In 1983 he was appointed ITT Executive Scientist and is staffed in World Headquarters, NY, and the Advanced Technology Center, Shelton, CT. He has also published a book entitled Optical Fiber System-Technology, Design and Applications.

Dr. Kao received many awards for his fundamental pioneering contributions to optical fiber communications. He received the 1976 Morey Award from the American Ceramic Society for outstanding contributions to glass science and technology and in 1977 was awarded the Stewart Ballantine Medal by the Franklin Institute for his conceptual work on optical fiber communication systems. He was the recipient in March 1978 of the Rank Prize of the Rank Trust Fund of England for his pioneering work in optical fiber communication. In 1978 he was honored with the Morris H. Liebmann Memorial Award of IEEE for making communication at optical frequencies practical by discovering, inventing, and developing the material, techniques and configurations for glass fiber waveguides and, in particular, for recognizing and proving by careful measurement in bulk glasses that silicon glass could provide the requisite low optical loss needed for a practical communication system. He was awarded the L. M. Ericsson International Prize in May 1979 for fundamental contributions to the long-distance transmission of information through optical fibers. He received the AFCEA Gold Medal in 1980 in recognition of his contribution to the application of optical fiber technology to military communications.

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Present Thrust of Optical-Fiber Telecommunications Research—An Individual Perspective

STEWART E. MILLER

Abstract—**A perspective of some of the principal topics of current research is given, including single-mode lasers and laser fluctuations, a broad-band low-dispersion fiber, potential system configurations for high-data-rate transmission, detectors, wavelength multiplexing components, and the status of work toward even lower loss fibers.**

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I. Introduction

In ORDER to provide background for a discussion of present and future optical-fiber telecommunications research, we may view briefly the present status of the commercial art. In the United States, there are now installations of lightwave interoffice metropolitan trunks in service in more than 50 cities. Intercity trunks from New York to Washington, DC are in place, with extensions to Boston, MA, and Richmond, VA under construction. Links in California destined to serve in the forthcoming Olympics are in place. In the local loop,

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fiber feeder links from the central office out to a serving interface are being used, with both aerial and underground cables. The total fiber in use in the United States is more than in the rest of the world put together. The New York–Washington link alone contains 30 000 miles of fiber. In the United Kingdom fiber systems are also proliferating [1], and the scientific community is very aware of the major thrust in fiber communication being carried out in Japan.

In all countries, predominant technical features of existing commercial installations are: multimode fibers (typically 50-μm core, 125-μm OD cladding, carrier wavelength in the 0.82–0.9-μm region, laser source with about 1-mW output or LED (for loop) with about 1/10th that power into the fiber. Direct digital modulation of the source is essentially universal (although a few video analog links are being used for short-distance unrepeatered operation). Bit rates in the U.S. are 6.3, 45, and 90 Mb/s, and in the U.K. are 8, 34, and 140 Mb/s. There are, of course, additional systems in the pipeline in all countries. In the U.S. plans for expansion in domestic fiber systems have been announced both by the Bell System and by other companies. In addition, although no formal announcement has been made, the Bell System expects to have a transatlantic fiber cable system ready for use in 1988. (In November 1983 contracts were awarded for a new transatlantic cable system (TAT-8) using fiber-optic transmission. U.S. organizations (AT&T) received 87 percent of the award, with the balance going to European organizations.)

These are the fruits of research that took place more than four years ago. In the meantime, research and newer development work has moved to somewhat higher bit rates, to the 1.3–1.55-μm wavelength region and to single-mode fibers. For example, other papers at this meeting report on a trial of undersea single-mode system components and of single-mode elements intended for domestic use.[1] There are good reasons for moving to the 1.3–1.55-μm region. The fiber loss in decibels can be an order of magnitude lower than at 0.85-μm ($\frac{1}{4}$ dB/km versus 2–3 dB/km), and the transmission delay distortion can be two orders of magnitude lower (1–2 ps/km · nm versus 100+ ps/km · nm). As Li pointed out some years ago [2], an LED system at 1.3 μm can compete at data rates and repeater spans comparable to those of a laser system at 0.85 μm.

This perspective will focus on the long wavelength region and on the research thrust. Considerable selectivity has been exercised in placing emphasis, and where references are cited the intention is to provide an example of the concept under discussion and not to provide comprehensive coverage of all relevant work. An excellent bibliography may be found in a recent publication [3].

II. LASERS

Perhaps the most significant research topic right now is injection lasers. They were invented about 1962, first ran CW in 1970, and in 1983 we reached the point of practicality for a truly single-mode (single-transverse and single-longitudinal-mode) laser. At the time the GaAs injection laser came on the scene, most of the optical telecommunications researchers were using HeNe lasers which ran beautifully in a single transverse mode, meeting all the needs of that period. Laser users assumed that injection lasers would soon perform similarly, but were frustrated for years. When long fiber transmission links were assembled in the laboratory, pulse jitter at the receiver (soon called mode partition noise) was discovered, and the key performance problem of this laser was identified [4]. Numerous contemporary studies illustrate and clarify existing injection lasers as rather noisy sources, especially at power outputs below 1 mW.

