

ADVANCES IN LIGHTWAVE SYSTEMS RESEARCH

Tingye Li is head of the Lightwave Systems Research Department at AT&T Bell Laboratories in Holmdel, New Jersey. He is responsible for research on various lightwave technologies and systems for long-distance and local-area communications applications. Mr. Li joined the company in 1957 and has a B.Sc. from the University of Witwatersrand, and an M.S. and Ph.D. from Northwestern University, all in electrical engineering.

Twenty years have passed since the first serious proposal was made to use a glass-fiber waveguide as a telecommunications transmission medium. Since then, vigorous research and development efforts have led to widespread applications of optical-fiber communication throughout the telecommunications industry. Today, lightwave systems research is exploring the vast potential bandwidth of low-loss single-mode fibers for long-haul and local-network applications. Laboratory systems with experimental single-frequency lasers and low-noise avalanche photodiodes have attained multi-gigabit-per-second transmission in single-mode fibers that are well over 100 km long. Coherent technology promises high receiver sensitivity and offers an efficient means for channel selection in a densely packed wavelength-multiplexed system. The first coherent-systems experiments have confirmed theoretical expectations but many challenges lie ahead. Other novel systems for local distribution and networking are also under study. This paper reviews recent research progress in these areas.

Perspective

Historically, telecommunications research has always been motivated to explore new technologies for expanding transmission capacity. Thus, the realization of the first laser in 1960 stirred intense interest in optical communications. The laser was envisaged as the requisite coherent source of an optical carrier on which information could be impressed at an unparalleled rate.

Research began on a broad front. But not until ten years later was a feasible, low-loss, transmission medium demonstrated. It was a

doped high-silica optical fiber with a loss of 20 dB/km. Coincidentally, continuous-wave operation at room temperature was achieved in the AlGaAs (aluminum-gallium-arsenide) semiconductor laser. The attainment of these two basic elements of an optical communications system was soon followed by a profusion of research advances that, in less than a decade, made optical-fiber communications a practical reality.¹

Deployed Fiber Systems. The first-generation fiber systems—introduced commercially in the late 1970s—operated at wavelengths of about 0.82 μm . They used AlGaAs injection lasers and multimode fibers of 3- to 4-dB/km transmission loss. Interoffice trunking was the main arena of application.

As these systems were being tested in the field just before their commercial introduction, two research advances were announced that affected the course of light-wave technology.

- The transmission loss of fiber was lowered dramatically to 0.5 dB/km in wavelength regions around 1.3 and 1.5 μm .
- Continuous-wave, room-temperature operation was achieved in an InGaAsP (indium-gallium-arsenide-phosphide) laser that could emit in the 1.0- to 1.7- μm wavelength range.

The wavelength region near 1.3 μm is especially significant. At this wavelength, the pulse spreading caused by material and waveguide effects (chromatic dispersion) in the fiber is minimal,^{2,3} making it possible to transmit over long distances at exceedingly high data rates. Also, because chromatic dispersion is proportional to source spectral width, opening the 1.3- μm transmission window allowed light-emitting diodes (LEDs) to be used in systems with moderate speed and distance requirements. For some applications (such as data links), the simpler LEDs are favored over lasers because they afford superior reliability, lower cost, and much less sensitivity to temperature variations.

Hence, the second-generation of lightwave systems operate at a wavelength of 1.3 μm , using either

LEDs or lasers as sources and multimode fibers as the transmission medium. For subscriber-loop applications, both LED- and laser-based systems operate at bit rates of up to 200 Mb/s. Laser-based systems, which can operate at higher speeds over longer distances, are deployed in metropolitan areas for interoffice trunking and in the long-haul plant.

Second-generation fiber systems have now been superseded by 1.3- μm , laser-based, single-mode systems that are designed for intercity and intercontinental service. These third-generation systems operate at several hundred megabits per second with repeater spans that exceed 40 km, and can be upgraded to speeds beyond 1 Gb/s (which is being planned). Many of these third-generation systems are now in commercial operation.

Fiber Systems Research. Current research in light-wave systems is exploring the vast potential bandwidth of low-loss, single-mode fibers. A minimum loss of 0.16 dB/km at $\lambda = 1.57 \mu\text{m}$ (which is close to the theoretical limit of Rayleigh scattering in silica) has been demonstrated in the laboratory. Typical high-quality production fibers exhibit minimum losses close to 0.2 dB/km.^{2,3}

For the 1.45- to 1.65- μm wavelength region of minimum loss, the potential bandwidth is 25,000 GHz. Imaginative and effective use of even a minute portion of this immense bandwidth can radically affect the telecommunications industry. The challenge to the research community is, therefore, intriguing and complex.

Meanwhile, researchers are trying to approach the limits that fiber loss and dispersion impose on transmission speed and distance. They have done systems experiments at data rates well beyond 1 Gb/s over single-mode fibers that exceed 100 km in length. Experiments that involved direct (intensity) modulation and detection required single-frequency lasers that have low frequency deviations (chirp) during modulation and high-sensitivity, broadband avalanche photodiodes (APDs). Such experiments have obvious implications for near-future long-haul systems.

Coherent lightwave transmission is being investi-

gated for possible application in both long-haul trunking and local networks because:

- It offers higher receiver sensitivity.
- Simple optical amplifiers could be used for boosting the signal.
- It provides an efficient way to select a particular channel from many closely spaced wavelength-multiplexed channels.

Coherent transmission requires narrow-linewidth single-frequency lasers. Initial successes are encouraging, but many challenges lie ahead. Other novel systems for local distribution and networking are also under study.

This paper reviews recent progress in lightwave systems research, emphasizing high-speed transmission and coherent technology. It discusses the limits that single-mode fiber imposes, as well as the requirements of the relevant devices. Applications in the long-haul and local arenas are considered.

Transmission Bandwidth

The maximum rate of data transmission in a single-mode fiber is determined by its chromatic dispersion, which depends on the fiber geometry, refractive-index profile, and material properties.^{2,3}

In a conventional single-mode fiber with a step refractive-index profile, the geometry and material effects combine to produce a dispersion minimum at a wavelength λ_0 slightly above 1.3 μm . Thus, the single-channel transmission bandwidth of a fiber that operates at the wavelength λ_0 can be very large, especially if the source has a narrow spectral width.

