Terabit-per-Second Fiber Optical Communication Becomes Practical

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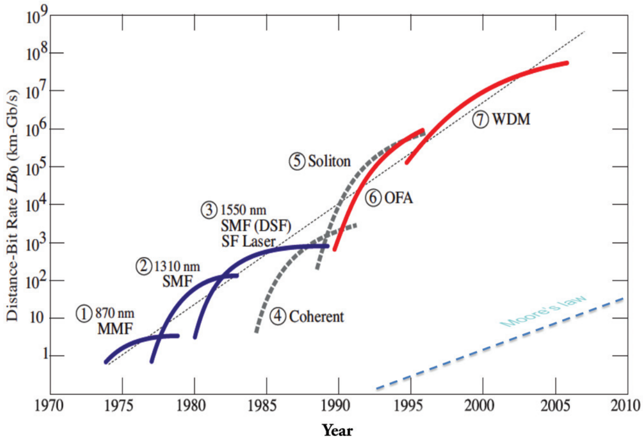
Humans used optical signals intuitively for the purpose of communication in ancient times. Modern day optical communication systems are instead based on the fundamental understanding of information theory and technological advances in optical devices and components. The Optical Society (OSA) played a vital role in making fiber-optic communication practical for the information age.

It is well known that the capacity of a communication channel is constrained by the Shannon limit, $W \log_2(1 + S/N)$, where W is the spectral bandwidth and S/N is the signal-to-noise ratio (SNR). The bandwidth of a communication channel is proportional to the carrier frequency, which is on the order of 200 THz for visible or near-infrared light. Therefore, a small fractional bandwidth around the optical carrier can provide a capacity much larger than the limited capacity supported by the spectrum of radio-frequency (RF) waves or microwaves [1]. The SNR of a communication channel is proportional to the received power and inversely proportional to the noise and distortion. The invention of the laser, which can produce high-power coherent optical radiation at the transmitter, fueled the migration from RF/microwave communication to optical communication. In fact, the first patent on lasers (more precisely masers) by Nobel Laureates Charles Townes and Arthur Schawlow, both OSA Honorary Members, was entitled "Maser and maser communication systems."

To make optical communication practical, however, the received optical power (not only the transmitted power) must be much stronger than the noise. This requires a low loss optical transmission channel. The loss in free-space transmission is determined by diffraction, which is much larger than that of RF/microwave in appropriate cables. Fortunately, light can also be guided by total internal reflection, a phenomenon known since the mid-nineteenth century. An optical fiber with a high-index core surrounded by a lower-index cladding can support guided "modes" inside the dielectric cylindrical waveguide that propagate without experiencing radiative loss [2]. As a consequence, the loss of the optical fiber is dominated by material loss. Glass fibers were initially deemed impractical for communication systems, as the measured attenuation was >1000 dB/km.

In 1966, Kao and Hockham showed that the measured losses were due to impurities rather than fundamental loss mechanisms and, without impurities, glass fibers could achieve losses below 5 dB/km. They also identified that fused silica fiber could have the lowest losses. OSA Fellow Dr. Charles Kao was awarded the 2009 Nobel Prize in Physics for his "groundbreaking achievements concerning the transmission of light in fibers for optical communication," which has fundamentally transformed the way we live our daily lives. It is the invention of the silica optical fiber and the semiconductor laser with significantly long life that ushered in the era of modern optical communication. (These inventions are described in separate essays in this section of this book.)

The first-generation fiber-optic communication system in the 1980s used multimode fibers and 0.8-μm multimode Fabry–Perot semiconductor diode lasers, supporting a data rate



▲ **Fig. 1.** History of fiber-optic communication systems. (Courtesy of Tingye Li, Alan Willner, and Herwing Kogelnik.)

of 45 Mbit/s [3], which was orders of magnitude larger than that of the microwave cable systems then in use. Since then, the capacity of optical fiber communication systems has grown in leaps and bounds. Throughout its history, fiber-optic communication has invented and reinvented itself many times over, as shown in Fig. 1, making terabits per second (Tb/s) practical. For example, the second-generation fiber-optic communication system operated at 1310 nm using single-mode fibers and single-mode semiconductor diode lasers. This brought about two improvements over the first-generation systems. First, the 0.3-dB/km loss of optical fiber at 1310 nm is much lower than 3 dB/km at 870 nm, which helped to overcome noise. Second, 1310 nm is the zero-dispersion wavelength for standard single-mode fiber. All of these different stages of technology development overcame different physical limitations of the optical communication system, pushing capacity toward the Tb/s fundamental limit. The physical limitations for fiber-optic communication arise from noise and distortion.

First let us focus on the sources of noises, which are closely related to modulation formats. Before 1980, the modulation format for optical communication systems was intensity-modulation direct detection, which is thermal noise limited with a sensitivity of thousands of photons/bit. In an effort to overcome thermal noise, the third-generation optical communication systems moved to 1550 nm, which is the minimum-loss wavelength for single-mode fibers, to increase the received optical power. As the additional power budget allowed gigabits-per-second transmission, distortions due to fiber dispersion could sometimes be the limiting factor. So in some third-generation systems, dispersion-shifted fibers for which the zero-dispersion wavelength was shifted to 1550 nm through proper design of the fiber index profile were used. In such systems, the capacity was still limited by thermal noise. Thus, starting from the mid-1980s, the optical communications community embarked on the development of coherent detection. Phase-shift keying (PSK) using coherent homodyne detection is limited by the shot noise of the local oscillator, and for binary PSK the sensitivity is 9 photons/bit, two orders of magnitude better than the thermal noise limit. However, coherent optical communication did not advance into commercial deployment because (1) phase locking and polarization management of the local oscillator was too complex and unreliable, and (2) the advent of the erbium-doped fiber amplifier (EDFA) made it unnecessary.

