Research and Development of Optical Data Links

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ODL (optical data link) modules are one of the basic components used in optical communication systems. When first intoroduced, ODL modules were developed as very simple module applicable for 1 Mb/s transmission. With the progress of optical transmission technologies, ODL modules evolved to become faster, smaller and multifunctional. Today, advanced ODL modules have a transmission rate exceeding 10 Gb/s, a dispersion penalty compensation function, and various control functions for stable transmission using built-in microprocessors.
Widely used in applications such as public communication systems, local area networks and mega server systems, ODL plays an important role in the Internet systems and information society. Sumitomo Electric has developed and shipped ODL modules as well as optical fibers and optical devices since 1970s. This paper describes the ODL development concept and technologies of Sumitomo Electric.

1. Introduction

An optical data link is one of the most basic components used in establishing optical communications. It converts electric signals into optical signals and efficiently transmits the signal to the transmission line, an optical fiber, on the transmitting side and converts optical signals into electrical signals on the receiver side [(1)-(3)]. An optical data link mainly consists of the optical transmitter module and the optical receiver module as shown in **Fig. 1**. There are three types of product configuration including an individual transmitter, receiver and transceiver. In addition, some smart compound modules are equipped with data processing functions for optical and electric signals and optical transmission systems. Although there is capability to transmit analog signals and to transmit digital signals in optical communications, an optical data link usually transmits digital signals. It is now used everywhere in broadband network as shown in **Fig. 2**.

The term 'optical data link' was not so common when optical transmission modules went into the market. Prior to being called 'optical data link,' the module of this type was often expressed as E/O and O/E in the optical communications system configuration diagram of telecommunications equipment manufacturers. Perhaps, our company was the first in the world to name the optical-electric module used in the optical communications 'optical data link.' Commercializing the optical transmission module named "SUMILINK" at the end of the '70s might have been the debut of the term 'optical data link.' SUMILINK was released as the analog TV signal transmission module SUMILINK AM-01, and the digital transmission module SUMILINK DX-01. This analog transmission module was developed into a custom product tailored to a visual information system, and developed as an optical transmission device for CATV, and is now widely used for CATV trunk line. However, SUMILINK AM-01did not become the widely used module. The digital transmission SUMILINK has been developed into NEW SUMILINK based on a hybrid IC technology, and then Super SUMILINK based on a molding technology, and widely commercialized as an optical data link for public communications and LAN. **Figure 3** shows the transition of the optical data link and the optical device research and development activities.

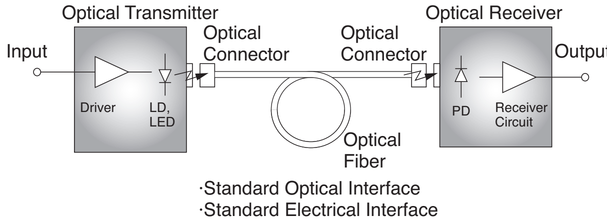

Fig. 1. Configuration of Optical Data Link

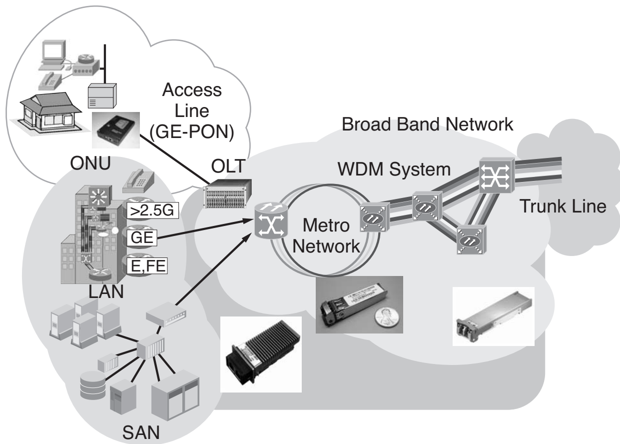

Fig. 2. Optical Network and Optical Data Link

2. Dawn of Our Optical Communications Technology Development

I examined old documents to see when our company launched the development of optical communication

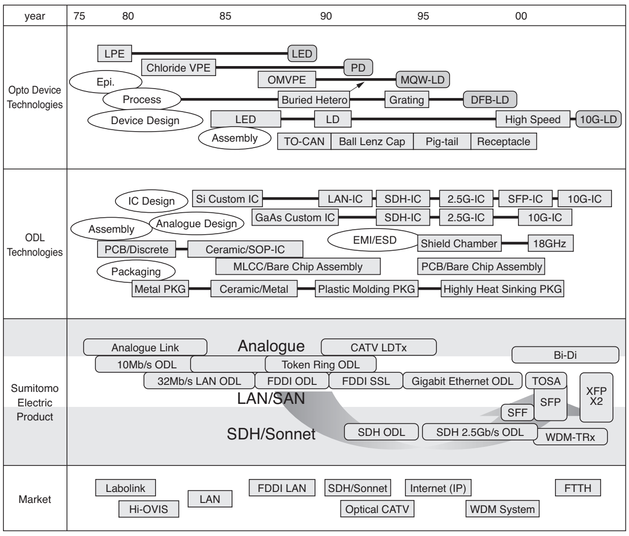

Fig. 3. Optical Device/ Optical Data Link Development

technology which leads to the optical link development, and found that the first optical communications system office meeting was held in Yokohama on June 13, 1975. Although research and study was carried out before that, this was the first de-facto project aiming a specific goal. Our development of optical fiber and optical device had already been launched before that period, and a little after the lunch of optical fiber and compound semiconductor development, the development of optical communications system has been started and led to the optical data link business today.

Following this project, it was this time that the optical transmission experiment has been started in parallel with the research of various optical transmission technologies, and in our first transmission experiment the visible light LED was used as a light source, and the 1.544 Mb/s system consisting of the silicon MOS-FET amplifier connected with the silicon photodiode (PD) was used for the reception. Since the error rate tester was not available in those days, the transmission experiment was carried out using handmade pseudo random pattern generators. The 200 m length fiber was used in the experiment. Passing the optical signal through a fiber is very obvious, I felt that 'seeing is believing' was the right phrase when I could see the signals transmitted by the optical fiber.

Around the same time, in 1976, we received a request to build a 1 Mb/s optical communications computer network (LABOLINK) [4] from School of Information and Mathematical Science, Faculty of Engineering, Kyoto University, and it was delivered in May, 1976. The light source was a near-infrared (0.91 μm) LED, and the light receiving element was a PIN photodiode, and the fiber was a 200 μm core diameter PCF (plastic clad fiber). At that time there was no single mode fiber or even silica multimode fiber available in the field. Because there was no fiber connecting technologies and the optical fiber-to-fiber connector was undeveloped, a single longer fiber cable was used at the installation site of receiver-transmitter, and then connected with the optical transmitter and receiver by attaching an optical connector to the end of optical fiber in the field. It was our first delivery of an optical communications system, and our first installation of optical fiber cable.

