OPTICAL FIBER COMMUNICATION 1986

CONFERENCE ON OPTICAL FIBER COMMUNICATION

1986

OPTICAL FIBER COMMUNICATION CONFERENCE

Technical Digest

Summaries of technical papers
presented at the
Optical Fiber Communication Conference,
24–26 February, 1986
Atlanta, Georgia.

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FOREWORD

The Optical Fiber Communication Conference (OFC) is the major annual North American conference relating to research, technology, and the application of optical fibers. This year's conference is the ninth in the series that began in Williamsburg, Virginia, in 1975. OFC is also part of the series of major international conferences that provide a worldwide forum for the dissemination of information on the most recent advances in optical guided-wave research and development. Every second year the regional conferences in North and South America, Europe and Africa, and the Far East combine to form, in addition to their regular annual meetings, the International Conference on Integrated Optics and Optical Fiber Communications (IOOC), the next of which will be held in Reno, Nevada, 1987. Additionally, Topical Meetings on integrated and guided-wave optics are sponsored by the Optical Society of America and the Institute of Electrical and Electronics Engineers to discuss work on planar waveguides, semiconductor light sources, and integrated optoelectronics. This year the Eighth Topical Meeting on Integrated and Guided-Wave Optics (IGWO'86) is meeting concurrently with OFC. Since 1984 OFC alternately meets on the East and West Coasts. It is planned that the Conference on Lasers and Electro-Optics (CLEO) will have the opposite geographical alternation to continue to bring the latest advances in related topical areas to the widest possible audience.

The activity in optical fiber technology is approximately doubling every year, giving OFC a broad mission to accomplish. At one end of the spectrum it must provide the most up-to-the-minute view of technical advances. At the other extreme it must also provide the mechanism for giving new people and organizations the overview necessary to enter this fast-moving field. OFC is structured with this in mind. The program contains tutorials, invited papers concerned with overviews and leading edge technology topics, contributed papers describing current work in the field as well as late-news papers for the most up-to-date technology advances. The rapid evolution and merging of communications and computing technologies are leading us into the information age, in which optical fibers and devices will play a major role in the transport, at affordable cost, of ever increasing information demands. While OFC is devoted to the technology of this revolution, it is important that we keep in mind that service and economic needs, as perceived by customers, equipment vendors, and regulators, as well as human needs that may drive societal changes to a more information-intensive mode, play an important role in controlling the pace of change. To this end, Melvin Kranzberg will deliver the keynote address: Technology is the Answer, but That's not the Question.

To further help new entrants into the technical area and to help those familar with one aspect of technology to broaden their scope, a series of nine tutorials covering all aspects from individual components to systems will be presented by world-recognized leaders in each area. A set of twenty-eight invited papers will provide a coherent overview of key aspects of the technology while the contributed papers included in three parallel sessions will present the latest results in the field. A poster session is also scheduled, in which papers of more complexity than normal oral presentations will be given. A technical exhibit with representation from over one hundred companies will provide attendees an opportunity to see the latest products related to optical fiber technology, as well as the implementation and practical embodiment of information first presented at past OFCs. The wide range of topics and multiple levels of presentation should provide conference attendees the information necessary to make it well worth their time.

The OFC'86 Program Committee wishes to extend its thanks to the scientists and engineers whose contributed work make this conference possible. The high quality of the papers illustrates the technical progress being achieved in the many laboratories and companies throughout the world. This continuing series of Optical Fiber Communication Conferences will follow and report on developments in optical fibers and guided-wave technology and enhance the exchange of technical information in the international forum.

We would also like to express our thanks to the marvelous staff of the Optical Society of America for planning and managing the logistics of this conference and its associated exhibit with the highest levels of skill, professionalism and thoughtfulness. Our thanks are also due to the exhibitors whose presentations represent an important part of this conference.

Interchange of information is essential to the growth and vitality of any field, be it in the technical or commercial area. We look forward to this and the succeeding conferences to provide a continuing forum for stimulating information interchange in optical fiber communication and technology.

Ninth Conference on
OPTICAL FIBER COMMUNICATIONS

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GTE Laboratories

Michael Ettenburg
RCA Laboratories

Technical Program Cochairs

Melvin I. Cohen
AT&T Bell Laboratories

Paul D. Lazay
ITT Corporation

Monday **MORNING**
24 February 1986 **MA**
SALONS I AND II

9:00 AM **Introductory Remarks**

Michael Ettenberg, RCA Laboratories, Cochair

9:15 AM **Keynote Address**

Melvin I. Cohen, AT&T Bell Laboratories, Presider

MA1 Technology's the answer but that's not the question

MELVIN KRANZBERG, Georgia Institute of Technology, Atlanta, GA 30332.

Although technology is frequently viewed as something mechanical and inhuman, it is one of the most basic human social characteristics and has played a large role in development of civilization. However, like most human activities, it is subject to misuse and abuse. Nevertheless, it is not simply a neutral human instrument; as Kranzberg's first law states: Technology is neither good nor bad, nor is it neutral. This is because technology interacts with the sociocultural milieu in a variety of ways which are not necessarily inherent in the technology itself and which can differ in varying contexts.

Although many of our current problems arise from the unforeseen human, social, and environmental consequences of previous technological applications, solution of those problems will require better and more effective use of technology. Unlike earlier times, our modern, sophisticated, and complex technology gives us options; we have choices regarding which technologies we apply and some awareness of the trade-offs—benefits and disbenefits—involved in selecting our technological means.

Fiber optics, for example, offers obvious scientific and technical advantages. Yet the history of the introduction of new technologies indicates that many problems—scientific-technical, socioeconomic, and the like—often hamper the immediate acceptance of innovations. Also, unexpected consequences sometimes emerge, so that sociocultural factors become decisive in determining the direction and use of many technical advances, especially in the field of communications.

Hence selection of our technological solutions will depend largely on our institutions and our value systems. These in turn involve such elusive matters as defining the quality of life, analyzing social benefits and disbenefits, and assessing sociotechnical impacts.

Yet, because we live in a man-made world, Kranzberg claims it is possible for man to remake it. Creating a better world in the future thus rests on utilizing our technology in accordance with our highest ethical and human values.

(Keynote paper, 45 min)

Monday **MORNING**
24 February 1986 **MB**
SALONS I AND II

10:45 AM **Communications Systems Architectures**

Paul D. Lazay, ITT Electro-Optics Products Division, Presider

MB1 Minitutorial: Communications systems architectures

STEWART D. PERSONICK, Bell Communications Research, Inc., Holmdel, NJ 07733

This tutorial describes how optical fiber technology is used to implement communications systems such as point-to-point trunks, data links, local and metropolitan area networks, and broadband distribution networks. We show how the unique characteristics of fiber technology (such as incrementally low-cost bandwidth) result in system architectures that are often different from those associated with copper cable or radio technologies.

S. D. Personick received his B.E.E. from CCNY (1967) and his Sc.D. from MIT (1970). From 1967–1978 he performed exploratory work on optical fiber technology and applications at Bell Laboratories. From 1978–1983 he managed transmission and switching hardware development departments and research organizations at TRW. Since January 1984, he has been Division Manager for Transwitching Technology Research at Bell Communications Research. He is the author of two books on fiber optics, a Fellow of the IEEE, and the holder of five patents. He is a frequent lecturer on fiber-optics technology and applications and was General Cochairman of OFC'85.

(Minitutorial, 60 min)

Monday **MORNING**
24 February 1986 **MC**
IMPERIAL B

10:45 AM **Integrated Optics and Lightwave Systems**

Robert Olshansky, GTE Laboratories, Presider

MC1 Minitutorial: Integrated optics for lightwave systems

ROD C. ALFERNESS, AT&T Bell Laboratories, Crawford Hill Laboratory, Holmdel, NJ 07733.

As lightwave technology evolves there is a progression to more sophisticated systems, for example, those employing coherent detection techniques, and to increasing penetration of fiber in the subscriber loop and local area networks. To implement these systems as well as proposed fiber sensor subsystems, a variety of cost-effective passive and electrically activated terminal devices such as switches, taps, modulators, star couplers, and tunable filters will be required. A goal of integrated optics research over the last decade has been to demonstrate compact thin-film fabricated, low-loss waveguide devices to provide these control functions. Recently there has been considerable progress in integrated-optic device research including achievement of low fiber-coupled insertion loss, larger optical switch arrays, an optical transmission experiment with record breaking bit rate · distance product using an external waveguide modulator and increased emphasis on devices for loop and local distribution. Given the evolution of single-mode lightwave systems and a maturing integrated-optic technology, the time appears ripe for the lightwave systems designer to understand the current and potential capabilities and limitations of integrated-optic devices which are reviewed in this tutorial.

Rod C. Alferness is head of the Photonics Circuits Research Department of AT&T Bell Laboratories, Holmdel, NJ. He joined Bell Laboratories in 1976 after receiving a Ph.D. in physics from the University of Michigan where his thesis research concerned optical propagation in volume holograms. Since then his research has centered on novel waveguide electrooptic devices—including switch/modulators, polarization controllers, tunable filters—and their applications in communication systems. Other research interests include high-speed optical measurement techniques, integrated-optic composite cavity semiconductor lasers for picosecond pulse generation, and optical switching techniques. Alferness is a fellow of the Optical Society and a member of the IEEE Lasers and Electro-Optics Society (LEOS). He is currently an elected member of the Administrative Committee for LEOS. Alferness has served on program committees for various conferences, including the Conference on Lasers and Electro-Optics, the International Conference on Integrated Optics and Optical Communication, and the Topical Meeting on Integrated and Guided-Wave Optics.

(Minitutorial, 60 min)

Monday **AFTERNOON**
24 February 1986 **MD**
SALON I

1:30 PM **Local Area Networks**

Albert D. Bender, FiberCom, Inc., Presider

MD1 Fiber-optic technology for broadband local area networks

DONALD J. CHANNIN and D. R. PATTERSON, RCA Laboratories, Princeton NJ 08540.

