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Fiber-Optic Communications

Last October, as the world rejoiced at the successful rescue of 33 miners trapped for 70 days inside Chile's San Jose mine, the *Wall Street Journal* highlighted on its front page [1] the important role that technology played in bringing this rescue to a happy ending. State-of-the-art fiber-optic communication technology allowed the trapped miners to remain in contact with the rescue effort evolving 800 m above their compartment. From the earliest days of its development, fiber optics has emerged as the dominant and indispensable technology that has made our multiply-connected world possible. In this article, we will review the history of fiber optics and how it has evolved to provide an ubiquitous broadband, high-quality communications infrastructure.

HISTORY OF OPTICAL FIBER DEVELOPMENT

Shortly after the demonstration of the first laser in May 1960, it was described as a "solution in search of a problem." In this context, the laser was to provide the solution to the ever-growing demand for bandwidth in communications, which resulted from increased telephone use, relaying of television signals, and other kinds of electronic data transmission. Prior to the 1960s, direct transmission of signals in data communications was carried out using coaxial cables, transmission lines, and radio frequency wireless. All of these technologies had severe limitations. Conduction of signals along any system that uses metal wires incurs losses that increase markedly with the data rate, and hence require the use of many repeaters for long cables. Transatlantic cables with a maximum operational frequency of 1 MHz had a repeater every 37 km and required operational voltages of thousands of volts. Wireless transmissions had limited bandwidth until satellite relays became available in the early 1960s. Long-range terrestrial wireless requires reflection off the ionosphere, which only occurs for relatively low carrier frequencies. Even when wireless transmissions moved into the microwave region, the carrier frequency still imposed significant limitations on the attainable data rates. The maximum data rates that were generally available even at C-band (4–8 GHz) and Ku-band (12–18 GHz) were less than 1 Mb/s. The progression to the very high data rates that we have today and the information revolution itself could not have happened if a new medium for the transmission of a high-frequency carrier had not been developed. For this, we owe much to Charles Kao, who was a corecipient of the 2009 Nobel Prize in Physics.

BACKGROUND

In the late 1950s and thereafter, Charles Kao was an electrical engineer working for Standard Telephones and Cables (STC) (now Nortel Networks) at their research center in Harlow, England. While working at STC in 1966, Dr. Kao, along with his colleague George Hockham, made the seminal observation that a dielectric waveguide made of very pure glass could have a propagation loss below 20 dB/km [2]. When he first proposed this, typical glasses had attenuations closer to 1,000 dB/m. Kao recognized that this high attenuation was not a fundamental limitation of the glass itself but resulted from impurities such as copper, iron, cobalt, manganese, nickel, and chromium, which absorbed strongly in the 0-6–1.6 μm spectral region. By purifying glasses so that these impurities were present only at concentrations below one part per million, Kao and Hockman demonstrated that a dielectric waveguide with attenuation below 20 dB/km could be made. Such attenuations were achieved using fused silica by Maurer and his coworkers in 1970 [3]. Subsequently even lower loss fibers with attenuation below 0.2 dB/km were achieved by further removal of impurities and reduction of the bound hydroxyl ions in the fiber to part-per-billion levels. The attenuation in these modern fibers can be as low as 0.17 dB/km at wavelengths near 1,550 nm. The variation of attenuation with wavelength in a modern silica fiber is shown in Figure 1.

The development of very low-loss optical fibers has enabled a worldwide advanced telecommunications infrastructure. The Internet and a myriad of other digital data communication applications would not be possible without it. Technological developments in fiber design, optical sources (especially semiconductor lasers), modulation protocols, and high-speed detectors have moved data rates per wavelength to 40 Gb/s and beyond.