This is illustrated in Figure 1, which gives the maximum single-channel transmission bandwidth—or data rate—of a conventional single-mode fiber, 100 km long, as a function of wavelength for sources of various spectral widths, $\Delta\lambda$. However, a single-mode fiber with a refractive-index profile that is more complicated than a simple step can have maximum transmission bandwidths that are very different from those shown.³

The calculations⁴ that Figure 1 represents take

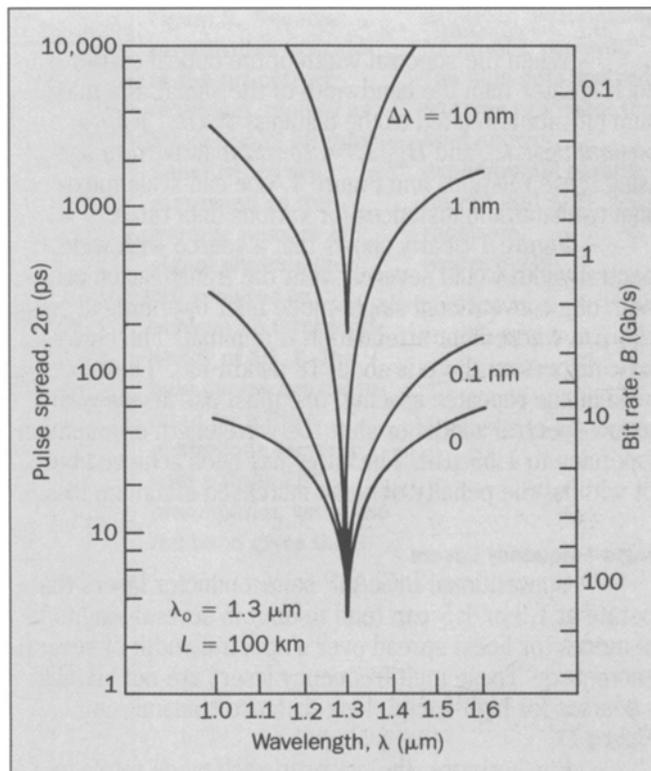


Figure 1. Theoretical maximum transmission bandwidth of a conventional single-mode fiber, 100 km long. The four curves represent sources of different spectral widths $\Delta\lambda$. The wavelength of minimum dispersion λ_0 is 1.3 μm .

into account higher-order waveguide and material effects, as well as performance degradation from intersymbol interference. The case labeled $\Delta\lambda = 0$ is akin to radio transmission in that the spectral width of the optical carrier is much narrower than the signal bandwidth, or bit rate, B . When this condition prevails, the maximum bit rate B_{max} for transmission over a distance L satisfies the relation $(B_{max})^3 L = \text{constant}$, for wavelengths near the dispersion minimum λ_0 . Away from λ_0 , the relation is

$(B_{max})^2 L = \text{constant}$.

When the spectral width of the optical carrier is much greater than the bandwidth of the signal, the maximum bit rate is related to the distance by $(B_{max})^2 L = \text{constant}$ near λ_0 , and $B_{max} L = \text{constant}$ away from λ_0 . Using these relations and Figure 1, one can scale maximum transmission distances for various data rates.

Figure 1 clearly shows that a source with wide spectral width would severely limit the transmission bandwidth of a conventional single-mode fiber operating at 1.55 μm where fiber attenuation is minimal. The chromatic dispersion there is about 18 ps/km-nm. Therefore, to maximize repeater spacing, one must use lasers with narrow spectral widths or shift the wavelength of minimum dispersion to 1.55 μm . The latter has been achieved but not without the penalty of some increased minimum loss.^{2,3}

Single-Frequency Lasers

Conventional InGaAsP semiconductor lasers that operate at 1.3 or 1.5 μm tend to emit in several longitudinal modes (or lines) spread over a spectral width of several nanometers. These multifrequency lasers are not suitable as sources for high-speed, long-distance transmission (Figure 1).

Furthermore, the power in each mode tends to fluctuate, especially under direct modulation, even though the total power remains constant from pulse to pulse. This power fluctuation among modes is converted through chromatic dispersion of the fiber into pulse-shape variations at the receiver, a phenomenon known as *mode partition noise*. Partition noise can impair system performance even for moderate transmission distances.⁵ Hence, sources for high-speed systems must operate in a single longitudinal mode.

Single-frequency operation can be obtained in a laser by using a coupled-cavity or distributed-feedback structure. The cleaved-coupled-cavity (C³) laser, used in early long-distance transmission experiments at $\lambda = 1.5 \mu\text{m}$, has two cavity sections that are coupled optically but isolated electrically.⁶ Single-frequency operation is

obtained by suitably adjusting the drive current through each section. The distributed-feedback (DFB) laser uses a grating to provide a distributed, but frequency-selective, feedback mechanism that confines emission to a single mode.⁷ Single-frequency operation is more robust in DFB lasers.

Under direct modulation, the instantaneous frequency of the semiconductor laser will vary with drive current, resulting in pulse spreading at the receiver.⁸ This phenomenon, known as *chirp*, arises because the refractive index of the laser depends on carrier density.⁹ As the refractive index varies, so does the wavelength (or frequency) of emission.

If one uses a structure to confine the optical field more tightly, nonlinear processes in the laser—when high optical field densities are present—tend to damp the large amplitude and frequency fluctuations, and leave a smaller, steady frequency shift. (A steady frequency shift with negligible transition time will produce negligible pulse spreading.) A low-chirp InGaAsP DFB laser that was amenable to high-speed direct modulation was built¹⁰ and used in long-distance transmission experiments at speeds up to 4 Gb/s.

APDs and High-Sensitivity Receivers

Simple, InGaAs PIN photodiodes have excellent frequency response and perform well in 1.5- μm receivers that operate at multigigabit-per-second data rates. (PIN stands for positive intrinsic negative; some authors may use p-i-n instead.) However, they lack the internal gain needed to enhance receiver sensitivity for high-speed transmission over long distances. Early attempts to make InGaAsP APDs were not successful because of the high dark current from tunneling and the degradation of frequency response from charge accumulation at heterojunction interfaces. Germanium APDs with low dark current and high gain have been developed and are now available commercially, but they contribute more excess noise than InGaAsP devices.