As mentioned above, our first optical transmission system achieved minimum performance requirements with primitive optical component technology. It used the TOSA (transmitter optical sub-assembly), ROSA (receiver optical sub-assembly), and some optical connector technologies, which was essential for the optical data link. This system was cultivated through the development of Hi-OVIS (Higashi Ikoma Optical Visual Information System) [5] started in 1976. This system was the state-of-the-art VOD (Video on Demand) system at that time. The famous book of Alvin Toffler, who predicted the information society, The Third Wave was published in 1980, and the Hi-OVIS was completed two years before the publication. So we can see this system was very advanced. TOSA consisted of a newly developed 4 mm ferrule diameter optical connector attached to a 0.83 μm emission wavelength LED [6]. **Photo 1** shows an external view of TOSA. ROSA consisted of a newly developed 800 μm light receiving diameter Si photodiode attached to a connector flange directly. The optical connector had a special structure that suppressed the fiber core protrusion unique to the PCF at that time. (This problem has been solved in the current Hard-clad PCF.) Hi-OVIS was successfully completed in spring 1978 by making use of these newly developed optical components and analog baseband video transmission technologies, and started its operation in July. Hi-OVIS was required to transmit the analog audio/visual signal and the control data because it was the VOD system, and the usual NTSC signal format was used for the audio/visual, and the frequency multiplication method that modulates the amplitude to 6.6 MHz was used for the control data. It was very helpful for the subsequent optical data link progress that the durable optical components essential to the optical data link were able to be developed through the Hi-OVIS development ahead of other companies. This enabled Sumitomo Electric Industries, Ltd. to stay ahead of other companies.

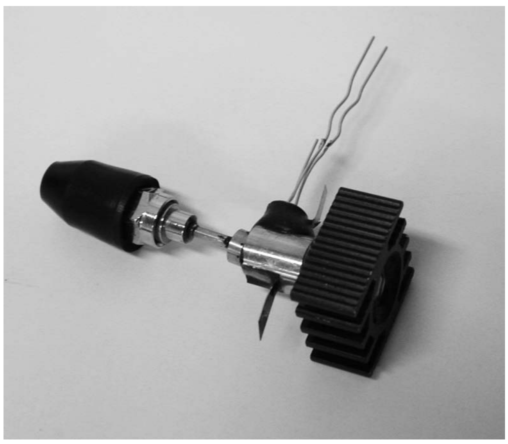

Photo 1. TOSA Used for Hi-OVIS
LED, Stub-fiber, Monitor PD and Heat-Sink

3. Early Stage of Optical Link Development

A basic optical communications technology was cultivated by the Hi-OVIS development, and the development of digital transmission technology was launched, starting a new chapter of the digital age. The first developed module as an optical data link had a TTL interface, whose transmission speed was 500 Kb/s. The transmission was made by simply turning the LED current ON/OFF making illuminating/quenching the LED, and the reception was made by detecting the resistance load circuit with voltage comparator IC and picking up received signals as voltage swing corresponding to the light reception level. The highly sensitive receiver circuit used MOS-FET was employed on the light receiver's front-end module in Hi-OVIS. For the optical data link, the method which inputs directly into the voltage comparator was employed and the front-end amplifier was omitted, because the single power supply and miniaturization were highly prioritized.

The development was advanced toward the policy that the low-cost, simple, and steady operation was our priority, even if some performance was sacrificed. The major problem was, however, that the cost for optical components developed with Hi-OVIS was very high, and the cost for entire optical link eventually would become high. Therefore, we aimed at lowering the cost of optical components.

Our major strategy for lowering component costs was the development of optical connector that was a plastic sleeve shaped not as a cylinder, but a truncated cone with the glass window installed to hold the fiber core in place. The optical data link with this optical connector, whose target fiber was PCF and the transmission distance was less than several kilometers, was mainly used for FA. This type of optical data link has been supplied as the SUMILINK[7] for the FA use, changing the optical connector into the world standard type, developing the dedicated IC for receiver-transmitter, and H-PCF for optical fiber. In the following paragraphs, the research and development of further high-speed and long-distance optical data link are described. **Photo 2** shows one example of the optical communication system equipped with optical data link technology of that time.

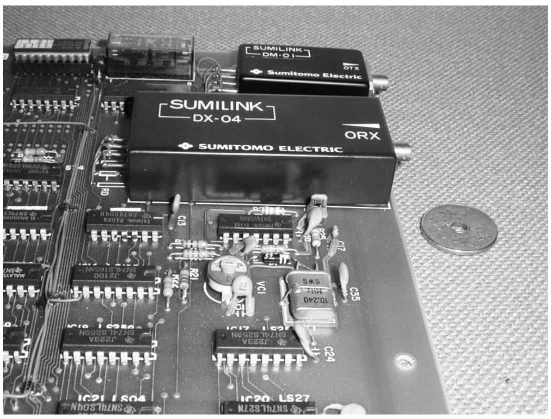

Photo 2. Early-Stage SUMILINK Mounted on SUMBUS - ST - LS

4. Development of Optical Data Link with HIC (Hybrid Integrated Circuit)

The optical data link was commercialized as the SUMILINK brand name, but its structure was so primitive that the printed circuit board was stored by threadably mounting TOSA/ ROSA on the folded plate chassis. In developing the HIC technology, the optical data link group immediately joined in the car electronics department's previously launched HIC development. It was the state-of-the-art mounting technology at that time, and greatly contributed to later development of optical data link. The car electronics department advanced the development of HIC itself and products using HIC, while the optical data link group focused on the marketing of HIC technology. Specifically, the HIC's technical development focused on reducing production errors of optical device/electronic device by the YAG laser function trimming of the HIC. In addition, the upgrading and miniaturizing of HIC technology was achieved by bare chip mounting. The module with various parts were used to adjust the optical output level, the pulse width distortion due to the rise/fall time variations of light-emitting device, and the "1"/"0" determination level by applying a laser trimming. As a result, the optical data link module that meets various strict standards and provides steady performance was able to be developed. This optical data link has been commercialized as the NEW SUMILINK brand name. The first commercialized modules were the high-speed Ethernet-compliant 20 Mb/s DM-02 and the token ring LAN-compliant 32 Mb/s DM-03. **Photo 3** shows the external view. Both transmitter/receiver were operated by single 5 V power supply in this module. Because only the IC that operates with ±5 V was able to be obtained on the receiving side, the DC/DC-IC that converts 5 V to -5 V was also assembled in the module. A major problem was getting low receiver sensitivity due to the interference of the DC/DC-IC's switching noise caused by the HIC's high conductor resistance. A copper conductor, so-called busbar was inserted for the HIC's ground wiring. In order to cancel the noise, the variable capacitor with the equivalent capacity to the photodiode was inserted into the differential input and generated the reverse phase signal of receiver's front-end module. Then each product was fine-tuned. After all these processes, the required receiver sensitivity was successfully ensured (See **Fig. 4**), and mass-production of the optical data link could begin. The target product was to use a multimode fiber, with light source was short wavelength (0.85 μm) and electric I/O was TTL interface.

