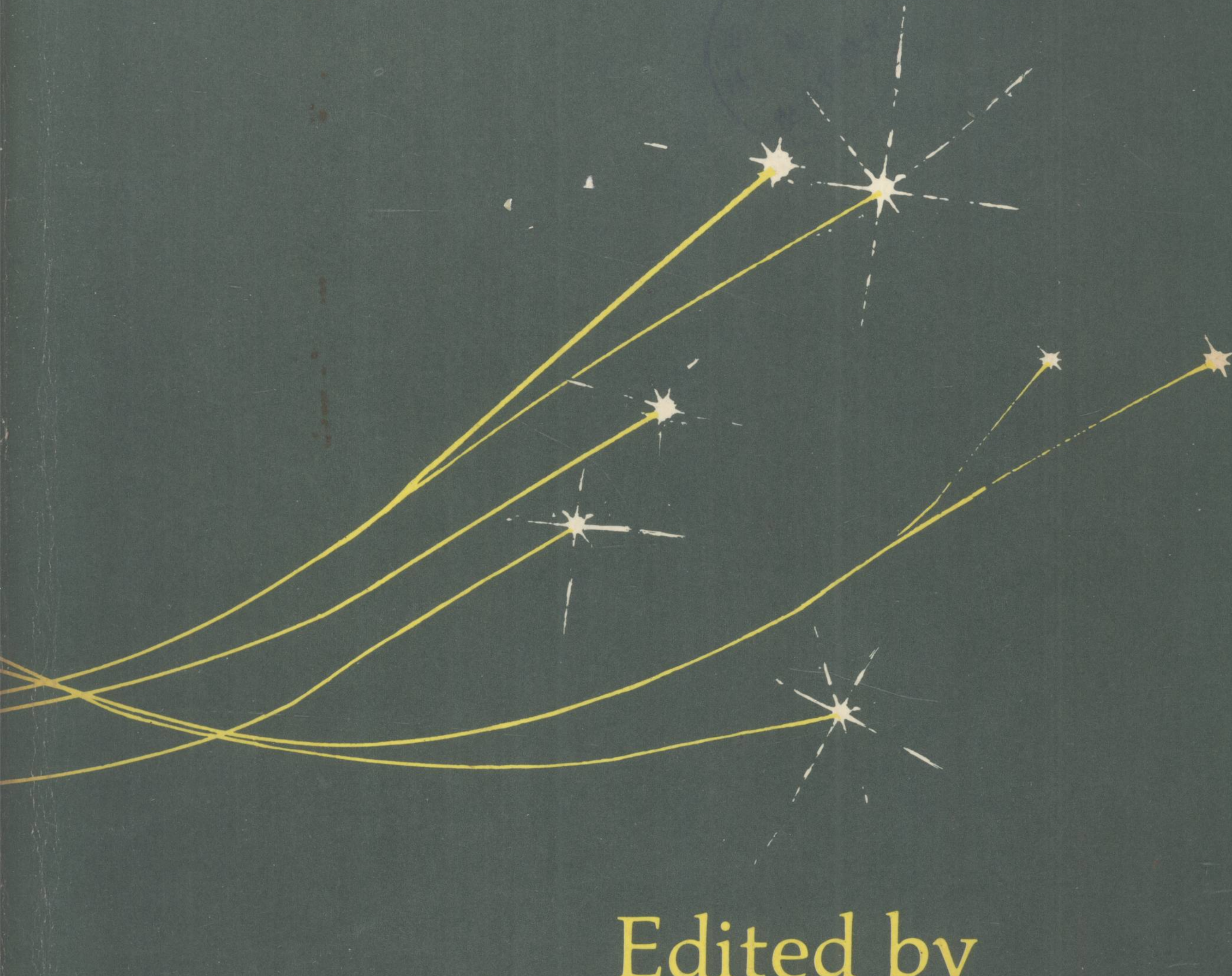
Fiber Optics Communications



Edited by
Henry F. Taylor

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ARTECH HOUSE, INC. 610 Washington St. Dedham, MA 02026