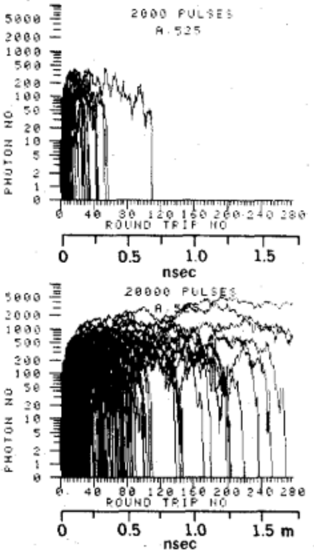

Fig. 1. Photon packet size versus number of round trips in the laser resonator. (After J. A. Copeland [5].)

Fig. 1 is based on a laser model proposed by Copeland [5]. In this model each spontaneous emission is followed as a packet of photons that grows through stimulated emission as it shuttles back and forth in the laser cavity. The ordinate is the number of photons per packet and abscissa is the number of round trips the packet has made in the laser cavity. The upper computer plot shows the result of 2000 spontaneous emissions; only one packet lasted for 0.7 ns. The lower plot is the result of 20 000 starts; three packets survived for 1.75 ns—89 percent failed to survive for 6 ps. From this and other calculations, Copeland concluded that the injection laser output is the result of a very few photon packets, resulting in large fluctuations.

Liu made observations on injection lasers which support this general idea [6]. Fig. 2 shows in the center row (right) the light output response due to a step function turn-on of the current drive—four single turn-ons are recorded. The mode in the center predominates above all others after 8 ns, but 5 ns of jitter in turn-on is observed. When the power is absent from the main mode, it is present in one of the neighboring modes—the total power output comes up reliably on every pulse. Those results are typical of 250-μm-long "single-mode" Fabry–Perot lasers.

Fig. 3 shows how a short cavity laser (about 50–70 μm long) responds to the same step function drive [7]. The turn-on repeats with jitter of less than $\frac{1}{4}$ ns. We can understand this improved behavior as follows: Fig. 4 shows the gain line in

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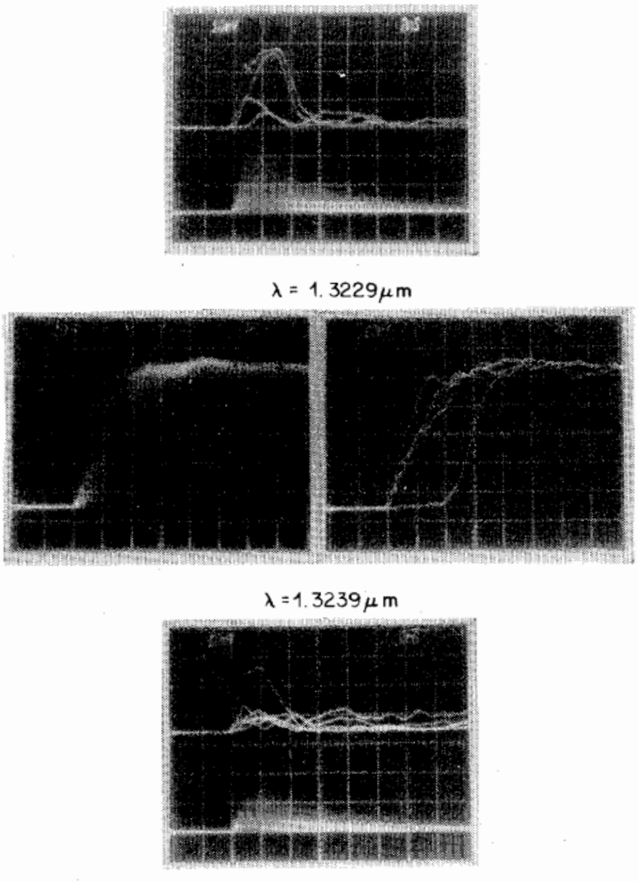
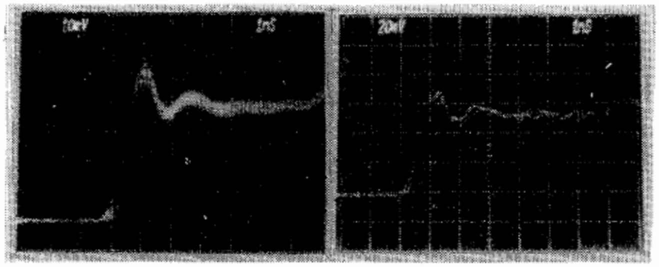


λ = 1.3229μm

λ = 1.3239μm

λ = 1.3249μm

Fig. 2. Laser light-output response to a step-function turn-on of driving current in a 250-μm long injection laser. Sharp traces are the recording of single turn-on events. Fuzzy traces are the superposed recordings of a very large number of turn-on events. (P. L. Liu *et al.* [6].)



λ = 1.2762μm

Fig. 3. Similar to Fig. 2, for a 60-μm long laser. No significant power in other wavelengths [6].

the semiconductor laser and the Fabry-Perot loss minima. The device output is greatest where the gap between the gain curve and loss curve is a minimum. Thus the side-lobe output power level is reduced by using a short cavity (dotted loss minima) with wider frequency spacing between resonances and larger vertical gaps between the semiconductor gain and the cavity loss. Another important laser-operation feature emerges from this diagram—the device operating temperature must be adjusted to keep the gain line nominally centered on one cavity loss peak if the adjacent-mode levels are to be kept low and approximately equal.