Since a certain skill had been acquired through a joint development of optical modem with a major computer manufacturer at that time, the rule had been set for the test items and the number of samples. Then, especially for the mass-production, the tests had been carried out and the results had been reviewed without fail.

In light of this situation, we received an inquiry, which triggered the development of optical data link with a long-wavelength light source, promising in speed-up and long-life. The development of 200 Mb/s optical data link was therefore launched. This inquiry was at first for the short-wavelength laser light source, but the counter

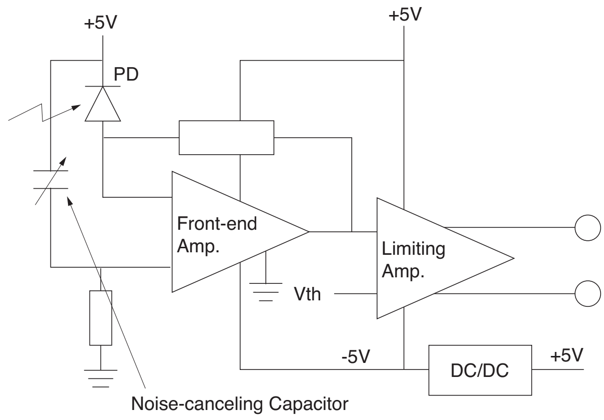

Fig. 4. DM-03 Receiver Block Diagram

Photo 3. Optical Data Link using HIC

Photo 4. Optical Data Link for FDDI (Upper) , Receiver (Lower) Receiver Front-end by GaAs-FET, SOP-IC is Custom-designed IC

proposal from Sumitomo Electric switched it to a long-wavelength LED specification [(8), (9)]. This optical data link development became the development race of three companies in Japan, U.S., and Europe including Sumitomo Electric. We suffered a setback because our company did not have a technology that achieves 200 Mb/s with single 5 V supply. (Especially it was essential to build a receiver's front-end module with single chip custom IC.) However, the development of self-manufactured long-wavelength LED had been advanced. Although the receiver module had two power supplies, the high-speed optical data link was successfully developed [(10)-(13)] and this product/technology greatly contributed to the development of FDDI (Fiber Distributed Data Interface) in the late '80s. Additionally, optical data link was employed in the LAN products [(14)] including our FDDI. The optical data link was quickly developed to include a self-manufactured ceramic package [(15)] applied to the chassis. **Photo 4** shows the external and internal views.

5. Development of Mold Type Optical Data Link

The optical data link had been developed using ceramic packages, but it was hard to differentiate our products from competitors. In light of this situation, the plan of next generation optical link was discussed between Osaka/Yokohama works in the committee named VICC. After about one year period of reviewing all the components of optical data link, it was finally decided to switch from a ceramic package to a plastic mold applied to the chassis. A plastic mold package is standard for the silicon IC, but it was a challenging goal to put both a low-quality finished optical device and a precision component, optical connector sleeve, into a mold package. The concept was the optical device should not be molded directly but molded after being installed in an appropriate package and built a TOSA/ROSA structure. This technique was an extremely unique and risky proposal, and only our company was able to materialize this technique. We named this module "Super Sumi-Link" (SSL) when we were drinking new product Asahi Super Dry beers in the Shinkansen buffet on the way to attend the VICC.

After receiving a VICC's policy, the development of the mold type optical data link was launched in 1988. The appeal of the molding packaging was its high reliability, not using any screws and soldering. This was the key advantage of optical data link for both optical data link manufacturers and users. The molded packaging allowed for reflow soldering and water cleaning of substrate. In contrast, this wasn't possible in conventional optical data link packaging, which required more complex and time-consuming processes. This molded packaging optical data link could be reflow soldered, washed with water, and manufactured entirely by machine.

In this development, it was required to develop not only a molding packaging technology but also a transmission/reception IC and an enclosure for optical device in parallel with it in order to make a compact electric circuit suitable for a mold structure. Other components were also fundamentally reviewed, and all the components except an LED chip were newly designed. The IC design team, circuit design team and mechanism design team concurrently advanced the technology development. Since it was necessary to simultaneously develop ceramic packages for ROSA (Itami Works), copper tungsten packages for TOSA, and LED and PD (Osaka Works), as shown in **Fig. 5**, this development was advanced with full cooperation of each department. Because there were development tasks and also drastic and unprecedented design changes, the reliability was carefully confirmed. Even for small amounts of samples in an experimental stage, the heat cycle, damp heat test, vibration test, and others were carried out. We made efforts to find problems early. For instance, a key concern of our new design was the large amount of pressure on the molded packaging. Its size was very large compared with normal molded ICs. Therefore, it was important to optimize the shape of internal components to avoid a package crack. The size was fixed performing strength calculations and test productions.

The last remaining big issue was the method of wiring TOSA/ROSA to the circuit board. It was already concluded that a thick aluminum wire bonding was best suitable after considering various requirements. A thick aluminum wire bonding was the technology used in vehicle equipment and power devices, and already established in that field. However, we redefined the specification for our use performing trial productions in the wire diameter, wire characteristic, and procedure and equipment for binding the wire to lead pins. It was necessary to establish the binding conditions for weak lead pins of TOSA/ROSA, and to test this by adding stress to aluminum wire after bounding and before molding. This bonding technology had a slow production compared with wire bonding for general electronic devices. Some defects, such as disconnection, occurred while manufacturing products, but no defective products were released in the market because very effective testing was done on all products. Many complaints about the conventional optical data links' assembly work of threadably mounting and hand soldering were constantly received about conventional optical data links. However, the optical link with molded package showed extremely high reliability, and very few complaints were received. This product received positive market evaluations which have been sustained in all later revisions. **Figure 6** shows the assembling process of optical data links.

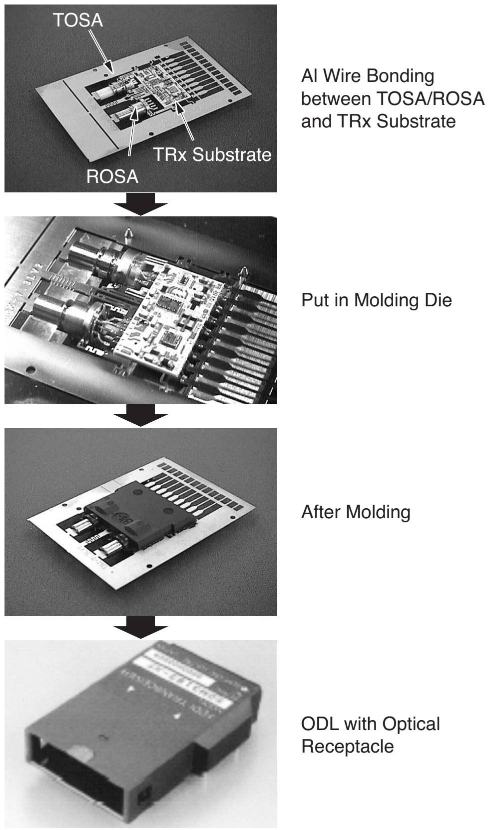

Fig. 6. Assembling Process of Plastic Molding ODL

This time, IC for driving LEDs, IC for receiver's front-end module (TIA), and 2R-IC (reshaping and regenerating) for receiving signals were developed. The IC processors were all silicon bipolars. The GaAs process was put into use for high-speed IC in Sumitomo Electric [16], [17], but this product was premature for optical data link use. The IC design/simulation was also done by a link development group to achieve maximum functionality for data link users. Two major domestic electronics manufacturers were chosen as IC manufacturers.