Local area networks (LANs) promise to be a major application area for fiber optics, perhaps rivaling the now well-established applications in point-to-point telecommunications and data links. Many architectures and signaling protocols are in use or are being investigated for use in LANs. In many cases these architectures and protocols require that the optoelectronic components perform under quite different conditions than for conventional point-to-point communication. To realize the broadband transmission potential of fiber optics in LAN applications, these special requirements must be fully understood by the system designer. This paper offers a review of the implications of LAN transmission systems on the capabilities required of the optoelectronic components.

LAN systems may be grouped into two broad categories: switched networks and broadcast networks. Switched networks make use of either central or distributed switching to establish communication channels between terminals during the duration of signal transfer. Broadcast networks send signals from a transmitting terminal to all receiving terminals and rely on operational protocols to establish message routing and priorities. Optoelectronic technology for switched networks may closely resemble conventional telecommunications technology. Broadcast LANs, however, generally require very different transmission technology from that of switched networks, and different types of broadcast LAN often have widely differing transmission requirements. For this reason, this paper deals mainly with broadcast LANs.

The following items suggest the type of problem that must be addressed in using fiber-optic technology in various types of LAN:

Tapped-bus architectures, the most practical and widely used architectures for metal-cable LANs, introduce a large signal loss at each tap of an optical system. Accumulated loss over a series of taps limits the total number of passive connections to ~10. Repeaters are necessary for more extensive systems. However, repeaters in tapped-bus architectures add substantial propagation delay. The need for many repeaters can exceed the total delay budget for some systems, such as the widely used IEEE 802 standard for CSMA-CD networks.

Passive-star architectures, although much more efficient than passive tapped-bus systems, still are limited by optical distribution losses to ~30–100 terminals for each passive star. The optical power dynamic range is large for passive LAN architectures and must be accommodated at high speed on an interpacket basis. Both statistical and worst-case approaches must be considered for optical power budget analysis. Contention-based protocols requiring collision detection are difficult to implement over a wide dynamic range.

Transmission of data packets rather than continuous data requires very rapid optical transmitter and receiver stabilization and synchronization. The use of laser diodes for high-speed transmission presents special problems for operating point control and background light suppression. Analysis of optical line signals and error rate measurement must be carried out on packets requiring new measurement and instrumentation techniques.

These and other issues will be discussed. Technical approaches that have been offered to solve these problems will be reviewed, and areas in which further work is needed will be identified. The prospects for development of very high-performance broadband LANs using fiber-optic technology depend on resolving the technical issues and on making appropriate choices among the many network systems now being investigated. **(Invited paper, 25 min)**

MD2 Wideband local networks exploiting single-mode fiber

CHRISTOPHER J. TODD, British Telecom Research Laboratories, Martlesham Heath, Ipswich, U.K.

Between 1980 and 1985 single-mode fiber replaced multimode GI as the standard long-haul transmission medium. Despite the large investment in multimode technology, single-mode succeeded because of its greater range, its bandwidth versatility, and its impact on system costs. Installation difficulties were accepted since single-mode was clearly the better investment.

In 1982 a program was initiated at British Telecom Research Laboratories to explore the technical opportunities that single-mode fiber and associated optoelectronic device technologies would bring to wideband subscriber networks.

Over distances of the order of 5 km, single-mode fiber offers the closest approximation to the lossless, bandwidth-unlimited transmission waveguide required for maximum flexibility in wideband network design. A variety of hybrid, planar optical, and optoelectronic components are currently being studied to enable a rich array of experimental wideband single-mode systems to be available for appropriate engineering in the future. It is becoming clear, especially in the U.K. and the U.S.A., that a common single-mode technology base will be applicable throughout the entire communication network, down to and including the local loop and the local area network. That common single-mode systems technology can draw on the reducing TDM costs in the long-haul sector and it can evolve, for example, via WDM toward extensive coherent spectral utilization, and/or via a number of optical space switching scenarios, to meet the network designs required for wideband service provision.

That demand for wideband services is not yet here on any economic scale. While single-mode fiber is rapidly becoming the cheapest optical medium, longer wavelength optoelectronic components remain expensive. Significant effort is still required to simplify single-mode installation procedures and, more importantly, to reduce installation costs. The challenge right now is to cost single-mode systems into the feeder and subscriber loop, especially at the 2–140-Mbit/s level. If this can be achieved, a backbone network of single-mode fiber will be in place to meet customer wideband needs as they arise. **(Invited paper, 25 min)**

MD3 Fail-safe nodes for fiber networks

K. W. LOH, M. KARR, and A. ALBANESE, Bell Communications Research, Inc., 435 South St., Morristown, NJ 07960; W. C. YOUNG, L. CURTIS, and J. BARAN, Bell Communications Research, Inc., 331 Newman Springs Rd., Red Bank, NJ 07701; L. McCAUGHAN, U. Wisconsin, 1415 Johnson Dr., Madison, WI 53706.

For fiber networks with regenerative (active) nodes, failure of a regenerative node usually leads to failure of the network. It is, therefore, desirable to have a fail-safe switch that can optically bypass the failed node. In addition, the node should be able to perform a self-test when the network fails (or just for a routine check) so that the healthy nodes can be reconnected to the network. This fail-safe switch can be either electromechanical (EM) or electrooptical (EO).

Figure 1 shows an electromechanical fail-safe switch. Six fibers are held in two halves of a silicon V-groove chip array. The fiber center-to-center distance is *d*. In the bypass (self-test) state as shown in Fig. 1, the node is not connected to the network as the input fiber is butting directly to the output fiber. In the self-test mode the system electronic generates test vectors which drive the laser through the loopback fiber into the receiver. Low insertion loss is necessary as very often some nodes in the network are not used until a later date. In the regenerative state, the right-hand side V-groove moves up electromechanically a distance *d*. The input fiber goes directly to the regenerator. Messages are dropped, added, or retransmitted through the system electronic which then drives the laser transmitting to the next node.

Several EM switches with millisecond switching speed have been fabricated. Previous results of switches having similar design demonstrated that they can be switched more than 250,000 times without failure. The insertion losses of one of the switches are

Bypass state
input fiber (SM) to output fiber (SM) 0.45 dB,
transmitter fiber (SM) to receiver fiber (MM) 0.21 dB.

Regenerative state
input fiber (SM) to receiver fiber (MM) 0.14 dB,
transmitter fiber (SM) to output fiber (SM) 0.43 dB.

Operation of the fail-safe node has been verified by transmitting a 2-Gbit/s pseudorandom sequence at 1.3 μm through three stations connected by 2 km of SM fibers. When the center station fails, that switch goes to the bypass state. The signal from the first station is received by the last station without error.

A 2 × 2 $LiNbO_3$ polarization-independent fail-safe switch shown in Fig. 2 has been designed to operate at 40 V, half of that previously reported. The result of a calculation indicates that when the TE mode is weighted to minimize sidelobes, the combined bar state has better voltage tolerance. For typical system parameters at 4 Gbit/s, to bypass one failed node, a crosstalk of −16 dB for the cross state and −22 dB for the bar state are required. To bypass two failed nodes, they are −22 and −28 dB, respectively. EO switches with the above properties are being fabricated. A switching speed of 100 ns and insertion loss (fiber to fiber) of 3 dB is expected.

For double buses, the laser can be shared between the upstream and downstream buses as shown in Fig. 3. For dispersion limited single buses, when the number of laser longitudinal modes is not allowed to increase, it is preferable not to modulate the laser but to use one-half of the structure in Fig. 3 instead. **(12 min)**

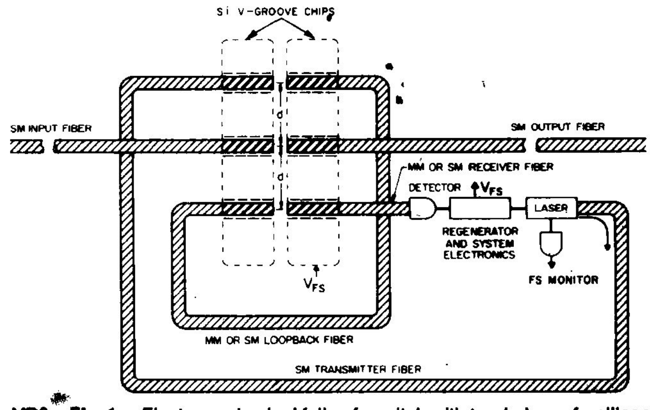
MD4 Fiber-optic modules for 500-Mbit/s local area network applications

D. R. PATTERSON, S. A. SIEGEL, and J. C. BARONI, RCA Laboratories, Princeton, NJ 08540; T. L. JONES, RCA New Products Division, Lancaster, PA 17601.

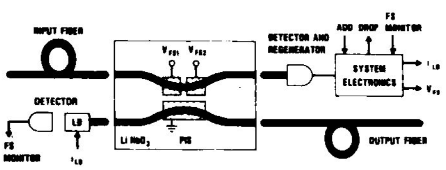
Recent papers have described the development of fiber-optic transmitters and receivers for point-to-point applications operating in the 1-Gbit/s range and beyond. Many of these systems have been used to establish new high-bit-rate long-distance records.[1] In most cases custom silicon or gallium arsenide (GaAs) integrated circuits were developed for these new applications.

Local area networks (LANs), like point-to-point links, have also been demonstrated at increasingly higher data rates.[2] The requirements of intermittent or burst mode data in some local area network topologies have required new laser stabilization and receiver designs necessary for burst mode transmission at these high data rates. As an example of new design approaches, a method of laser stabilization that utilizes the inherent propagation delay in a star-connected token-passing network will be described.