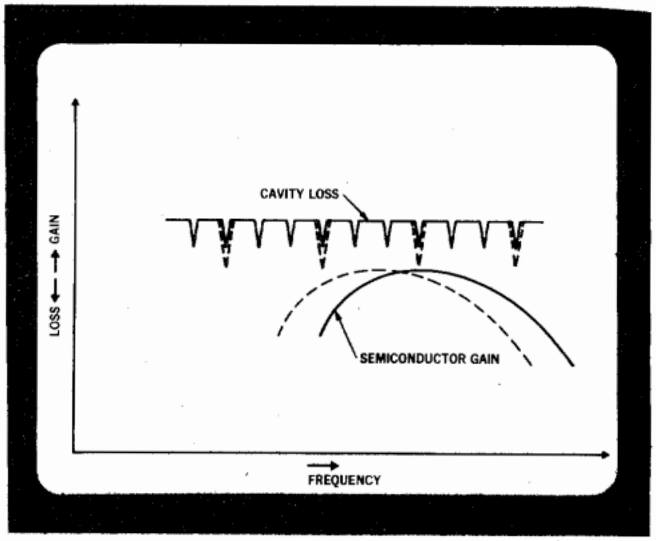


Fig. 4. Diagram of laser cavity loss versus frequency (or photon energy) and semiconductor gain for two device temperatures.

One might expect more normal output during continuous operation, but fluctuations still may be troublesome in gigabit-rate systems. Fig. 5 shows the observed probability density for the laser output on a good single-mode laser running CW at 1.2-mW average power [8]. The abscissa represents the sampled value of power output, and the ordinate is the logarithm of the rate of occurrence of the abscissa. Liu used a sampling gate that was about 100 ps wide. We see the probability density is down only 4 orders of magnitude at $\frac{1}{2}$ average power level. Again, this data is for 1.2-mW average output. Higher power levels or lower bit rates alleviate this problem, but with a typical objective of 10(−9) error rate, it is clear that laser fluctuations in simple Fabry-Perot lasers can be troublesome.

Contemporary research is seeking a solution to these problems in several ways. Distributed-feedback lasers, first demonstrated by Kogelnik and Shank in 1971 [9] are being developed in semiconductor form in several Japanese laboratories [10]. The challenge to fabricate this structure reproducibly is formidable, but excellent progress is reported. In work at British Telecom Research Laboratory, an injection laser was incorporated into a 20-cm-long cavity having a diffraction grating as one cavity reflector [11]. Both the high-Q cavity and the distributed feedback device have yielded narrow-spectral-width single-mode lasers, and other approaches, for controlling injection-laser fluctuations, are being pursued. It is clear that a successful single-mode laser will become available, but there is not yet a consensus on the preferred form or forms.

III. Fibers

In contrast to the laser situation just discussed, fiber loss presents few problems. Very low transmission losses are responsible for much of the excitement that lightwave systems offer. The curve of Fig. 6 was taken from a multimode fiber measurement—right now single-mode fibers are better in the 1.5-μm region (near $\frac{1}{4}$ dB/km). We contemplate the use of the entire 1.3–1.55-μm region. In order to enhance the utility of this broad wavelength band, the OH(−) ion overtone at 1.39

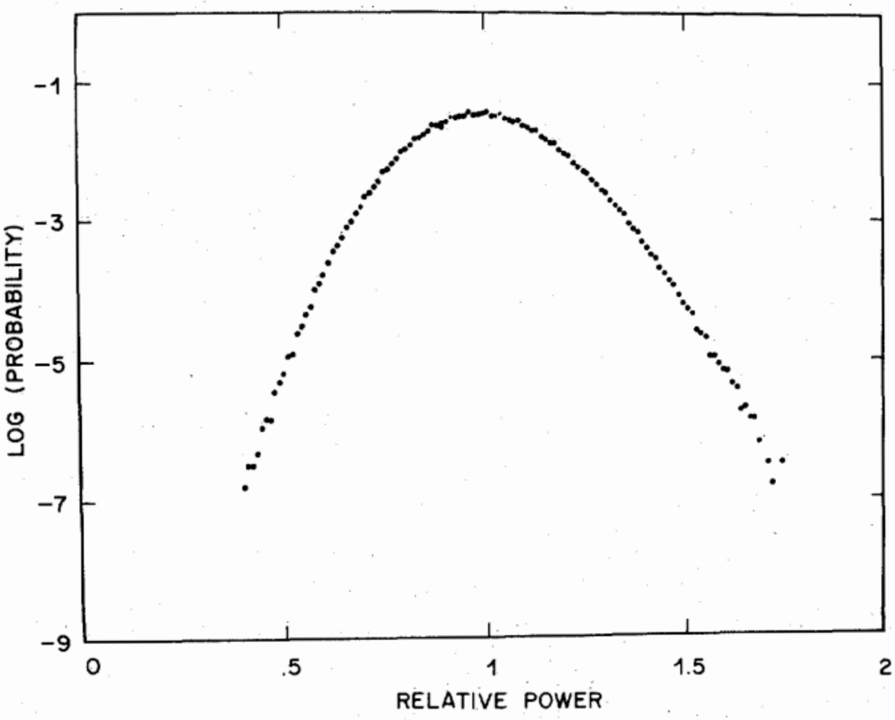


Fig. 5. Probability density versus sampled power output (~100 ps gate) for a good single-mode Fabry-Perot injection laser running continuously at 1.2 mW. (After P. L. Liu, [8].)