To solve the problems of tunneling dark current

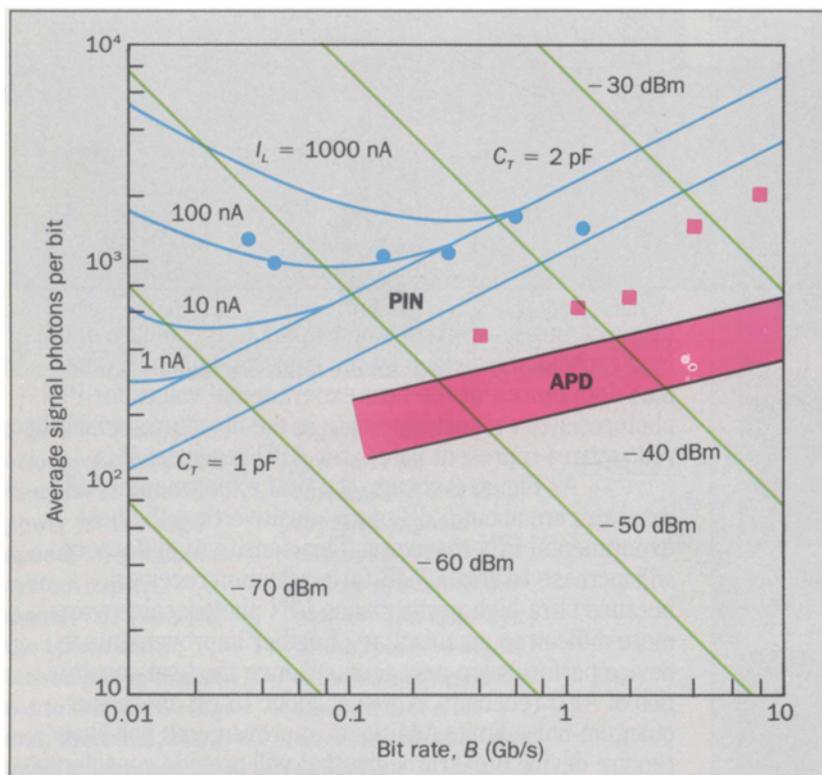


Figure 2. Receiver sensitivities of state-of-the-art optical repeaters, plotted as a function of bit rate. Sensitivities are expressed as the average number of signal photons (per bit) required to achieve an error probability of 10^{-9} . The blue curves are calculated for a PIN photodiode receiver with a GaAs FET preamplifier, while the red band gives the

expected performance for an APD receiver. The blue dots and red squares represent the best known-experimental results for PIN and APD receivers, respectively.

and interface charge accumulation, a structure that consists of several layers of InGaAsP in varying compositions was tried and proved successful.¹¹ Its use of a narrow-bandgap InGaAs layer for light absorption and a wide-bandgap InP (indium-phosphide) layer for carrier multiplication overcame the problem of dark current. A grading layer of InGaAsP added at the heterojunction reduced charge accumulation. The resulting device—known as the separate absorption, grading, multiplication (SAGM) avalanche photodiode—has worked well in experimental high-speed systems. With its gain-bandwidth product as high as 60 GHz, the SAGM APD is the best performing photodetector for high-speed operation at 1.5 μm .

Wideband, low-noise preamplifiers are as crucial

as high-performance photodetectors for attaining high sensitivity in optical receivers. (A useful definition of receiver sensitivity in a digital repeater is the minimum input power required to achieve an error probability of 10^{-9} .) The sensitivity of an optical receiver is limited by the quantum (or shot) noise associated with the primary photogenerated signal current in the detector. In practice, excess noise from the photodetector, thermal noise from the input circuit, device noise from the transistor preamplifier, and shot noise from leakage currents all contribute in varying degrees to prevent receiver performance from reaching the quantum-noise limit.

Figure 2 summarizes the performance of experimental optical receivers designed to operate in the spectral

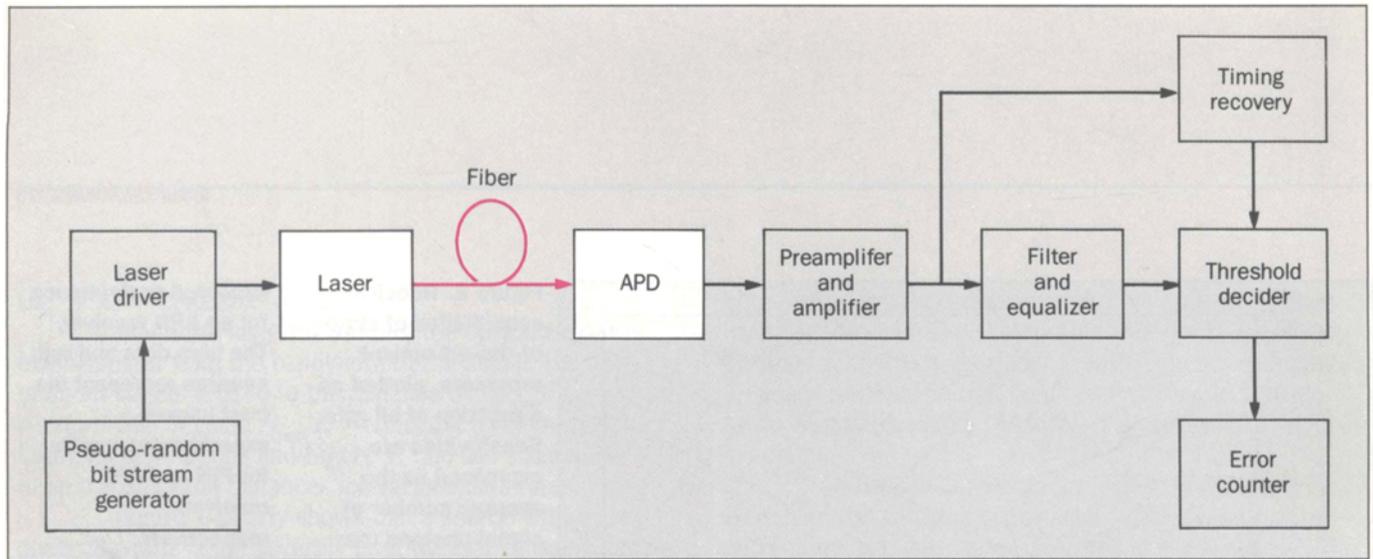


Figure 3. A typical lightwave system experiment.

region of 1.3 to 1.5 μm . The ordinate is the average (minimum) number of photons required to achieve an error probability of 10^{-9} in a time interval equal to the reciprocal of the bit rate, assuming an equal distribution of ones and zeros. This number is proportional to the average energy per bit. The abscissa is the bit rate.

The blue curves are the results of calculations based on parameters of currently available PIN photoreceivers that use GaAs (gallium-arsenide) field-effect transistors (FETs) as preamplifiers. The red shaded band represents the expected performance for APD receivers. The green diagonal grid lines convert the energy per bit into power in decibels referenced to 1 mW (dBm), assuming a 1.5- μm operating wavelength. The horizontal line at the bottom represents the ultimate sensitivity of ten photons per bit, as limited by the fundamental quantum noise. Noises that arise from thermal effects in circuits and devices cause degradations from this limit.

The straight blue lines whose slopes are proportional to the square root of the bit rate represent the theoretical performance for a receiver that consists of an ideal PIN photodiode followed by a GaAs FET preamplifier with a 50-mA/V transconductance, a total capacitance C_T of either 1 or 2 pF, and no leakage current. The blue curves that slope upward to the left represent performance when various leakage currents I_L are present. As can be seen, leakage currents are not important at high bit rates where the determining factor is the FET's channel con-

ductance noise, which is proportional to the square of the total capacitance divided by the transconductance. The blue dots represent the best experimental values for PIN photoreceivers reported to date in the literature, while the red squares represent values for APD receivers.¹²

As Figure 2 shows, the best experimental APD receivers are about 5 dB more sensitive than the best experimental PIN receivers. This sensitivity difference will increase to about 7 dB for production receivers because ultra-high-performance PIN photoreceivers are more difficult to manufacture. Further improvements in device performance may soon enhance the best sensitivities of APD receivers to a level about 15 dB above the quantum-noise limit. Additional improvements will likely require device breakthroughs that will provide considerably less excess noise from the APD.