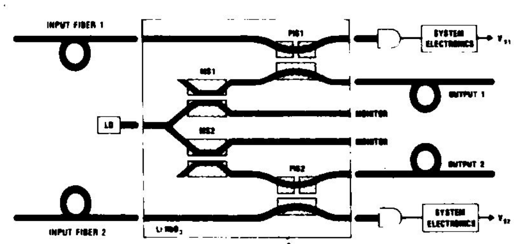
As the equivalent nonreturn-to-zero data rate of these systems exceeds 1000 Mbit/s, the high-frequency characteristics of both the laser and its package become a significant factor in pulse fideli-



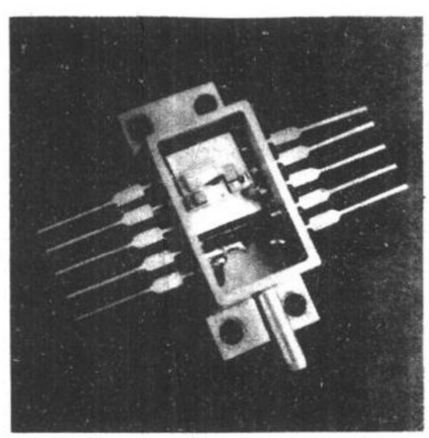
MD3 **Fig. 1. Electromechanical fail-safe switch with two halves of a silicon V-groove chip array. Switch is in the bypass state. To go into the regenerative state, the right half moves up electromechanically a distance *d*.**



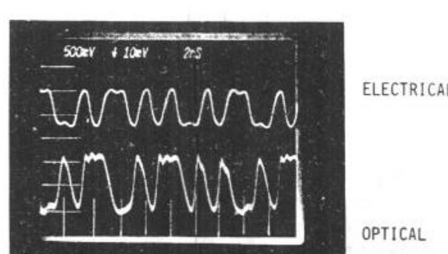
MD3 Fig. 2. Polarization-independent $LiNbO_3$ fail-safe switch for single bus.



MD3 Fig. 3. $LiNbO_3$ fail-safe switch for double bus (*MS* = polarization dependent, *PIS* = polarization independent).



MD4 Fig. 1. High-frequency laser package.



MD4 Fig. 2. 500-Mbit/s Manchester data.

ty performance. Special high-frequency packaging has been developed to reduce parasitic resonance effects in the optical response of the lasers. A 3-dB bandwidth in excess of 1000 MHz has been achieved with a laser and wedge-coupled fiber arrangement in a multipin metal package. An open package of the new design without fiber is shown in Fig. 1.

This paper reports on the development of very high-speed (500 Mbit/s, Manchester encoded data) optoelectronic transmitters and receivers for local area networks that make use of commercially available GaAs logic circuits.

GaAs integrated circuits[3] provide the necessary subnanosecond interfaces for the high-speed optoelectronic devices not previously possible with existing silicon bipolar logic elements. Gallium arsenide logic gates and comparators are used in the transmitter and receiver designs. Figure 2 shows the emitter-coupled logic compatible electrical input signal and the optical output from a 500-Mbit/s transmitter. Additional details of the circuit approaches will be presented along with a discussion of the special considerations encountered in interfacing a new high-speed digital logic family to the transmitter modulation and receiver comparator elements of the LAN modules.

The data rates achieved in the modules described are the highest reported for burst-mode (LAN) applications. The ability to achieve this performance with commercially available GaAs logic rather than custom integrated circuits greatly increases the commercial viability of high-speed fiber-optic systems for local area networks and similar large-scale applications. **(12 min)**

1. D. C. Gloge and K. Ogawa, "Technology for Intercity Lightwave Systems," in *Technical Digest, Conference on Optical Fiber Communication* (Optical Society of America, Washington, D.C., 1985), paper WB1.
2. D. J. Channin, J. B. Sergi, D. R. Patterson, S. A. Siegel, and J. P. Viola, "Fiber-Optic 200-Mbit Local Area Network," in *Technical Digest, Conference on Optical Fiber Communication* (Optical Society of America, Washington, D.C., 1984), paper WC2.
3. J. Barresa, B. Hoffman, and D. Wilson, "Digital GaAs IC's Hit Gigahertz Speed Mark," Microwaves and RF (Feb. 1984).

Monday **AFTERNOON**

24 February 1986 **ME**

SALON II

1:30 PM Photonic Switching and Device Packaging

Joseph C. Williams, ITT Electro-Optics Products Division, Presider

ME1 Photonic switching: present status and future prospects

PETER W. SMITH, Bell Communications Research, Inc., Holmdel, NJ 07733.

The rapid development and installation of optical fiber transmission systems have served to stimulate the present interest in studies of optical switching and signal processing devices and techniques.

Plans for near-term applications of photonic switching involve primarily either mechanical devices for slow switching (patch panels) or fixed couplers for signal processing systems. Substantial development has been carried out on electrooptic switching and multiplexing elements, most of which are based on $LiNbO_3$ technology. Although such devices are able to switch the large bandwidth channels available with lightwave systems, they have at present a number of limitations in terms of stability, reliability, and speed. In many cases they may turn out not to be economically superior to their electronic counterparts.

If the present trend toward very high-capacity communications systems continues, severe problems will be experienced in using electronics to process signals at sufficiently high bit rates. For these applications, the introduction of optical signal processing (which does not suffer from the same bit rate limitations) appears very attractive. One can picture a stage of optical signal processing to multiplex signals to high bit rates compatible with optical fiber transmission and a stage of optical signal processing at the other end to demultiplex down to rates that electronics can comfortably handle. We will give examples of possible configurations for such optical devices and describe current research aimed at bringing such devices closer to reality.

We conclude by describing what we believe to be important areas for future research. Some of these areas are: nonlinear optical materials; integrated optics fabrication techniques; and optical systems architecture. With progress in these areas, photonic switching is likely to have a major impact in lightwave communications systems of the future. **(Invited paper, 25 min)**

ME2 Real-time alignment of small optical components

J. GOODWIN, Northern Telecom Canada, Ltd., 8 Colonnade Rd., Nepean, Ontario, K2E 7M6 Canada.

The small dimensions of laser diode emitting areas, single-mode fiber cores, and some detector active areas make their mutual alignment difficult requiring precision positioning devices. This difficulty can be attributed to the high spatial sensitivity of the coupling efficiency between the two small optical components. However, the high spatial sensitivity can be utilized to cause a small fluctuation in the coupled light by imposing a small vibration (e.g., 10 nm) on one of the components. The amplitude of the coupled light fluctuation and its phase contain information about the relative offset of the components. This information is easily extracted with a phase sensitive detector. By providing feedback of the dc output of the phase sensitive detector to the transducer which is vibrating one of the optical components, that component will lock onto the optimum coupling position, where the optical fluctuations are minimal. Figure 1 is a schematic diagram of the real-time alignment setup. Alignment of an orthogonal axis has been incorporated simply by having the dither in this axis take place at a different frequency, with another phase-sensitive detector used to produce the dc error signal for the orthogonal driving transducer.

This real-time alignment procedure has several attractive features: speed; drift immunity; freedom from operator or software interference; and a relatively low optical power requirement to allow alignment. A fiber-to-fiber alignment apparatus fabricated in the laboratory has achieved optimum coupling in 3 ms, with less than −50 dBm of peak coupled power. Alignment has also been achieved with less than −70 dBm of coupled power but with a longer lock-on time.

Two-axis fiber–fiber alignment and laser–fiber alignment have been demonstrated in the laboratory. Using the real-time alignment capability of the apparatus, the laser–fiber alignment can be maintained during the curing of bonding material. The fast alignment capability has potential applications in the area of moving fiber switches, so that the tight tolerances of mechanical stops for the moving fiber can be eliminated. **(12 min)**

ME3 A 1.3-μm module for an undersea transmission system

E. GRARD and E. DUDA, Laboratoires de Marcoussis, route de Nozay, 91460 Marcoussis, France; G. BOURRET, CIT Alcatel, Centre de Villarceaux, 91620 Nozay, France.

The requirements for a practical module for an undersea system[1] are high coupling efficiency, good stability with respect to temperature variation, high reliability, and easy fabrication. We have developed for transatlantic transmission (TAT 8) the module shown in Fig. 1, designed to satisfy these requirements. We use a buried heterostructure laser[2] selected for a submarine system. High coupling efficiency (−4 dB) is achieved using a tapered single-mode fiber with a spherical tip. The optical power levels are checked by a germanium photodetector which monitors the rear laser diode output.

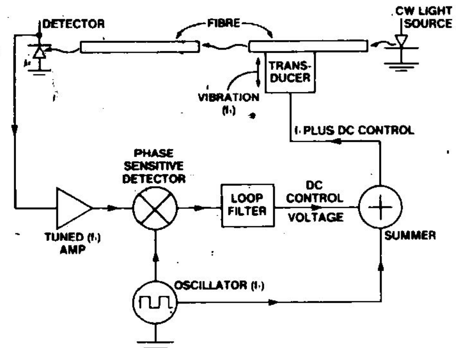
To obtain good stability with respect to temperature variation and negligible performance deterioration during aging, soldering techniques have been used for module fabrication. The module construction has been optimized to avoid coupling offset due to the thermal expansion difference of fiber and package. For example, beryllium oxide has been used as a laser submount.

For fiber soldering a new method using a heating resistance has been developed. The coupling efficiency was determined for the fabricated modules. Coupling efficiency varies from −3.5 to 5.2 dB with a mean value of −4 dB. Output stability with respect to ambient temperature was measured in the +10 to +30°C and −20 to +50°C ranges. The coupling efficiency variations are 0.2 dB in the 10–30°C temperature range and 0.7 dB in the −20 to +50°C temperature range. Fiber output power was recorded for 100 cycles in the 10–30°C temperature range. The fiber output variation is <0.15 dB after cycling.

