Optical Fiber Systems: Technology, Design, and Applications

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The editors for this book were Barry Richman and James T. Halston, the designer was Jules Perlmutter, and the production supervisor was Thomas G. Kowalczyk. It was set in Vermilion by The Kingsport Press.

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Preface

Technology is always socially relevant. Too often we allow ourselves to be mesmerized by the wonders of technology and devote our energy to its advancement without the necessary reflection on its social relevance. This practice could lead to incomplete realization or inappropriate use of the full potential of a technology. In optical fiber system technology we are dealing with one of the cornerstones of our information age in which the efficient utilization of information governs our well-being. The understanding of its sociological implications is extremely important.

With this in mind, this book is written to give the readers a glimpse of the range of application and the impact of this technology, as well as to introduce the associated technology of optical fiber systems in a concise and, hopefully, clear manner. The reader will be able to see the interrelationship of the technology and its implications and will be able to construct the basis of a system design and perceive the relative advantages and disadvantages.

Chapter 1 delineates the roles of optical fiber systems from a sociological evolutionary point of view. It introduces the major characteristics of such systems. Chapter 2 gives the design rules but avoids explicit discussion of the design approaches. Chapters 3–7 introduce the key components and their associated background technology. The discussions aim at providing the readers with an understanding of the interrelation of the salient features from a system point of view. References are given for readers to access complete theoretical derivations. These chapters cover fiber, cable, sources, detectors, and couplers. Chapter 8 provides a view of a selected number of systems for a variety of applications. These examples are chosen to highlight where optical

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fiber systems offer advantages. Chapter 9 illustrates the design process via a specific example. It shows how the knowledge of different components is needed to achieve a viable design. It brings the algorithm outlined in Chapter 2 into focus. Chapter 10 looks at the system economics to bring the book to a close.

This is a textbook but not a source book. It complements other books written more explicitly as textbooks as well as special treatises, so that the reader can get broader viewpoints and finer insights.

Over the period this book was in preparation, I was helped by my wife, son, and daughter, who gave me the understanding and support needed. I am indebted to the various secretaries who typed the manuscript at different stages, particularly Mrs. Havens, who typed and compiled the final manuscript. I would like to thank my colleagues at ITT and other colleagues in the optical fiber field who allowed me to refer to their work and gave me much valuable assistance. Last, but not least, I would like to express my gratitude to a great number of scientists, engineers, managers, and people from many walks of life who have and who are contributing to this technology, for without them I would not be able to write this book.

Charles K. Kao

Abbreviations

AGC automatic gain control
APD avalanche photodiode
BER bit-error rate
CCIR International Radio Consultative Committee
CCITT International Telegraph and Telephone Consultative Committee
CCTV closed-circuit TV
CVD chemical vapor disposition
CW continuous-wave
ECL emitter-coupled logic
EMI extromagnetic interference
FCC Federal Communications Commission
FDM frequency-division multiplex
FET field-effect transistor
FSK frequency-shift keying
IF intermediate frequency
IR infrared
LED light-emitting diode
LSI large-scale integration
MTBF mean time before failure
MTF modulation transfer function
NA numerical aperture
NRZ nonreturn-to-zero
NTSC National Television Standards Committee
OD outer diameter
PCM pulse-code modulation
PIN positive-intrinsic-negative
PSK phase-shift keying
PTT post, telephone, and telegraph
PVAC present value annual cost
RF radio frequency
RMS root-mean-square
RTV room temperature vulcanization
RZ return-to-zero
SNR signal-to-noise ratio
TDM time-division multiplex
TTL transistor-transistor logic
VLSI very large scale integration

Contents

Chapter

1

The Role of Optical Fiber Systems

Optical fiber waveguides are vital in an "information society," where the primary preoccupation in life is generation, dissemination, and management of information. In such a society we can readily appreciate that job efficiency, productivity, and meaningfulness of our endeavors are improved by a better organization and control of our information resources. Our ability to transport information efficiently is highly relevant to our well-being.

An optical waveguide is a threadlike structure capable of handling the transportation of a large volume of information traffic. We need it as the building block of our information highway system to help us in managing our energy resources, transportation, and communications; delivering health care and community services; strengthening our military defense; developing business; and providing materials for our entertainment and education. Optical waveguides are destined to find a myriad of applications in a ubiquitous role.

The move from our material-based society into an information-based society is prompted by economic and technological developments. The growth of population has reached a point where our survival is based increasingly on a complex set of criteria. We need to extend further our physical and mental capabilities in order to cope with increasing production needs and decreasing energy availability. In recent years

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our technological advances have provided us with three important innovations which enable us to develop tools to tackle the tasks at hand. The invention of the transistor and its evolution into the integrated circuits allow densely packaged, complex, and powerful electronic circuits to be designed. These are required to extend our capability to implement complex control functions, provide large information storage, and exercise fast information processing. In particular, a full range of computers is now available to extend our mental capability. The invention of lasers enables us to utilize the optical wavelength range of the electromagnetic energy spectrum. The optical lasers are equivalent radio-frequency (RF) oscillators and can serve as information carriers. Because of their high frequency ($\sim 3 \times 10^{14}$ Hz), they can theoretically accommodate many orders of magnitude more bandwidth of information than can an RF information carrier. The invention of the optical fiber waveguide provides us with the transmission media par excellence. The transportation and distribution of information at a high rate becomes feasible.