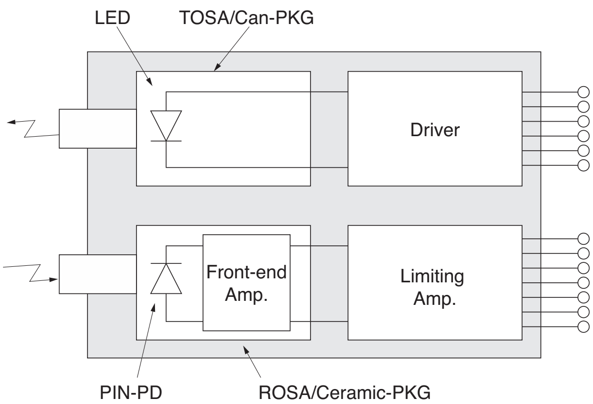

Fig. 5. Plastic Molding ODL Block Diagram

A structure of receiver's front-end module IC is shown in **Fig. 7**. It had some problems in noise tolerance compared with the current technology, but it was the world first receiver's front-end module IC with differential output stage to the author's knowledge. This IC has been improved in the noise tolerance of a molded package which is more noise sensitive compared conventional metal package. Improved noise tolerance meant improved operational stability in optical data link, and now almost every receiver's front-end module IC in competitors' products has a differential output stage [18], [19].

The FDDI mold type optical data link (SSL) [20], [21] was commercialized in March, 1990. At same time, four powerful US and European competitors came out with pin-compatible products. Our optical data link received strong customer interest. However, there was no comparison between huge Western information communication/electronics manufacturers and an obscure manufacturer, and our products were only purchased by small amount of users who valued the functionality of SSL. We were in trouble because of risking everything on this optical data link development, but somehow found a bright idea. Four competitors' board pin configuration was a two-row pin, and ours was a one-row pin style in orthogonal orientation. Therefore, as shown in **Fig. 8**, an H type, which could accommodate both our one-row pin style chip and our competitors' two-row pin style chips, was found. Immediately, we appealed to users because our H pattern board allowed our optical data link to be used, and also competitors' chips could be used if necessary. As a result, the number of users who adopted our products gradually increased, and users began to trust the reliability about our product. Moreover, some users adopted a one-row pin pattern because a higher performance compact board could be designed due to the reduced mounting area used by the chip. Almost in tandem, one of the four Western competitors started OEM sales of SSL, and our company eventually became the top in the market share of FDDI optical data link, and the one-row pin configuration dominated the market. Following this, large FDDI optical connectors were starting to be replaced with Duplex SC optical connector, next generation compact module. All dominant manufacturers modified their design to be our one-row pin configuration. **Photo 5** shows the FDDI optical data link and the Duplex SC type optical data link [22], [23].

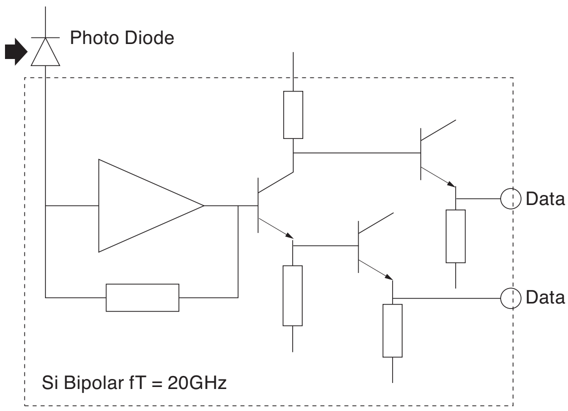

Fig. 7. Receiver Front-end IC

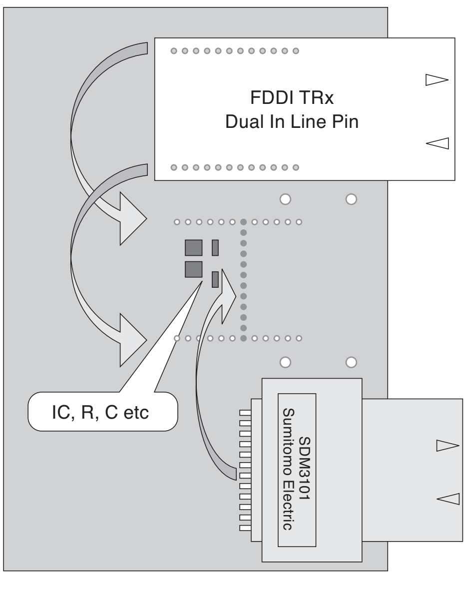

Fig. 8. H Pattern Board Layout for FDDI LAN System

Photo 5. Comparison of FDDI and Duplex SC ODL

6. Development of Optical Data Links for Public Communications

The development of FDDI mold type data link was completed in 1991 and transferred to administrative department. The next target of optical data link development was to produce a module for public communications, because the SONET/SDH communications standard specifications [24], [25] were established by the ITU (International Telecommunication Union) in the late '80s. Most of the modules for public communications had been self-manufactured based on individual specifications by transmission equipment manufacturers, but they were anticipated to be used widely due to the standardization of transmission specifications. **Table 1** lists the standard specifications of SONET/SDH. There were doubts whether our company, a LAN optical data link manufacturer, had a good chance of winning contracts to develop modules for public communications, which have strict reliability requirements and specifications. However, its development was advanced because it was believed that it would be successful if its key advantage, a molded enclosure, was successfully promoted. In order to make best use of the molded enclosure, its size was fixed to a 24-pin footprint (pin layout, size), which was the same as widely used electronic devices. **Photo 6** shows its external view. This was less than one quarter of the size of competitors' modules with similar functions [26], [27].