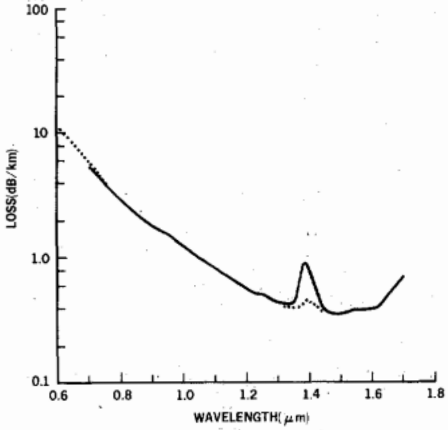


Fig. 6. Sample of current fiber loss versus wavelength.

μm should be reduced. There are several ways to reduce the 1.39-μm loss peak. A conventional way is to use chlorine to dry the glass particles before they are consolidated into the fiber preform. Another approach is to use an ion exchange process (OD(-) for OH(-)) to shift the 1.39-μm loss peak out of the region of interest (Fig. 7) [12]. The heavier OD(-) ion has its overtone absorption at longer wavelengths than OH(-), where they are less of a problem. At present this technique is an alternative to chlorine treatment or can be used in combination with chlorine dehydration.

Fiber dispersion properties are the key to numerous future fiber system possibilities. Conventional single-mode fibers have just one dispersion minimum (Fig. 8). To build a transmission system with the maximum channel capacity, one would place it near 1.3 μm and use enough laser power to bring the loss limit and dispersion limit into balance. How high a bit rate could this yield?

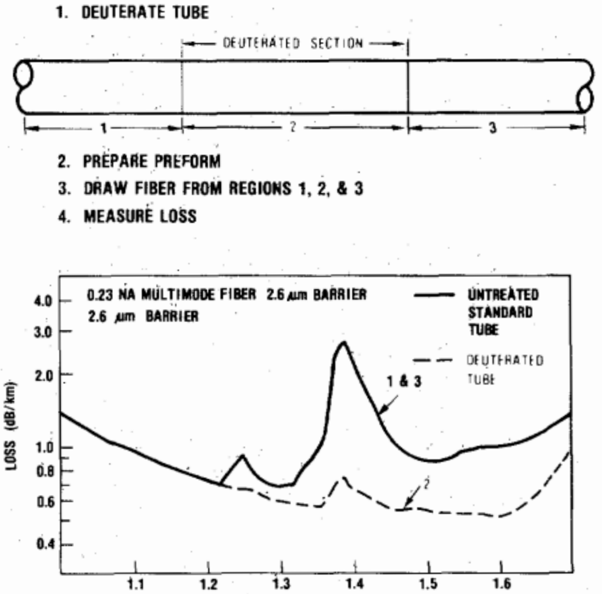


Fig. 7. Illustration of reduction of 1.39-μm loss (due to OH^-) by use of OD-OH exchange [12].

Fig. 9 shows calculations of input pulsewidth as abscissa and output pulsewidth as ordinate [13]. At the end of 50 km, with reasonable laser spectral width (2-3 Å) and reasonable tolerance on the fiber dispersion minimum (0.01 μm) we find that 10 ps pulses will be satisfactory—100 Gb/s. How much laser power will this require? Fig. 10 shows the required laser power (when the pulse is on) versus bit rate, assuming a receiver which yields 10(-9) error rate on 1000 signal photoelectrons/bit. For 100 Gb · s we find 200 mW is needed. That is a proper challenge for research.

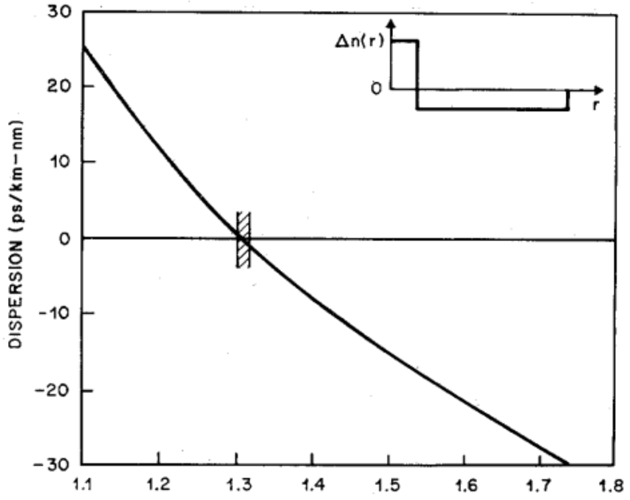


Fig. 8. Possible system usage of conventional single-mode fiber.

