

Preface to the Second Edition

The First Edition of this book provided an in depth coverage of fundamental aspects of linear fiber-optic systems based on directly modulated semiconductor laser transmitters. This type of link is overwhelmingly prevalent in linear fiber-optic systems, which constitute the foundation of Hybrid-Fiber-Coax (HFC) infrastructure, on which present day CATV services to, and cable modem internet access from the home depend. Important new aspects of linear fiber-optic transmission technologies covered in Part IV of this Second Edition include discussions in Chap. 17 of a high-level system architectural issue in optimal assignment of subcarrier frequencies to achieve the lowest inter-channel interference, at the required modulation index to maintain the carrier-to-noise/interference ratio needed for the functions/services involved. These algorithms for deriving the optimal frequency assignment of sub-carrier channels can be applied to any multi-channel transmission system without regard to the specific hardware employed, and apply equally well to fiber-optic systems employing directly modulated or externally modulated laser transmitters. As a matter of fact, some of these frequency assignment algorithms have their origin in satellite transmission where high power Traveling Wave Tube amplifiers employed on board satellites exhibit considerable nonlinearities.

Another systems issue addressed in this Second Edition concerns the use of Erbium-Doped Fiber Amplifier (EDFA) in linear fiber-optic systems. EDFAs are proven and ubiquitous in present day fiber-optic telecommunication systems for transmission of digital data. Their ready commercial availability these days makes them logical candidates for deployment in linear fiber-optic systems as well, yet the stringent requirements for linear fiber-optic transmission above and beyond those for digital transmission necessitates a closer look at the fundamental mechanisms responsible for distortion generation in EDFA's (Chap. 18).

Significant examples of field deployed military systems enabled by linear fiber-optic links described in Appendix G include:

1. Aerial fiber-optic towed decoy in military aircrafts (Sect. G.1) presently available from BAE Systems, a defense and security aerospace company headquartered in UK.

2. Transmission of fast single-shot data collected by sensors in nuclear test events (Sect. G.2), an early application of high speed wide-band fiber-optic links offered in the early-mid 1980s by Ortel Corporation of California (acquired by Lucent in 2000 and now a division of Emcore Corporation.) Described in the literature for the first time. These systems were the earliest commercial field deployment of linear fiber optic links which were the fore-runners of linear fiber-optic system products offered by Ortel Corp. for the (financially more significant) HFC market. The “consumable” nature of this application provided a consistent recurring revenue source for the company in its early years prior to the emergence of the HFC market.

Acknowledgements

The portion of new materials in this Second Edition on optimal frequency planning (Chap. 17) and employment of Erbium doped Fiber Amplifiers in multichannel Linear Fiber Optic System (Chap. 18 and Appendix F) is extracted from original research contributions of Prof. Lian-Kuan Allen Chen of the Department of Information Engineering at the Chinese University of Hong Kong, in the course of his doctoral dissertation research in the department of Electrical Engineering at Columbia University in the City of New York under the joint supervision of Prof. Emmanuel Desurvire and the author during 1989–1992. The author owes a debt of gratitude to Prof. Chen for his kind permission to adopt these materials in this book.

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Preface to the First Edition

Fiber-optics are firmly established as the dominant medium of terrestrial telecommunication infrastructure. Many excellent references and textbooks exist today that treat this subject in great detail. Most of these books cover device and systems aspects of digital fiber-optic transmission. For this reason, digital fiber-optic systems will not be a subject of discussion at all in this book. In the current communication infrastructure, a sizeable portion of “access” traffic is carried by Hybrid-Fiber-Coax (HFC) infrastructure [1], which employs subcarrier transmission¹ (essentially an analog format)² to support both CATV³ and cable modem Internet access. A similar situation exists in some military radar/communication systems where personnel and signal processing equipments are remoted from the physical antennas, which are often in harms way of homing weapons. The format of transmission in these systems is also analog in nature. Various nomenclatures have been given to these systems, the most popular of which are – RF photonics, linear/analog lightwave transmission, the former being popular with the defense establishment, the latter with commercial establishments serving the HFC infrastructure.

¹ Subcarrier transmission is essentially frequency division multiplex in the RF domain modulated on an optical carrier.

² Most subcarrier transmissions use QPSK or higher “-nary” modulation of the RF carrier, and are thus digital in content; but the criteria used to gauge the quality of the signals are still RF in nature. It is thus a matter of semantics or opinion whether subcarrier modulation is “analog” or “digital.” The author prefers to interpret subcarrier modulation and transmission as “analog” because the principal criteria used to gauge their performances are analog in nature.