High-Speed Systems Experiments

Systems experiments are conducted to demonstrate the feasibility of transmission and explore the limits of technology regarding how individual components behave and affect the performance of an entire system. Figure 3 illustrates the basic elements of a system experiment.

To evaluate the behavior of each component in a system and assess the system's performance, one measures the bit error rate (BER) as a function of the received power for various operating conditions. Eye diagrams, which consist of superpositions of traces of the signal in a time slot (of one bit), are used as a diagnostic tool for analyzing component or subsystem behavior.

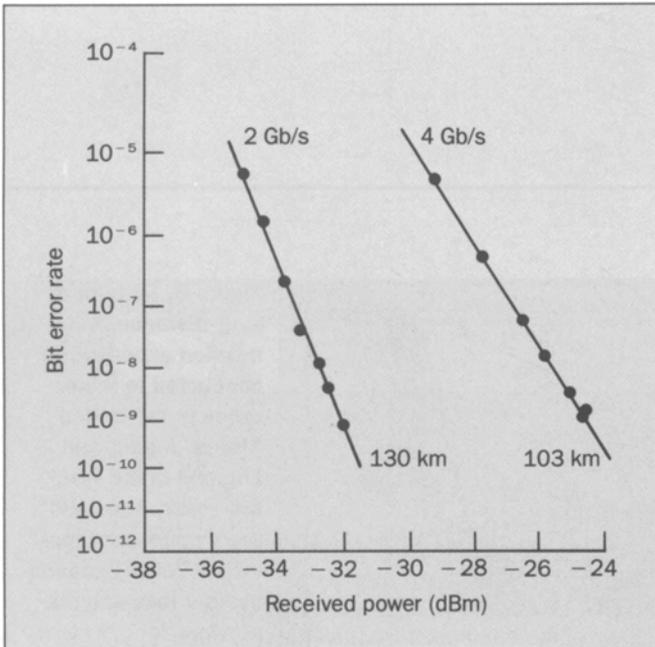
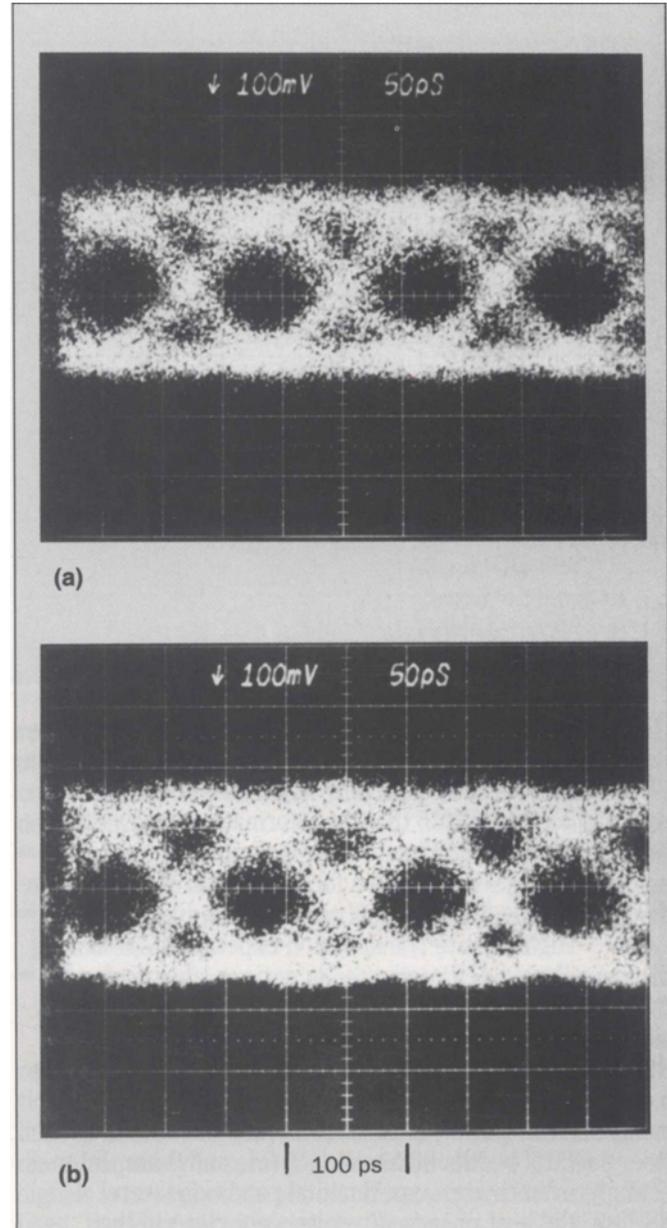


Figure 4. Measured error probability as a function of received power for two high-speed, long-distance system experiments.^{13,14} For both, the lasers were biased above threshold to minimize chirp and, therefore, maximize transmission distance.

Figure 5. Eye diagrams of (a) transmitted and (b) received signals observed in the 8-Gb/s system experiment.¹⁶ The open eye of the received signal after traversing 68 km showed that a bit-error rate of 10^{-9} was obtained.

Figure 4 shows measured BER data taken in two high-speed experiments that operated at 2 and 4 Gb/s and achieved transmission distances of 130 and 103 km, respectively.^{13,14} The experimental low-chirp single-frequency DFB laser, high-speed SAGM APD receiver, and very-low-loss single-mode fiber with a core of nearly pure silica (0.21 dB/km) all contributed to the successes of the record-setting experiments.

To avoid laser chirp, one could let the laser operate continuously and gate the optical carrier with an external modulator. Indeed, further record-setting high-speed transmission experiments at 4 and 8 Gb/s attained transmission distances of 117 and 68 km, respectively.^{15,16}