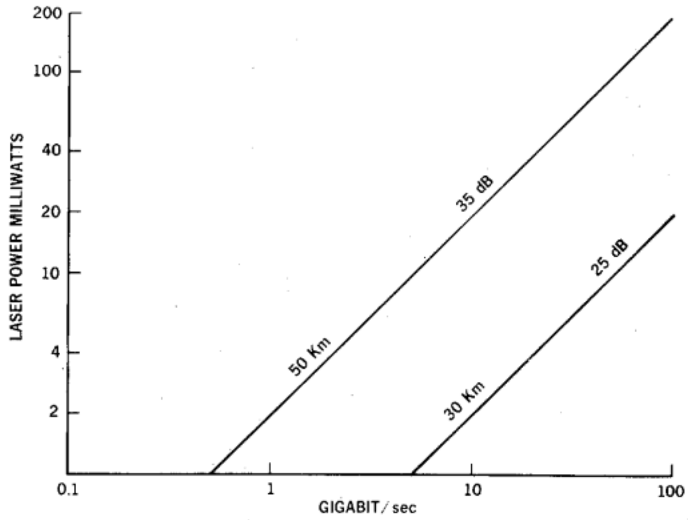


Fig. 10. Required laser power versus bit rate with a receiver sensitivity of 1000 signal-photo-electrons per bit.

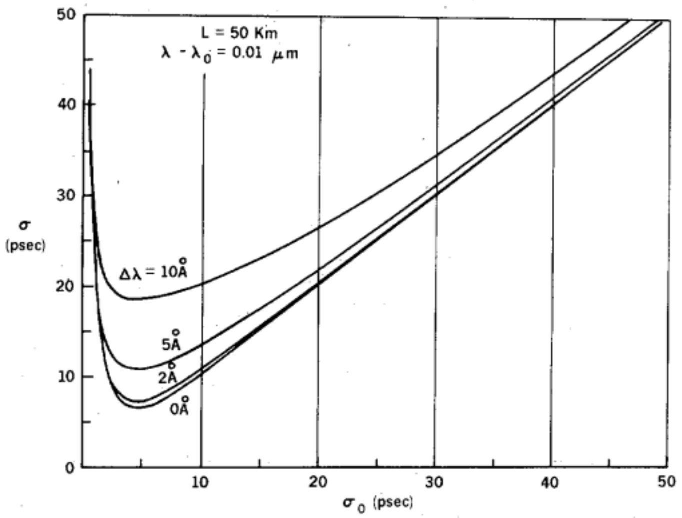


Fig. 9. Output pulsewidth (ordinate) versus input pulsewidth for 50 km of single-mode fiber, $\Delta\lambda$ laser spectral width, and (λ-λ_0) displacement between the fiber's minimum dispersion wavelength and the laser's central wavelength. (Marcuse and Lin [13].)

Powers of this magnitude raise questions of nonlinearity. One potential problem is stimulated Raman scattering in the silica fiber, a phenomenon which shifts power from the transmitted wave to longer wavelengths. For single-channel systems (no worry about crosstalk from any other channel), powers of 300^+ mW appear acceptable. For multi-channel systems in which the Raman emission appears in another channel's passband, power levels on the order of 20 mW must not be exceeded. For multichannel systems, therefore, at 50-km spacing this brings us down to a few gigabits per second bit rate—limited by nonlinear fiber phenomena. With the conventional fiber, two high-speed channels might be located astride the dispersion minimum at 1.3 μm, each running at 2 or 3 Gb/2 as just mentioned.

The 1.3-μm dispersion minimum can be shifted to 1.55 μm by suitable choice of core size and core index. This has recently been done with only a small increase in 1.55-μm loss, leaving a net loss lower than at 1.3 μm. The channel layout options just described for 1.3 μm can thus be applied to the dispersion-shifted fiber at 1.55 μm.

New quadruply-clad fibers have two dispersion minima, which can be placed near the 1.3- and 1.55-μm regions [14] (see Fig. 11). Now we can place high-speed channels right on the two dispersion minima, and run at upwards of 2- or 3-Gb/s rate signals in each, with single-mode lasers. Alternatively, we could run 800-Mb/s rates in each channel with lasers operating in a few longitudinal modes, using the very low fiber dispersion to cope with the laser spectral width. Alternatively, four channels could be used straddling the two dispersion minima, at 2 or 3 Gb/s each with single-mode lasers or at 500–800 Mb/s with lasers that emit a few longitudinal modes.

Finally, the entire region from below 1.3 to above 1.55 μm might be filled with channels (Fig. 12). The quadruply clad fiber can hold the dispersion within about 2 ps/km · nm over this region which leads to a single-channel capacity of 2 or 3 Gb/s at 50-km span, limited by nonlinear fiber effects with single-mode lasers. With multimode lasers at 50-km spacing, perhaps $\frac{1}{2}$ -1-Gb/s pulse rate could be achieved.

Use of very high bit rates (i.e., 2 Gb/s or more) would be more attractive if electrical integrated-circuit assemblies were available. However, bringing on-line a new level of speed in IC's can be expensive and require a great deal of time. This is somewhat analogous to opening up a new optical wavelength band—and may require a new material system and new processing and new lithography techniques.

It is apparent that there are many technological tradeoffs in choosing between the above-mentioned configurations. There are other application-related factors, cited below, which guide system choices and hence applied research directions.

Detectors are far more reliable and reproducible than lasers, and are readily available in the InGaAsP material system. Look first at the dual-wavelength p-i-n detector on the right hand side of Fig. 13. There are two p-n junctions having quaternary compositions of different band gaps. This provides separate absorption regions for the two input frequencies. The dash-dot curves (below) show the individual detector responsivities.