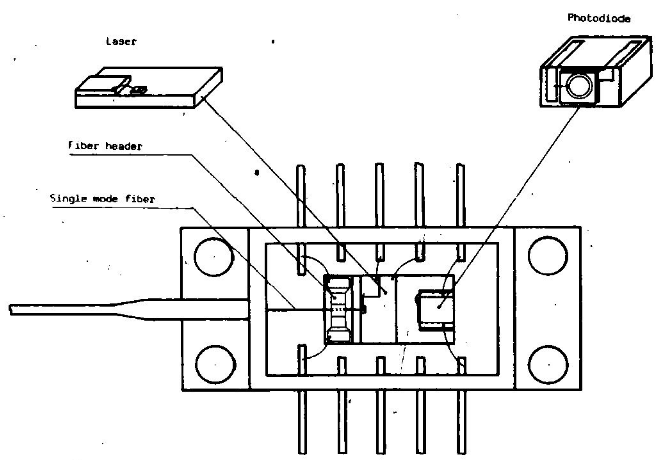
The performance of the module was tested using a circuit that provides bias and modulation current and controls output power. Figure 2 gives the NRZ light eye diagrams at 295.6 MBit/s using a $2^{23}-1$ digit pseudorandom pattern.

The transmitted signal was measured (see Fig. 3) under modulation (trace *a*) and without modulation (trace *b*) using a high-speed photodiode and spectrum analyzer. The difference *x* between the maximum signal spectral density and the noise equivalent spectral density is 43 dB. For a system margin of 6 dB optical, *x* has to be larger than 31 dB. The obtained *x* value is far beyond the required minimum value. The error rate characteristics were measured using single-mode fibers with and without dispersion. For the TAT 8 link, a 1-dB optical dispersion penalty for a bit error rate of 10^{-9} is taken into account. It was shown that the penalty dispersion due to the spectral characteristics of the module is negligible. The module was tested at a higher bit rate. We have demonstrated that it can operate up to 750 Mbit/s. **(12 min)**

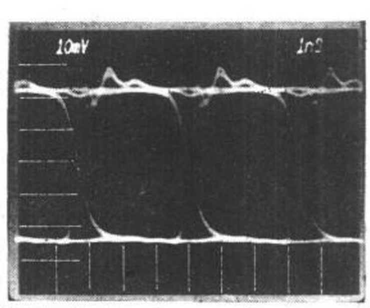
1. F. Bosch, G. M. Palmer, L. D. Sallada, and C. B. Swan, IEEE/OSA J. Lightwave Technol. **LT-2**, 952 (1984).
2. B. Fernier *et al.*, Efoc Lan 85, Montreux, Switzerland, 81 (1985).



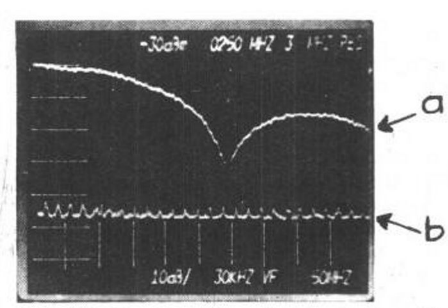
ME2 Fig. 1. Schematic diagram of a fiber-to-fiber alignment apparatus.



ME3 Fig. 1. A 1.3-μm laser diode module with single-mode fiber.



ME3 Fig. 2. Eye diagrams of the laser module at 295.6 Mbit/s.



ME3 Fig. 3. Signal (trace *a*) and noise (trace *b*) spectral density.

ME4 Distributed-feedback laser diode module with a novel and compact optical isolator for gigabit optical transmission systems

T. CHIKAMA, S. WATANABE, M. GOTO, S. MIURA, and T. TOUGE, Fujitsu Laboratories, Ltd., 1015 Kamikodanaka, Nakahara-ku, Kawasaki 211, Japan.

The distributed feedback laser diode (DFB-LD) is a promising light source for gigabit long-haul transmission systems because of its single-longitudinal-mode operation even under high-speed modulation. However, the intensity noise degradation caused by optical feedback from single-mode fiber ends is more critical in DFB-LD because of its high coherence. Therefore, we have developed a DFB-LD module with an optical isolator.

Figure 1 is a drawing of our DFB-LD module optical arrangement. A lens system composed of a 0.8-mm diam TaF_3 collimating lens and a 3-mm diam BK-7 focusing lens is employed for coupling between a DFB-LD and single-mode fiber. A 1.3- or 1.55-μm InGaAsP DFB-LD chip[1,2] is mounted in the package with low stray capacitance and inductance (C = 0.3 pF, L = 2 nH). An InGaAs-PIN photodiode with low dark current is adopted as the back power monitor for automatic power control.

The optical isolator inserted between the two lenses is composed of two slant uniaxial birefringent rutile (TiO_2) prisms, a YIG Faraday rotator and a SmCo permanent magnet.[3] The isolator is 9.5 mm in diameter × 5 mm long. The optical axis of prism P2 is tilted 45° to that of prism P1, and the polarization of the LD beam rotates 45° in a 2-mm YIG for 1.3-μm and 2.6-mm YIG for 1.55 μm. The LD beam feels the same refractive index in each prism through the isolator in the forward direction. Therefore, the output beam through the optical isolator is parallel to the incident beam. On the other hand, reflected light is fed into prism *P2* and divided into two beams dependent on the polarization. Polarization of returned beams rotates 45° in the YIG to the same direction as mentioned before, and then the beams reenter prism *P1*. The beams feel different refractive indices in each prism. Therefore, these beams are deflected 10.6 and 13.7°, respectively, from the direction of the LD chip. Low insertion loss, 0.3 dB, and high isolation, 35 dB, as the average over 40 samples can be obtained. The LD to fiber coupling efficiency is more than 30%. All optical components are antireflection-coated and fixed by the YAG laser soldering technique. We have good temperature characteristics of coupling efficiency with <0.5-dB variation from 10 to 50°C.

The effect of the feedback light can be measured by the relative intensity noise (RIN). RINs of the DFB-LD chip and module are shown in Fig. 2. We obtained good noise characteristics in spite of ~5-dB degradation caused by the near-end reflection from lenses. The power penalty caused by laser noise is an estimated 0.2 dB. Good and stable error rate performance is obtained.

Figure 3 shows the lasing spectrum and clean optical waveform of the 1.3-μm DFB-LD module under 1.8-Gbit/s RZ modulation. The spectral width is <0.1 nm, and the side mode suppression ratio is more than 30 dB. More than 3-GHz modulation bandwidth can be obtained.

High performance of our DFB-LD module with a novel optical isolator has been demonstrated in high-speed optical transmission systems.

(12 min)

1. H. Imai, K. Wakao, H. Tabuchi, T. Tanahashi, H. Ishikawa, and M. Morimoto, J. Opt. Soc. Am. A **1**, 1287A (1984).
2. K. Wakao *et al.*, Electron. Lett. **21**, 321 (1985).
3. M. Shirasaki and K. Asama, Appl. Opt. **21**, 4296 (1982).

ME5 High-intensity fiber-coupled diode laser array

CONNIE CHANG-HASNAIN, PHIL WORLAND, and DONALD R. SCIFRES, Spectra Diode Laboratories, 3333 North First St., San Jose, CA 95134-1995.

For many applications such as the use of star-coupled local area networks, optical surgery, pyrotechnic ignition, OTDRs, and remote optical powering of sensors, it is desirable to obtain the highest possible optical power level and power density in a small core diameter multimode fiber. In this paper, we describe the excitation of a 50-μm core diam optical fiber with a GaAlAs diode laser array. Previously, 140 mW cw of optical power was reported to be transmitted through a 100-μm core 0.3-N.A. optical fiber by using a laser diode array.[1] The coupling efficiency in this case was ~50%. In this paper, the excitation of a special 50-μm core 0.3-N.A. optical fiber with a similar butt-coupled laser diode array is described.

Shown in Fig. 1(a) is a plot of the laser drive current vs optical output power which is emitted from the end of such a 50-μm core fiber. As shown, a cw catastrophic damage limit of 850 mW is obtained. This is a brightness increase of ~24 times that of the previous report.[1] The coupling efficiency of the laser diode to the fiber is over 80%.

Shown in Fig. 1(b) is a plot of the pulsed laser diode output taken directly from the laser as well as out of the end of the fiber. The laser is pumped by a train of 200-ns long current pulses at a 10-kHz repetition rate. The peak power output from the 50-μm core fiber can be >2.8 W. The measured coupling efficiency for this laser is 77%.

A single-lobed far-field pattern with a FWHM of 12° was emitted from the fiber regardless of the far-field pattern of the laser array [Fig. 2(a)]. Virtually all the fiber output power is contained within a 36° cone angle corresponding to a 0.3 N.A. The light propagating in the fiber is guided by its 50-μm core as depicted by the 50-μm wide near-field intensity distribution at the fiber output end Fig. 2(b)]. That is, no cladding modes of significant intensity exist. A speckle pattern due to the coherence of the laser diode emission in the multimode fiber is observed in both the near and far field. This speckle is substantially reduced relative to that obtained from a single-mode laser diode owing to the broad (~20-Å) spectral bandwidth of the laser array.

Finally, a Hewlett-Packard comb generator (HP 3300 4B) was used to modulate a laser array that is biased at 1.05Ith. A train of 200-ps optical pulses with a repetition rate of 500 MHz was observed as shown in Fig. 3 illustrating the rise-time capability of the laser diode array.

In conclusion, a laser diode array has been butt-coupled to an optical fiber with a 50-μm core 0.3-N.A. output. This yields the highest power and power density reported from such a laser diode/fiber configuration. Further details of the laser diode geometry, fiber configuration, and performance limits will be included. **(12 min)**

1. D. R. Scifres, R. D. Burnham, and W. Streifer, Appl. Phys. Lett., **41**, 118 (1982).

Monday **AFTERNOON**
24 February 1986 **MF**
IMPERIAL B

1:30 PM **Introduction to Optical Fibers**

Arnab Sarkar, Lightwave Technologies, Inc., Presider

MF1 Minitutorial: Introduction to optical fibers

ALAN J. MORROW, Corning Glass Works, Corning, NY 14831.

This minitutorial, intended for workers new to the field, examines the basics of optical fiber design, fabrication, and testing. Topics covered include the sources of optical loss in silica-based fibers, dispersion in multimode and single-mode fibers, trade-offs among fiber designs for specific applications, a review of the principal manufacturing techniques from glassmaking through draw and coating, and the effect of environmental factors such as stress, temperatures, hydrogen, and radiation on fiber properties.