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Preface

The purpose of this book is quite simply to be as useful as possible to those who are working in the field of fiber optical communications or interested in learning about the subject. Obviously, it was not an easy task to select fifty or so reprints from among the thousands of papers which have been published in the field. Since there are by now many texts and reprint collections covering earlier work, it was decided to emphasize recent publications and trends. Review papers are also well represented throughout the text, including the three papers in Chapter 1 which provide a general overview of the state-of-the art. Chapters 2-8 are concerned with the fabrication of components and their characteristics, and Chapters 9-11 deal with systems issues. The reader will thus find a wide range of perspectives, from semiconductor device physics and waveguide theory to the design of systems and experience in cable installation and maintenance. The technology is now relatively mature ("high on the learning curve") in most areas, leading us to feel confident that the majority of the selections will continue to be useful for years to come.

Introduction

Fiber optical communication has emerged almost overnight as a major industry. Sales in the United States for components, equipment, and systems using fiber optics are expected to exceed $500 million in 1983 [1], and worldwide sales should reach a $1 billion annual rate during the same year. Growth rates are running at better than 50% per year for both domestic and foreign markets. The single most important development has been a commitment on the part of American Telephone and Telegraph to use the technology for major new long-haul and metropolitan installations in the US. By the end of 1982 nearly 200,000 kilometers of fiber and 10,000 repeaters had been installed in the Bell System [2]. Telephone companies in Canada, Great Britain, France, Germany, Japan, Italy, and Argentina either have major installations in operation or are moving rapidly in that direction.

The strong telecommunications interest has been a relatively recent development in the evolution of optical fiber technology. The researchers who produced the first clad glass optical fibers in the early 1950s were not thinking of using them for communication — they wanted to make imaging bundles for endoscopy. During the 1950s and 1960s, methods for making fiber optic bundles were developed — incoherent bundles for illumination and coherent bundles for image transmission. Automobile instrument panel illumination, decorative lighting, cathode ray tube faceplates, cockpit displays for aircraft, and endoscopes were among the commercial applications. When the famous paper by Kao and Hockham [3] suggesting the use of low-loss optical fibers for communication appeared in 1966, fiber optics was already a well-established business.

The first low-loss (20 dB/km) silica fiber was described in a publication [4] which appeared in October 1970. (A piece of this fiber has been accorded a place alongside many other technological "firsts" in the Smithsonian Museum of History and Technology in Washington, DC.) The date of this publication is often cited as the beginning of the era of fiber communication. Although this development received considerable attention from the research community at the time, it was far from clear that an industry would eventually evolve. The 20 dB/km loss figure was still too high for long-haul telecommunications systems. The fibers were fragile, and a way to protect them would have to be found. (Breakage factors in flexible boundles of that period were expressed in percent per foot!) There were no suitable light sources. Connectors with much closer mechanical tolerances than their electrical or microwave counterparts would be needed, and it was not known whether field termination and splicing of optical cables would ever be practical. Finally, there were very serious doubts as to whether these components could ever be produced economically enough for the technology to play a major role in the marketplace.

Although the technological barriers appeared formidable, the potential return was obviously high. As a consequence, reasearch and development activities expanded rapidly, and a number of the important questions were answered during the early 1970s. Success in material purification and the use of new core dopants led to further dramatic loss reductions in silica fibers. Development of graded-index fibers provided a favorable trade-off in terms of source coupling efficiency and fiber bandwidth. Researchers learned to protect silica fibers with polymer coatings and cable them without breakage. Diode lasers were operated continuously at room temperature for the first time, and high-radiance light emitting diode (LEDs) capable of efficient coupling to single fibers were made. Prototype connectors and fusion splicing techniques were developed.

