

Global Optical Access Systems Based on ATM-PON

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This paper discusses a global optical access network architecture to consolidate an economical ATM-PON (Asynchronous Transfer Mode-Passive Optical Network) that is compliant with the international standard, a flexible access node configuration with a growable IP functionality and legacy service support, and a regional transfer network. The GFR service support functionality and dynamic ATM-PON bandwidth allocation to cope with IP traffic growth are discussed. Also, since cost-effectiveness is the key factor in the access network, we also present an optical device and assembling technology. The main parts of this architecture and technology have been successfully hardware-implemented.

1. Introduction

The explosive increase of traffic in data communications is a clear sign that we have truly entered the multimedia information age. Various kinds of access networks such as wired (metallic, coaxial, fiber) and wireless networks will support users' demands both economically and efficiently. Among these networks, optical access systems are considered to be essential to support the type of high-speed, wide-band, and convenient multimedia services shown in **Figure 1**. To cope with the ever-increasing needs and traffic, the development of global optical access networks based on equipment that is mass-produced and therefore inexpensive is expected.

A global optical access network will be configured to efficiently support data traffic such as Internet traffic as well as constant bit-rate traffic such as that of the legacy service. Also, ATM technology with data or IP support functionality will continue to play an important roll in the access networks as the key technology for multimedia service support. This is because the ATM can handle heterogeneous access schemes uniformly

and provide several required QoSs (Quality of Services).

To configure the above access network, the ATM-PON (Asynchronous Transfer Mode - Passive Optical Network)^{1,2)} is considered to be the most promising candidate. Currently, efforts to construct a world-standard economical access system are being promoted in the FSAN (Full Services Access Network),³⁾ the ATM-Forum, the ITU-T, and so on. As a result of these efforts, the recommendation for the ATM-PON physical layer was formally approved as G.983.1 in the ITU-T SG15 meeting on October 1998. This ATM-PON provides a transport vehicle to support FTTH/B (Fiber-to-the-home or building) and FTTC/Cab (Fiber-to-the-curb or cabinet), which accommodates xDSL metallic interfaces currently defined based on the ATM. Thus, we can expect to see the construction of global and economical optical access systems that are based on a worldwide standard and mass-produced ATM-PONs.

In this paper, we describe an ATM-PON global optical access network architecture and its equipment and focus on IP support functionality

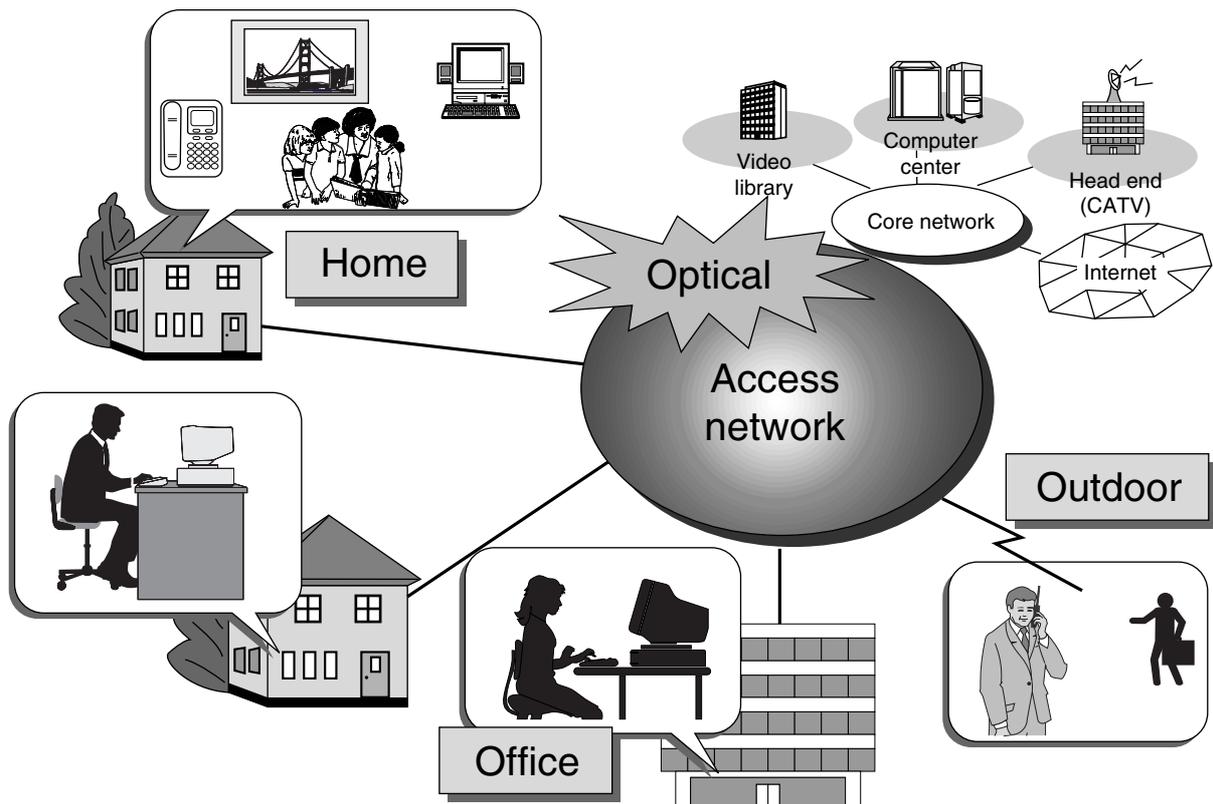


Figure 1
Access network for multimedia information era.

in the access node and ATM-PON layer. Also, the key technologies to construct an economical access system, i.e., optical devices and assembling technologies, and several examples of their implementation are described.

2. Global optical access system

2.1 Flexible optical access network and node architecture

An optical access network should be configured economically and flexibly to accommodate various services such as POTS, ISDN, leased lines, CATV, multimedia services of the Internet, VOD, and so on. To attain this objective, we considered a consolidated access network with an ATM-PON for economical optical subscriber access, an access node of the ATM switch core engine that supports various kinds of interfaces and upgradable IP functionality, and a ring network as a regional transfer network for efficient bandwidth utilization.

All functionality is based on global standards that will be applicable worldwide.