³ “CATV” stands for Community Antenna TV in which a large satellite antenna at a remote location with good reception of satellite signals transmission from TV stations located around the country, typically in analog FDM format. The satellite antenna is often collocated with video processing and Internet access equipments. Collectively these facilities are known as the “Head End.” Linear (analog) fiber optic links carry the signals to subdivision hubs. From there it is distributed to individual homes through a coaxial cable network – hence the name “Hybrid Fiber Coax.” Employment of linear fiber-optic components and systems eliminates the need for serial placement of numerous high linearity RF amplifiers (“in-line amplifiers”) to compensate for the high loss of coaxial cables in the long span from the head end to subdivision hubs. Failure of a single RF amplifier results in loss of service to an entire subdivision.



Fig. P.1 Aerial view of Deep Space Network (DSN) at Goldstone, Mojave Desert, Southern California. The giant 70 m dish is in the foreground, a dozen other smaller dishes are located around it spaced up to 10 km's from one another

While the most significant commercial application of linear fiber-optic systems has been the deployment of HFC infrastructure in the 1990s, the earliest field-installed RF fiber-optic transmission system was made operational in the late 1970s/early 1980s at the “Deep Space Network” (DSN) at Goldstone, Mojave Desert in Southern California, just north of Los Angeles. The DSN⁴ is a cluster of more than a dozen large antenna dishes, the largest of which measures 70 m in diameter (Fig. P.1).

The DSN is operated by Jet Propulsion Laboratory (JPL) of Caltech and used by NASA (National Aeronautics and Space Administration) over the past two decades to track and communicate with unmanned space probes exploring the solar system to its very edge and beyond. In particular, the two “Voyager” space probes (Voyager I & II) were designed and destined to head out of the Solar system into interstellar

⁴ The DSN antenna network consists of three clusters of large antennas each identical to the one at Goldstone, the other two are located near Madrid, Spain, and Canberra, Australia. These three DSN sites are located roughly evenly in longitude around the globe, to enable maximum round the clock coverage of the interplanetary space probes.

space.⁵ At >8 billion miles from earth, the signal power received by/from these interstellar spacecrafts is minuscule to the extent that even a single 70 m diameter giant antenna dish alone at DSN was inadequate to carry out the task of communications/tracking. A fiber-optic network was installed at the Goldstone DSN in the late 1970s/early 1980s, with the sole purpose of transmitting to all antennas in the network an ultra-stable microwave reference signal at 1.420405752 GHz (the 21 cm line of atomic hydrogen, accurate to within parts in 10^{15} , generated by a hydrogen maser in an environmentally controlled facility). All antennas in the network are synchronized to this ultra-stable frequency reference enabling them to act as a single giant antenna using the phase array concept, capable of communicating with the spacecrafts as they head out to interstellar space.

This extreme stability requirement of microwave fiber-optic links necessitates active feedback stabilization techniques to compensate for any and all physical factors that can affect lightwave propagation in the optical fiber cable, including temperature, humidity, and mechanical effects. A scheme to achieve this was disclosed in a patent, the front page of which is shown in Fig. P.2. Readers interested in the details of this stabilization scheme should consult the full patent, downloadable from the U.S. Patents and Trademark Office web site – <http://www.uspto.gov/> and search for patent #4,287,606.

Among the numerous nomenclatures used to describe this type of analog fiber-optic transmission systems, “linear lightwave transmission” has gained traction over others, even though in substance there is no distinction between “linear lightwave transmission” and the more traditional, technically descriptive “analog/RF lightwave transmission,” the rationale being:

1. The financial community generally offers higher reward to non-defense related businesses than those otherwise, presumably because the well being of the latter depends too heavily on the often unpredictable international political climate.
2. “linear” lightwave systems surpasses “analog” lightwave systems, in terms of marketability of hardware manufacturers to the financial community because the latter conjures up undesirable archaic impressions.

Cable TV distribution and associated cable modem Internet access really belong in the realm of “access” and not telecommunications, but they are nonetheless an important and integral part of present day communication infrastructure.