During the mid and late 1970s, the rate of progress towards marketable products accelerated as the emphasis shifted from research to engineering. Fibers with losses approaching the Rayleigh limit of 2 dB /km at a wavelength of 0.8μm, 0.3 dB/km at 1.3 μm, and 0.15 db/km at 1.55 μm were produced in the laboratory. Microbend loss problems were overcome through the use of improved fiber buffering and cabling techniques. Rugged cables and multifiber connectors were produced for field installation. Room temperature threshold currents for commercial gallium aluminum arsenide diode lasers operating in the 0.8 μm to 0.85 μm spectral region were reduced to the 20-30 mA range, and projected lifetimes in the 100,000 to 1,000,000 hour range were claimed for both lasers and LEDs. Light sources and improved photodetectors for operation near 1.3 μm were developed to take advantage of the low fiber loss and dispersion in this "longer wavelength region." Encouraging data on the reliability for longer wavelength lasers and LEDs fabricated in the indium gallium arsenide phosphide quaternary alloy system were also obtained. A number of major field trails were undertaken during this period, including AT&T's Atlanta experiment (1976) and Chicago installation (1977), and Japan's *Hi Ovis* subscriber access project (1977).

Improvements in component performance, cost, and reliability by 1980 led to major commitments on the part of telephone carriers. Although many users have preferred the double-window multimode fiber designed for high bandwidth at both 0.83 and 1.3 μm wavelengths, confidence in the longer wavelength sources and detectors has increased to the point that many long-haul systems are now being designed to operate exclusively in that spectral regime.

Following not far behind the move to longer wavelenghts has been the trend to single mode fiber for long-haul systems. Single mode provides a bandwidth advantage which translates into greater repeater spacings for high data rate systems. Immunity from modal noise, which has been a major problem in multimode systems, is also realized. Coupling and splicing problems for the small-core single mode fibers are now essentially solved, although there is still a substantial cost premium for demountable single mode connectors because of the close mechanical tolerance.

In spite of the recent expansion, the potential of fiber optics in telephone systems is only beginning to be realized, and several other markets of considerable potential are almost untouched. We can expect a continuing growth in the telephone market worldwide until fiber optics is the dominant technology for both intercity links and interoffice trunks. The development schedule for undersea fiber optics systems has accelerated to the point that some such systems could begin service in the mid-1980s. After a slow start, fiber optic peripheral links and data busses for computer systems are beginning to make their presence felt in the marketplace. Significant military markets are also just beginning to emerge with the award of engineering development contracts for the US Army's long-haul cable system. Wideband subscriber access systems, providing such services as cable television, picturephone, and interactive data bases, also have great commercial potential In fact, this could eventually become the most important application of fiber optics technology, but component costs must drop considerably below today's levels to make widespread use of these broadband services economically feasible.

Because the applications for fiber optics span a wide range of line lengths and signal bandwidths, it is not likely that one type of light source or fiber will emerge to dominate the industry. Rather, we can expect to see a mix of long and short wavelength LEDs and laser diodes, and both multimode and single mode fiber in use for the foreseeable future. The most significant changes will occur in the multiplexing and switching areas. The optical portion of the great majority of present systems consists of single-channel point-to-point links, with multiplexing and switching functions performed by conventional electronic circuits. A variety of components for performing these functions optically are beginning to appear in commercial systems. Carrier frequency multiplexing (sometimes known as "color" or "wavelength" multiplexing) provides several communication channels on a single fiber, and star couplers and access ("Tee") couplers will be used for data distribution in multiterminal systems. Optical switches and switching matrices will also be used in a manner analogous to electronic switches in conventional communication systems. In the near future, optical multiplexing and switching will be performed by discrete components made from fibers or bulk optical elements. Eventually, these might be replaced by "integrated optical circuits" fabricated on planar substrates. We can, therefore, expect research in new fiber optic components and integrated optics to continue for years to come.

Contents

CHAPTER ONE
Reviews

The emergence of fiber optics as a major industry has been paced by the ability of component manufacturers to produce high quality, reliable products at a reasonable cost. The state of the art in components is reviewed by **K. Shirahata, W. Susaki,** and **H. Namizaki** in **"Recent Developments in Fiber Optic Devices."** The next two papers emphasize trends in the technology for long-haul, wideband telecommunications systems. In **"Single Mode Systems and Components for Longer Wavelengths," T. Kimura** describes components for the 1.3 μm spectral region and the results of transmission experiments using those components, and **"The State of the Art and Application of Optical Fiber Systems Operating at the Longer Wavelengths of 1300-1600 nm,"** by **C. J. Lilly** ,encompasses recent developments in both multimode and single mode technology.