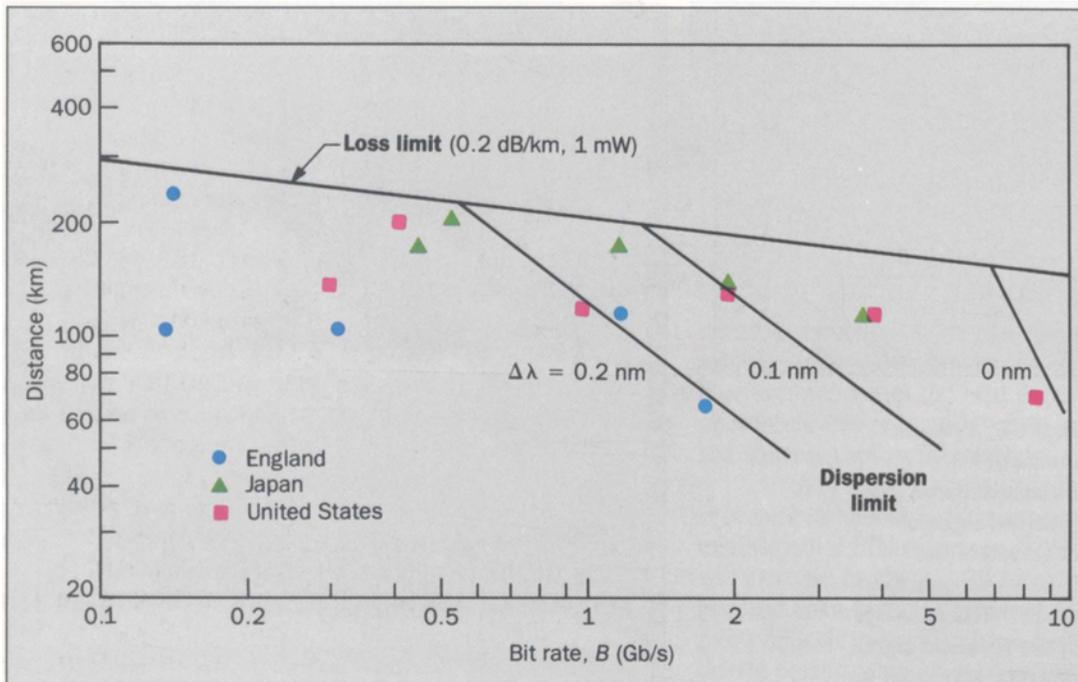


Figure 6. Results of long-distance transmission experiments conducted in laboratories in the United States, Japan, and England in the last few years. The solid lines represent theoretical limits imposed by fiber loss and dispersion, for a system that uses conventional single-mode fiber and state-of-the-art devices, and for various laser spectral widths ($\Delta\lambda$).

High-power C^3 lasers and titanium-diffused lithium-niobate waveguide modulators were used in both experiments. The 8-Gb/s experiment is especially significant because it was the first demonstration that the information bandwidth of the signal was a significant factor in limiting the transmission distance. (See the curve for $\Delta\lambda = 0$ in Figure 1.) Eye diagrams of the 8-Gb/s signal are shown in Figure 5.

High-bit-rate transmission experiments over long distances have been conducted in various laboratories in the last few years. Figure 6 plots the achieved transmission distances versus bit rate. The solid lines represent theoretical limits from fiber loss and dispersion, assuming a conventional single-mode fiber with 0.2-dB loss, 1-mW launched laser power, experimental APD receivers, and laser spectral widths of $\Delta\lambda = 0.2, 0.1,$ and 0 nm. Interestingly, even though experimental conditions were diverse, the best observed results were close to the

theoretical limits. Clearly, long-distance (>100 km) transmission at ultra-high (>10 Gb/s) data rates will require *dispersion-shifted* fibers, with λ_0 in the $1.5\text{-}\mu\text{m}$ region of minimum loss.

Of course, the transmission capacity of a light-wave transmission system can always be increased by using wavelength-division-multiplexing (WDM). The ability of a WDM system to grow gracefully with traffic demand makes it attractive where traffic growth is unpredictable. The disadvantage is that each multiplexed channel requires its own repeater, resulting in multiplied costs. However, the cost increase may be alleviated somewhat by possible large-scale integration of devices and circuits in a multiple-repeater package.

In a laboratory WDM experiment, light from ten carefully chosen DFB lasers were multiplexed onto a single-mode fiber to simulate a system with a total capacity

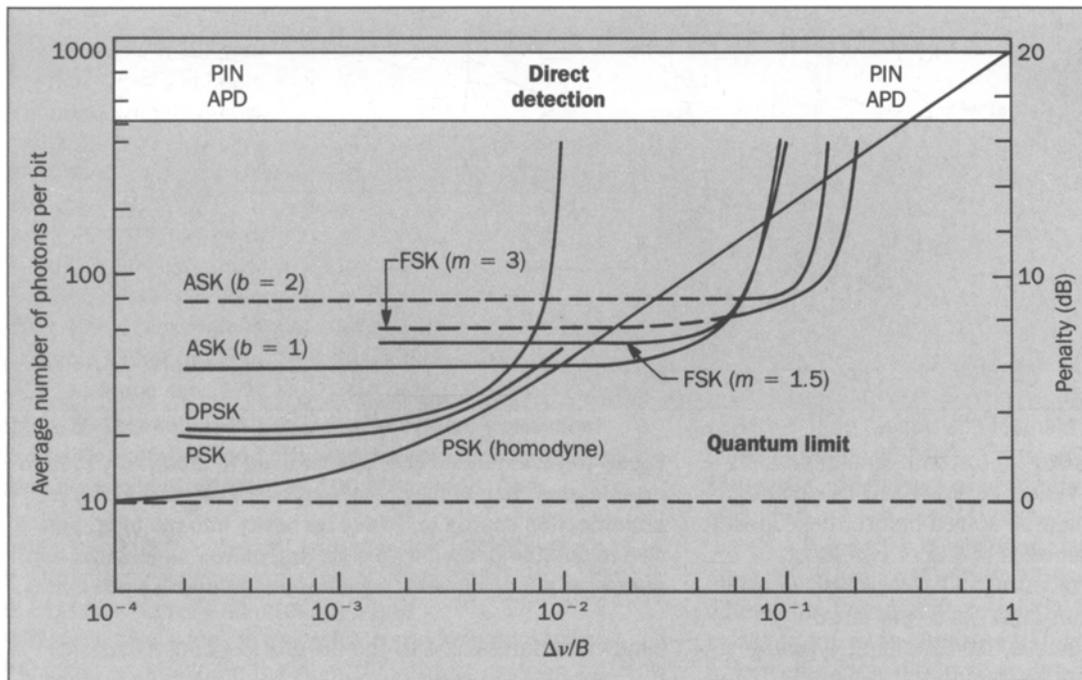


Figure 7. Receiver sensitivities for coherent modulation and detection as functions of the combined transmitter and local-oscillator laser linewidth ($\Delta\nu$) normalized to the bit rate B . Receiver sensitivity is expressed as the average number of photons (per bit) required to achieve an error probability of 10^{-9} , or as a power penalty relative to the quantum limit of direct detection. Except for the curve labeled PSK (homodyne), all others are calculated for heterodyne detection. The shaded band shows performance of experimental receivers that use direct detection.

of 20 Gb/s.¹⁷ The grating-type wavelength multiplexer and demultiplexer had a channel spacing of 1.35 nm (17 GHz) centered around 1.545 μm . A transmission distance of 68.5 km was demonstrated.

Coherent Transmission

In coherent lightwave transmission, modulation is applied as amplitude, frequency, or phase variations in the optical carrier. The received signal and the output from a local-oscillator (LO) laser are mixed in the photodetector of a heterodyne receiver to generate an intermediate-frequency (IF) signal that typically falls in the microwave-frequency range. Ordinary microwave techniques can then be used to demodulate the IF signal.

If the LO power is large enough, quantum (or shot) noise in the detector will predominate over thermal and device noise in the preamplifier, thus affording high

receiver sensitivity. The following motivates interest in coherent modulation and detection:

- The promise for increased receiver sensitivity
- The ability to select among densely packed WDM channels
- The potential for using wideband optical amplifiers to boost *en masse* a large group of WDM signals.