This device provides a simple means for taking two lightwave signals at different wavelengths from a single fiber and providing separated baseband outputs in the electrical circuitry

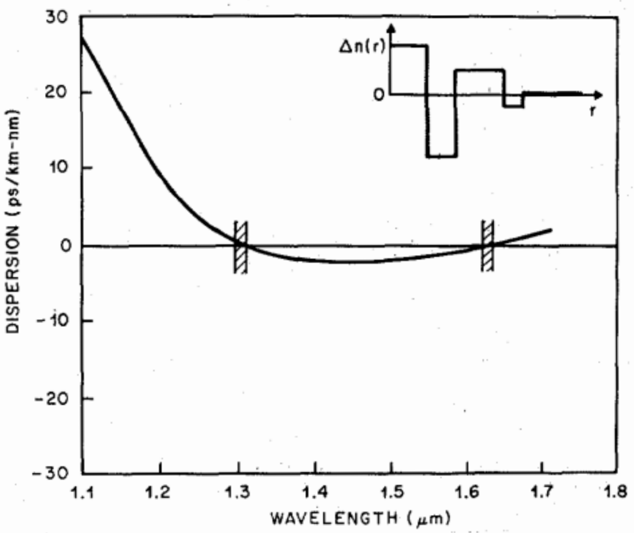


Fig. 11. Possible system usage of doubly clad single-mode fibers [14].

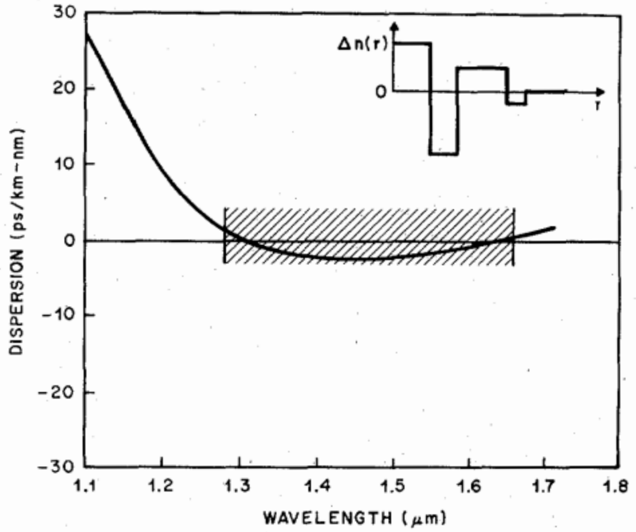


Fig. 12. With suitable reduction of OH^- losses in the quadruply clad fiber, the entire wavelength region from below 1.3 to above 1.5 μm can be used at high data rates and long span.

[15]; this combined wavelength-demultiplexer detector has no polarization sensitivity (unlike some alternatives). It has been demonstrated at modest bit rates and has the potential of gigabit rates.

The more familiar single-channel p-i-n type detector [16] (drawing on the left side of Fig. 13) is regularly made with 70-percent quantum efficiency. High-speed detectors have been made with 50-percent quantum efficiency. Fig. 14 shows the response to a light-pulse input of about 5 ps; the detector output pulsewidth is 30 ps (FWHM) [17].

Avalanche photodiodes for the 1.3-1.55-μm region are coming along despite intrinsic material problems. The quaternary materials have less desirable ionization ratios for holes and electrons as compared with those in silicon and have objectionable dark currents. A clever structure causing photon absorption in InGaAs and avalanching in InP appears to overcome the ionization-ratio problem, but dark current remains a problem. At bit rates above 100 Mb/s the leakage current requirements are less demanding, and the goal of a high-speed avalanching detector is being achieved in the laboratory [18].

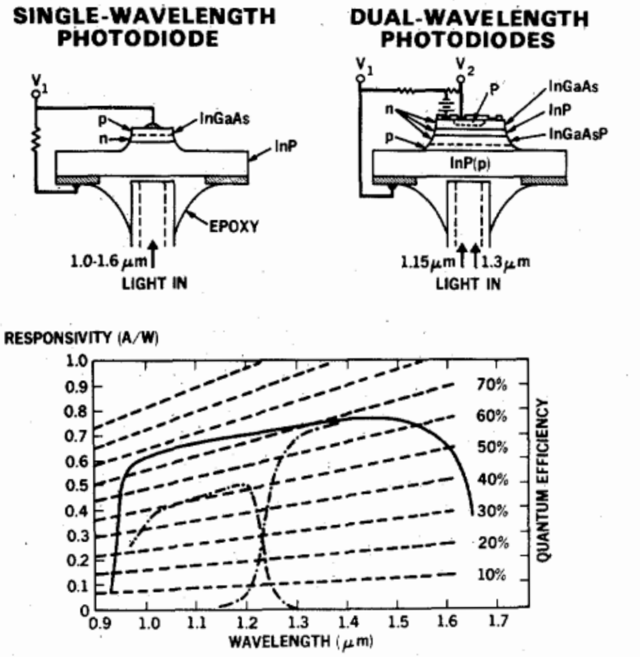
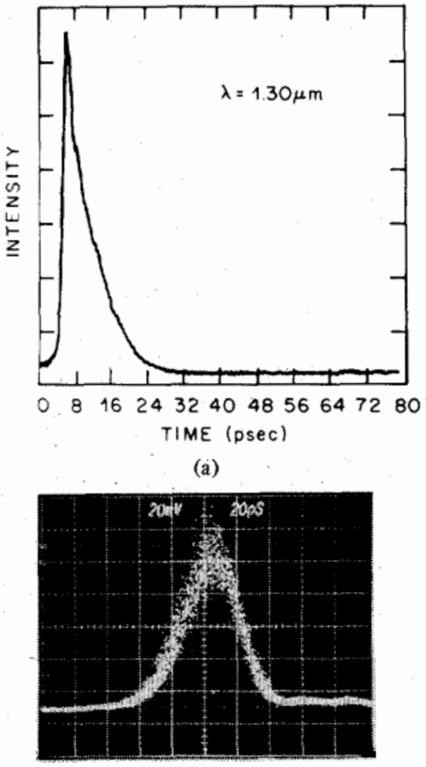