Optical Fiber Systems in Sociological Evolution

The physical and mental needs of the people in an information society are both materialistic and service-oriented. The materialistic aspects refer to the basic production of food and the conversion of raw materials into general merchandise. The service aspects require a new industry to improve the efficiency of the distribution of material goods, balance the resource allocation, and enrich life with new pursuits. At the basis of this service industry are optical fiber systems forming the communications links.

ENERGY RESOURCES

Until the control of thermal nuclear fusion can be perfected in the twenty-first century, available basic energy resources are limited. Many of the readily available resources such as oil and gas are rapidly being depleted. As a result, energy cost is increasing rapidly. This calls for a careful examination of the mode of energy usage, with a view to fulfill the increasing demand more efficiently and safely. It is a process in which the consumption of oil, natural gas, coal, solar energy, and other resources for domestic and industrial activities is balanced for cost and availability. It is time to trade heavy energy-expending activities, such as the making of articles for rapid consumption, for the manufacture of more durable goods. It is time to explore alternative primary energy resources while taking precaution against undesirable environmental impacts.

Here the fiber system plays a minor but important role. The characteristic of fiber—of immunity to electromagnetic interference—allows fiber systems to be used with advantages in electrical generation and transformer stations to improve control and communications functions.

TRANSPORTATION

The physical movement of people and goods is an essential part of life, and different transportation requirements are met by different means. For mass transit and bulk goods movement, there are buses, trains, ships, and large trucks. For individual journeys, there are automobiles and bicycles. For rapid transit, there are airplanes. Together, these methods of transportation keep the society functioning.

The volume of traffic has been expanding rapidly as population and trade increase. The total expenditure of energy for transportation has reached a level which is sufficiently large, compared with the level of energy reserve, to warrant attention. More efficient use of the transportation system is important.

The role of fiber systems in transportation is indirect. In mass transit systems the operation can be made much more efficient with the provision of reliable means of control. This usually involves locating the position and speed of the vehicles on the railway. Along the high-speed electrified railway line, such a need is most obvious. Fiber control systems can be installed with advantage along the electrified track where copper wire systems would encounter serious electromagnetic interference problems.

COMMUNICATIONS

The introduction of optical fiber systems will revolutionize the communications network. The low-transmission loss and the large-bandwidth capability of the fiber systems allow signals to be transmitted for establishing communications contacts over large distances with few or no provisions of intermediate amplification. Also, more information can be transmitted over a shorter time than with the use of alternative systems. This means that the optical fiber communications network can provide more services at a lower cost.

The telephone network, based on copper wires as the transmission lines, has provided us with a very valuable communications network. The instant audio contact through a telephone has increased business efficiency, reduced the need to travel, and provided many services which otherwise would not be available.

The communications network, based on optical fiber as the transmission lines, has several orders of magnitude more information-carrying capacity per unit time than does the telephone network and can provide a host of services, including video services, which require a bandwidth much greater than that used in the telephone service. Such a communications network allows video, audio, and data transmission, and in association with computers, it literally allows our visual senses and certain of our brain functions to be extended. The power of such a network would create a completely new sociological environment—one which befits the information age.

The evolution toward such a communications network is likely to be relatively slow and deliberate. The existing network represents a huge monetary investment and cannot be written off overnight. Neither can this investment of an even larger sum of money to create the new network be done instantaneously. There will be a gradual evolution.

The advantages of a fiber system can be exploited most readily in the existing network in a number of important areas. In metropolitan areas copper cables are installed mainly in underground conduits, providing connection between busy exchange offices. Fiber cables with equal traffic-carrying capacity are much smaller in size and can provide interexchange office connection without intermediate repeaters in most cases. The lifetime system cost—which includes installation, maintenance, and hardware costs—favors fiber systems, especially where traffic density and growth are high. Intercity routes with high traffic densities can also be served better and more economically by fiber systems. These are the areas where fiber systems are being introduced into the existing network. The network between a satellite ground receiving station and a distribution hub provides another opportunity for early fiber system entry. Trunking of television signals over distances of several kilometers and upward can be most attractive on fiber.

The increased usage of fiber systems will result in reduction of their cost, when the economy of scale takes effect. Fiber systems will then be preferred on the basis of cost alone, even in areas where their advantages of large bandwidth and low loss are not needed. Early introduction of fiber cable into the subscriber distribution network will then be possible, thus laying the foundation of the wide-bandwidth information network of the future.