OPTICAL DATA TRANSMISSION TECHNOLOGY

Some of the key technological developments that have made this possible are worthy of mention. Optical fibers themselves are cylindrical dielectric waveguides, which guide light by total internal reflection. In their simplest form, they have a core doped with

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Digital Object Identifier 10.1109/MSP.2011.941096
Date of publication: 15 June 2011

1053-5888/11/$26.00©2011IEEE

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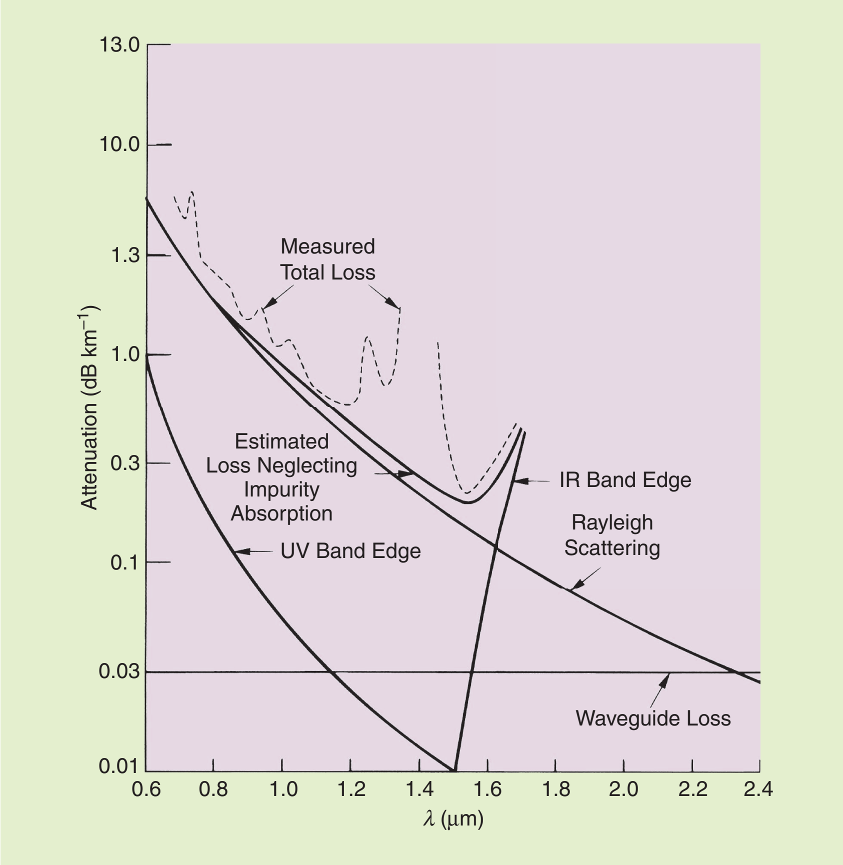

[FIG1] Variation of attenuation with wavelength of a modern low-loss germania–doped fiber [4].

germania, phosphorus pentoxide, or alumina, which has a slightly higher refractive index than a surrounding cladding region. Some fiber designs have regions where the refractive index is locally reduced by doping with boron oxide. Single mode fibers have a core diameter that is typically smaller than 10 μm, which ensures that only one mode (called the HE_{11} mode) can propagate. For long distance communication, optical fibers must not only be low loss, but must have the modal and waveguide propagation characteristics required for long distance, high data-rate communications. A modulated optical signal will become impaired because of dispersion when propagating along an optical fiber. In its simplest sense, dispersion means that a short optical pulse will broaden as it travels. In a single mode fiber several dispersion effects are still present. These include the following:

- chromatic dispersion (CD) with two contributors
  - material dispersion (dn/dλ), which is the change in refractive index with wavelength
  - waveguide dispersion $\beta(\omega)$, which is the change in waveguide propagation constant with frequency
- polarization mode dispersion (PMD), which results from a lack of perfect cylindrical symmetry along the fiber. This causes the otherwise degenerate orthogonal polarization states of the HE_{11} mode in the fiber to have different propagation constants.

The magnitude and direction of this anisotropy varies unpredictably along the length of the fiber and causes the energy to mix between the two polarization states. Advanced fiber designs, which involve engineering the radial refractive index profile, and selection of dopants and operational wavelengths have reduced all these dispersion effects to manageable levels.

There are three principal spectral regions where fiber-optic communications has been extensively implemented. Early on, the 800–900-nm region was used because GaAs/GaAlAs lasers and silicon detectors work well in this region. But loss and dispersion in fibers are much worse in this spectral region than is the case for the currently used regions near 1.3 μm and 1.55 μm. Near 1.3 μm, fiber loss is low and chromatic dispersion is close to zero over a range of wavelengths. The region near 1.55 μm dominates in long-haul applications, both because this region is where the attenuation is lowest and also because of the availability of erbium doped fiber amplifiers (EDFAs), which enable all-optical amplification without detection and retransmission. Table 1 summarizes the optical telecommunication bands currently in use for broadband optical communications .