Figure 2 shows a global optical access network and node architecture that Fujitsu has proposed. For subscriber access, a single star, an active double star, and a passive double star topology are supported. For the UNI interfaces, various kinds of interfaces such as legacy interfaces and IP optimized interfaces are expected to be applied. In the access node, various interfaces are terminated and data are routed with appropriate signal processing, for example, QoS assurance, to designated interfaces. Multicasting for video distribution and IP support functionality such as the GFR (Guaranteed Frame Rate) service^{4),5)} and LAC (L2TP access concentration) for dynamic selection of ISPs (Internet Service Providers) are expected to be included. On the ring network, bandwidths shared by several nodes are used efficiently, and the DWDM (Dense Wave-

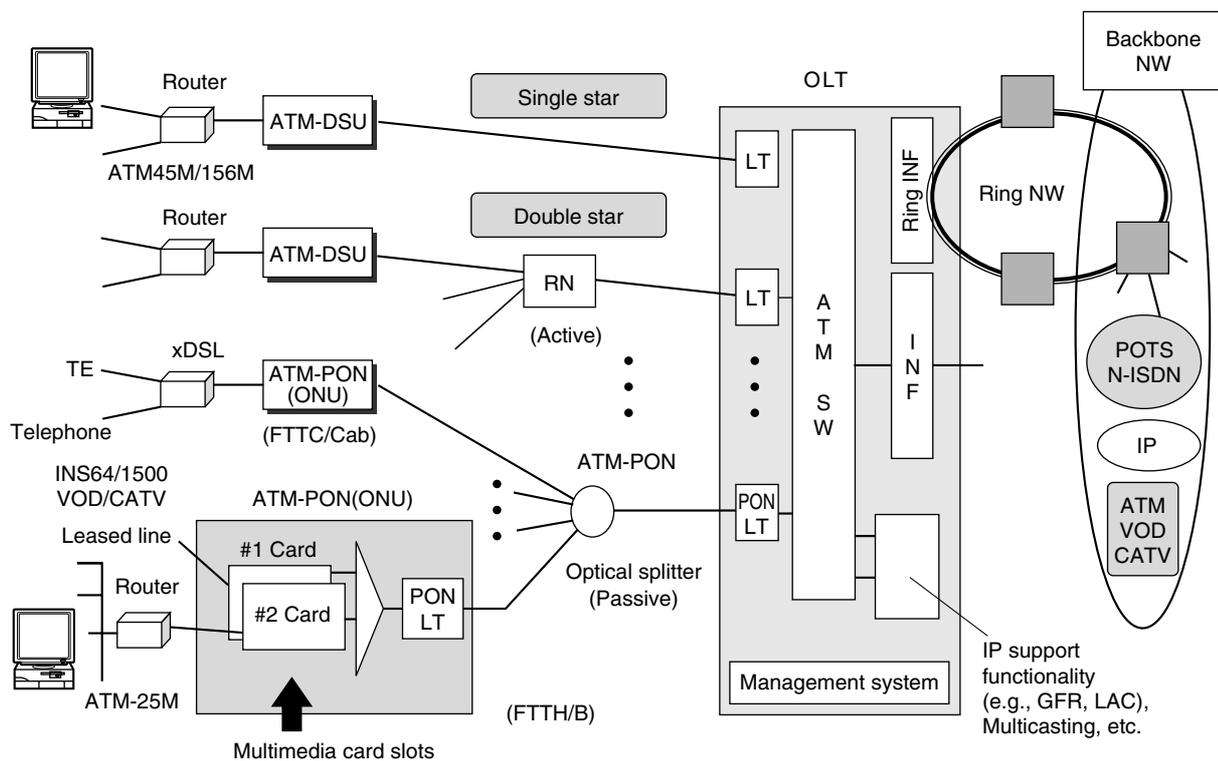


Figure 2
Global optical access network and node architecture.

length Division Multiplexing) scheme can be applied for large-capacity needs.

2.2 ATM-PON

A PON (Passive Optical Network) topology provides cost-effective shared media for multiple users, and an ATM transport scheme is suitable for supporting various kinds of multimedia services. An ATM-PON with both of these characteristics can configure an economical optical access network.

A schematic diagram of an ATM-PON is shown in **Figure 3**. An ATM-PON consists of an OLT (Optical Line Terminal) and ONUs (Optical Network Units) which are connected via optical fibers and a 1:n optical star coupler. The transmission scheme of downstream traffic (OLT to ONU) is continuous TDM (Time division multiplexing), and ONU receives designated cells. The transmission scheme of upstream (ONU to OLT)

traffic is burst mode TDMA (Time Division Multiple Access), and the ONU transmits data according to timeslot allocation information that is generated by the OLT and included in the downstream frame. Thus, the OLT in the ATM-PON allocates upstream bandwidth or timeslots flexibly to each ONU. Single fiber WDM (Wavelength Division Multiplexing) is employed for bi-directional transmission to reduce costs. A burst mode transmission using a 1.31 μm wavelength for the upstream and continuous mode transmission at 1.55 μm for the downstream are applied.

The key issues are to accommodate burst or IP traffic efficiently as well as the legacy services and to produce cost-effective optical modules/devices. These items are discussed in Section 3.2 and Chapter 4, respectively.