Single-Mode Systems and Components for Longer Wavelengths

TATSUYA KIMURA, SENIOR MEMBER, IEEE

Invited Paper

***Abstract*—Single-mode optical fiber transmission technology in the 1.0–1.8-μm wavelength region is reviewed. Owing to low fiber loss in the spectral region and to wide-band single-mode fiber characteristics, long-wavelength single-mode fiber transmission systems are capable of high data-rate transmission over tens of kilometers distance without intermediate repeaters.**

The advantages of the systems and progress in fibers, fiber splicing, and devices are reviewed in detail. Using low-loss fibers and recently developed semiconductor lasers, transmission performance is confirmed at 1.05, 1.1, 1.3, and 1.5-μm wavelengths. At 1.3 μm, where fiber dispersion almost vanishes, gigabit-per-second pulse signals are successfully transmitted over 20 km without intersymbol interference. The maximum tested data rate is 1.6 Gbit/s, at which 13-km nonrepeatered transmission is confirmed. At 1.5 μm, where ultimate low-loss characteristics are expected in silica fibers, 100 Mbit/s transmission is successfully demonstrated over a 29-km repeater span.

These high data-rate transmission capabilities over long fiber spans are attractive for future communications networks which may provide a variety of services at reduced system cost and with improved maintenance and installation convenience.

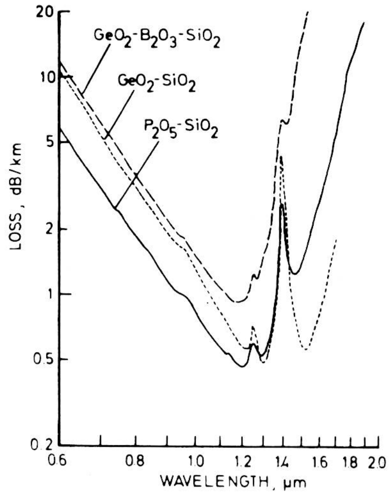

Fig. 1. Spectral loss characteristics of doped silica fibers [7]. Dopant effect on long wavelength limit is shown.

I. Introduction

SINCE THE successful demonstration of single-mode fibers [1] after the pioneering work of Kao *et al.* [2], and continuous operations of AlGaAs double heterostructure semiconductor lasers at room temperature [3] in 1970, research efforts have been made to realize optical fiber transmission systems with studies carried out on fibers, fiber cables, optical devices, and system performance. Most of these studies, however, were concentrated on the 0.8–0.9-μm wavelength band where the losses of fibers fabricated at that time exhibited a minimum and at which miniature semiconductor lasers were available. Matured silicon technologies can be applied for detectors in this wavelength region. State-of-the-art technology up to 1973 is well summarized in the literature [4], [5].

Another low-loss band at 1.05-μm wavelength, which appeared in the data measured up to 1.1 μm, was recognized as promising provided that efficient optical power sources and sensitive photodetectors could become available. With respect to Rayleigh scattering as a predominant loss mechanism, fiber losses in the 1.05-μm band are about one-half those at 0.85 μm. Efforts have been made to develop optical devices for wavelengths longer than 1 μm, such as miniaturized solid-state lasers, quaternary semiconductor lasers, guided wave electrooptical modulators and semiconductor photodiodes.

It was demonstrated in the spring of 1976 that, by reducing OH radical concentration, a fiber loss as low as 0.5 dB/km can be realized at a wavelength of 1.2 μm in multimode fibers [6]. Further studies on dopants suitable for low-loss fibers [7] and on ultimate silica material loss [8] showed that the low-loss region can be extended up to 1.8 μm, as shown in Fig. 1. The upper wavelength limit is imposed by an infrared absorption tail of a SiO_2 molecular vibration, and the minimum loss is predicted to be around 0.2 dB/km at 1.5–1.6 μm.