After receiving B.S. and M.S. degrees in ceramics at the Massachusetts Institute of Technology in 1973, Alan Morrow joined Corning Glass Works in Raleigh, NC, where he developed materials and processes for multilayer ceramic capacitors. In 1977, he moved to the R&D Laboratories in Corning, NY, where he is currently involved in development of optical fiber products using the outside vapor deposition process. Morrow is the author of five publications and holds two patents in this field.

(Minitutorial, 60 min)

Monday **AFTERNOON**
24 February 1986 **MG**
IMPERIAL B

2:45 PM **Single-mode fiber measurements**

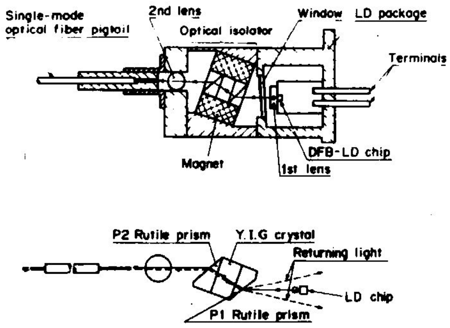
Koichi Abe, Northern Telecom, Presider

MG1 Minitutorial: Single-mode fiber measurements

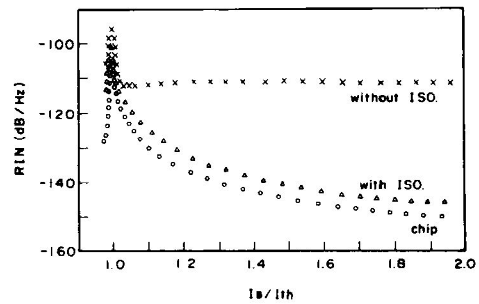
DOUGLAS L. FRANZEN, U.S. National Bureau of Standards, Boulder, CO 80303.

Values assigned to single-mode fiber parameters depend in many cases on definitions and methods of measurement. This tutorial discusses the latest recommendations from standards groups and gives typical examples of measurement agreement and precision. Methods and apparatus to determine attenuation, cutoff wavelength, mode-field diameter, and chromatic dispersion are covered. Where appropriate, comparisons are made with similar measurements in multimode fiber.

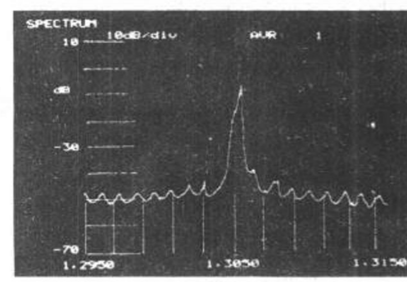
Douglas Franzen received his B.S., M.S.E.E., and Ph.D. degrees in electrical engineering from the University of Minnesota. Since that time he has been with the National Bureau of Standards in Boulder, CO, where he held an NRC/NBS Postdoctoral Research Fellowship. His current interests include optical fibers and picosecond optoelec-



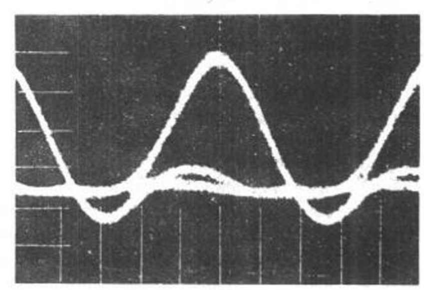
ME4 Fig. 1. Schematic view of the distributed feedback laser diode module with an optical isolator and principle of operation of the isolator.



ME4 Fig. 2. Relative intensity noises of the DFB-LD chip and the module with and without an optical isolator.

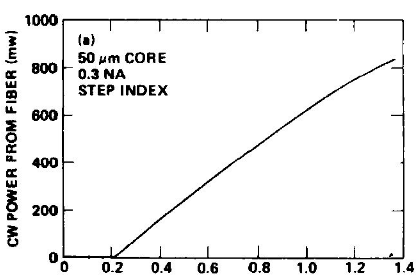


(a)

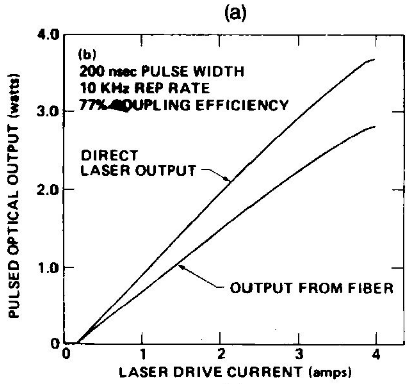


(b)

ME4 Fig. 3. (a) Lasing spectrum (*V:* 10 dB/div, H: 2 nm/div and resolution 0.1 nm) and (b) the optical waveform (*H:* 100 ps/div) under 1.8 Gbit/s RZ modulation and *Ib*/Ith = 1.1 (Ith = 12.5 mA) of the 1.3-μm DFB-LD module.



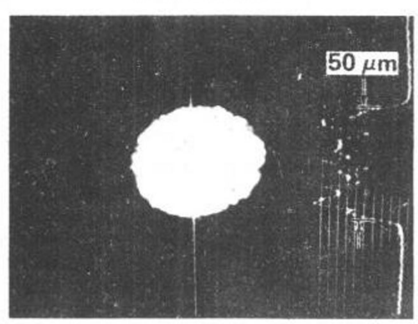
(a)



(b)

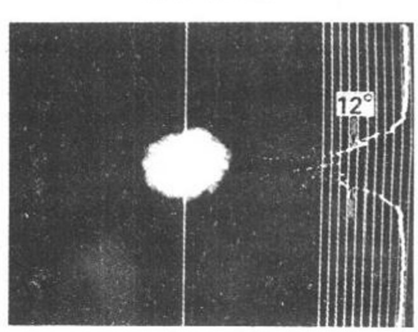
ME5 Fig. 1. (a) Continuous wave power transmitted through the fiber vs laser drive current. (b) Pulsed laser array peak front facet output power and peak power transmitted through the fiber vs peak drive current.

NEAR FIELD



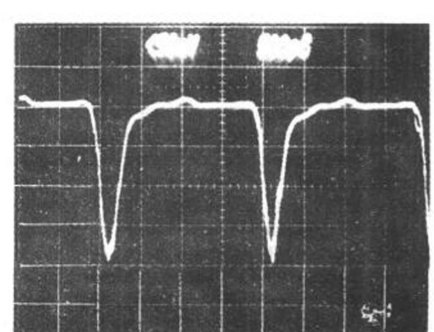
(a)

FAR FIELD



(b)

ME5 Fig. 2. (a) Far-field pattern and intensity distribution of the fiber output. (b) Near-field pattern and intensity distribution at the output end of the fiber.



ME5 Fig. 3. Output from the fiber coupled to a laser array under impulse modulation.

tronics. He is chairman of an EIA Committee on the interlaboratory testing of optical fiber measurement procedures and a past organizer of the NBS Symposium on Optical Fiber Measurements. He is a member of the OSA and IEEE and was awarded the Department of Commerce bronze and silver medals for his efforts in optical fiber measurements. **(Minitutorial, 60 min)**

Monday **AFTERNOON**
24 February 1986 **MH**
SALON I

3:30 PM **Subscriber Loop**

Marcus C. Farrant III, Contel Service Corp., **Presider**

MH1 Wideband integrated services over fiber in the loop

P. J. LAURIELLO, AT&T Bell Laboratories, Whippany Rd., Whippany, NJ 07981.

In the loop plant of the future, migration of an optical fiber directly to the customer's home or business will allow economic delivery of wideband integrated services. These services include multiple telephone lines, telemetry, alarms, data, broadcast, and two-way full motion video.

To make the loop plant of the future a reality, there needs to be major breakthroughs in reducing the costs of optics technology. In particular, this must occur in the distribution plant where a system range to the customer is a few kilometers and the bandwidth needs are a couple of hundred Mbits/s. In short, technology needs to be advanced for lowest cost and not ultimate capability. Clearly it will be a combination of economics and features which will eventually allow fiber-based systems to migrate into the home and office in large numbers.

Today lightguide already exists in the feeder portion of the Loop. It was first introduced in 1982 in the AT&T fiber SLC digital loop carrier system. In this system, electronics located in the central office and remote site are interconnected with lightguide. Copper pairs interconnect the remote site electronics to the customer.

The next step is to replace those copper pairs by bringing the lightguide directly to the customer's doorstep and allow him to use the increased bandwidth it can deliver as he sees fit. For both residence and business customers, it means combining a variety of service offerings through the intelligent use of both electronics and optics.

A typical offering for the business customer is shown in Fig. 1. Here bandwidth is offered in such small chunks as a few hundred bits/s all the way up to Mbit/s rates for video teleconferencing. In fact, the combination of the AT&T DDM-1000 multiplexer and VIVID system is a product now or soon to be available that will begin to offer such bandwidth flexibility.

For the residential customer, AT&T is currently involved in deployment of a first-generation prototype system. Such new services as broadcast video with pay per view features are being provided. The performance of the system will allow an immediate evaluation of the capability of an all fiber loop as well as its service and economic potential. Experience gained in outside plant deployment of an all fiber loop is also a critically important factor for the creation of the next generation system, one with a fiber design and interconnection scheme consistent with the installation, maintenance, and economic needs of a distribution plant-type environment.

Unlike the feeder plant, where expenses are spread over many customers, distribution hardware is amortized on a per customer basis. It is, therefore, in the photonic systems for the distribution plant where cost breakthroughs in design, processing, and manufacturing must be made. **(Invited paper, 25 min)**

MH2 Fiber-optic subscriber loop system for integrated services: strategy to spread fiber into the subscriber network

SADAKUNI SHIMADA and KUNIO HASHIMOTO, NTT Yokosuka Electrical Communication Laboratories, P.O. Box 8, Yokosuka-shi, Kanagawa-ken 238-03, Japan.