As early as 1964, rare-earth metal-doped glass fiber was proposed and demonstrated as a gain medium for optical amplification [4]. However, it was not until the late 1980s when two groups published work demonstrating high-gain EDFAs for fiber-optic communication—first by the group led by David Payne [5] and then by Emmanuel Desurvire [6]—that EDFA revolutionized the field of optical communication. Payne and Desurvire received the John Tyndall Award from OSA in 1991 and 2007, respectively. In terms of noise performance, optical pre-amplification (using an EDFA in front of the photodetector) changes the dominant noise source to the amplified spontaneous emission of the EDFA rather than the thermal noise of the photodetector. The fourth-generation optical communication system employed pre-amplified direct detection, which has a sensitivity of 39 photons/bit. (An essay on fiber optical amplifiers is in this section of this book.)

In fact, the gain bandwidth of an EDFA is ~3 THz, much wider than the single-channel bandwidth, which is limited by the speed of electronics. As a result, EDFAs enabled the fifth generation of wavelength-division-multiplexed (WDM) optical transmission systems. In these systems independent data streams are simultaneously transmitted on multiple wavelength channels in a single fiber and amplified together in a single EDFA, similar to frequency-division multiplexing in radio communication. WDM systems, championed by Dr. Tingye Li, 1995 OSA President, provided a multiplicative expansion of the fiber-optic bandwidth and thus multiplicative growth in fiber-optic communication system capacity. The development of WDM systems, a major leap forward in optical communication, began in the late 1990s.

Now let us focus on distortions in fiber-optic communication. Chromatic dispersion and polarization-mode dispersion (PMD) are linear distortions that exist in optical fibers. With the availability of EDFAs, optical power became an abundant resource that was extremely useful in combating the effects of noise. But high optical power also introduced nonlinear distortions in optical fiber that do not have analogies in radio communication. This is because optical fibers exhibit an intensity-dependent refractive index called the Kerr nonlinearity. Kerr nonlinearity leads to self-phase modulation and intensity-dependent spectral broadening, which in conjunction with dispersion ultimately leads to amplitude noise and timing jitter. In addition, for WDM systems Kerr nonlinearity also manifests itself in cross-phase modulation and four-wave mixing (FWM). Four-wave mixing requires phase matching of the four waves or momentum conservation of the four photons. As a result, FWM is very strong in dispersion-shifted fiber and can be effectively suppressed in fibers with a small amount of dispersion. For WDM systems, FMW is a dominant nonlinear distortion. Therefore, WDM systems must have dispersion to avoid strong nonlinearity. But dispersion is detrimental because it introduces linear distortion. The solution to this dilemma is the dispersion- and nonlinearity-managed WDM system consisting of fibers with positive dispersion and negative dispersion in cascade. And because local chromatic dispersion is never zero, nonlinear distortions are suppressed. As a result, the net overall chromatic dispersion is zero, so there is no linear distortion. Dispersion- and nonlinearity-managed WDM systems account for the majority of undersea systems all over the world. Dr. Andrew Chraplyvy and Robert Thack received the John Tyndall Award from the OSA in 2003 and 2008, respectively, for their contribution to the fundamental understanding of linear and nonlinear distortions.

After the turn of the new millennium, coherent optical communication made a comeback. This was made possible by advances in digital signal processing (DSP) and large-scale application-specific integrated circuits. In sixth-generation digital coherent optical communication, hardware phase locking and polarization management in conventional coherent optical communication of the 1980s were replaced by digital phase estimation and electronic polarization demultiplexing using multiple-input–multiple-output techniques. On the surface, it may seem incremental to migrate into coherent optical communication when the improvement in sensitivity is rather limited and the price to pay is the complicated DSP. The answer lies in the fact that DSP can perform not only phase and polarization management but also a number of other functionalities better than or impossible for optics in WDM systems. First, digital coherent communication enables electronic compensation of all linear distortions/impairments, including chromatic dispersion, PMD, and non-ideal frequency response of all components in the transmitter and receiver. Electronic dispersion compensation eliminates the need for dispersion-compensation fibers (DCFs), which leads to even less nonlinearity considering that DCFs have a small effective area and fewer amplifiers, and thus reduced noise. Reduction in both nonlinear distortions and noises improves system performance. Theoretically, it is even possible to use DSP to compensate nonlinear distortions. Digital coherent optical communication truly brought current fiber-optic systems to the fundamental capacity limit, the so-called nonlinear Shannon limit, of the single-mode fiber.

Fueled by emerging bandwidth-hungry applications and the increase in computer processing power that follows Moore's law, internet traffic has sustained exponential growth. This trend is expected to continue for the foreseeable future. As today's dense (D)WDM optical communication technology has already taken advantage of all degrees of freedom of a lightwave in a single-mode fiber, namely, frequency, polarization, amplitude, and phase, further multiplicative growth has to explore new degrees of freedom. Since the 2010 Optical Fiber Communications Conference, mode-division multiplexing in which every mode in a multimode fiber transmits independent information has emerged as a promising candidate for the next multiplicative capacity growth for optical communication. Suffice it to say that innovations for petabits-per-second (Pb/s) fiber-optic communication will continue in the foreseeable future.

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