Based on the anticipated low loss in the longer wavelength region than in the conventionally studied 0.85-μm band, detailed discussions of low-loss fiber system performance and expected advantages were published [9]. Long repeater spacing, which is possible with reduced fiber losses, is beneficial for system economy and reliability. Prospects in the long wavelength systems from the optical device and communication technology point of view have also been discussed [10], [11]. Further progress in fiber fabrication technologies enabled low-loss fibers to approach the ultimate silica loss, as shown in Fig. 2.

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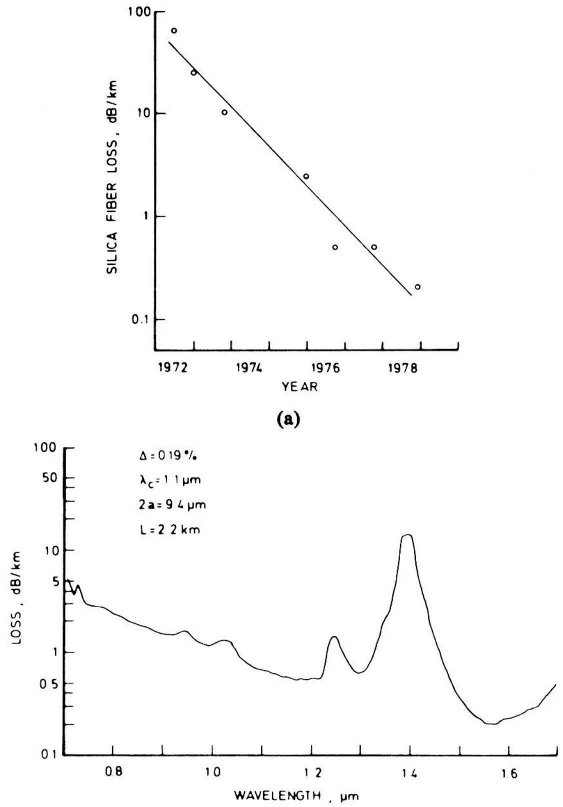
The author is with Musashino Electrical Communication Laboratory, Nippon Telegraph and Telephone Public Corporation, Mushshino-shi, Tokyo 180, Japan.



(b)

Fig. 2. Fiber losses. (a) Loss reduction trend in silica fibers. (b) Low-loss single-mode fiber [20], [21].

The single-mode fiber is recognized as a broad-band transmission medium, because its frequency response is not influenced by intermodal group delay difference. An early experiment on single-mode fiber transmission of digital signals showed that wavelength dispersion in the dominant mode influences received pulsewidth and this results in attainable repeater spacing restriction by intersymbol interference [12]. It was shown, by using Sellmeyer's refractive index formula on undoped vitreous silica, that material dispersion vanishes at 1.27 μm [13]. By taking into account the waveguide dispersion, which is the other factor governing wavelength dispersion, the wavelength which gives vanishing total dispersion shifts to 1.3–1.5 μm, depending on fiber structure [9]. When the wavelength dispersion vanishes, pulsewidth broadening is kept sufficiently low even when a light source has finite spectral width. These low-dispersion characteristics in the long wavelength region are favorable for high-speed digital transmission systems with expanded repeater spacing.

Difficulties in mutual connection and light coupling in a single-mode fibers were previously considered to be obstacles preventing system realization. But elaborate technology in fiber splicing and connectors has made it possible to achieve low-loss single-mode fiber connection.

Efficient and reliable optical devices in the long wavelength region are now essential for exploitation of these low-loss and low-dispersion fibers. Continuously operating semiconductor lasers using ternary and quaternary III–V compounds have been studied at wavelengths up to 1.5 μm. InGaAsP/InP double heterostructure semiconductor lasers exhibit similar characteristics to AlGaAs DH lasers, including high-speed modulation capabilities. Solid-state lasers using materials containing Nd ions and low-drive voltage optical modulators with guided wave structures are possible alternatives in the 1.05- and 1.32-μm wavelengths.

The germanium avalanche photodiode is one of the sensitive detectors beyond 1-μm wavelength, where silicon detector sensitivity becomes low. Shortcomings of large dark current and excess avalanche noise factor in the Ge device are expected to be overcome by using III–V compound semiconductors, which are now under extensive study.