Information services for the home and business premises already being used include document transmission (facsimile); telex; 1200- to 9600-baud data for computerized banking; airline, hotel, and other reservations; dial-a-message service on telephones for weather, local events, and other information; and stored messages from special customer services. Some prospective services being tested include package switching networks for improved data services and computer access, video text for stored information such as restaurant guides, train timetables, programmed teaching, or, for more specific customers, stock market information, inventory control, and so on, and for improved security and energy management, remote alarm and meter monitors. Services envisaged for the future usually involve the use of increased bandwidth to provide faster information transfer and the use of live video information in an interactive manner. While most of the services can be provided without the need of a broadband transmission medium, the increased use of information would result in broadband transmission in an increasingly larger area of the communications network. Eventually with the widespread use of broadband services, the capability of broadband distribution to individual subscribers would be required.

Fiber cost is expected to decrease substantially to a level where its use in the distribution network becomes non-cost-prohibitive. Its use is expected to be very widespread, and it will lay the foundation for the present network to evolve into the future broadband network.

HEALTH SERVICES

Health care delivery requires individual consultation by physicians and massive specialist hospitals with sophisticated equipment. Communications both within large hospitals and to and from these establishments is vital for operational efficiency and effectiveness. If a physician can call for the relevant records of a patient, vital statistics, rapid analyses, and a glossary of information aids at the hospital or at the home of a patient, the health care delivery would be vastly more effective.

Fiber systems can provide the communications links capable of handling visual instruments and fast computer-controlled data equipment without suffering from electromagnetic interferences which are often associated with high-powered hospital equipment, such as x-ray machines. The visual observation aids are particularly important. Remote monitoring of patients and recalling of specialized symptomatic information and surgical procedures in visual form can bring the massive resources of a specialist hospital to the assistance of a physician in a remote village.

In a role rather different from that of an information transmission line, an optical fiber as a conductor of light and visual images is exploited in medical instruments for illumination and observation of inaccessible areas. As transmission along a fiber is better controlled, fibers capable of transmitting images in real-time holographic mode can be envisaged. Single-fiber systems can be designed to deliver a precise amount of optical power for pathological analysis and as a surgical tool or as new means of curing certain diseases such as the control and destruction of tumors.

COMMUNITY SERVICES

The wired-city concept has been proposed in which a community is intimately wired together in such a manner that a host of community-related facilities such as local news, shopping guide, neighborhood festivities, community library, rescue squad, and a computer bank are available to the community as a whole.

Experimental system has shown that the value of a wired city is associated with the perception of the people. It is a sociological experiment with far-reaching implications, but the results so far are too influenced by the main social trends to be really meaningful. Even in this context, wired-city development can be seen to promote a new community spirit and a different way of utilizing services.

Fiber systems can and will be the leading contender as the principal transmission media for wired cities. The provision of integrated services over a wide-bandwidth, low-loss transmission system is a desirable solution.

MILITARY DEFENSE

The special features of an optical fiber are small size, light weight, strength, flexibility, wide temperature range, and interference freedom, in addition to wide bandwidth and low loss. These features are key to improving the strategic and tactical capabilities of the military forces.

More powerful communications networks can be created and installed under various conditions. In the strategic base communications application, the more compact cable enables the cables to be easily transported and permits a variety of permanent and mobile configurations to be implemented easily. The remote connection to radar sites from the signal processing station can be rapidly deployed, and the wide bandwidth and the low loss allow longer spacing between the radar site and the station, thus allowing a greater safety for the operating personnel. The electromagnetic interference freedom characteristics can be used with great advantage on ships, airplanes, and armored vehicles, where much data are being processed under electrically noisy environment. The interference freedom also allows the system to preserve a high degree of privacy. This is utilized in systems where sensitive data are to be transmitted. The high strength and the flexibility allow fiber systems to be envisaged for tactical applications. Wire-guided weapons can be made to cover a longer range and with more precise guidance or even with visual target search capabilities. Fibers can also improve the capabilities of towed surveillance vehicles by improving the information and mechanical performance of the towing cable. The propagation characteristics of the fiber can be utilized to indicate strain and temperature change. This can be considered for sensor applications with improved sensitivity. Acoustic and magnetic field sensors and a fiber gyroscope have been identified as possibilities.

BUSINESS DEVELOPMENT

Akin to the wired-city concept is the "office-of-the-future" concept, where business functions of information retrieval, distribution, dissemination, and analysis are performed by equipment available within the office of the future. A general manager can call for financial and operational data with the touch of a button or a simple voice command. A document can be typed into a word-processing machine to allow for easy editing. Subsequent production of personalized versions can be automatically routed internally, thus enabling staff in other parts of the office to access the document on their terminal equipment in a display or hard-copy form and externally, for remote distribution. Inventory control, numerical control of machines and payroll preparation are just a few of the many automated services which an office of the future may have. Audiovisual conferencing and interactive graphics are other possible features.

The technical realization of such a system is not too different from the wired city, but since the system may be confined to a single building, and since the community involved has a more homogeneous and identifiable requirement, the system requirements can be more readily met.

ENTERTAINMENT

The pursuit of happiness often starts with a satisfying job, followed by spending the affordable surplus earnings on entertainment. We are lured to a world of service industry aimed at entertainment. The spectator sports, the stage, the movies, the radio, and television (TV) programs, as well as toys and books, are just a handful of more pertinent examples.

Perhaps TV has emerged as the most influential of all entertainment media. Backed by revenue from advertising, television broadcasters

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