Fig. 13. Single p-i-n (upper left) and dual-wavelength p-i-n photodiodes and their detection responsivities.



(a)

(b)

Fig. 14. Input lightwave-pulse waveform (obtained by autocorrelation) and detector current response (30 ps FWHM) for a p-i-n InGaAs detector (Lee, Burrus, and Dentai, [16].)

Conventional wavelength multiplexing devices are also available. The form shown in Fig. 15, based on the GRIN lens or SELFOC element, is in common use. The directional coupler type, shown in the lower portion of Fig. 16, is now applicable only to single-mode systems. However, polarization independence has been achieved, and gigabit rate switching appears feasible. An impulse response of 60 ps FWHM has been ob-

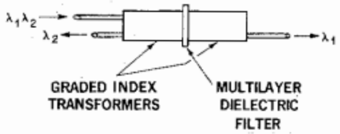


Fig. 15. Wavelength-division multiplexing filter.

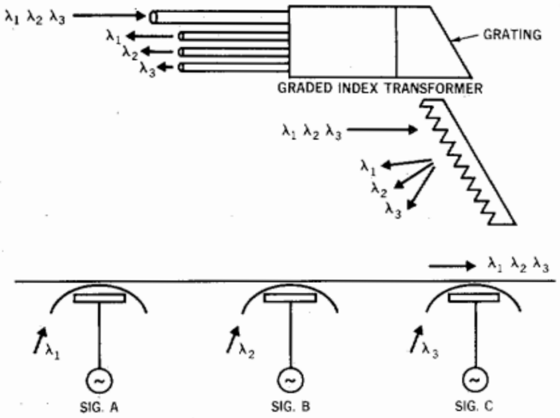


Fig. 16. Illustration of grating-type (upper diagram) and directional-coupler type wavelength multiplexing filters.

served by Alferness [19]. This suggests the possibility of combining wavelength multiplexing and modulation in a single device.

The grating-type multiplexer (Fig. 16, top) can be used with either multimode or single-mode fiber systems under some conditions and presents potential advantages.

Return now briefly to the choice of system configuration, and note the influence of the application. Contrast a multirepeater undersea-cable application with a domestic intercity application. In the former no upgrading of the electronics (undersea) is feasible after initial installation. Thus the system designer needs to optimize a frozen state of the art—which for good system ecocomics might require a system lifetime of around 20 years. An overland system with easy physical access to the repeaters can take advantage of repeater research done after initial cable installation, either by later-date equipping of initially unused fibers or by replacing the repeaters initally installed. The cable clearly must initially have the capability that is to be utilized ultimately. This places great premium on early achievement of sophisticated cable characteristics.

IV. COHERENT OPTICAL SYSTEMS

Coherent optical systems were explored by DeLange *et al.* and were shown to be technically feasible in 1969 [20]. Using HeNe lasers, coherent reception after as much as 36 mi of travel was demonstrated in a folded optical path using periodic refocusing of the laser beam. The signal-to-noise ratio actually observed for the coherent system was the same as for a direct detection system, and some further advantage for the coherent system seemed available. With the appearance of attractive losses in fibers and the associated preference for semiconductor lasers, the most attractive system configuration became direct detection. Work on coherent systems was temporarily set aside. As the system and injection-laser art matured it became timely to resume exploration of the advantages of configurations of coherent systems for fiber-optical transmission. Reports have appeared from the British Telecom Research Laboratories [21] and from the Electrical Communication Laboratory of Nippon Telegraph and Telephone Public Corporation [22] in Japan. In an FSK system experiment using AlGaAs lasers, one per million error rate was achieved on a 100-Mb/s data stream at -43-dBm received signal power; the need for narrower spectral-width lasers was emphasized [22]. In another experiment an 8-Mb/s data stream was transmitted via heterodyne ASK over 30 km of installed fiber using a HeNe laser at 1.523 μm; the required mean received signal power was -65 dBm at one per billion error rate [21]. No special form of fiber for maintaining polarization was utilized.