Using the fibers and devices mentioned above, the feasibility of single-mode fiber transmission systems has been demonstrated. These systems operating at wavelengths of 1.05, 1.1, 1.3, and 1.5 μm. Repeater spacings attained at 1.3 μm, where fiber dispersion almost disappears, are 30 km at 100 Mbit/s, 20 km at 800 Mbit/s, 23 km at 1.2 Gbit/s, and 13 km at 1.6 Gbit/s. In the 1.5-μm region, where ultimate minimum fiber loss is predicted, a 29-km long fiber transmission experiment has been successful. These demonstrations have shown the advantages of single-mode fiber transmission systems using long wavelength carriers.

The present paper reviews the progress of single-mode fiber transmission systems and components. Main features of longer wavelength fiber systems are reviewed in Section II. In Section III, single-mode fiber properties including loss and dispersion will be discussed. State-of-the-art fiber connection technology will be described in Section IV, and optical devices suitable for 1.0–1.8-μm wavelength operation will be briefly reviewed in Section V. Long fiber span system performance will be discussed in Section VI.

II. Fiber Systems with Long Wavelength Carriers

Optical fiber systems using low-loss fibers have many advantages [9]. The minimum receiving optical power level to give a 10^{-9} error rate is estimated in Fig. 3 for avalanche and nonavalanche photodetectors. Here, the avalanche photodiode is assumed to have a quantum efficiency of $\eta = 0.5$, effective ionization ratio of electrons and holes [14] $k = 1$ or 0.1. and capacitance of $C = 2.5$ pF. Bipolar transistor front-end impedance multiplied by diode capacitance is chosen to be a reciprocal of data rate and the current multiplication factor is optimized to give maximum signal-to-noise ratio. When there is a dark current as large as 100 nA, as indicated by the broken lines in Fig. 3, the receiving level deteriorates, especially at low data rates. The nonavalanche photodiode is assumed to have $\eta = 0.8$ and $C = 2.5$ pF. A high impedance preamplifier is assumed. The nonavalanche photodiode re-

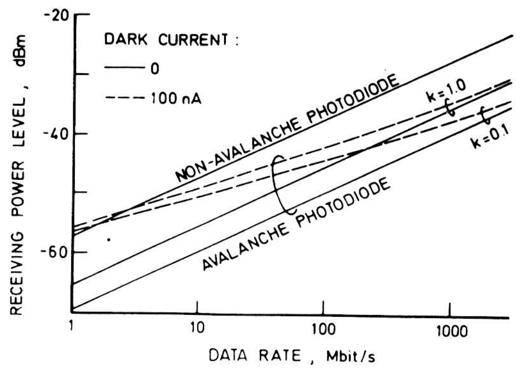


Fig. 3. Receiving power level versus data rate at 1.3-μm wavelength. Avalanche and nonavalanche photodiodes with and without dark current are assumed [9].