To market the product, we needed to ensure its size was limited to the 24-pin size molded package. This was achieved by producing a multi functional reception 3R-IC chip (reshaping, retiming, regenerating), which included the vital clock-recovery function. The IC was planned

Table 1. Specification of SONET/SDH

	STM−1 (155Mbps)	STM−4 (622Mbps)	STM−16 (2.4Gbps)	STM−64 (10Gbps)
Short Reach (Intra office)	1.3μm 2km -15dBm -23dBm (FP-LD) (PIN-PD)	1.3μm 2km -15dBm -23dBm (FP-LD) (PIN-PD)	1.3μm 2km -10dBm -18dBm (FP-LD) (PIN-PD)	1.3μm 2km -6dBm -11dBm (DFB-LD) (PIN-PD)
Inter mediate Reach (Short Haul)	1.3μm 15km -15dBm -28dBm (FP-LD) (PIN-PD)	1.3μm 15km -15dBm -28dBm (FP-LD) (PIN-PD)	1.3μm 15km -5dBm -18dBm (DFB-LD) (PIN-PD)	1.55μm 40km -1dBm -13dBm (EA-LD) (PIN-PD)
Long Reach (Long Haul)	1.55μm 80km -5dBm -34dBm (DFB-LD) (PIN-PD)	1.55μm 80km -3dBm -28dBm (DFB-LD) (PIN-PD)	1.55μm 80km -2dBm -28dBm (DFB-LD) (APD)	1.55μm 80km -2dBm -26dBm (EA-LD) (APD)

Wavelength, Transmission Distance, Power Output, Receiver Sensitivity
Optical Source, Detector

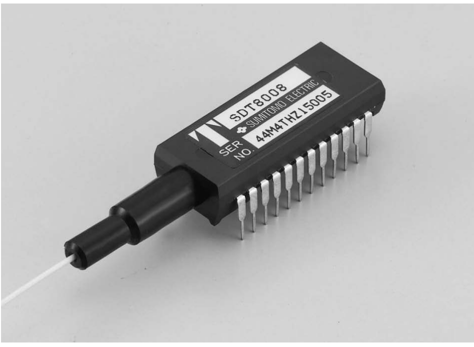

Photo 6. Outline of Plastic Molding ODL for SONET/SDH

to be developed with a major domestic electronic equipment manufacturer. After repeating the technologic study with the manufacturer, the 3R-IC which could be used for both 155 Mb/s (STM-1/OC-3) and 622 Mb/s (STM-4/OC-12), and operated without manual adjustment, was determined to be developed.

It was necessary for the retiming function to synchronize the clock signal with received data. Conventional product was tuned the signal timing individually before being shipped to users because of significant variations in manufactured products. Since manual adjustment could not be applied for a molded package product, it was required to achieve retiming automatically. Therefore, repeating an IC design and detailed simulation including analysis of delay time temperature dependence of data signal and clock signal, the IC development was advanced finding acceptable design conditions. In spite of designing with extreme caution, the IC operation became unstable due to the large noise from retiming clock pulse generating circuit, and the development was proceeded with difficulty. However, its operational stability was eventually obtained with out-of-the-box circuit architecture which excluded a power supply bypass capacitor. Also an inductor was inserted in power supply line of the clock pulse generating circuit, electrically isolating it from other IC parts. This IC was developed based on our specification without relying on IC manufacturers, and contributed to maintaining a competitiveness of our SONET/SDH optical data link. **Figure 9** shows a block diagram and an internal structure of the receiver module using this IC.

The SAW filter method, which was expected to have the most stable performance at that time, was used in the retiming device. The SAW device which was a differential I/O and durable against a molding heat history was jointly developed with an outside manufacturer.

For the IC for receiver's front-end module, a bipolar device was studied at first, but the problem with dynamic range could not be overcome. Consequently, our GaAs-IC was adopted to an IC for receiver's front-end module because it was essential to use FET, which has an excellent saturation characteristic. It also had a clipping function to expand the dynamic range [(28), (29)].

Major components for transmission module were a laser diode, a laser driving IC, and an automatic optical output control IC. Our GaAs-IC was used for the laser driving IC because its laser output waveform was more stable than silicon bipolar IC [(30)].

This SONET/SDH optical data link was developed concurrently with a molded package and IC, and the first performance target of optical data link [(31), (32)] was successfully achieved in about two years. The exterior of this optical data link had appearance similar to common electronic devices. In contrast, the competitors' optical link had a metal chassis [(21), (22)]. The module was compliant

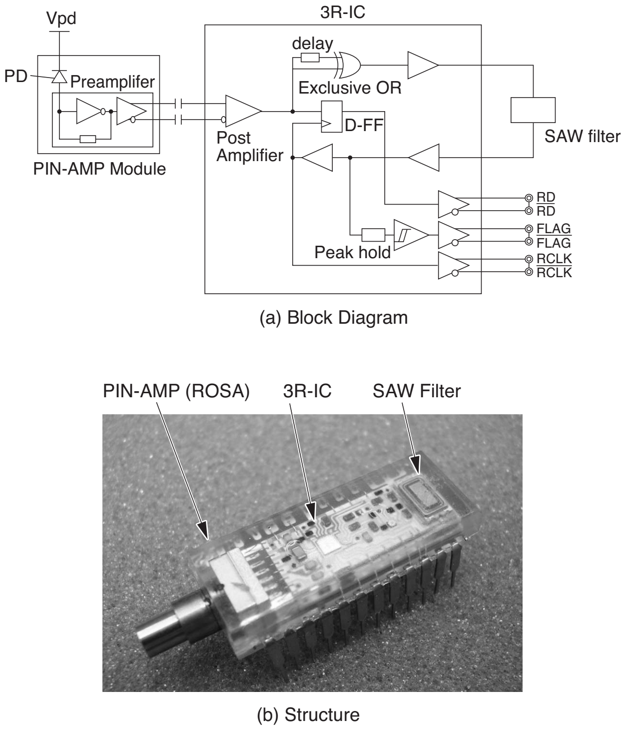

Fig. 9. ODL Using 3R-IC

with the SONET/SDH standard. The module included a retiming function, and was widely adopted by domestic and overseas transmission equipment manufacturers. This module gave us a toehold in the market of public communications.

7. Development of High-Speed Optical Data Links for Public Communications

The development and commercialization of the 155 Mb/s and 622 Mb/s optical data link for SONET/SDH was smoothly advanced, completed, and transferred to administrative department in the spring of 1995. The next target transmission rate was decided as 2.5 Gb/s. The module of this class had been previously developed as a custom product for PCM video transmission equipment (33)-(35), but was for the first time developed as a widely used product. The question was which market should be aimed at using what kind of technology.

In conclusion, a 24-pin mold package used in SONET /SDH was chosen for the transmitter module, and a metal package was chosen for the receiver module since a 24-pin was judged to be not applicable. The target specification was short distance transmissions. We aimed to miniaturize and decrease power consumption. **Photo 7** shows the external view of the finished product, and **Fig. 10** shows its power consumption and physical size. The size of both transmitter/receiver modules was 18cc (36)-(40).