3. IP traffic accommodation technology

The remarkable growth of data and IP traf-

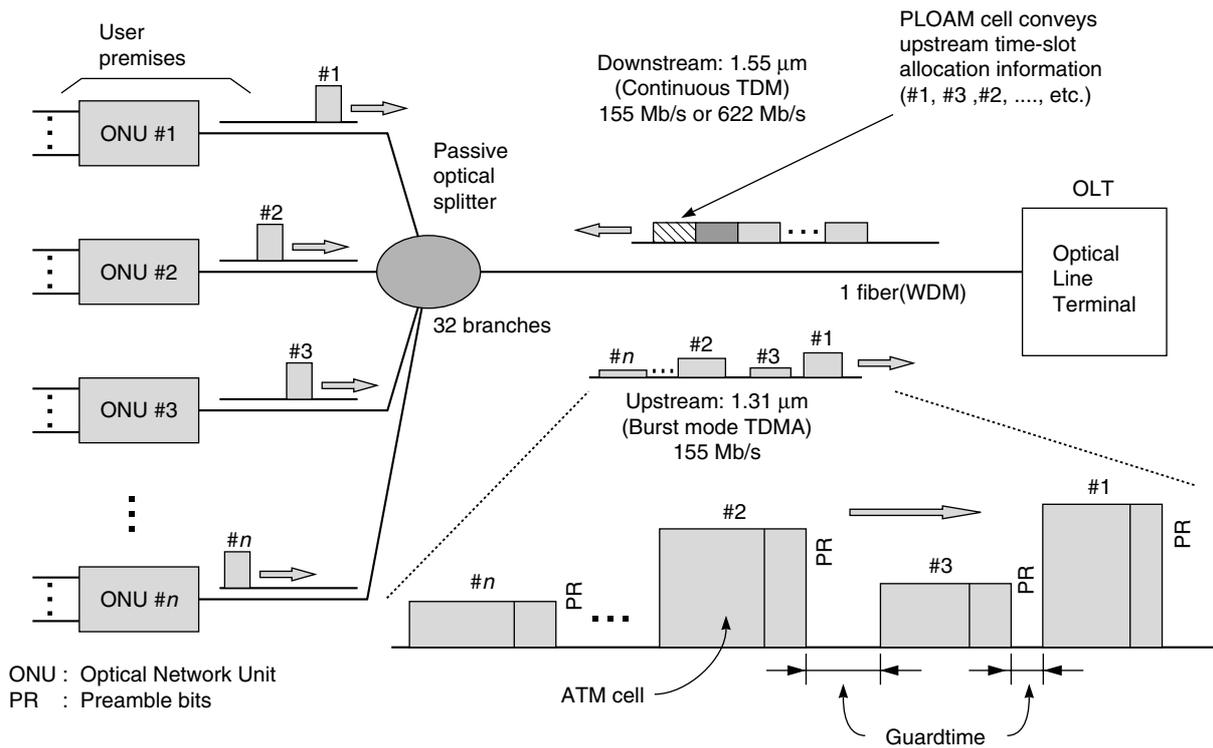


Figure 3
Schematic diagram of ATM-PON.

fic requires economical accommodation of the access networks and the backbone networks. The following describes an efficient service support function in the access node and the ATM-PON layer for such bursty traffic as Internet traffic. The key functions to accommodate Internet traffic economically will be an ATM-based traffic concentration or bandwidth sharing both in the access node and the ATM-PON layer.

3.1 GFR support function

There are several candidate ATM service classes, for example, ABR (Available Bit Rate), UBR (Unspecified Bit Rate), and GFR (Guaranteed Frame Rate), to support bursty traffic such as Internet traffic.

We consider that most users want a service which provides a kind of guaranteed QoS without any special function. The GFR is designed to accommodate burst traffic efficiently with some level of service guarantee and without complicated in-

teraction between users and networks. Therefore, we adopted the GFR as a new service support function to enable users to explore the Internet over ATM access networks economically.

From the viewpoint of resources and bandwidth allocation, the resources that guarantee bandwidth for the MCR (Minimum Cell Rate) of each connection are reserved and the residual resources are dynamically shared by users. We developed a GFR function that includes a group-based FIFO queuing concept.⁶⁾ It provides an MCR guarantee capability by using the EPD (Early Packet Discard) technique. A novel scheme based on a virtual tagging technique is also implemented to achieve fair sharing with the FIFO queue.

For implementation of GFR, an extra ATM cell buffer memory is required to perform resource sharing and MCR guarantee. Based on a flexible node architecture, we can easily add GFR features on the OLT by using the loop-back function and the line-interface-plugin-compatible card.

Among several alternatives, we adopted FIFO queuing for the GFR support because it has a simple and compact implementation which makes it possible to efficiently use the buffer space between multiple VCs. In this FIFO queuing, we have introduced a group-based GFR buffer or a per-group FIFO queuing. Each group buffer consists of a FIFO and independently provides GFR for VCs accommodated in the group. The readout control for the multiple queues is carried out in proportion to the allocated group bandwidth, i.e., the so called “weighted round robin method” is used.⁷⁾ Also, the concept of grouped VPs is applied.

In order to guarantee the minimum cell rate (MCR), a tagging function is used in conjunction with the FIFO queuing. When the input rate exceeds the MCR given for each VC, the ATM cells are tagged as CLP (Cell Loss Priority) = 1 or CLP = 0. An EPD function is also implemented to preserve the AAL5 frame structure even in a congested state. To support the EPD, two thresholds for the queue length are set. The low threshold guarantees the MCR, and the high threshold is to avoid cell discarding by buffer overflow.

Figure 4 shows the evaluation of MCR guarantee at an ATM layer. In this evaluation, two VCs share a group bandwidth of 20 Mb/s. The MCR of both VCs is 2 Mb/s. The input rates of the measured VC are 3, 5, and 10 Mb/s, and the rate of the background VC is controlled from 0 to 100 Mb/s. As the background traffic increases, the output rate of the measured VC decreases. However, even if it is heavily congested, for example, when the total input is over 100 Mb/s, the output rate of the measured VC stays above the MCR.

Since we adopted the FIFO queuing, the excess resource is shared in proportion to the input rate of each VC. A user who sends more data frames could obtain many resources. Moreover, the long or tandem connection traversing multi FIFOs tends to get fewer throughputs compared to short connections. To achieve fair sharing for the FIFO queuing, we adopt a virtual tagging technique. In this scheme, the frame tagging is

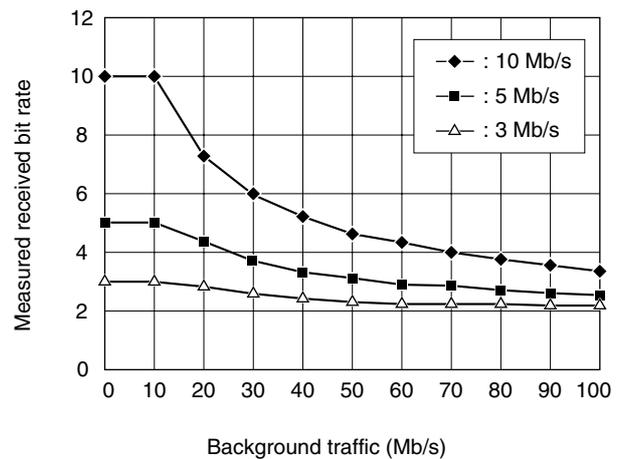


Figure 4
Evaluation of MCR performance at ATM layer.

performed based on a virtual MCR (V-MCR), not on MCR. Here, the V-MCR is proportional to the MCR and the total V-MCR is equal to the output rate of the FIFO. Thus, the available resource is shared by active connections in proportion to each MCR. To avoid excess untagging caused by the V-MCR instead of the MCR, we also introduce a virtual CLP. The real CLP is set in correspondence to the real MCR, and the virtual CLP is set according to the V-MCR. The virtual CLP is only used for the input control of the FIFO and is never transmitted across networks. Our proposed scheme can achieve fair sharing in proportion to the MCR, whereas the conventional FIFO could not achieve fair sharing between a long and short path.