Yet another emerging means of access and enterprise private communication infrastructure construct is free-space point-to-point millimeter-wave (“mm-wave”) links,⁶ capable of high data rates (in multi-Gb/s’) due to the high carrier frequency in the mm-wave range. It also offers ease of construction – the only criterion

⁵ On May 31, 2005 and August 30, 2007 Voyager I and Voyager II respectively passed the heliosphere, the critical boundary at 8.7 billion miles from the sun that marks the transition from the solar system into interstellar space. For more information, visit <http://voyager.jpl.nasa.gov/>.

⁶ Examples of commercial offerings of this type of products are – <http://www.loecom.com/>, retrieved: 2008/07/25, 4:25PM and <http://www.bridgewave.com/>, retrieved: 2008/07/25, 4:26PM.

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4,287,606

United States Patent [19][11] **4,287,606**

Lutes, Jr. et al.

[45] **Sep. 1, 1981****[54] FIBER OPTIC TRANSMISSION LINE STABILIZATION APPARATUS AND METHOD**

- [76] Inventors:** Robert A. Frosch, Administrator of the National Aeronautics and Space Administration, with respect to an invention of George F. Lutes, Jr., Glendale; Kam Y. Lau, Pasadena, both of Calif.

[21] Appl. No.: **188,160**[22] Filed: **Sep. 17, 1980**[51] Int. Cl.³ **H04B 9/00**[52] U.S. Cl. **455/617; 455/610;**..... **455/615; 455/612**[58] Field of Search **455/610, 612, 615, 617****[56] References Cited****U.S. PATENT DOCUMENTS**

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[57] ABSTRACT

A fiber optic transmission line stabilizer for providing a phase-stabilized signal at a receiving end of a fiber optic transmission line (26) with respect to a reference signal

at a transmitting end of the fiber optic transmission line (26) so that the phase-stabilized signal will have a predetermined phase relationship with respect to the reference signal regardless of changes in the length or dispersion characteristics of the line (26). More particularly, a reference signal of RF frequency modulates a 0.85 micrometer wavelength optical transmitter (20). The output of the optical transmitter (20) passes through a first optical filter (24) and a voltage-controller phase shifter (22), the output of the phase shifter (22) being provided to the fiber optic transmission line (26). At the receiving end of the fiber optic transmission line (26), the signal is demodulated, the demodulated signal being utilized to modulate a 1.06 micrometer optical transmitter (34). The output signal from the 1.06 micrometer optical transmitter (34) is provided to the same fiber optic transmission line (26) and passes through the voltage-controlled phase shifter (22) to a phase error detector (36). The phase of the modulation of the 1.06 micrometer wavelength signal is compared to the phase of the reference signal by the phase error detector (36), the detector (36) providing a phase control signal related to the phase difference. This control signal is provided to the voltage controlled phase shifter (22) which alters the phase of both optical signals passing therethrough until a predetermined phase relationship between modulation on the 1.06 micrometer signal and the reference signal is obtained.

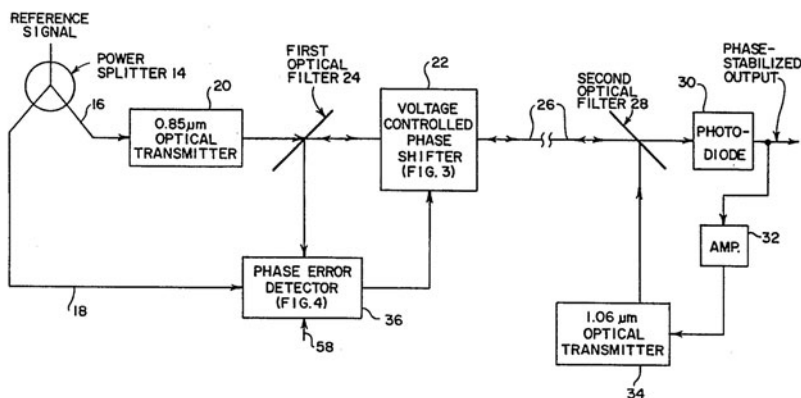
21 Claims, 8 Drawing Figures

Fig. P.2 Front page of patent disclosure detailing method and apparatus of fiber-optic transmission of ultra-stable frequency reference for antenna synchronization at NASA Deep Space Network