Fiber optics has played an important role in communication networks, particularly in repeater systems, and is expected to play a continuing role in subscriber networks to offer various types of service. NTT's strategy for future fiber-optic subscriber system development is to promote the following approaches in parallel:

Approach I: The development of economical fiber-optic subscriber systems for near future commercial use.

Approach II: The development of ultimate integrated fiber-optic subscriber systems.

Approach I is a practical way to replace a coaxial cable for video distribution services or for local area networks by an optical fiber cable. However, with the first step of Approach I, simple replacement of optical fiber cable would not be economically beneficial. One way to solve this dilemma is to add highly advanced services such as interactive systems or to combine existing services into fiber-optic subscriber systems. As a result, fiber-optic subscriber systems would reach a cost target corresponding to customer demand. A fiber-optic subscriber system introduction would accelerate the fiber-optic equipment and device cost reduction and would result in further growth of fiber-optic subscriber systems.

In accordance with this strategy, we have developed a fiber-optic subscriber system combining video distribution services and 64-kbit/s digital service as the first step of Approach I. System parameters are shown in Table I.

The commerical test will be held in Apr. 1986. The system has a star topology which facilitates future broadband exchange services. Video distribution service accompanies a two-way 4-kbit/s data path for advanced services such as interactive reservations, interactive teleshopping, and interactive pay-per-view services. Precise cost reduction efforts have been made in equipment design; for example, LEDs using direct intensity modulation techniques are employed, since a 2-km subscriber loop length can cover the greater part of the service area in urban areas.

In Approach II, fiber-optic subscriber systems should seek to be function-effective as well as cost-effective. Function-effectiveness may be achieved by versatile service integration including value-added service, such as multiservice access, multipoint access, and time-scheduled leased-line service. Cost-effectiveness may be achieved by system integration with a single fiber-optic connection unit as well as by full digitization which immediately results in equipment cost reduction. Fiber-optic subscriber system features in Approach II are shown in Table II.

In relation to the Approach II system, it is necessary to study the following items:

(1) network architecture for ultimate integrated fiber-optic subscriber systems;

(2) user–network interface which meets equipment portability requirements;

(3) development of a network synchronization technique in higher digital hierarchy layers and an adaptive multiplexing technique for multiservice access in subscriber systems;

(4) optical devices and electrical devices for inexpensive single-mode fiber transmission systems such as low-coupling-loss laser diode modules, automatic splicers, and low-power LSIs.

Moreover, optical signal processing is expected to be used three-dimensionally, as shown in Fig. 1, namely, time division, space division, and wavelength division. For example, high-speed optical logic circuits, high-density guided-wave matrix switches, and wavelength-based functional devices will play significant roles in the future. Especially the wavelength-based functional devices using optical amplifier, wavelength-controllable optical tuner, and wavelength-variable optical source have the potential to replace time-based synchronized switches.

Combining these techniques will produce fiber-optic networks providing broadband/high-speed services as well as 64-kbit/s digital services. NTT Electrical Communication Laboratories have already started developing these networks. The Approach II system is expected to be more cost-effective than the Approach I system in about 10 years. **(Invited paper, 25 min)**

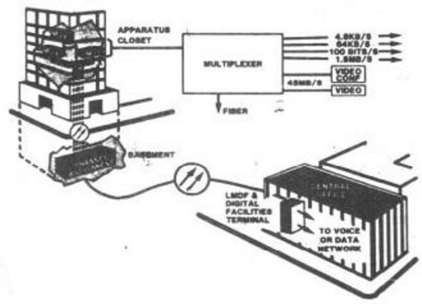
MH3 LEDs for single-mode fiber transmission systems

DONALD M. FYE, GTE Laboratories, Inc., 40 Sylvan Rd., Waltham, MA 02254.

Due to its tremendous information-carrying capacity, single-mode fiber has become the dominant transmission medium for new fiber-optic system installations. Since the optical coupling efficiency between LEDs and single-mode fiber is substantially less than that of diode lasers, it was until recently assumed that single-mode systems would require diode laser sources. A number of recent experiments[1–3] have demonstrated that light-emitting diodes can be used instead of diode lasers to satisfy many short to medium distance single-mode system requirements. When compared with diode lasers, LEDs offer the advantages of higher reliability, reduced temperature sensitivity, less complicated drive circuit requirements, immunity to optical feedback, and lower cost due to high yields and simpler packaging technology. These issues are critical to the introduction of single-mode fiber into subscriber loops, where LEDs can be used to satisfy economically present requirements, and diode lasers can be used for future service upgrades.

Both surface-emitting and edge-emitting 1.3-μm LEDs have been reported for use with single-mode fiber. Mesa-structure surface-emitting LEDs can couple 2 μW into single-mode fiber,[4] which is sufficient for a link length of $>$10 km at a data rate of 140 Mbit/s. In contrast, edge-emitting LEDs have coupled more than 60 μW into single-mode fiber,[5] with coupled powers in excess of 100 μW expected for optimized devices. Edge-emitters with low internal gain have been observed to have spectral widths of 60–80 nm, while superluminescent devices have spectral widths of 30–40 nm. The narrower spectral width and higher output power of superluminescent LEDs increase the available bit rate distance product at the price of higher temperature sensitivity. Single-mode fiber transmission experiments using edge emitters have yielded link lengths in excess of 30 km at data rates of 140–180 Mbit/s.[2,3] Extrapolated lifetimes in excess of 10^8 h have been reported for both surface and edge-emitting InGaAsP/InP LEDs.[2]

It is now clear that LEDs will offer an economical and reliable alternative to the use of diode lasers in many single-mode fiber systems. This paper will review the status of LED technology for single-



MH1 Fig. 1. Business wideband system.

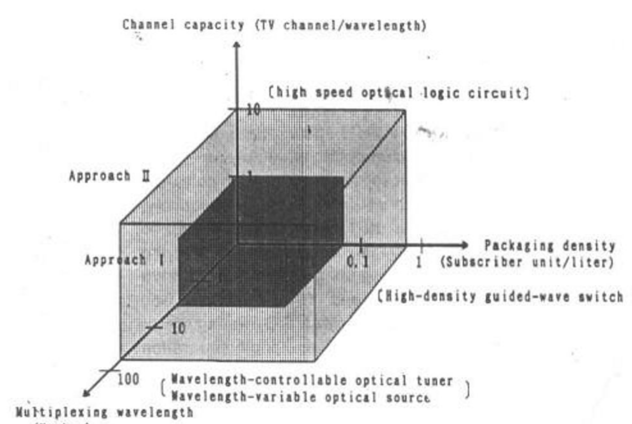
MH2 Table I. Fiber-Optic Subscriber System (First Step of Approach I)

Service	· Video distribution service (analog NTSC) with two-way 4kb/s data × 2ch · 64kb/s digital service		
Topology	Star		
Length	~ 2km		
Wavelength (μm)	0.78	0.88	1.30
Transmission bandwidth	6.5MHz	6.5MHz	192kb/s
optical source	LED	LED	LED
optical detector	APD	APD	PIN
Direction	↓	↓	↑
Fiber	50/125 graded index fiber		

↓ : Office to subscriber ↑ : Subscriber to office

MH2 Table II. Fiber-Optic Subscriber System Features (Approach II)

Service	· Video distribution service (digital) · Video exchange service (digital) · 64kb/s digital service · High speed digital service
Topology	Star
Transmission bit rate	100 ~ 400 Mb/s
Length	~10km
Optical source/detector	LD/APDorPIN→OEIC
Fiber	Single mode fiber



MH2 Fig. 1. Optical technology development in fiber-optic subscriber systems.

mode fiber applications and discuss important device design and system considerations.

(Invited paper, 25 min)

1. J. L. Gimlett, M. Stern, L. Curtis, W. C. Young, N. K. Cheung, and P. W. Shumate, Electron. Lett. **21**, 668 (1985).
2. R. H. Saul *et al.*, Electron. Lett. **21**, 773 (1985).
3. L. W. Ulbricht, M. J. Teare, R. Olshansky, and R. B. Lauer, Electron. Lett. **21**, 860 (1985).
4. T. Uji and J. Hayashi, Electron. Lett. **21**, 418 (1985).
5. R. Olshansky *et al.*, Electron. Lett. **21**, 730 (1985).

MH4 Simultaneous bidirectional fiber-optic transmission using a single source

P. J. DUTHIE, M. J. WALE, J. HANKEY, M. J. GOODWIN, W. J. STEWART, I. BENNION, and A. C. CARTER, Plessey Research (Caswell), Ltd., Allen Clark Research Centre, Caswell, Towcester, Northants, U.K.

We have demonstrated simultaneous bidirectional transmission of signals over a 2-km monomode fiber link utilizing only a single light source. This is potentially significant for subscriber loops and local area networks wherein a major part of the cost may be contained within semiconductor lasers used as the source elements. In the system described here, one source is used both to provide data transmission in one direction and as a light source for transmission in the other direction, the encoding being achieved in the latter case by means of an integrated optic modulator in a reflecting configuration. The data rates employed in our demonstration system are 565 Mbit/s (forward direction) and 34 Mbit/s (reverse direction). Both signals are carried simultaneously by a single monomode fiber.

The experimental system is shown in Fig. 1. A Plessey laser module was used to launch approximately −0.5 dBm into the system at 1.3-μm wavelength and was injection current modulated at 565 Mbit/s. At the far end of the link, a fraction of the light (~20%) was directed to a PIN-FET receiver, and the remainder was routed through an integrated-optic modulator to a mirror. After reflection the light traveled once again through the modulator and was returned to the fiber. The modulator used in this demonstration was a lithium niobate alternating $-\Delta\beta$ directional coupler switch.

Since the modulator response is sensitive to the polarization of the incoming light, a simple polarization controller of the type described by Lefevre[1] was included in the system. The modulator was driven at 34 Mbit/s.