Chromatic dispersion effects can be minimized at 1.55 μm by moving the zero dispersion point into this region with dispersion-shifted fiber, which has a core with a radial triangular, trapezoidal, or Gaussian refractive index profile. Dispersion-flattened fibers have a relatively flat group velocity dispersion over some wavelength range, and can have near zero dispersion across the entire C band.

In these spectral regions, various III-V heterostructure lasers, such as InGaAsP/InP, generally using single and multiple quantum wells, are used to transmit the data, and InGaAs photodetectors are used in the receivers.

Fiber-optic networks can be broadly divided into local area networks, (LANs), metropolitan area networks (MANs), and long-haul networks (LHNs). LANs encompass short distances, and data rates that can cover a broad range, from Mb/s to Gb/s. Because the data rates and distances involved are not very great, LANs use multimode or even plastic optical fibers (POFs), the latter offer simplicity of installation and interconnection. POFs are widely used in short range (~100 m) fiber to the home applications,

[TABLE 1] PRINCIPAL TELECOMMUNICATION WAVELENGTH BANDS.

BAND	DESCRIPTION	WAVELENGTH RANGE
O BAND	ORIGINAL	1.260–1.360 μm
E BAND	EXTENDED	1.360–1.460 μm
S BAND	SHORT WAVELENGTHS	1.460–1.530 μm
C BAND	CONVENTIONAL (“ERBIUM WINDOW”)	1.530–1.565 μm
L BAND	LONG WAVELENGTHS	1.565–1.625 μm
U BAND	ULTRALONG WAVELENGTHS	1.625–1.675 μm

in-home networks, and even as data buses in automobiles. MANs provide the capacity to interconnect multiple LANs, and generally offer data capacities that range upwards from synchronous optical network (SONET) (2.3 Gb/s) to higher data capacities. LHNs interconnect multiple MANs along trunk lines at every increasing data capacity and span the world's oceans for intercontinent connectivity. The first long-haul fiber-optic links used a single wavelength with regularly spaced repeaters, for example 65 km apart on the first transatlantic fiber cable (TAT-8), but this has been supplanted by the use of multiple wavelengths in a single fiber, with each wavelength carrying an independent stream of high data rate information. This is wavelength division multiplexing (WDM).

OPTICAL AMPLIFICATION AND WAVELENGTH DIVISION MULTIPLEXING

WDM was made practical by the invention of the EDFA. The current most widely used International Telecommunications Union (ITU) standards for WDM separate the different wavelengths by 50 or 100 GHz. By using spectrally efficient modulation techniques, such as polarization division multiplexed (PDM) quaternary phase-shift keying (QPSK) paired with coherent detection, a spectral efficiency of 2 b/Hz can be achieved, which allows 100 Gb/s channel data rates with 50 GHz spacing [5]. WDM has allowed aggregate data rates to reach 69 Tb/s over 240 km using 432 wavelengths covering the C and extended L bands in a single fiber [6]. One challenge to using WDM in long-haul links is that dispersion effects are cumulative, which was not the case in single wavelength, optical-to-electronic-optical, repeater-based systems, where pulse shapes could be corrected at each repeater before retransmission to the next repeater. Dispersion can be compensated for by inserting sections of special fiber with dispersion of the opposite sign. PMD is more difficult to manage as it is random along the length of the fiber, and also in time, but PMD compensation modules have been developed that can be placed at receivers in the network to compensate for its effects.

ADVANCED MODULATION FORMATS

Because of the tremendous available bandwidth, there was very little incentive until recently for telecommunication providers to develop spectrally efficient modulation techniques for optical communication. By far, the most prevalent modulation format used in optical communication is on-off keying (OOK): modulating the intensity of a laser between two states to represent a binary series of ones and zeros. Using fast modulators and detectors, such systems can easily reach data rates of 40 Gb/s. When more bandwidth was required, it was much easy to simply add another, independently modulated, optical wavelength. Much of the development in the past 20 years was therefore focused on the technologies needed to enable this type of wavelength-division multiplexing: optical bandpass filters, spectral multiplexers, and wide-band optical amplifiers. In contrast to the wireless domain where spectral bandwidth is allocated and sold, often at great cost, fiber communications uses an interference-free infrastructure. Wireless communication engineers never enjoyed the luxury of a bandwidth surplus, and they were forced to develop advanced modulation formats to more efficiently utilize the available bandwidth.