It is agreed by most workers that direct detection fiber systems will prevail in telecommunications applications throughout the 1980's, but special requirements such as may be found in fiber sensor technology may lead to practical applications of coherent systems earlier [23]. Research on multiplexing techniques which take advantage of coherence will proceed immediately [24]-[26], and the critical improvements in injection-laser spectral control will be given added impetus. PSK signaling and high-power nonlinearities in the fibers are also among the topics being explored to strive for very long unrepeatered links. We may note that coherent systems using very narrow band optical carriers may encounter noise from either stimulated Brillouin [27], [28] or spontaneous Brillouin effects [29]. When very long (greater than 100-km) fiber spans are contemplated or power levels greater than a few milliwatts are used with very narrow-band systems (less than 100 MHz) the Brillouin effects must be included in the system design. (Wide-band pulse systems do not encounter these problems because of reduced Brillouin gain on spectra greater than 20-MHz wide.) Competitive direct-detection technology using avalanche photodiodes is also advancing currently [18], and the final outcome is likely to be no more than a 6-10-dB signal-to-noise advantage for coherent telecommunications systems. The challenge is to achieve this potential advantage with acceptable added complexity.

V. THE LONGER RANGE FUTURE

Looking further into the future, research is being supported in several countries to explore the feasibility of fiber transmission in the 2^{+}-μm region. Material theory shows that the reduced Rayleigh scattering at longer wavelengths might make possible lower losses than the 0.2-dB/km minimum available in silica-glass fiber. Table I shows some achieved and projected losses [30]. In addition to the telecommunications interest, 2^{+}-μm materials might be important to transport laser beams for medical or industrial instrumentation.

For the present, this field will be explored by a few highly skilled materials scientists, and the telecommunications specialists will watch with great interest.

Another longer range field is integrated optical and integrated optical-electrical circuitry. Lithium niobate circuitry has been developed for military [31], [32] and telecommunications applications [33] and has reached a rather sophisticated level of realization. Gigabit-rate switches, tunable frequency-

TABLE I
PROJECTED ULTIMATE LOSS

	BEST ACHIEVED LOSS	PROJECTED	
	dB/km	dB/km	A_t (μm)
SiO_2 - BASED GLASS	0.16	0.16	1.5
GeO_2 - BASED GLASS	5	0.06	~2.5
HEAVY OXIDE GLASSES (e.g. $PbO \cdot T\ell_2O \cdot Bi_2O_3 \cdot$ etc)		0.02	~3
CHALCOGENIDE GLASSES (e.g. $AsSe_3$)	50	0.01	~4.5
FLUORIDE GLASSES (e.g. CaF_2-BaF_2-YF_3-$A\ell F_3$)	12	0.001	~$3\frac{1}{2}$
SINGLE CRYSTAL HALIDES (e.g. $KC\ell$)		0.0001	~5

selective filters, and hybrids have been demonstrated. To this author's knowledge, however, these devices have not yet been produced commercially. Perhaps this will come, with hybrid additions of semiconductor devices to provide gain where needed. An alternative is integrated optical-electrical circuitry using semiconductors. The InGaAsP system is ideal in making possible lattice-matched compositions with band gaps corresponding to 1.2-1.6 μm for a wide variety of light sources, low-loss lightguides and detectors, and in the same assembly making possible electrical devices such as transistors and diodes. High-speed phototransistors and FET's, and optical-waveguide directional couplers have been demonstrated. Much remains to be done, but one day extremely high-speed logic as well as lightwave switching will become feasible.

VI. CONCLUSION

Lightwave research is still a fast-moving field. We can expect continued rapid change in the future.

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InGaAsP/InP Current Confinement Mesa Substrate Buried Heterostructure Laser Diode Fabricated by One-Step Liquid-Phase Epitaxy

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***Abstract*—New InGaAsP/InP buried heterostructure laser diodes fabricated by one-step liquid-phase epitaxy are described, in which the InGaAsP active region completely embedded in InP is grown on the top of the mesa stripe formed on the InP substrate while, simultaneously, current confinement structure is automatically formed on both sides of the mesa stripe. These current confinement mesa substrate buried heterostructure laser diodes (CCM-LD's) have current confinement structure which very effectively blocks unwanted leakage current bypassing the light emitting region which has enabled laser operation with a threshold current as low as 20 mA, 70-mW maximum CW output at room temperature, and 125°C maximum CW operation temperature. Life tests over 6000-h CW operation at 70°C and 5 mW/facet have confirmed good reliability of these devices.**

I. INTRODUCTION

SINCE the transmission loss in fused silica fibers is very low in 1.0–1.7-μm wavelength range [1], InGaAsP/InP double heterostructure laser diodes which emit wavelength range are desirable as light sources for optical communication systems. In optical communication systems, laser diodes are frequently required to operate at a temperature higher than room temperature. However, conventional InGaAsP/InP double heterostructure laser diodes cannot, in general, operate at very high temperatures, because the threshold current for those diodes is more sensitive to temperature change than that for AlGaAs/GaAs double heterostructure laser diodes [2].

Besides the high-temperature operation, stable fundamental transverse mode operation is required for the light sources so as to obtain good coupling efficiency for the laser output into the optical fibers, especially into single-mode fibers. For fundamental transverse mode oscillation, several different types of buried heterostructure laser diodes have been reported [3]–[15].

Buried heterostructure laser diodes (BH-LD's) can achieve not only stable fundamental transverse mode operation but also high-temperature operation, because they have very low threshold current resulting in less temperature rise in the active regions than that for other laser structures. However, the BH-LD's fabrication tends to be rather complicated, requiring two-

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