3.2 Dynamic PON bandwidth allocation on an ATM-PON

In the ATM-PON, the OLT (Optical Line Terminal) allocates upstream bandwidth or timeslots to each ONU (Optical Network Unit). It is possible to accommodate constant bit-rate traffic like the legacy service by allocating timeslots periodically. However, for data traffic generated by PCs, routers, Web servers, etc., it is not efficient to allocate timeslots periodically because it is not constant bit-rate traffic but burst

traffic. Several studies⁸⁾⁻¹⁰⁾ have been reported on this issue. We have studied dynamic bandwidth allocation in the ATM-PON as a solution for this issue and confirmed that the dynamic allocation method is effective for IP burst traffic accommodation.

Below, we describe a simulation which showed the effectiveness of this method. We assumed two kinds of user traffic via UNI; one is constant bit-rate traffic, which is generated by legacy services like POTS/N-ISDN, and the other is data traffic, which is generated by PCs or LANs. To accommodate the two different kinds of traffic effectively, we prepared individual transmission-waiting FIFO buffers for each kind. In the legacy service, the cell delay, cell delay variation, and cell loss rate should be kept to a minimum. To accomplish this, cells for legacy traffic must have precedence over data traffic in the service multiplexer block in the ONU. Moreover, the bandwidth used for transporting the legacy service is, at the least, pre-assigned to decrease the cell delay of legacy traffic. The bandwidth of the pre-assigned band is set by the operator and is not changed by the bandwidth request/allocation algorithm. By using a dynamic bandwidth allocation method to share the shared band among connected ONUs for the data traffic, we can get a statistical gain and accommodate data traffic effectively. The bandwidth of the shared band is the total upstream bandwidth minus the bandwidth of the pre-assigned band. The ONU generates bandwidth requests in accordance with the queue status in the waiting FIFO, and the OLT dynamically allocates some bandwidth to each ONU from the shared band according to each bandwidth request. Legacy service traffic such as POTS traffic was simulated in a periodic cell generation. The bandwidth of this traffic was 0.76% of the total upstream bandwidth. A three-state source model was used for simulating burst data traffic, the average bandwidth of which was 9.24% of the total upstream bandwidth for each ONU. The peak cell rate of the burst data traffic in the three-state

source model was 25.6 Mb/s.

In the simulation, we assumed that eight ONUs are connected to one OLT interface and all ONUs have the same conditions. The transmission rate, frame structure, and cell length are based on FSAN or ITU-T G.983.1 specifications. The transmission rate is 155.52 Mb/s for each direction, and one timeslot is 56 octets for the upstream. An upstream timeslot can transfer a user cell (which consists of an ATM cell and a three-octet PON header), a PLOAM cell, or some short cells. Short cells can be used for the MAC (Media Access Control) channel for such actions as bandwidth requests. One frame is constructed from 53 upstream timeslots. The propagation delay from the ONU to the OLT (T_p) is assumed to be 30 timeslots (i.e., 17.3 km equivalent). The bandwidth for user traffic is 52/53 of the total upstream bandwidth in the following cases.

- 1) Condition 1: Bandwidth request using short cells
The ONU uses short cells to request upstream bandwidth. The OLT allocates the timeslot of the shared band in proportion to the notified queue length from each ONU. Assuming that one short cell has a seven-octet length and 32 ONUs can be connected to one OLT interface, eight ONUs can send each short cell in one timeslot and the time interval of short cells is four frames.
- 2) Condition 2: No dynamic bandwidth allocation
All upstream bandwidths are pre-assigned to each ONU equally. This condition was simulated for reference.

Figure 5 (a) shows the required length of the transmission waiting FIFO buffer in the ONU.

The dynamic bandwidth request/allocation method can drastically reduce the size of the transmission-waiting FIFO buffer required for data traffic as compared with that in the case of no dynamic bandwidth allocation.

Figure 5 (b) shows the cell delay distributions for each condition. The buffer length for

evaluating cell delay is assumed to be long enough to ensure that no cells are lost. Compared to Conditions 1 and 2, the cell delay without the dynamic bandwidth request/allocation is much larger than that with the dynamic bandwidth request/allocation.

These simulation results indicate that the dynamic bandwidth allocation on the ATM-PON layer is useful for accommodating burst data traffic efficiently from the viewpoints of the required buffer length in the ONU and the cell delay reduction in data traffic.

4. Optical device and assembling technologies

4.1 Optical transceiver on ATM-PON

A burst mode transmitter/receiver is required to not only keep costs low but also to achieve a performance that is high enough for flexible installation. Techniques for the optical transceiver modules in the ONU and OLT on single fiber WDM ATM-PON systems that emphasize a feed forward method for the ONU transmitter and a newly developed PD slow tail-current compensation technique for the OLT receiver are described below.¹¹⁾

4.1.1 Burst mode transmitter

To enable a simultaneous response, we adopted an automatic power control (APC) free

technique by using a feed forward method which controls the laser diode (LD) drive current according to the ambient temperature instead of by APC. Using non-bias current modulation to obtain a high extinction ratio, the turn-on delay increases with temperature due to an increase in the LD threshold current (I_{th}). Pulse duty deviations due to the LD turn-on delay time (t_d) degrade the OLT receiver sensitivity.

To prevent this effect, we have developed a feed forward method to control the duty. **Figure 6 (a)** shows the principle of this method. The drive current pulse duty is adjusted to compensate for an insufficient t_d (T) according to the temperature to keep the duty of the optical output constant. **Figure 6 (b)** shows the optical output waveform for a 155.52 Mb/s non-bias modulation using the above duty compensation method. We confirmed that the optical output waveform duty deviation was kept to nearly zero.

4.1.2 Burst mode receiver

A burst mode receiver is required for high-speed, high-sensitivity, and a wide detectable power difference between burst cells (loud/soft ratio) for flexible installation. On the other hand, a higher transmission efficiency requires a reduction of the PON overhead (OH) and a short guard