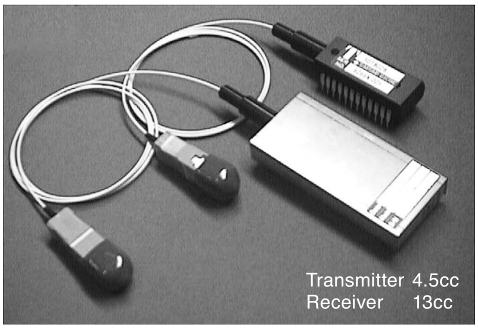

Photo 7. ODL for 2.5 Gb/s SDH/Sonnet

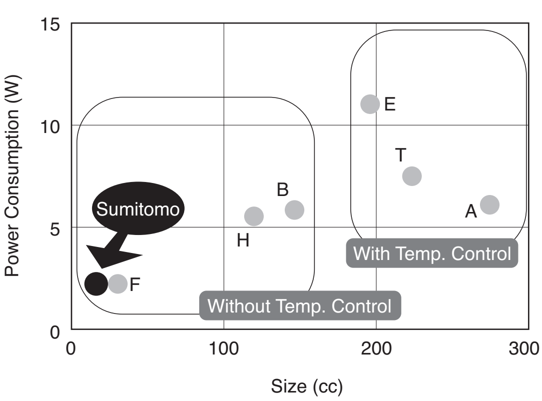

Fig. 10. 2.5 Gb/s ODL Size vs. Power Consumption

A GaAs-IC was newly developed for a laser driver for transmitter (41). The retiming method for the receiver was the SAW filter method. The SAW filter method was used for the 155/622 Mb/s SONET/SDH. The mass-production started initially using overseas manufactured SAW filters, but a diamond SAW filter (42) was later designed and manufactured by our company, and replaced overseas-manufactured SAW filter. The diamond SAW filter performed consistently, and showed good receiving sensitivity in the large temperature range shown in **Fig. 11**. A receiver's 3R-IC was jointly developed with the IC manufacturer who previously jointly developed an SONET/SDH 3R-IC with us.

This time the receiver's 3R-IC was implemented using two chips. Also, it was required to adjust a clock signal timing. It was very difficult to deal with noises from clock pulse generating circuit in the 155/622 Mb/s SONET /SDH development. For these reasons, the clock pulse generating circuit and a data recovery circuit were separated into two chips, equipped with a retiming function.

Moreover, a programmable phase shift circuit, which the IC manufacturer proposed, was adopted for the timing adjustment. **Figure 12** shows the block diagram and chip configurations of the receiver module. It was required to carefully design the wiring length because the

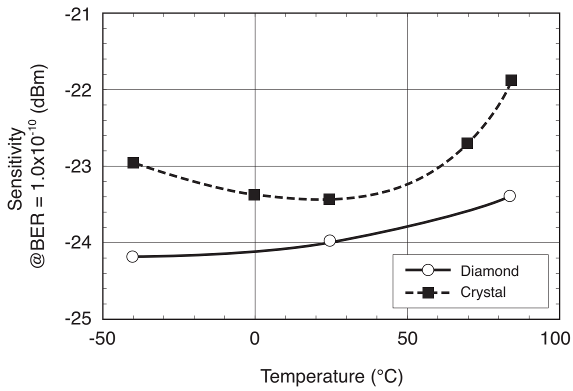

Fig. 11. Sensitivity of 2.5 Gb/s Optical Receiver

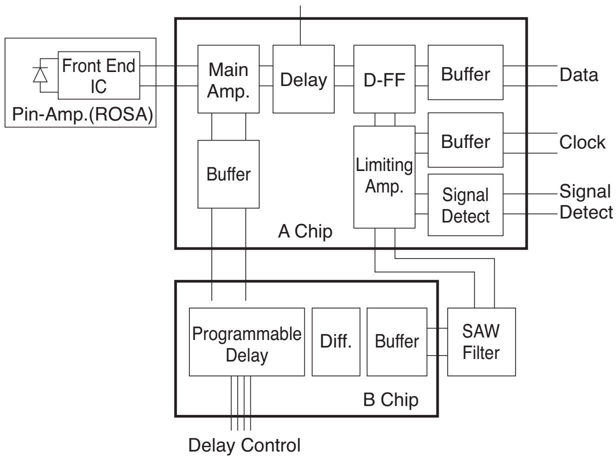

Fig. 12. Block Diagram of 2.5 Gb/s Receiver

delay on overlapping a clock noise varies according to the length of wire between two chips. The adjustable two-chip style was fortunately suitable for this situation. Furthermore, the implementation of the first IC design was successful, and its sample was shipped in the fall of '96, and the mass-production advanced smoothly [43], [44]. **Figure 13** shows the receiver module's characteristics.

Soon after mass-production began, we received a request from a major user to build a long distance module that used a 1.55 μm wavelength light, with a large fiber wavelength dispersion. At that time the laser temperature was usually controlled using a peltiert device on the transmitting side of a long distance module. Transmitting signals in a long distance using a laser without adjusting temperature seemed impossible but we decided to start the development. The problem was how to control the laser's emitted wavelength variation (chirp) over a large temperature range. The transmitter module which can transmit a maximum of 80 km transmission was finally able to be completed because:

1. The optical output of self-manufactured DFB laser was high, and chirp characteristics were good [45]-[48].
2. The wavelength characteristics of self-manufactured GaAs-IC designed for 2.5 Gb/s signals were relatively favorable, and the fall time was short without bouncing.
3. The wiring between a bear chip mounted driver IC and a laser chip was short in a mold structure.
4. Laser bias current was fine-tuned by a resistor chip attached outside the molded package.

Using an APD (avalanche photodiode) and a bias circuit with precise temperature compensator were essential for ensuring high sensitivity of the receiver's module. Compact circuits have since been preliminarily developed in anticipation of even longer distance transmission requirements. Since an 80 V supply was required for APD, a compact DC/DC converter was developed with a power supply manufacturer. The samples were successfully shipped and the mass-production began. However, the yield rate of mass-production was not good, and receiver modules with defective temperature characteristics were frequently found. The cause was an IC design error, which was easily corrected by redesign and testing under various conditions. The IC was redesigned and the mass-production became steady. This module gained great popularity with transmission equipment manufacturers and rode the wave of the optical communication boom. The optical data link business was also greatly expanding before the collapse of the bubble economy.