The signal returned from the far end of the link was directed through the 1:1 coupler to a 34-Mbit/s PIN-FET receiver. This signal was, of course, also modulated at 565 Mbit/s, but the asymmetry in the data rates allowed the receiver to integrate out the fast modulation completely. Clearly it is essential that the encoding of the fast data stream should be performed so that long intervals of zero intensity cannot arise: this implies, for example, use of Manchester coding.

Figures 2 and 3 show the signals received at the two ends of the link during simultaneous bidirectional transmission. The signal level at the 565-Mbit/s receiver is approximately −18 dBm; the receiver sensitivity was −36 dBm for 10^{-9} BER. Detailed evaluation of the bit error rates and system margin achievable in the reverse direction are in progress and will be reported.

Any system employing reflective modulation must return a certain amount of light toward the laser cavity unless nonreciprocal components are available. In the experiments described here, however, we have not found it necessary to use an isolator.

A link utilizing different data rates in the two directions is a common requirement. Asymmetric data rates are not, however, inherent in reflective modulation systems. In the event that two equally high data rates are needed, alternative modulation schemes can be employed, for example, using interleaving of words or blocks of data.

In conclusion, we have demonstrated that a bidirectional fiber-optic link can be realized with a single laser source rather than the two employed in alternative realizations with potentially significant savings in cost. Systems of this type may play a key role in implementation of subscriber terminals.

(12 min)

1. H. C. Lefevre, "Single-Mode Fibre Fractional Wave Devices and Polarisation Controllers," Electron. Lett. **16**, 778 (1980).

MH5 Wavelength division multiplexing system using a monolithically integrated laser array and an integrated-optic multi/demultiplexer

T. ITO, M. TAKAMI, M. ITO, T. ATSUMI, H. FUJIMA, H. OKUDA, and M. KANAZAWA, Toshiba R&D Center, Komukai-Toshiba-cho 1, Saiwaku, Kawasaki 210, Japan.

Wavelength division multiplexing (WDM) is one of the most promising approaches for increasing transmission capacity in an optical communication system.[1] The integrated-optic technique makes it possible to produce stable reliable optical devices for use in single-mode transmission systems. Here we describe a new WDM system using a monolithically integrated multiwavelength GaInAsP/InP laser array with 50-Å wavelength separation[2] and an integrated-optic multi/demultiplexer employing the waveguide technique.

The experimental setup is shown in Fig. 1. The laser array employed in this system has a distributed feedback structure with five different grating periods and a center wavelength of 1.31 μm. The lasing wavelength temperature dependence was 1.2 Å/°C so that a temperature control unit was used for wavelength stabilization and tuning. The laser array was butt-coupled to a Ti-diffused $LiNbO_3$ multiplexing waveguide optical coupler with a polarization-maintaining single-mode fiber output. The fiber input optical power was greater than −15 dBm. Figure 2 shows the basic structure of the integrated-optic demultiplexer. Two aspherical geodesic lenses were used to collimate and focus an incident light beam, respectively. The $1/e^2$ spot size at the focal plane was measured to be 4.5 μm, which is 1.3 times larger than the diffraction limit. The grating with a 1-μm groove pitch, 0.2-μm depth, and 100-μm length was formed on a Si-substrate glass/SiO_2 waveguide.

In the WDM system, the wavelength separation is given by

$$\Delta\lambda = \frac{\Delta x}{f_2} n_{\text{eff}} \Lambda \cos\left\{\sin^{-1} \frac{\lambda_B}{2n_{\text{eff}}\Lambda}\right\},$$

where Δx is the required spot separation in the demultiplexer focal plane, f_2 is the focal length of the focusing lens, n_{eff} is the effective index of the waveguide, Λ is the groove pitch, and λ_B is the Bragg wavelength. To provide good channel separation characteristics for the WDM system, we determined the parameters to be $\Delta x = 50$ μm, $\Lambda = 1$ μm, and $f_2 = 13.74$ mm. To avoid crosstalk between each optical channel, a relative wavelength accuracy of ±4.8 Å was needed. The insertion loss and crosstalk were found to be <10 and −17 dB, respectively. Figure 3 shows the spectrum of the optical transmitter output signal and the intensity profile at the output plane of the integrated-optic demultiplexer. The output optical signal from the demultiplexer was coupled to the integrated five-channel InGaAs/InP PIN photodiode array with a 30- × 80-μm sensitive area and an array element pitch of 50 μm. The sensitivity of the receiver circuits was −35 dBm at a bit rate of 32 Mbit/s for BER of 10^{-9}.

To summarize: We have demonstrated a new WDM system. Experimental results show that the WDM system using integrated-optic devices can be expected to provide acceptable performance for multichannel optical transmission. **(12 min)**

1. N. A. Olsson *et al.*, in *Technical Digest, Conference on Optical Fiber Communication* (Optical Society of America, Washington, D.C., 1985), paper WB6.
2. H. Okuda *et al.*, Jpn. J. Appl. Phys. **23**, L904 (1984).

Monday **AFTERNOON**

24 February 1986 **MI**

SALON II

3:30 PM **Diode Lasers for Coherent Communication**

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MI1 Single-frequency semiconductor lasers?

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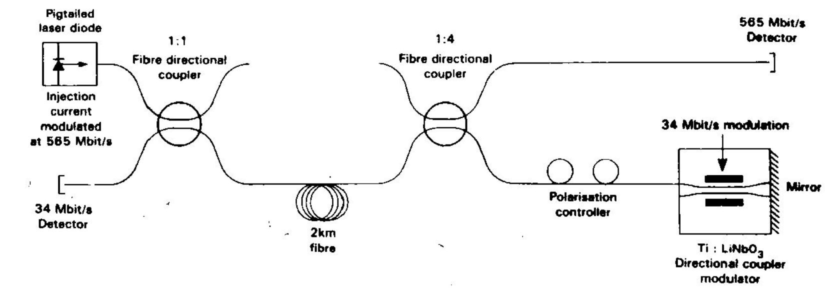
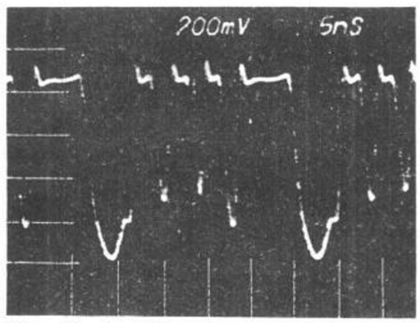
Within the last decade, very significant advances have been made in semiconductor lasers. These advances were direct results of the various specific requirements demanded by optical fiber communications on semiconductor lasers as the light source. In the 1970s, research and development have been concentrated in laser stripe geometries for achieving stable transverse fundamental-mode operation required for efficient and stable coupling into then multimode optical fibers. In the early 1980s, with the advent of low-loss single-mode fiber at 1.57 μm, it became obvious that development of a single-frequency semiconductor laser operating at 1.57 μm would be very important in very high-data-rate long-distance transmission. This fueled the research and development of semiconductor laser schemes for single-longitudinal-mode control. Two schemes of major interest are distributed feedback (DFB) and cleaved-coupled-cavity (C^3). While the wavelength of a DFB laser is fixed at the time of manufacturing by the grating period, that of a C^3 laser is electrically tunable. While the side-mode suppression, linewidth, and threshold of a DFB laser depend on the relative position of the end facet with respect to the grating period, those of a C^3 laser depend on the gap separation between the two coupled cavities. While the DFB scheme is incorporateable only to certain stripe-geometry laser structures and is technologically feasible for lasers beyond certain lasing wavelengths (due to difficulties in fabricating very short grating periods), the C^3 scheme is applicable to all laser structures and wavelengths. Thus the choice depends on the specific applications in mind. Although these lasers were called single-frequency sources, they fell very short of their given name for th[illegible] major yet unresolved problems.

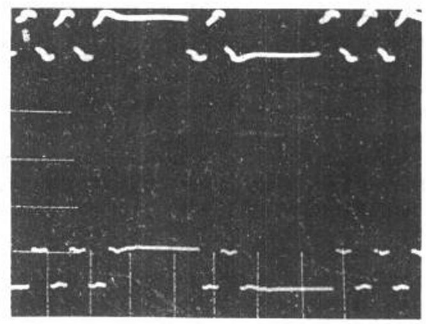
(1) In cw operation, these lasers have a typical best spectral-width-power product of ~30 MHz



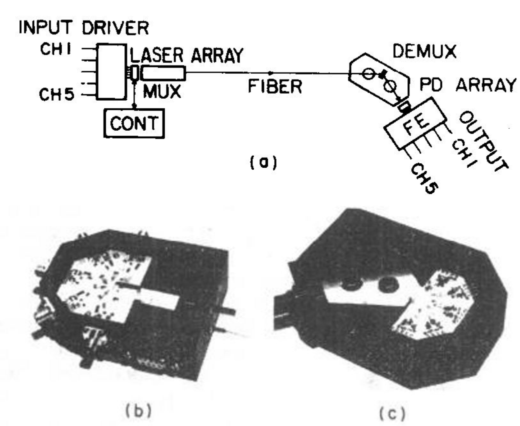
MH4 Fig. 1. System configuration.



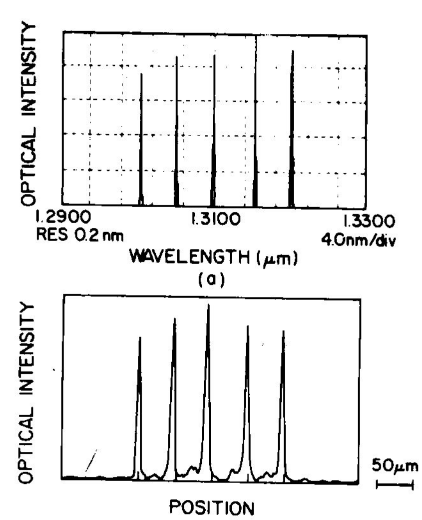
MH4 Fig. 2. 565-Mbit/s signal obtained at the receiver output.