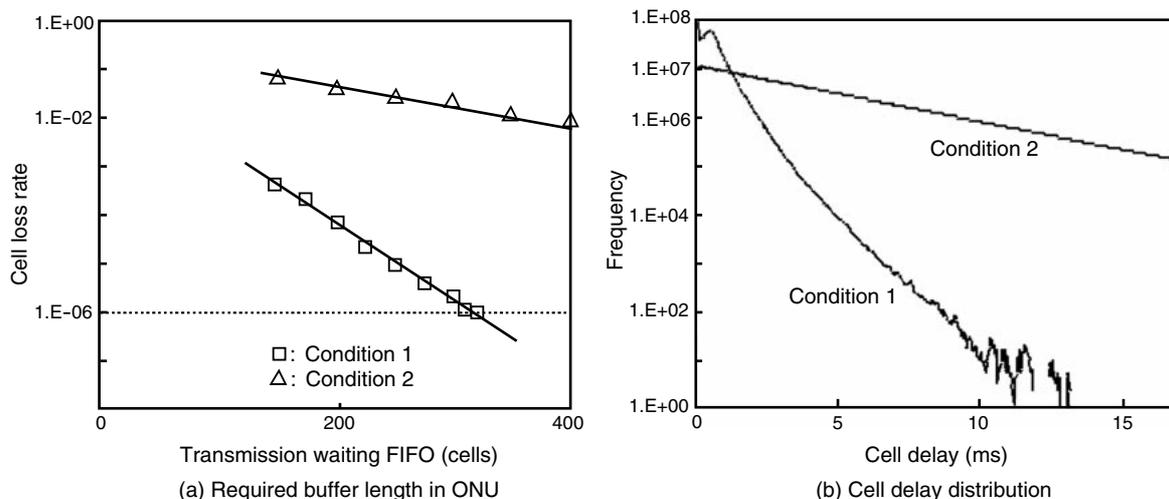


Figure 5
Dynamic bandwidth allocation in ATM PON.

time between burst cells.

However, after the input light to a photo diode (PD) is turned off, the PD exhibits a slow tail current due to its minority carriers, and this causes bit errors at the next cell if the guard time is not enough to decrease the PD tail current with a high loud/soft ratio. This characteristic of the PD is a problem in burst mode receivers. To solve the PD tail current problem, a circuit compensation technique is needed. We therefore developed a PD tail current compensation method that eliminates the slow response current and a high-speed

automatic threshold level control (ATC) circuit to detect the decision level.

The slow tail current response after the input light is turned off is similar to the behavior of a CR integrator. Therefore, a compensator can be made from a simple CR circuit connected to the PD anode which detects these phenomena and a voltage follower (VF) whose output is connected to the preamplifier (PRE) input through a resistor. The operation of this tail current compensator is shown in **Figure 7 (a)**. If a high-power signal is input to the PD, the VF output level changes as

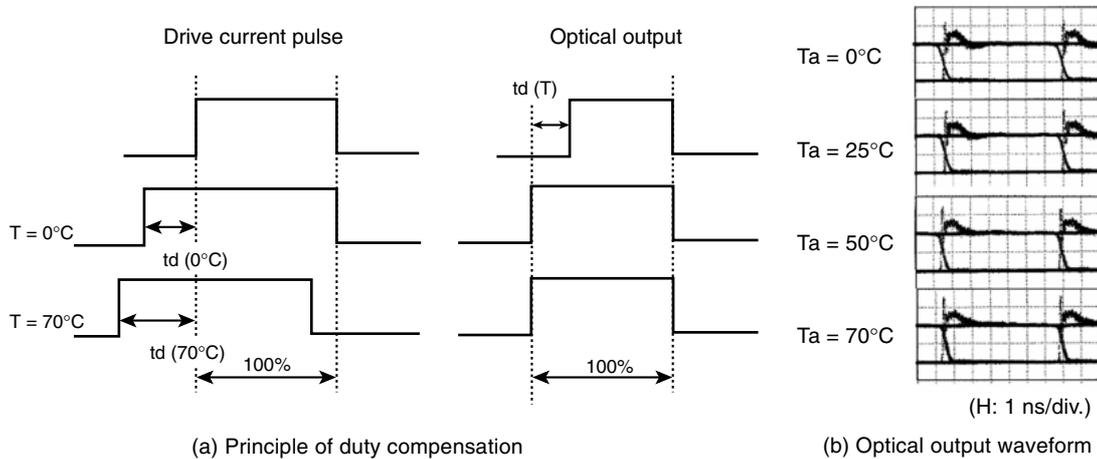


Figure 6 Principle of duty compensation and optical output waveform.

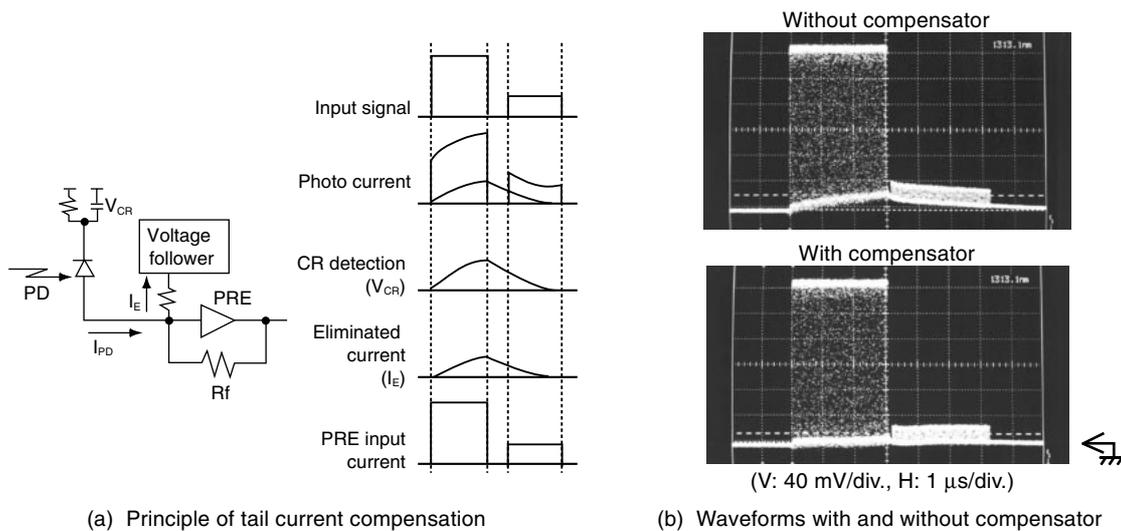


Figure 7 Principle of tail current compensation and PRE output waveform.

the CR circuit charges/discharges, passing the eliminated current through the resistor according to the voltage difference between the VF output level and the PRE input bias level. **Figure 7 (b)** shows the PRE output waveform.

The developed ATC circuit consists of a high-speed peak detector, DC-feedback (FB), and a 1/2 circuit. The peak detector quickly senses the input signal's high level while the DC-FB holds the input signal's low level. The 1/2 circuit generates the mid level of the input signal as a decision level. **Figure 8** shows the results of experiments with an IC implementation of this circuit using a 12-bit PON-OH (guard time: 4 bits, preamble: 8 bits). The new tail current compensator achieves a loud/soft ratio of 27.4 dB and improves the minimum sensitivity for a bit error rate of 10^{-10} by 5.0 dB.

4.2 Assembling optical devices

The manufacture of cost-effective, high-performance, mass-produced equipment requires inexpensive optical devices. To meet this require-

ment we have been developing innovative technologies for optical devices.¹²⁾ These technologies include a technology for plain assembly of optical devices such as electronic devices and an integration technology for optical circuits for various functions.