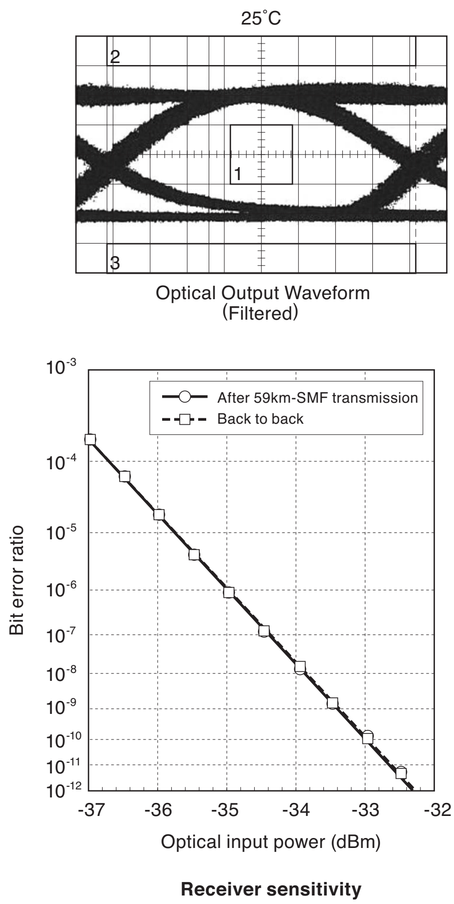

Fig. 13. 2.5 Gb/s ODL Characteristics

8. Further Miniaturization, Speed-up, and High-Performance

The miniaturization of optical data link was studied in parallel with the development of a 2.5 Gb/s long-distance communication optical data link. As stated in chapter 5, a 9-pin one-row type using a SC2 core optical connector became a MSA. Because a more compact LC type optical connector was developed, the width as the optical data link also tried to be reduced to 13.6 mm (0.55 inch), which is the same width of optical connector. At this point, the development of optical data link with two-row pin configuration was advanced, since the one-row pin became impossible in structure. This type of optical data link is called SFF (small form factor) and is shown in **Photo 8**. In this construction, a transparent plastic molding was applied to optical devices at first [49], but a problem with a long-term reliability of optical devices and plastic molding was exposed. Therefore, electronic circuit parts were mounted

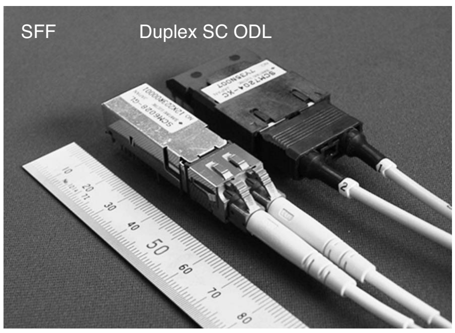

Photo 8. SFF and Duplex SC ODL
Width of SFF; 0.55 inch, Duplex SC ODL; 1 inch

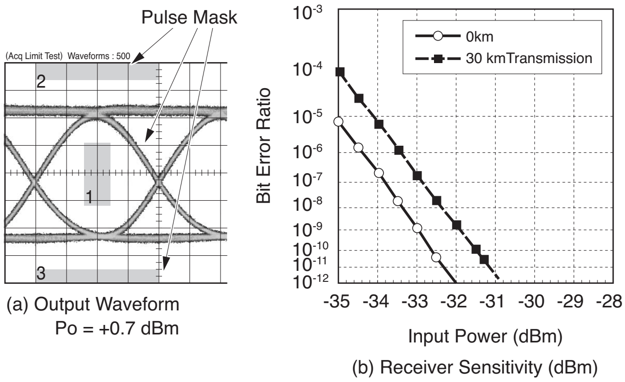

Fig. 14. Characteristics of 2.5 Gb/s SFF

on a board, and conventional TOSA and ROSA were decided to be used. **Figure 14** shows typical characteristics of SFF [(50), (51)]. The favorable performance was retained though the size had been reduced. This module shape was further developed into a SFP (small form factor pluggable) [(52)-(54)], which is detachable and doesn't require soldering to a system board. Most of current optical data links less than 2.5 Gb/s transmission speed, including the public communication use, apply this shape. The clock recovery function (3R) was not basically embedded in a SFP. There had been no need to fit the 3R function into an optical data link including a public communication use, due to the improvement of IC performance and board design technology. The IC that has a microprocessor or equivalent functionality was fundamentally embedded in an SFP device to transmit supervisory signals of SFP type. These signals included light transmitting state and light receiving state, and were sent to the network control module.

Photo 9 shows an external view of SFP. SFP also has a module using a DWDM (dense wavelength division multiplex) method [(55), (56)] because of a highly-miniaturized peltiert device used for laser temperature stability and lower consumption current [(57), (58)]. **Figure 15** shows an external view and structure of TOSA used for DWDM. In recent years, a Bi-Directional function, which enables two-way communication by single core fiber, has been built for use in the FTTH (fiber to the home) system [(59)]. The SFP having this

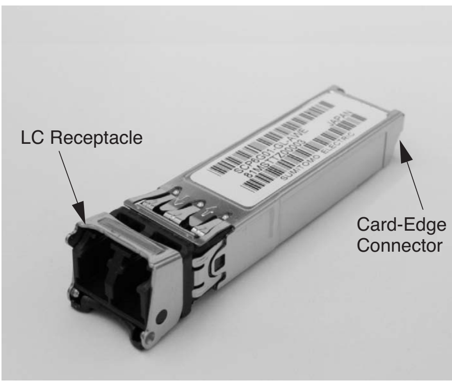

Photo 9. Outline of SFP

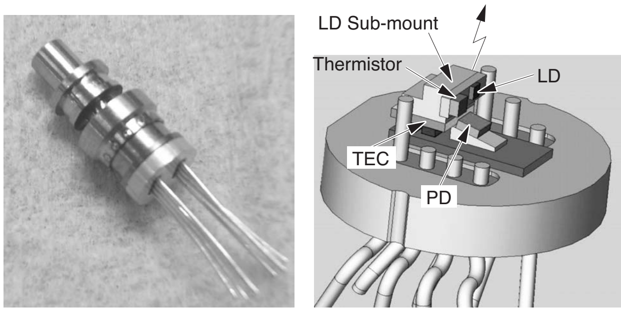

Fig. 15. DWDM-TOSA (Left) and Structure (Right)

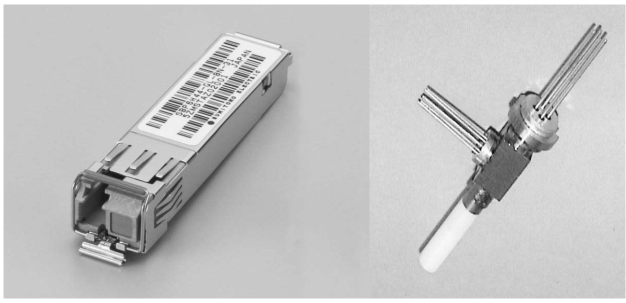

Photo 10. Bi-Directional SFP and BOSA
(Bi-directional Optical Sub-Assembly)

function was also developed (See **Photo 10**).