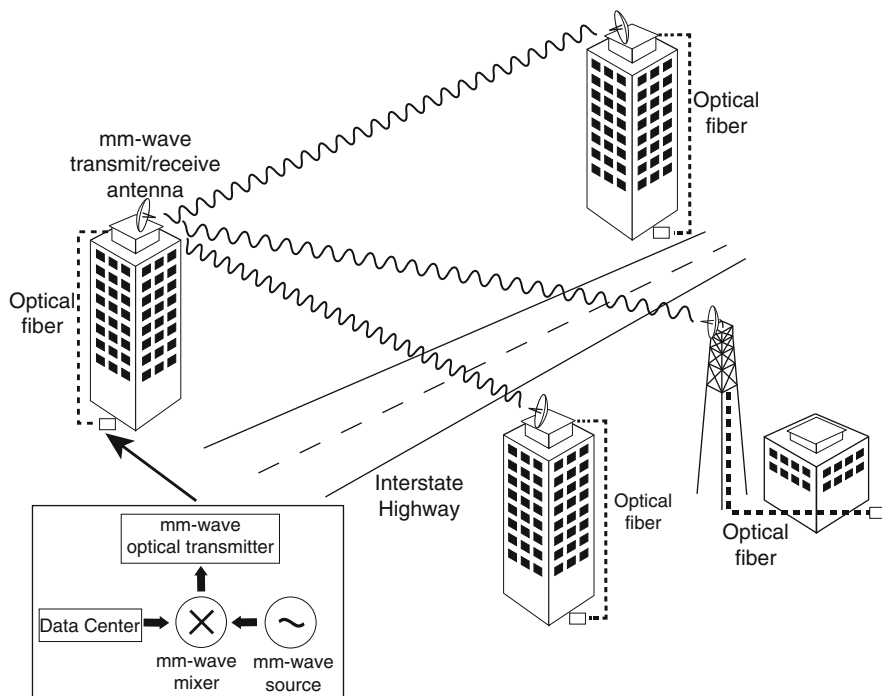


Fig. P.3 Schematic of a campus-scale free space mm-wave network

being locating and gaining access to line-of-site vantage points for the transmitting and receiving antennae. The physical alignment of these mm-wave links are substantially more forgiving than corresponding free-space optical links, and in contrast to the latter, suffers only minimal free-space propagation impairment under less-than-ideal weather conditions. Another desirable factor for this type of systems over a wire-line infrastructure, in addition to savings in construction cost and time, is avoidance of onerous issues of negotiating right-of-ways. This is all the more apparent, for example, in the situation of construction of a high speed private data network between buildings within a corporate campus which spans across an interstate highway with no right-of-way access for private enterprise (Fig. P.3).

It is also desirable for this type of commercial systems to have the mm-wave transceiver equipments located remotely from the antenna sites, even though the antenna sites are not at risk of being targeted by homing destructive vehicles. The reasons are two-folded:

1. FCC stipulates that licensees of mm-wave bands hold their emission frequencies tightly, to the extent that economical free-running mm-wave oscillators operating in an uncontrolled outdoor environment do not suffice; they must be locked to a stable reference located remotely in an environmentally controlled location or else the data to be transmitted are “pre-mixed” onto the mm-wave carrier at

a remote location and then “piped” to the remote antenna site for free space transmission.

2. The amount of service work required at the remote antenna sites (which are often difficult to access and subjected to inclement weather conditions) can be minimized.

Given the above rationale, the problem then becomes that of innovating means of transporting mm-wave subcarrier signals over intermediate distances (up to ~ 10 's of km's.) Use of mm-wave waveguides or coaxial cables are simply not viable due to dispersion/loss, in addition to being bulky, heavy, and prohibitively expensive.

The use of optical fiber should be an ideal solution. This book deals with the subject of modulating and transmitting mm-wave subcarrier signals on an optical carrier, and associated fiber transmission effects.