Key issues to be solved are as follows:

- 1) For cost-effective, mass-produced devices, we must achieve an innovative reduction in the number of components such as the optical lens and components for assembly and an

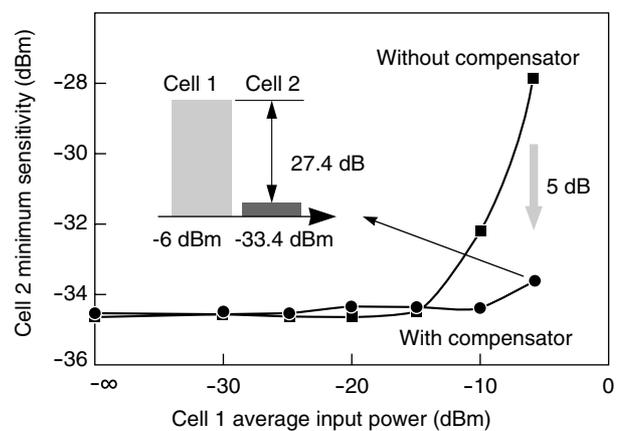


Figure 8 Experimental results for receiver sensitivity.

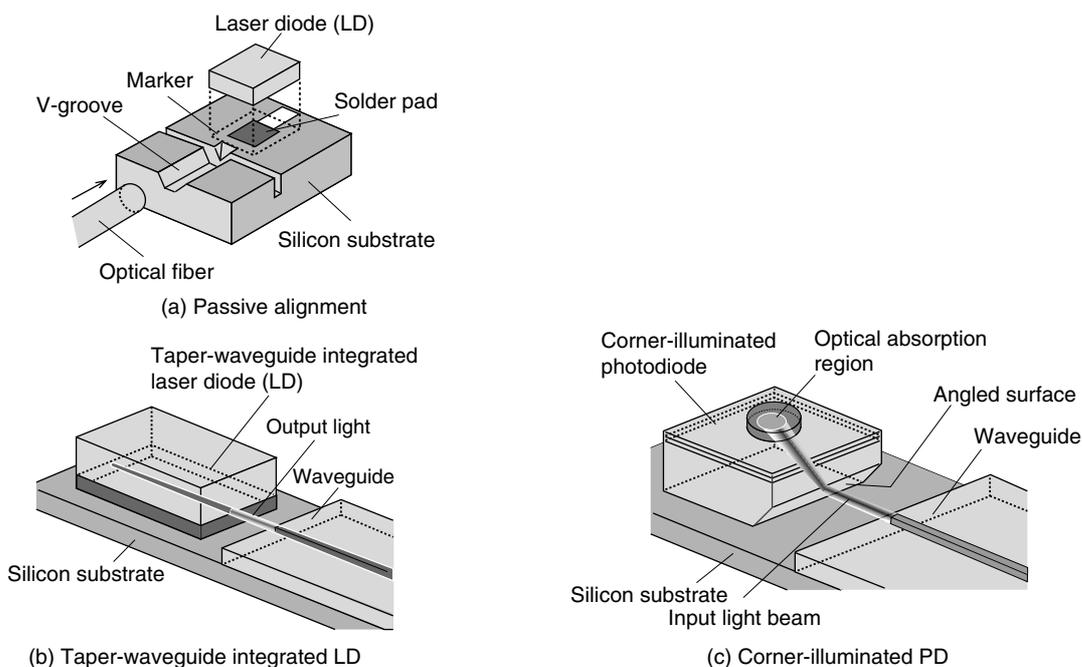


Figure 9 Optical device assembling technique.

innovative assembly process (particularly for the alignment for optical semiconductor devices).

- 2) For high-performance devices, one key issue is effective assembly of optical devices for wavelength division multiplexers.

To satisfy the first requirement, we have developed an innovative assembly technology for optical semiconductor devices such as laser diodes and photo-detectors. Conventionally, the alignment is carried out with the semiconductor devices active, i.e., the lens is adjusted with the optical beam. This technique has some disadvantages: it requires expensive alignment components, takes a long time to align, and requires complicated facilities. To overcome these disadvantages, we have developed an innovative assembly technique called “passive alignment”. As shown in **Figure 9 (a)**,

optical alignment is carried out with only a mechanical alignment of the laser diode to a marker on a silicon substrate and mechanical fixing of the fiber to a V-shape groove etched on the silicon substrate. We have achieved a highly uniform optical coupling efficiency with this technique.

Moreover, to realize a high coupling efficiency, which will lead to various applications of the passive alignment technique, we have developed new optical semiconductor devices. For laser diodes used as a light emitter, a taper-waveguide (**Figure 9 (b)**) has been integrated into a laser diode. This structure is equivalent to an integrated lens in a laser diode, and it provides a high optical coupling efficiency without the need for an optical lens. For a photodiode used as a light receiver, we have realized a high optical coupling efficiency for corner illumination with an angled-