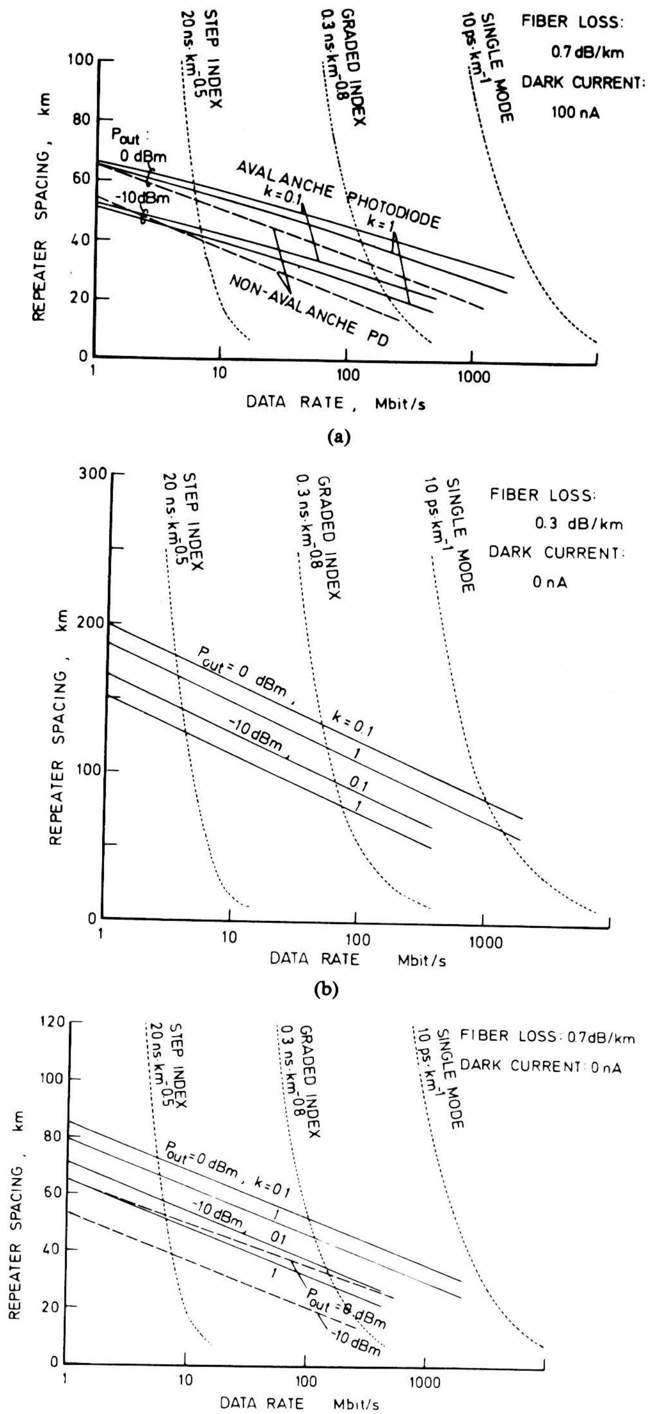
ceiving level is insensitive to dark current, as long as it is less than 100 nA.

A low fiber loss at long wavelength is favorable for long repeater spacing. By assuming the transmitting power level to be 0 or − 10 dBm, and using the receiving level of Fig. 3, expected repeater spacing is obtained as shown in Fig. 4. In Fig. 4 (a), repeater spacing for a 0.7-dB/km fiber loss including splice and cabling loss and for 100-nA detector dark current is depicted as a function of data rate. In the figure, fiber bandwidth limit is superimposed by dotted lines. When the dark current is improved, repeater spacing can be extended as shown in Fig. 4 (b). With further reduction of fiber loss down to 0.3 dB/km, repeater spacing longer than 100 km seems to be feasible, as shown in Fig. 4 (c), up to several hundred Mbit/s-data rates.

The long repeater spacing is favorable for system cost reduction and increased repeater reliability. In large capacity systems, in which repeater cost is estimated to be predominant, an improvement in the annual system charge is expected as shown in Fig. 5.

To evaluate repeater reliability performance, it will be assumed that the system unavailability objective alotted to repeaters is 0.001 and mean time to repair a failed repeater is 8 h. When supervision and control section length is 100 km for 20-km repeater spacing and 280 km for 40-km repeater spacing, and a single standby is provided for 100 installed systems, required repeater mean time between failures will be about 5×10^4 h. It will thus be possible to meet the reliability requirement if laser lifetime exceeds 10^5 h.

Besides these advantages, it will be possible to install repeaters in repeater stations or huts instead of in manholes. When repeaters are installed in huts, power can be locally supplied and power-supply metal wires are not necessary in fiber cables. Moreover, the number of systems to be installed will not be restricted by the size of manholes. Elimination of metal power feeders is also favorable since this will allow an increase in the number of fiber strands in cables in a given underground duct space. Repeater maintenance will be more convenient and



(c)

Fig. 4. Expected repeater spacing [9]. (a) Fiber loss = 0.7 dB/km, detector dark current = 100 nA. (b) Fiber loss = 0.7 dB/km, detector dark current = 0 nA. (c) Fiber loss = 0.3 dB/km, detector dark current = 0 nA.

the mean time required for repeater repair will be shortened.

Low-loss fiber cables are beneficial for subscriber loop service area expansion. They are also applicable to submarine cables to connect the mainland and individual