The theoretical sensitivity of a coherent-detection receiver can approach the *quantum limit* of direct detection of ten photons per bit. For example, the sensitivity limit of an ideal homodyne receiver (in which the intermediate frequency is zero) for phase-shift-keyed (PSK) signals is nine photons per bit. If heterodyne detection is used, the ideal sensitivities are 18 photons per bit for PSK

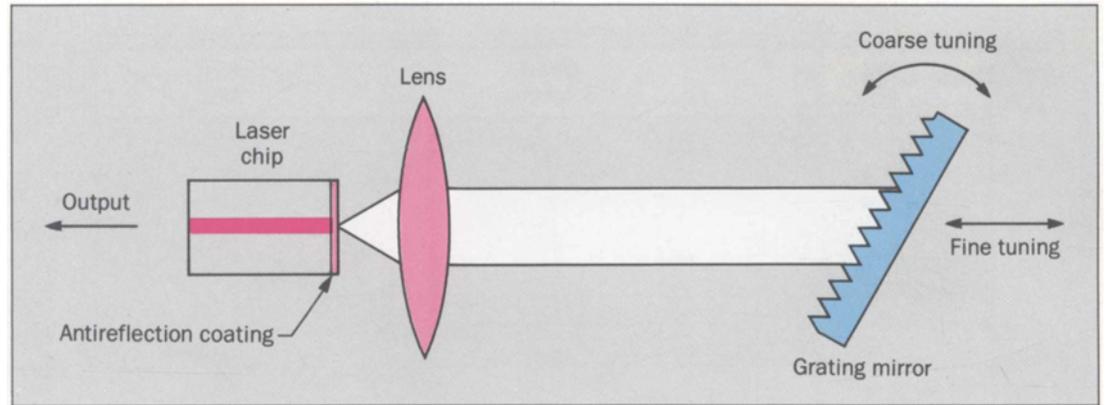


Figure 8. An extended cavity laser used in laboratory system experiments. One facet of the semiconductor laser chip is antireflection coated to extend its cavity into the long, passive region terminated by the grating mirror. Linewidths as narrow as a few kilohertz have been obtained in such lasers.

modulation and 36 photons per bit for both amplitude-shift-keyed (ASK) and frequency-shift-keyed (FSK) modulation.

Many problems must be solved before these ideal sensitivities can be approached in practice. Foremost among them is laser spectral purity. The linewidths of single-frequency semiconductor lasers are very large (compared to microwave sources, for example), typically from several megahertz to a few hundred megahertz.

These large spectral widths are caused by phase noise that arises from refractive-index fluctuations (caused by carrier-concentration fluctuations), and from the high level of spontaneous emission in the laser cavity.¹⁸ Phase noise can dramatically degrade receiver performance. The degradation can become so large that a 10^{-9} BER is impossible to attain, no matter how high the received power.

Figure 7 illustrates receiver performance for a variety of modulation and detection conditions. The ordinate is the average (minimum) number of photons per bit required to achieve 10^{-9} error probability. The abscissa is the combined linewidth of the transmitter and LO laser, normalized to the bit rate B . The quantum limit and experimental direct-detection sensitivities are shown as a dashed horizontal line and shaded region, respectively.

Except for the curve labeled PSK (homodyne), all other curves are calculated for heterodyne detection.¹⁹⁻²³ The ASK curves represent two values of b , which is the IF

bandwidth normalized to the bit rate B . Those marked FSK are for two values of m , which is the frequency deviation normalized to the bit rate B .

It is possible to narrow the linewidth of a conventional or DFB laser by extending the length of its cavity. The linewidth reduction factor is approximately equal to the square of the ratio of the total cavity length to the active cavity length.¹⁸

Figure 8 is a schematic of an extended-cavity laser in which a grating mirror is used to achieve single-frequency operation. Coarse tuning of the wavelength of operation is obtained by tilting the grating, while fine tuning or frequency tracking is done by changing the cavity length or the laser drive current. Linewidths around 10 kHz are commonly observed in such extended-cavity lasers designed for laboratory experiments.²⁴ Practical narrow-linewidth *tunable* lasers that are suitable for field applications are not yet available.

Besides laser spectral purity, tunability, and stability, researchers also have been studying other important

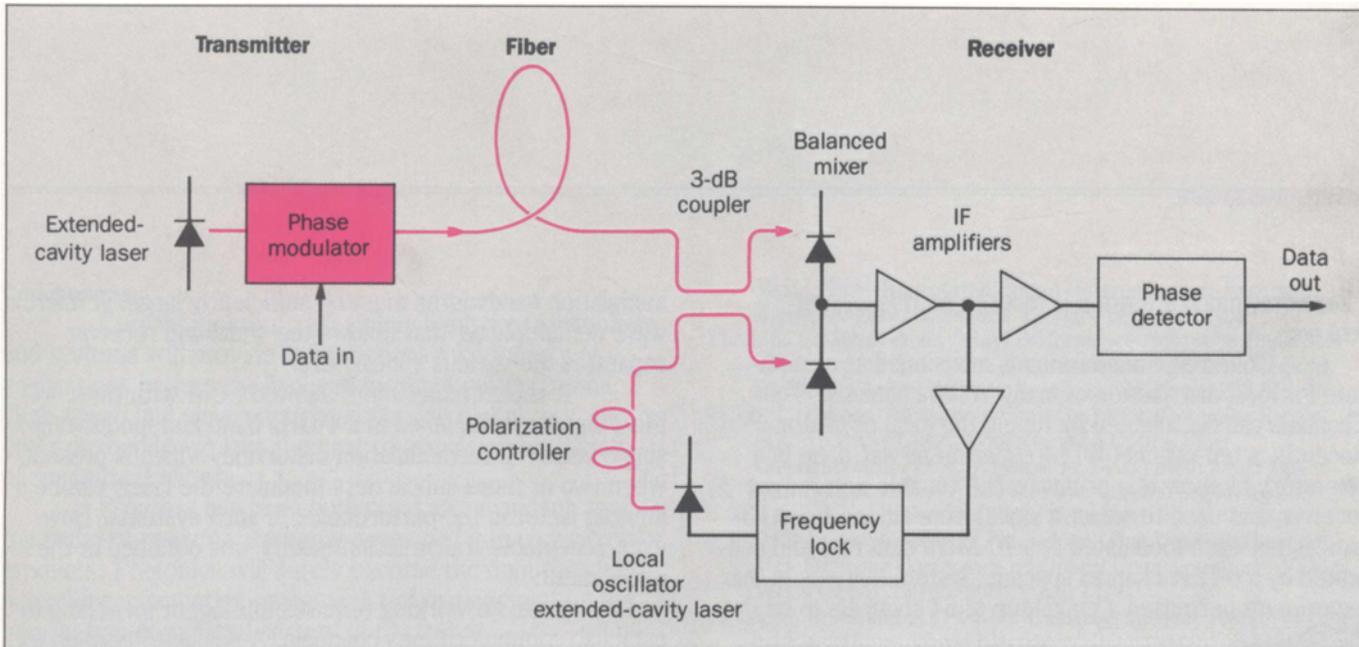


Figure 9. This coherent-transmission system experiment used differential-phase-shift-keyed modulation and heterodyne detection at bit rates of 400 Mb/s and 1 Gb/s.

issues specific to coherent transmission, including:

- Direct frequency modulation of injection lasers
- LO laser power and intensity noise
- Optical phase-locked loops for homodyne detection
- Nonlinear effects in the fiber that impair system performance
- Polarization properties of fibers and components.