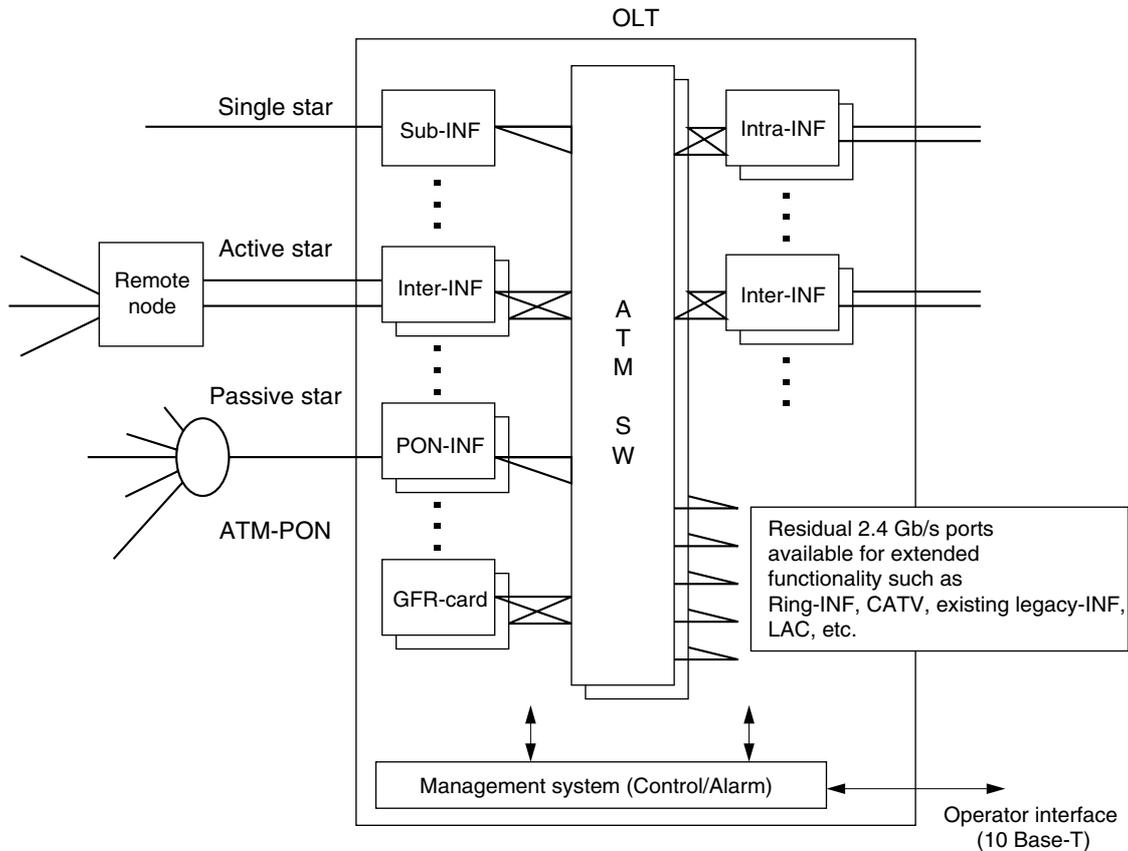


Figure 10
OLT configuration.

surface (**Figure 9 (c)**). This structure is more suitable for a surface mounting configuration than the conventional one.

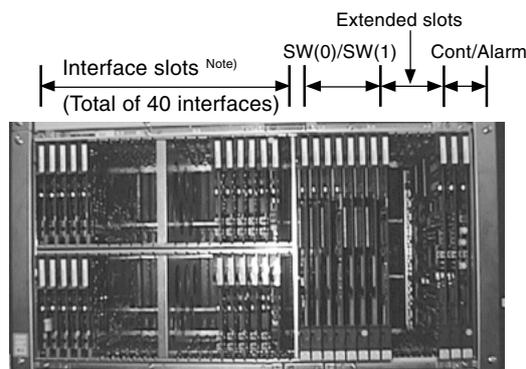
To realize a high-performance function for the second requirement, we have developed a hybrid integration assembly technology for planar light-wave circuits (PLCs) and optical semiconductor devices on a silicon substrate, which we call the PLC platform technology. An embodied implementation is described in Section 5.4.

5. Hardware implementation for global optical access system

The global optical access system architecture described above was applied to fabricate an economical and flexible access system. The main hardware implementation to be made commercially available is described below.

5.1 Equipment implementation

Figures 10 and 11 show the configuration and a photograph of the fabricated OLT, respectively. A total of 40 ATM-PON interfaces, subscriber-line interfaces based on SDH, or intra-office and/or inter-office interfaces based on SDH can be accommodated per unit. Using a 150 mm × 330 mm printed circuit board for these interfaces achieves high-density subscriber accommo-



Note: Total of 40 interfaces for ATM 155 Mb/s-Subscriber INF (non-redundant), PON-INF (non-redundant), ATM 155 Mb/s/622 Mb/s Intra-/Inter-office INF (redundant), or GFR card (redundant)

Figure 11
Photograph of OLT.

...ation, which leads to an economical node. These interface cards are slot-compatible (slot-interchangeable) and they are configurable with both a non-redundant and redundant scheme for intra-office and inter-office interfaces. The ATM-SW core engine provides a 20 Gb/s throughput and supports the QoS for CBR and UBR services and also the GFR service with an add-on GFR card. Some residual 2.4 Gb/s ports of the ATM-SW are prepared for supporting the global optical access node functionality described in Chapter 2; that is, for supporting the ring interfaces, CATV interfaces, inter-working interfaces for existing legacy telephony services, or IP-specific functionality such as LAC. For the ATM-PON interface, a 60 byte-PON cell (7 byte-overhead and 53-byte ATM

Table 1
Main features of prototype GFR card.

Item	Specification
Interface speed	622.08 Mb/s
Max. number of VCs	4096
Max. number of groups	2048
MCR	0.1 to 6.0 Mb/s for each VC
Output rate	0.1 to 149.76 Mb/s for each group
Total buffer size	29127 cells
Power consumption	18 W

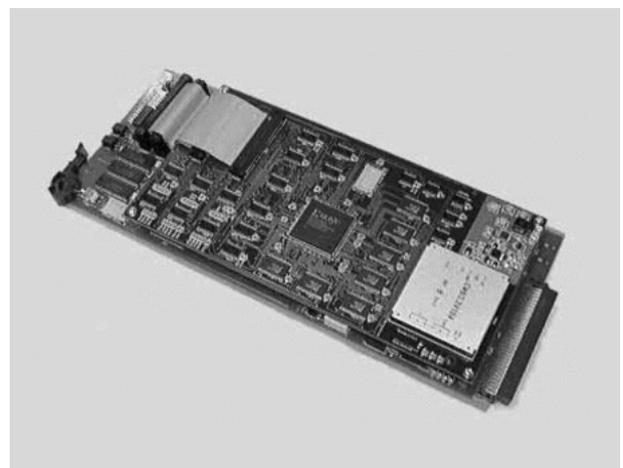


Figure 12
Prototype GFR card.

cell) structure was used in this implementation and a recently defined ITU-T G.983.1 compliant interface will be introduced with a dynamic bandwidth allocation method.

5.2 GFR implementation

Table 1 shows the specifications of the prototype GFR card, and Figure 12 shows a photograph of it. By using a 150 mm × 330 mm printed circuit board with an attached sub-board, this card has been made plug-compatible with a 622 Mb/s interface card. Simply plugging this card into any interface slot gives the GFR service function to the OLT. Using the GFR card, 4096 VCs can share the bandwidth with guaranteed MCR.

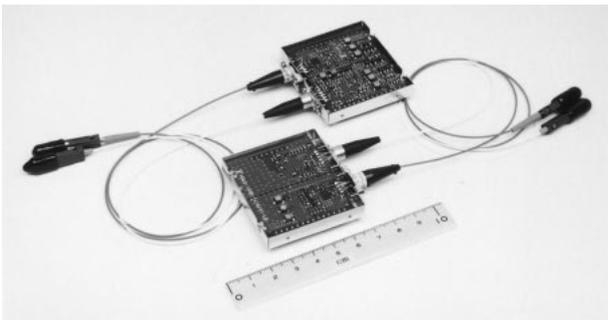


Figure 13
OLT/ONU optical modules for ATM-PON.