With the ever-growing demand for optical bandwidth, a similar trend is now emerging in optical communications. A key step in this process has been the development of optical receivers that simultaneously measure both the in-phase and quadrature component of the optical field in both polarization states. Although these coherent photoreceivers are larger and more costly than the earlier-generation intensity detectors, and they have yet to be widely deployed, they have paved the way for more sophisticated modulation formats including optical QPSK, which is equivalent to a 4-quadrature amplitude modulation (QAM) constellation modulation scheme, higher-order QAM modulation schemes, and polarization multiplexed transmission.

[SIGNAL PROCESSING IS NOW PLAYING A GROWING ROLE IN OPTICAL COMMUNICATION SYSTEMS.]

THE ROLE OF SIGNAL PROCESSING

With the advent of coherent detection schemes and fast (>10 GS/s) analog to digital converters, signal processing is now playing a growing role in optical communication systems [7].

If the optical receiver can detect both the in-phase and quadrature component of the optical field, it is possible, using electrical signal post-processing, to compensate for a variety of optical signal impairments, including chromatic dispersion. Real-time adaptive digital filtering can also be used to dynamically compensate for changing polarization state and for drift in the laser frequencies; two problems that had traditionally plagued coherent receivers.

As an example of the potential role that signal processing can play and its advantages over more traditional methods, consider the problem of chromatic dispersion. In optical fiber, the group velocity at which signals propagate depends on the wavelength (or optical frequency.) As a result, any optical data signal comprised of pulses or other symbols will necessarily spread in time, causing neighboring symbols to overlap and interfere with one another. This effect, called chromatic dispersion, can limit the maximum transmission distance for a fiber-optic channel, or conversely it can constrain the maximum data transmission rate for a given fiber distance. The traditional solution to this problem is to compensate for the dispersion by inserting a fiber or other optical device with opposite dispersion. The drawback of this approach is that the dispersion compensation element must be tailored to match a specific fiber span, and it cannot be easily tuned or adjusted for different fiber paths. Moreover, dispersion compensation elements introduce latency and unneeded delays into the transmission path. Engineers have therefore sought ways to compensate for dispersion in the electrical domain, by processing the electrical waveforms received after the optical signal is detected in a photoreceiver. This approach has historically proved challenging, because the standard photodetection process recovers only the envelope (or intensity) of the optical signal and not the phase.

Coherent optical receivers, by contrast, rely on the interference between the incoming signal and a locally generated optical reference signal, or "local oscillator." Unlike their direct-detection counterparts, coherent receivers can be sensitive to the magnitude, phase, and polarization stage of the incoming signal. If the magnitude and phase are measured with sufficient resolution, it is possible to construct the complex electric field vector of an optical signal, from which one can mathematically compensate for chromatic dispersion using real-time digital signal processing. For example, in 2008, Nortel engineers demonstrated a 40 Gb/s optical receiver that used real-time digital signal processing to compensate for chromatic dispersion and polarization mode dispersion [8]. Their system employed four 6-b 20 Gsample/s complementary metal–oxide–semiconductor (CMOS) analog-to-digital (ADC) converters integrated with a dedicated signal processing application-specified integrated circuit (ASIC). Chromatic dispersion equalization was achieved using a 152-tap finite-impulse-response filter, which is capable of compensating for the chromatic dispersion of approximately 3,000 km of conventional single-mode fiber with no observable penalty.

The use of code division multiple access (CDMA) techniques in the optical domain has also become attractive because of advances in digital coder/decoder technology. CDMA transmissions can copropagate with WDM signals and this hybrid WDM-CDMA scheme achieves high spectral efficiency because it uses the unused extra bandwidth around each WDM channel [9]. For example, in 2009 a WDM-CDMA system distributed 10-Gb/s signals to eight users simultaneously over 100 km using 16-chip encoders and decoders operating in the optical domain using sampled fiber gratings[10].