Reflected power that is fed back into the laser cavity can cause linewidth variations and must be minimized using isolators.²⁵

The issue of polarization is especially important because efficient coherent detection requires that the polarization state of the received signal be matched to that of the LO signal at the photodetector. Because the output polarization of conventional single-mode fibers tends to fluctuate randomly, one must find a way to maintain polarization in the fiber or compensate at the receiver for changes in the polarization. Experimental observations suggest that polarization variations are slow enough to make tracking and compensation possible.

The first coherent-lightwave-transmission experiments, which used *semiconductor* (rather than gas) lasers as transmitters and local oscillators, were reported in

1984.^{26,27} The modulation formats were ASK and FSK at bit rates near 100 Mb/s. Later experiments at higher speeds attained receiver sensitivities that were closer to ideal.^{28,29}

Figure 9 is a schematic of one of these experiments that operated at 400 Mb/s and 1 Gb/s with differential-phase-shift-keyed (DPSK) modulation.²⁸ With a balanced mixer to suppress LO intensity noise and use LO power efficiently, the system achieved a record receiver sensitivity of 45 photons per bit at a 400-Mb/s bit rate.

Operation at higher bit rates for coherent transmission is difficult because of the stringent requirements for flat response over a large bandwidth in the receiver front end and the following linear channel. Additionally, higher LO power is required to overcome thermal noise. Nevertheless, a transmission distance of 200 km at 1 Gb/s has been achieved.²⁸ The longest distance for high-speed coherent transmission reported to date is 290 km, in an experiment at 400 Mb/s using an optimal form of FSK, called continuous-phase (CP) FSK.²⁹

Local Distribution and Networking

Until now, lightwave technology has not had a widespread effect in the local arena. Successful introduction of future integrated wideband services will depend on how various photonics technologies will be applied to solve the problems of local distribution and networking.

Therefore, much attention is focused on this area of research.

Coherent transmission is envisioned as a candidate for local distribution of many WDM channels. Channels can be selected by tuning the local oscillator. Recently, a ten-channel WDM experiment was done in a laboratory to show this principle.³⁰ A tunable heterodyne receiver was used to select a signal from among ten 0.83- μm lasers, each modulated at a 70-Mb/s data rate and separated by a 6-GHz channel spacing. System margins in this experiment permitted a maximum of 64 channels to be distributed.

A novel scheme for channel selection in a densely packed WDM system without resorting to coherent technology is the *photon star*. It exploits backward Brillouin scattering in a single-mode fiber to provide amplification in a narrow bandwidth.³¹ Because the required pump power is around 10 mW, tunable single-frequency semiconductor lasers can be used at the receiver for channel selection.

The advantages of this scheme are:

- Polarization is not important.
- Lasers with extremely narrow linewidth are not necessary.
- Simple direct detection receivers with baseband electronics can be used.

A disadvantage is that a requisite length of single-mode fiber (<5 km) is needed to provide the Brillouin gain. In a recent experiment, data at 45 Mb/s were detected error-free in the presence of a signal in an adjacent channel as close as 140 MHz.³¹

A few channels (say about 50 channels of 50 Mb/s each) could be sent using microwave subcarrier multiplexing (SCM).^{32,33} In this scheme, the lightwave carrier is intensity-modulated by signals that ride on microwave subcarriers. For example, several 50-Mb/s channels can individually modulate several microwave subcarriers at different microwave frequencies. The combined microwave signal can then intensity-modulate a laser, or be grouped in different frequency bands to modulate different lasers. The lasers need not operate in a single frequency, but their

modulation bandwidths must be sufficiently large. A microwave demultiplexer that follows the wideband receiver separates the various subcarriers.

A recent experiment showed SCM with three 44-Mb/s signals multiplexed in a 4-GHz band and modulating a single laser.³² Intermodulation distortion, which is present when two or more subcarriers modulate the laser, can be a limiting factor in the performance of such systems. However, acceptable transmission quality was obtained in the experiment.

Local networking requires intelligent switching to establish communications channels. A possible scenario for future local networks could be one where high-bit-rate time-division-multiplexed (TDM) lightwave signals carried by fibers are detected, demultiplexed, and then switched by electronic switching systems as lower-bit-rate channels of various services. For example, a 1-Gb/s lightwave channel with multiplexed voice, data, and video would serve each subscriber. Electronic switches that use high-speed silicon or gallium-arsenide integrated circuits would switch the various services that run at bit rates up to 100 or 200 Mb/s. Both circuit and packet switching techniques could be employed. This evolutionary approach can easily be made compatible with today's networks and systems that are under development.

On the other hand, the vast bandwidth of optical fibers challenges the imagination and ingenuity of research workers to innovate revolutionary systems that promise greatly enhanced technical capability and offer important economic advantages. Both WDM and TDM techniques are being explored for local switching and networking. Different network topologies and various protocols with distributed intelligence for accessing a network are being investigated. These system pursuits are exerting strong influences on device research. For example, *tunable* narrow-bandwidth optical filters and *tunable* narrow-linewidth lasers are being pursued for WDM applications. The work on local distribution and networking is just beginning. Which technologies will eventually prevail is difficult to predict.

Conclusions

Current vigorous research in lightwave technology and systems will provide many options for a variety of applications in the long-haul and local-networking arena. High-speed and wavelength-multiplexing techniques are being pushed to explore the vast transmission bandwidth of single-mode fibers.

Progress has been both rapid and abundant, and the fruits of research are being developed into commercial products. Photonics will surely become the dominant technology for information movement and management in the information-dominated society of the future.