Field Programmable Gate Arrays (FPGAs) in conjunction with control memories perform the main functions of GFR such as CLP tagging, EPD, and input/output control of buffer memories.

5.3 Optical modules

Figure 13 shows a photograph of the ONU/OLT modules. These modules are 55 × 49 × 8.5 mm. By using an external WDM filter, they can be applied to single fiber WDM ATM-PON systems. The OLT module is composed of a continuous mode transmitter and a burst mode receiver, and the ONU module is composed of a burst mode transmitter and a continuous mode receiver. Figures 14 (a) and (b) show the block diagrams of the OLT transceiver module and the ONU transceiver module, respectively.

Table 2 summarizes the performances of both modules without a WDM filter. These modules have been applied to commercial systems.

5.4 PLC platform technology

As shown in Figures 15 (a) and (b), various optical functions, for example, a wavelength divi-

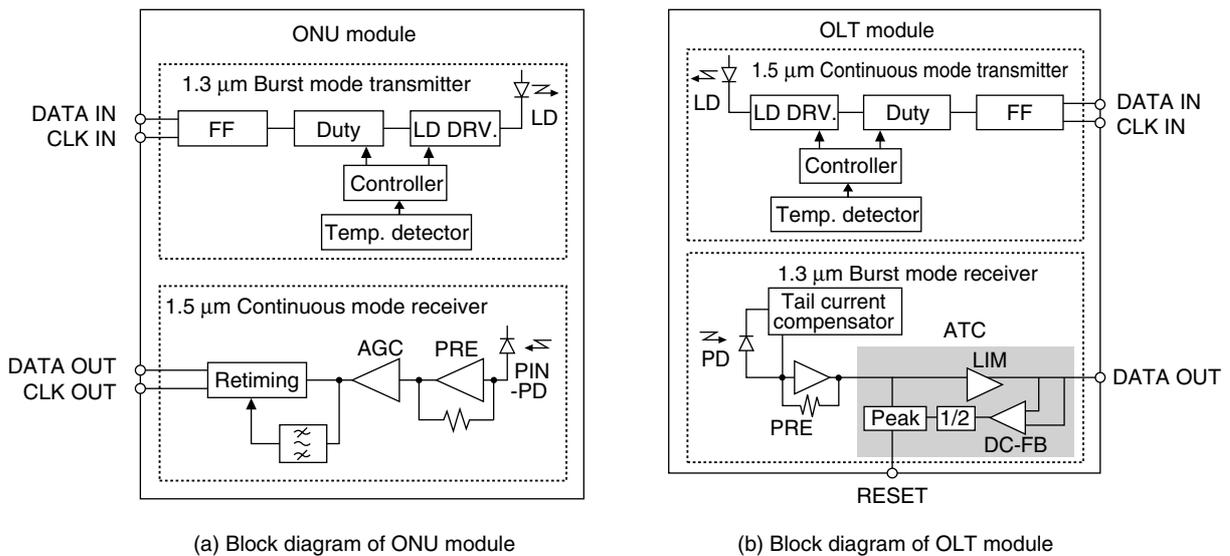


Figure 14
Block diagrams of OLT and ONU optical modules.

sion multiplexer and a splitter were fabricated by using PLC platform technology. For further improvement, we have developed technologies such as the encapsulation of optical semiconductor devices with plastic materials. For the application of the plastic encapsulation techniques commonly used in LSIs to optical semiconductor devices, we developed a double plastic-layer technique. Around optical semiconductor devices, we use a transparent silicone resin which passes light signals and relieves thermal stress. We then

encapsulate with epoxy resin to improve humidity resistance. The optical modules based on the PLC platform technology will be used in the next commercial systems.

6. Conclusion

We presented a global optical access network architecture and equipment to provide an economical and efficient multimedia service support, focusing on the ATM-PON and IP support functionality such as GFR service support and dynamic

Table 2
Main features of OLT/ONU optical modules.

Items	ONU	OLT
Transmitter	Burst mode	Continuous mode
Wavelength	1297.1 to 1327.8 nm	1553.3 to 1558.6 nm
Mean launch power	+0.6 to +0.9 dBm	+0.6 to +0.9 dBm
Continuous "0" output level	≤ -80 dBm	—
Extinction ratio	—	≥ 11 dB
Pulse duty deviation	≤ 3 %	—
Receiver	Continuous mode	Burst mode
Minimum sensitivity	-37.2 dBm	-33.5 dBm
Maximum overload	-3.0 dBm	-6.0 dBm
Receivable power difference	—	27.4 dBm
Operating temperature range	0 to 70°C	10 to 60°C
Supply voltage	+3.3 V \pm 5%	+3.3 V \pm 5%
Size	55 \times 49 \times 8.5 mm	55 \times 49 \times 8.5 mm
Power consumption	≤ 0.8 W	≤ 0.9 W

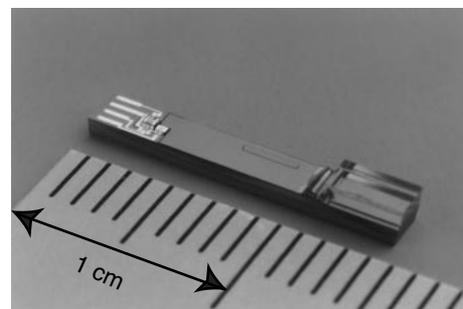
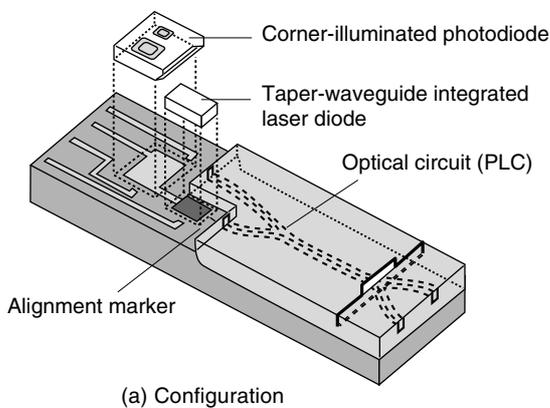


Figure 15
PLC platform technology.

bandwidth allocation in the access node. We then described the key technologies for constructing an economical optical access system; namely, a high-performance burst mode transmitter/receiver, innovative techniques for reducing components, and the PLC platform technology. This architecture and technology has been successfully applied to commercial systems. A dynamic bandwidth allocation mechanism and fully PLC-based optical modules are currently under development for the next commercial systems.

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