In traditional telecom infrastructure long haul links use externally modulated laser transmitters in order to minimize optical frequency chirp and resultant signal degradation due to fiber dispersion. The “external” modulator in telecom long haul transmission is actually an electro-absorption (EA) modulator monolithically integrated with a CW laser, the “EML” (Electroabsorption Modulator Laser). Within the metropolitan arena the fiber infrastructure is dominated by $1.3\text{ }\mu\text{m}$ links employing directly modulated Distributed FeedBack diode lasers, “DFB's.” In terms of the raw number of laser transmitters deployed, directly modulated $1.3\text{ }\mu\text{m}$ lasers far outstrip that of “IML”. The situation is similar in HFC networks, where directly modulated $1.3\text{ }\mu\text{m}$ linear laser transmitters transporting RF signals over longer spans within subdivisions are far more prevalent than long reach links feeding subdivision nodes from the “head-end”. In terms of economics, directly modulated linear laser transmitters thus carry more weight. This is also the case for the type of fiber-optic distribution infrastructure supporting the type of mm-wave free-space interconnection networks as described above. For economic reasons, it is preferred that short spans for transporting mm-wave signals up to roof tops or tall towers/poles (“short-reach” links) employ $1.3\text{ }\mu\text{m}$ Single Mode Fibers “SMF's” using inexpensive directly modulated laser transmitters, which are only slight variants of those deployed in telecom, where economic advantages of the latter's mass production capacity can be exploited, while “long-reach” links serving a wider region consist of $1.55\text{ }\mu\text{m}$ SMF's, (not necessarily of the dispersion-shifted type.) Transmitters for these long-reach links employ CW laser diodes in conjunction with a high frequency external modulator, of which the velocity-matched Mach-Zenhder type is a logical choice. Similar to the case of HFC networks, the raw number of directly modulated $1.3\text{ }\mu\text{m}$ “short reach” links far outstrips that of “longer reach” $1.55\text{ }\mu\text{m}$ links requiring externally modulated transmitters. To reflect this practical reality and the innovative challenges in constructing low-cost “telecom-type” directly modulated laser diodes capable of operating at mm-wave frequencies for the “short-reach” spans. A considerable portion of this book (Chaps. 8–11) is devoted to this subject.

“Longer reach” $1.55\text{ }\mu\text{m}$ links for transport of millimeter-wave signals up to 50–100km employing external electro-optic Mach-Zenhder modulators are described in Chaps. 12 and 13 for dispersion-shifted and non-dispersion-shifted

fibers respectively. The basic principle of high frequency velocity-matched modulators are presented in Appendix C.

The core material (Parts II and III) in this book represents research results on this subject generated by members of the author's research group in the 1990s in the Department of Electrical Engineering and Computer Sciences at U.C. Berkeley. These materials are augmented by discussions, in Part I of the book, of general baseband modulation of semiconductor lasers and associated fiber transmission effects, which constitute the basis of understanding of directly modulated laser transmitter prevalent in metropolitan and local area fiber optic networks, as well as subcarrier fiber-optic links in HFC networks today.

These traditional baseband direct modulation approaches, however, does not appear to have the potential of extending into the mm-wave frequency range. Innovative approaches are therefore needed to accomplish the task of transporting mm-wave subcarrier modulated optical signals in optical fibers, as covered in Parts II and III of this book. Following is a review of the current understanding of direct modulation of semiconductor lasers (Chaps. 1–6) and some related noise and impairments due to laser-fiber interaction (Chap. 7) in Part I of the book, Part II describes an innovative approach known as “resonant modulation”, which is basically a “small-signal” version of the classic technique of mode-locking applied at the mm-wave frequency range to *monolithic*, standard telecom laser diode structures for transmission of subcarrier signals beyond the baseband limit (into the mm-wave frequency range). Part III discusses fiber transmission effects of mm-wave subcarrier signals in general (Chaps. 12, 13), as well as a high level systems perspective of a particular application to fiber-wireless coverage (Chap. 14). Chapter 15 discusses the effect and mechanism of suppression of interferometric noises (such as modal noise in MMF (Multi-Mode Fiber) links or intensity noise generated by conversion from phase noise of the laser by multiple retroreflections in SMF (Single-Mode Fiber) links) by superposition of a high frequency tone in the modulation current input to the laser (Chap. 15). Part III concludes with another innovative, powerful approach to optical transmission of mm-wave subcarrier signals – “Feed-forward Modulation” (Chap. 16), which circumvents a significant disadvantage of the “resonant modulation” approach, namely that the laser device must be customized for transmission at a given mm-wave subcarrier frequency, and cannot be freely varied electronically thereafter. This is precisely the capability of “Feed-forward Modulation”, albeit at the cost of higher complexity and part count.

Notes on common metrics of RF signal qualities can be found in Appendix A. Basic Principles of high speed photodiodes and narrow-band photoreceivers intended for subcarrier signals are discussed in Appendix B. Basic principles and state-of-the art external optical modulators are briefly reviewed in Appendix C.

Appendix D describes theoretical direct modulation response of “superluminescent lasers” – laser diodes with very low end mirror reflectivities operating at a very high internal optical gain, using the full nonlinear, spatially non-uniform traveling-wave rate equations, the computed response is compared to that of conventional laser diodes using the simple rate equations, the validity of the spatially uniform rate equations is thus established.

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