communications) from the New Jersey Institute of Technology, Newark and a B.Tech in Engineering Physics from IIT-Bombay.

After completing his Ph.D., he worked as a staff engineer at MKE-Quantum, Louisville and then at ReadRite Corporation, Fremont designing magnetic hard disk drives. As a manager he has borne the responsibility for products from the early stages of the design cycle during wafer fabrication to the final stages of characterization and failure analysis in the manufacturing plant at ReadRite, Bangpa-in, Thailand. He joined IIT-Madras at the Centre for Intelligent Optical Networks in 2002.

Dr. Prabhakar has authored 14 journal publications and more than 20 conference publications. His interests in microwaves and optical engineering include the characterization of RF-MEMS, fractal antennas, optical amplifiers and quantum optics.