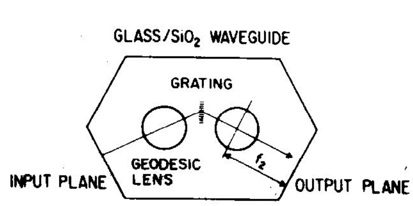
MH4 Fig. 3. 34-Mbit/s signals: from bottom to top, drive signal to modulator, receiver output and output from receiver comparator.



MH5 Fig. 1. (a) Experimental setup for WDM system using integrated-optic devices. (b) External view of optical transmitter section. (c) External view of optical receiver section.



MH5 Fig. 3. (a) Optical spectrum of transmitter output signal. (b) Optical intensity profile observed at integrated-optic demultiplexer output plane.



MH5 Fig. 2. Basic structure of integrated-optic demultiplexer.

mW with the linewidth decreasing with increasing output power. However, with DFB lasers it was observed that beyond a certain value the linewidth increases drastically with further increase in power. For DFB lasers, several schemes have been proposed to reduce the linewidth by having very long cavities (~2 mm), a large grating coupling coefficient, and electrically adjustable phase control. But so far the improvement has been minimal reaching a narrowest linewidth of ~4 MHz with added sacrifice in external quantum efficiency. For C^3 lasers with an adjustable air gap, a linewidth-power product of 2.5–3 MHz mW was obtained with a value of 250 kHz at 10 mW.

(2) Under high-speed modulation, the rapid changes in excess carrier density caused frequency chirping. Furthermore, this frequency chirping varies from pulse to pulse resulting in additional noise. This chirping limits the linewidth to a lowest value of ~0.3 Å when the laser is modulated beyond 1 Gbit/s. At present, no controlled method has been available. In the case of the C^3 laser, a split-modulation technique has been shown to improve the amount of chirping.

(3) They are still susceptible to reflected power returning from external components for reflections as small as −30 dB. Such reflections cause mode hops among different longitudinal modes if the side-mode suppression is not much greater than 20 dB. Values as high as 40 dB may be required by multigigabit per second systems. Even just Rayleigh backscattering from optical fibers into a DFB laser, although causing a narrowing in linewidth, induces frequency jittering within the range of the single longitudinal mode. This broadens the effective linewidth to ~100 MHz.

With these problems unsolved, the recent interest in coherent systems propelled semiconductor laser research yet into another new horizon: the research for a semiconductor laser that is truly single frequency with a linewidth <1 MHz, immune to external reflection, and electrically tunable. Thus far, the only methods shown to achieve such a narrow linewidth have been by the adjustable-gap C^3 laser and using long external cavity lasers. The latter yielded a linewidth of below 1 kHz in a 10-cm external cavity. To maintain such a linewidth for coherent applications, the source must be stabilized with extreme temperature and mechanical control. Wavelength tuning by electrical means has been achieved previously in C^3 lasers and recently demonstrated in three-terminal double-section DFB and DBR lasers and by integrated thermoelectric control. The search for a monolithic electrically tunable and truly single-frequency semiconductor laser has just begun.

(Invited paper, 25 min)

MI2 Techniques and results of linewidth narrowing of semiconductor lasers for coherent system applications

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Increasing interest is being shown worldwide in the use of coherent techniques for optical fiber communication systems because of their improved sensitivity and selectivity compared with conventional direct detection systems. These improvements are obtained at the expense of increased system complexity, however, and, in particular, highly coherent sources are required for the transmitter and local oscillator. PSK homodyne systems, for example, have the most stringent requirements and will require laser linewidths between 10 and 100 kHz for reasonable data rates and phase locked loop bandwidths. This is to be compared with typical free-running linewidths of >10 MHz for conventional semiconductor lasers; some form of external line narrowing will clearly be required.

We review techniques for achieving linewidths of this order or better and show how other desirable properties, such as broadband tunability, may also be obtained. In addition, problems associated with packaging and long-term stability of narrow-linewidth semiconductor laser sources and their susceptibility to environmental influences are discussed together with some practical solutions.

(Invited paper, 25 min)

MI3 Linewidth reduction of 1.5-μm grating-loaded external cavity and semiconductor lasers

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To meet the stringent linewidth requirements for coherent optical fiber communication, a dispersive passive cavity has been added to the multimode laser to impose a strong spectral selectivity so that a narrow linewidth single longitudinal mode is allowed to oscillate.[1] Optical feedback level, power, and facet reflectivity are the important parameters affecting the laser linewidth. We report here the study of the strong influence of laser geometry on the laser linewidth of such external cavity lasers.

The semiconductor laser linewidth of a solitary single-mode laser $\Delta\nu_{sol}$ is described by the modified Schalow-Townes formula[2]

$$\Delta\nu_{sol} = \frac{R_{sol}}{4\pi\bar{n}_{sol}}(1+\alpha^2), \qquad (1)$$

where R_{sol} is the average spontaneous radiation rate, $\bar{n}_{sol}$ is the total lasing photon number in the cavity, and α is the linewidth enhancement factor. The total photon number in the composite cavity is larger than that of the solitary laser by the volume ratio of composite to solitary cavities. The averaged spontaneous radiation rate into the lasing mode is also reduced by the same geometric factor. These arguments yield the following relation similar to the results of Patzak *et al.*[3]:

$$\Delta\nu_{ecl} = \Delta\nu_{sol}\frac{L_{sol}^2}{(\eta L)^2} \approx \frac{R_{sol}L_{sol}^2(1+\alpha^2)}{4\pi\bar{n}_{sol}}\frac{1}{(\eta L)^2}, \qquad (2)$$

where η is the laser-passive cavity coupling efficiency. This work confirms that this relation holds for the cavity lengths L less than a certain value. However, this relation is not adequate to describe the laser linewidth for a cavity length longer than this level.

A typical rf spectrum from the self-heterodyne measuring system is shown in Fig. 1. From Fig. 2, where the 3-dB linewidths are plotted against $1/L^2$, an inverse square dependence on the cavity length of the 3-dB linewidth is obvious when the cavity length is shorter than 7 cm. The straight dashed line of 6.5 × 10^5-cm^2 slope is the result of least-squares fitting the points with laser cavities shorter than 7 cm. Figure 2 also shows that the linewidth does not reduce below 18 kHz. This deviation from $1/L^2$ dependence is believed to originate from the excessive low-frequency phase noise causing the line shape to be non-Lorentzian with a resulting broadening of the 3-dB rf width.[4]

Figure 3 shows the power dependence of the linewidth in the region where the cavity length is longer than 7 cm. The least-squares fitted slope is 18 kHz · mW. If the linewidths in this region are affected by the low-frequency phase noise, the approximate $1/P$ dependence leads to the following conclusion: the low-frequency phase noise is smaller at higher laser power. This observation is consistent with the result of phase noise spectra obtained by Walther *et al.*

To summarize: The theoretically predicted relationship between the laser linewidth and the cavity length for a grating loaded external cavity laser holds true with a cavity length smaller than 7 cm. Above this range, the relationship breaks down. Any theoretical analysis would have to include the low-frequency noise to explain this experimental observation. **(12 min)**

1. R. Wyatt and W. J. Devlin, "10kHz Linewidth 1.5 μm InGaAsP External Cavity Laser with 55 nm Tuning Range," Electron. Lett. **19**, 110 (1983).
2. R. Loudon, *The Quantum Theory of Light* (Oxford U.P., London, 1979), Chap. 10. C. H. Henry, "Theory of the Linewidth of Semiconductor Lasers," IEEE J. Quantum Electron. **QE-18**, 259 (1982).
3. E. Patzak, A. Sugimura, S. Saito, T. Mukai, and H. Olesen, "Semiconductor Laser Linewidth in Optical Feedback Configurations," Electron. Lett. **19**, 1026 (1983).
4. F. G. Walther and J. E. Kaufmann, "Characterization of GaAlAs Laser Diode Frequency Noise," in *Technical Digest, Topical Meeting on Optical Fiber Communication* (Optical Society of America, Washington, D.C., 1983), paper TUJ5.

MI4 Measured dynamic linewidth properties of a 1.5-μm DFB-GRIN rod coupled-cavity laser under direct high-frequency modulation

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A coherent optical system offers two advantages over the conventional system with intensity modulation and direct detection. First, the receiver sensitivity may approach the shot-noise limit; and, second, the much greater frequency selectivity may allow more channels to be transmitted at close wavelength separation than by conventional wavelength multiplexing in direct detection systems. The frequency selectivity is specially suitable for applications in the local access and exchange networks. Optical sources used in such coherent systems, however, require narrower linewidth and greater frequency stability than that normally exhibited in a solitary semiconductor laser. Various schemes to reduce the linewidth of a semiconductor laser have been demonstrated.[1-3] Recently, we reported[4] a new coupled-cavity laser consisting of a distributed feedback laser (DFB) coupled to a graded-index rod (GRIN rod). Use of the DFB laser has improved the frequency stability over that of the cleaved-coupled cavity (C^3) laser previously investigated.[3] The linewidth of the new coupled-cavity laser is comparable to or narrower than that obtained with a C^3 laser. We report, for the first time, the dynamic linewidth properties of the DFB-GRIN-rod external coupled-cavity (DFB-GRECC) laser under direct high-frequency modulation by the injection current. The implication of the results for its application in a FSK system is discussed.

The construction of the DFB-GRECC laser is similar to that reported previously.[4] A schematic diagram is shown in the inset in Fig. 1. A short external cavity, consisting of a 4-mm long 0.23-pitch graded-index rod lens with large N.A., was aligned axially with the DFB laser. The GRIN rod was mounted on a piezoelectric crystal to allow fine tuning of the distance from the rear facet of the laser. The GRIN rod serves as both the collimating and mirror elements in a compact and stable assembly. The focusing properties of the GRIN rod have been found to be relatively forgiving, thus allowing for ease of optical alignment.

The level of the optical feedback was varied by defocusing the GRIN-rod lens with respect to the laser rear facet. The percent of the optical feed-