While coherent receivers are significantly more costly than conventional direct-detection photoreceivers, they offer a degree of flexibility and adaptability that earlier systems could not provide. The ever-increasing performance and decreasing cost of high-speed CMOS ADC circuits could soon make coherent optical receivers a more affordable replacement for direct photodetection, and could usher in a new era of fiber-optic communications in which signal processing plays a much greater role. Wireless communication systems have long relied on digital signal processing, in part because of the complex modulation waveforms used and the time-varying propagation channel. In the coming years, fiber-optic communication systems may begin to follow the same trend.

The capabilities of extremely high data rate optical fiber links are well established, so much of the current developments in fiber-optic communications are occurring in fiber-optic networks. Advanced fiber networks are moving towards all optical routing, switching, and encryption. A key system development is the reconfigurable optical add-drop multiplexer (ROADM). An ROADM allows individual wavelengths to be added or dropped from a fiber without the need for optical to electronic to optical conversion using wavelength selective filtering. This allows the routing of packets in the network in a wavelength selected architecture. If necessary, data traveling on a channel at one wavelength can be transferred optically to a new wavelength. This provides great flexibility in the ability of the network to provide many different kinds of data services to subscribers with different bandwidth requirements [11].

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REFERENCES

[1] M. Moffett, A. Esposito, and C. Pica (2010, Oct. 14). Chile's rescue formula: 75% science, 25% miracle. *Wall Street J.* [Online]. p. A1. Available: http://online.wsj.com/article/SB10001424052748703673604575550521510542814.html

[2] K. C. Kao and G. A. Hockham, "Dielectric-fibre surface waveguides for optical frequencies," *Proc. Inst. Elect. Eng.,* vol. 113, no. 7, pp. 1151–1158, 1966.

[3] F. P. Kapron, D. B. Keck, and R. D. Maurer, "Radiation losses in glass optical waveguides," *Appl. Phys. Lett.,* vol. 17, no. 10, pp. 423–425, 1970.

[4] C. C. Davis, *Lasers and Electro-Optics*. Cambridge, U.K.: Cambridge Univ. Press, 1996.

[5] J. Renaudier, O. Bertran-Pardo, G. Charlet, M. Salsi, H. Mardoyan, P. Tran, and S. Bigo, "8 Tb/s long haul transmission over low dispersion fibers using 100 Gb/s PDM-QPSK channels paired with coherent detection," *Bell Labs Tech. J.,* vol. 14, no. 4, pp. 27–45, 2010.

[6] A. Sano, H. Masuda, T. Kobayashi, M. Fujiwara, K. Horikoshi, E. Yoshida, Y. Miyamoto, M. Matsui, M. Mizoguchi, H. Yamazaki, Y.Sakamaki, and H. Ishii, "69.1-Tb/s (432 x 171-Gb/s) C- and extended L-band transmission over 240 Km using PDM-16-QAM modulation and digital coherent detection," presented at *OFC*, San Diego, CA, Mar. 23–24, 2010.

[7] S. J. Savory, "Digital filters for coherent optical receivers," *Opt. Express*, vol. 16, no. 2, pp. 804–817, 2008.

[8] H. Sun, K.-T. Wu, and K. Roberts, "Real-time measurements of a 40 Gb/s coherent system," *Opt. Express*, vol. 16, no. 2, pp. 873–879, 2008.

[9] G. P. Agrawal, *Fiber-Optic Communication Systems*, 4th ed. Hoboken, NJ: Wiley, 2010.

[10] N. Kataoka, N. Wada, X. Wang, G. Cincotti, A. Sakamoto, Y. Terada, T. Miyazaki, and K. I. Kitayama, "Field trial of duplex, 10 Gbps × 8-user DPSK-OCDMA system using a single 16 × 16 multi-port encoder/decoder and 16-level phase-shifted SSFBG encoder/decoders," *J. Lightwave Technol.,* vol. 27, no. 3, pp. 299–305, 2009.

[11] H. Zang, J. P. Jue, and B. Mukherjee, "A review of routing and wavelength assignment approaches for wavelength-routed optical WDM networks," *Optic. Networks Mag.*, vol. 1, pp. 47–60, Jan. 2000.

[SP]