In the transmission rate standard of SONET/SDH, the upper rate of 2.5 Gb/s standard is 10 Gb/s. A demand for 10 Gb/s optical data link with an electric multiplex/demultiplex function [(60)] came out from the late 1990s, and our company also started to develop this module. Furthermore, the development of microminiature XFP (10G small Form-factor Pluggable) [(61)-(63)] was advanced with the ICS (Innovation Core SEI, Inc.) established in the U.S. Silicon Valley at the core, aiming at further miniaturization/lower power consumption. In this project, a standard was established by Sumitomo Electric, ICS and ten powerful manufacturers such as JDSU and Tyco as founders. Today an XFP is becoming a mainstream of 10G optical data link. **Figure 16** shows the block diagram. The function that forms electric signal waveforms (signal conditioner) is built in, because the electric interface with system board is a card edge connector type with 10 Gb/s high-speed transmission. Furthermore, X2 [(64), (65)] is widely used for 10G Ethernet. The electric output of X2 is 3.125 Gb/s x 4 lane parallel interface (XAUI), and the optical communication is established converting into serial signals of 10.3125 Gb/s inside the X2. **Photo 11** shows an external view of XFP and X2. Both XFP and X2's physical sizes were reduced, while maintaining 10 Gb/s transmission speed. This required extremely high technologies for securing transmission performance, heat dissipation, and suppressing electromagnetic emission noises. Required performance is secured repeating simulations and actual measurements in our development [(66)]. Moreover, in spite of the compact size, the module with an EDC (electronic dispersion compensation) function that electronically

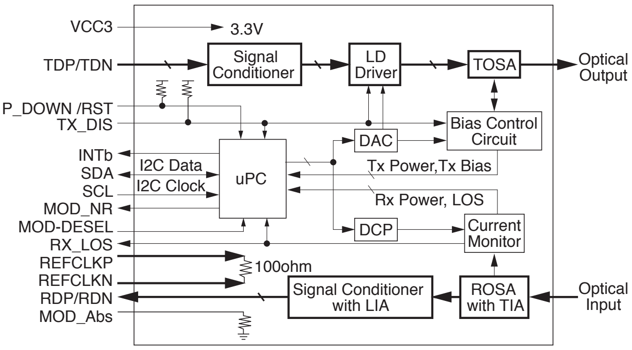

Fig. 16. XFP Block Diagram

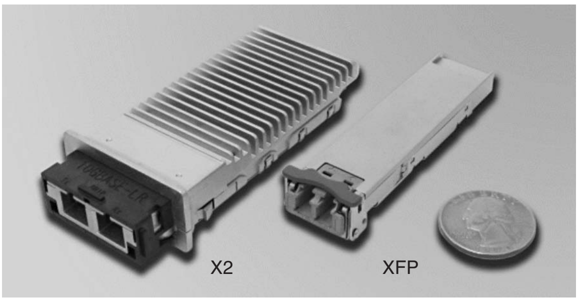

Photo 11. 10 Gb/s Pluggable Optical Data Link

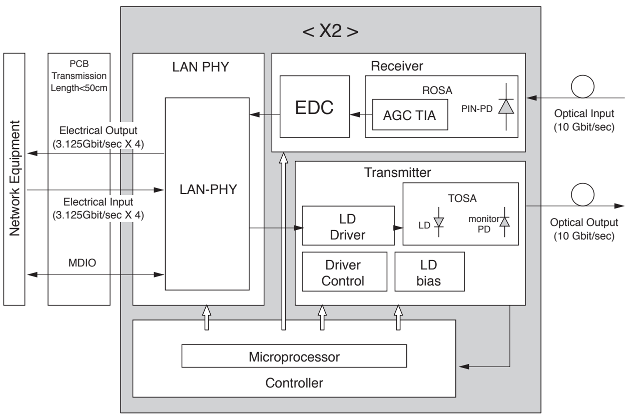

Fig. 17. Block Diagram of X2 with Fiber Dispersion Compensation EDC (Electronic Dispersion Compensator) inside the Receiver

compensates for transmission bandwidth shortage due to the wavelength dispersion characteristics of optical fiber has been developed and included (67). **Figure 17** shows the block diagram.

9. Future

Now the transmission rate of optical data link has been increased to 10 Gb/s and moreover, and products having a function that compensates for transmission bandwidth restrictions by using fiber's wavelength dispersion have been developed. Furthermore, in DWDM, the optical data link which enables 200 km distance transmission with SFP shape has already been put to practical use. These products have become more intelligent having a microprocessor and functions that control laser's optimum operations and monitor optical levels. Further speed-up has been discussed in IEEE802.3 Higher Speed Study Group, and 40G or 100G transmission optical data link is being developed. Since there is a problem with fiber's wavelength dispersion, PMD (polarization mode dispersion), in both 40G and 100G, using a multiple wavelength technology (about four waves) has been studied. On the other hand, in the DWDM system, there are requests to make the network more flexible and to have higher maintenance performance. The future will be an information society with an increasingly sophisticated internet. Optical data link will be grown as a key component of this progress. Even lower power consumption is important as a global climate change countermeasure. To achieve very low power consumption, it will be important to develop a VCSEL (vertical-cavity surface-emitting laser), its low-power consumption driving technology, and state-of-the-art high speed electronic device technology.

10. Closing

In these developments, I still feel a technology has its season. The technologies that were applied to an optical data link in chronological order were a short-wavelength LED, a long-wavelength LED, a long-wavelength LD, a hybrid IC, and a molding technology. For the dedicated analog IC, the technology progressed from a silicon bipolar to CMOS, and finally a GaAs was used. These technologies progressed quickly, and we continually changed production materials to achieve better results.

In the optical data link functionality, a clock recovery function (3R) was previously required for the pubic communication use. However, there became no need to build it in optical data links due to the improvement of IC performance and board design technology. On the other hand, for a 10 Gb/s transmission rate, there are some optical data links which require the 3R function to execute sophisticated functions such as dispersion compensation. Moreover, performance errors were previously corrected by a variable resistor and laser trimming. Now these errors are able to be adjusted by a built-in microprocessor with a high degree of accuracy, and by a remote control even in operation. For mechanical parts, high-performance modules are produced making full use of the latest materials and processing technologies. In order to make maximum use of the state-of-the-art optical communication technology for manufacturing the optical data link, a wide range of technologies must be considered.

The author has told optical link engineers that an optical data link business is similar to a restaurant. In other words, it is important to cook optical devices, electronic devices, optical parts, mechanism parts, and others well and provide delicious meals to eaters (data link users). And so, it's required to produce hard-to-get high-quality ingredients (optical devices) in a directly-managed farm. Special ingredients (custom ICs) will be produced in a contract farm. It is essential to cook using the perfect recipe, to become a well-reputed restaurant (business), and to meet the users' (communication network manufacturers') needs. A meal must be at least more delicious than a user's home-cooked meal. Otherwise, users will obtain various ingredients and cook by themselves.

In fact, when an optical transmission system was first put to practical use, there were few optical data link specialized manufacturers, and optical transmission division was, therefore, building optical communication modules. Our company has produced optical devices in a directly-managed farm, and in our case, also a directly-managed restaurant. Our restaurant has received several stars from users as a reputable restaurant. I strongly believe that we will continue to develop a discerning eye for the latest and freshest ingredients. We will continue to develop better ingredients, devices, and keep having a hot hand capable of cooking delicious dishes.

* SUMILINK is trademark of Sumitomo Electric Industries, Ltd.
* Ethernet is a trademark of Xerox Corporation.

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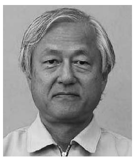

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