References

1. T. Li, "Advances in Optical Fiber Communications: An Historical Perspective," *IEEE Journal on Selected Areas in Communications*, Vol. SAC-1, April 1983, pp. 356-372.
2. S. R. Nagel, J. B. MacChesney, and K. L. Walker, "Modified Chemical Vapor Deposition," *Optical Fiber Communications*, Vol. 1, Fiber Fabrication, edited by T. Li, Academic Press, Orlando, Florida, 1985, pp. 1-64.
3. D. Kalish and L. G. Cohen, "Single-Mode Fiber: From Research and Development to Manufacturing," *AT&T Technical Journal*, Vol. 65, No. 6, November/December 1986, pp. 19-32.
4. D. Marcuse and C. Lin, "Low Dispersion Single-Mode Fiber Transmission—The Question of Practical Versus Theoretical Maximum Transmission Bandwidth," *IEEE Journal on Quantum Electronics*, Vol. QE-17, June 1981, pp. 869-877.
5. R. A. Linke et al., "Mode Power Partition Events in Nearly Single-Frequency Lasers," *IEEE Journal of Lightwave Technology*, Vol. LT-3, June 1985, pp. 706-712.
6. W. T. Tsang, N. A. Olsson, and R. A. Logan, "High-Speed Direct Single-Frequency Modulation with Large Tuning Rate and Frequency Excursion in Cleaved-Coupled-Cavity Semiconductor Lasers," *Applied Physics Letters*, Vol. 42, April 1983, pp. 650-652.
7. H. W. Kogelnik and C. V. Shank, "Stimulated Emission in a Periodic Structure," *Applied Physics Letters*, Vol. 18, February 1971, pp. 152-154.
8. R. A. Linke, "Modulation Induced Transient Chirping in Single-Frequency Lasers," *IEEE Journal of Quantum Electronics*, Vol. QE-21, June 1985, pp. 593-597.
9. T. L. Koch and J. E. Bowers, "Nature of Wavelength Chirping in Directly Modulated Semiconductor Lasers," *Electronics Letters*, Vol. 20, December 1984, pp. 1038-1040.
10. T. L. Koch et al., "1.55- μm InGaAsP Distributed Feedback Vapor Phase Transported Buried Heterostructure Lasers," *Applied Physics Letters*, Vol. 47, July 1985, pp. 12-14.
11. J. C. Campbell et al., "High-Performance Avalanche Photodiode with Separate Absorption Grading and Multiplication Regions," *Electronics Letters*, Vol. 19, September 1983, pp. 818-819.
12. B. L. Kasper, "Sensitivity Limits on Direct Detection Receivers," *Technical Digest*, Conference on Optical Fiber Communication, OSA, Washington, D.C., 1986, paper WJ4.
13. B. L. Kasper et al., "A 130 km Transmission Experiment at 2 Gb/s Using Silica-Core Fiber and a Vapor Phase Transported DFB Laser," *Conference Proceedings (Post Deadline Papers)*, 10th European Conference on Optical Communications, VDE-Verlag GmbH, Berlin, 1984, paper PD-6.
14. A. H. Gnauck et al., "4 Gb/s Transmission Over 103 km of Optical Fiber Using a Novel Electronic Multiplexer/Demultiplexer," *Technical Digest (Post Deadline Papers)*, Conference on Optical Fiber Communication, OSA, Washington, D.C., 1985, paper PD-2.
15. S. K. Korotky et al., "4 Gb/s Transmission Experiment Over 117 km of Optical Fiber Using a Ti:LiNbO₃ External Modulator," *Technical Digest (Post Deadline Papers)*, Conference on Optical Fiber Communication, OSA, Washington, D.C., 1985, paper PD-1.
16. A. H. Gnauck et al., "Information-Bandwidth-Limited Transmission at 8 Gb/s Over 68.3 km of Single-Mode Optical Fiber," *Technical Digest (Post Deadline Papers)*, Conference on Optical Fiber Communication, OSA, Washington, D.C., 1986, paper PDP-9.
17. N. A. Olsson et al., "68.3 km Transmission with 1.37 Tbit·km/s Capacity Using Wavelength Division Multiplexing of Ten Single-Frequency Lasers at 1.5 μm ," *Electronics Letters*, Vol. 21, January 1985, pp. 105-106.
18. C. H. Henry, "Theory of the Linewidth of Semiconductor Lasers," *IEEE Journal of Quantum Electronics*, Vol. QE-18, February 1982, pp. 259-264.
19. J. Salz, "Coherent Lightwave Communications," *AT&T Technical Journal*, Vol. 64, No. 10, December 1985, pp. 2153-2209.
20. B. Gance, "Performance of Homodyne Detection of Binary PSK Optical Signals," *IEEE Journal of Lightwave Technology*, Vol. LT-4, February 1986, pp. 228-235.
21. G. Nicholson, "Probability of Error for Optical Heterodyne DPSK System with Quantum Phase Noise," *Electronics Letters*, Vol. 20, November 1984, pp. 1005-1007.
22. G. Jacobsen and I. Garrett, "Error-Rate Floor in Optical ASK Heterodyne Systems Caused by Nonzero (Semiconductor) Laser Linewidth," *Electronics Letters*, Vol. 21, March 1985, pp. 268-270.
23. I. Garrett and G. Jacobsen, "Influence of (Semiconductor) Laser Linewidth on the Error-Rate Floor in Dual-Filter Optical FSK

- Receivers," *Electronics Letters*, Vol. 21, March 1985, pp. 280-282.
24. R. Wyatt and W. J. Devlin, "10 kHz Linewidth 1.5 μm InGaAsP External Cavity Laser with 55 nm Tuning Range," *Electronics Letters*, Vol. 19, February 1983, pp. 110-112.
 25. R. W. Tkach and A. R. Chraplyvy, "Regimes of Feedback Effects in 1.5- μm Distributed Feedback Lasers," *IEEE Journal on Lightwave Technology*, Vol. LT-4, November 1986, pp. 1655-1661.
 26. M. Shikada et al., "100 Mbit/s ASK Heterodyne Detection Experiment Using 1.3 μm DFB-Laser Diodes," *Electronics Letters*, Vol. 20, February 1984, pp. 164-165.
 27. R. Wyatt et al., "140 Mbit/s Optical FSK Fibre Heterodyne Experiment at 1.54 μm ," *Electronics Letters*, Vol. 20, October 1984, pp. 912-913.
 28. R. A. Linke et al., "Coherent Lightwave Transmission Over 150 km Fiber Lengths at 400 Mbit/s and 1 Gbit/s Data Rates Using Phase Modulation," *Electronics Letters*, Vol. 22, January 1986, pp. 30-31.
 29. K. Iwashita et al., "Linewidth Requirement Evaluation and 290 km Transmission Experiment for Optical CPFSK Differential Detection," *Electronics Letters*, Vol. 22, July 1986, pp. 791-792.
 30. E.-J. Bachus et al., "Ten-Channel Coherent Optical Fibre Transmission," *Electronics Letters*, Vol. 22, September 1986, pp. 1002-1003.
 31. A. R. Chraplyvy and R. W. Tkach, "Narrowband Tunable Optical Filter for Channel Selection in Densely-Packed WDM Systems," *Electronics Letters*, Vol. 22, September 1986, pp. 1084-1085.
 32. T. E. Darcie et al., "Lightwave System Using Microwave Subcarrier Multiplexing," *Electronics Letters*, Vol. 22, July 1986, pp. 774-775.
 33. J. E. Bowers, "Optical Transmission Using PSK Modulated Subcarriers at Frequencies to 16 GHz," *Electronics Letters*, Vol. 22, October 1986, pp. 1119-1121.

(Manuscript received October 15, 1986)