

Fiber-to-the-Home Services Based on Wavelength-Division-Multiplexing Passive Optical Network

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Invited Paper

Abstract—It is anticipated that more than 75 Mb/s per subscriber is required for the convergence service such as triple-play service (TPS). Among several types of high-speed access network technologies, wavelength-division-multiplexing passive optical network (WDM-PON) is the most favorable for the required bandwidth in the near future. Furthermore, WDM technologies, such as athermal arrayed-waveguide grating (AWG) and low-cost light source, have matured enough to be applied in the access network. In this paper, the authors propose and implement a WDM-PON system as a platform for TPS. The system employs an amplified spontaneous emission (ASE)-injected Fabry-Pérot laser diode scheme. It has 32 channels of 125 Mb/s and adopts Ethernet as Layer 2. Multicast and virtual local area network features are used for the integration of services such as Internet protocol high-definition broadcast, voice-over Internet protocol, video on demand, and video telephone. The services were demonstrated using the WDM-PON system.

Index Terms—Convergence of services, ethernet, fiber-to-the-home (FTTH), multicast, passive optical network (PON), triple-play service (TPS), wavelength-division multiplexing (WDM).

I. INTRODUCTION

SINCE the Internet and broad-band access networks were introduced during the last decade, the communication industry has been experiencing dramatic changes. Network providers are facing the challenge of developing new business models through innovation of their existing network infrastructure. Triple-play service (TPS) is believed to be a promising business model for the network providers. Voice, data, and video services can be integrated in the form of TPS, which is delivered through a single network. The capacity of the backbone network can be expanded relatively easily by wavelength-division-multiplexing (WDM) technology. However, the improvement of access networks involves much more complicated aspects.

There exist various competing technologies for high-speed access networks, and adoption of technology depends on several

factors, such as cost, demand of bandwidth, and subscribers' environments. In addition, access networks need to evolve according to the increasing demand of bandwidth. Since the inception of high-speed access service, the network providers had to upgrade their access networks without increasing revenue because of the competition and increased demand for bandwidth. The upgrade cost is significant for the network providers, and therefore, it is important for network providers to build a future-proof access network. In addition, the current demand of bandwidth is approaching the limit of transmission capacity of copper-based technologies such as digital subscriber line (DSL) or cable modem.

Therefore, network providers are urged to deploy optical fiber deeper and deeper in the access network to accommodate the bandwidth demand. The optical access network can be categorized as fiber-to-the-curb (FTTC), fiber-to-the-building (FTTB), and fiber-to-the-home (FTTH), depending on the degree of opticalization of the access network. Even though it is very difficult to predict the future demand of bandwidth for subscribers, it is generally agreed that the demand will keep increasing. As video communications such as video telephone and video on demand (VOD) becomes popular, the partial opticalization of access network such as FTTC may not be able to provide the required bandwidth. While various types of FTTH schemes have been proposed, passive optical networks (PONs) are most favorable for the network operators in terms of maintenance and operation. Even though time-division multiple-access (TDMA)-PON utilizes the bandwidth of fiber effectively, it has limitations in the increase of transmission speed. On the other hand, the wavelength-division multiple-access (WDMA) scheme, WDM-PON, becomes more favorable as the required bandwidth increases. In addition, the effect of statistical multiplexing is insignificant in multimedia communications environments. Even though WDM-PON has several advantages over TDMA-PON, it has failed to attract attention from industries because of the high cost of the WDM light source. Recently, amplified spontaneous emission (ASE)-injected Fabry-Pérot laser diode (FP-LD) was proposed as a low-cost WDM light source [1]. It is distinguished from other options in that all the elements in the system are readily available and costs are low.

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The ASE-injected FP-LD scheme was employed to build a WDM-PON system that supports high-definition television (HDTV) broadcasting, voice-over Internet protocol (VoIP), plain and old telephone service (POTS), and video telephony. The system consists of an optical physical media dependent (PMD) layer, a WDM-PON media access control (MAC) layer, layer 2, and layer 3. Ethernet adaptation and switching is processed in layer 2, and Internet protocol (IP) routing, subnetting, and dynamic host configuration protocol (DHCP) server functions are performed in layer 3. In addition, time-division multiplexing (TDM) is processed for POTS. The HDTV broadcasting, video telephony, and VoIP services were successfully demonstrated using the WDM-PON system in the laboratory.

In this paper, a WDM-PON system is presented that can function as a service platform for TPS. In Section II, the future service and required bandwidth will be predicted, and it will be shown that WDM-PON is most favorable for a converged network for future services. Section III presents the operation principles and performance of WDM-PON which employs ASE-injected FP-LD scheme. Section IV contains the architecture and protocol stack of the proposed WDM-PON system for TPS. In Section V, the demonstration of new services through the implemented WDM-PON system will be explained.

II. BACKGROUND

Since the successful deployment of asymmetrical digital subscriber line (ADSL) access network, the penetration of a high-speed access network is increasing worldwide. In addition, the demand for higher speed is ever increasing. Initial application of the high-speed access network has been the Internet access. As the number of Internet users increases and the bandwidth improves, the contents of Internet websites tend to shift from a text-based page to a picture- and video-based page. In addition, the usage pattern of Internet shifts from web surfing to download and streaming of multimedia contents.

Another motivation for the implementation of a high-speed network is the convergence of broadcasting and telecommunication. Currently, voice, broadcasting, and data are delivered to subscribers in separate networks, that is, public-switched telephone networks (PSTNs), cable television (CATV) networks, and DSL. However, it is believed that the three separate services can be offered in the integrated form of TPS which is delivered by a single network. Further, the services may be displayed by a single piece of equipment. In the multimedia communication environment such as TPS, the statistical multiplexing effect is not significant, and the guaranteed bandwidth, rather than the maximum bandwidth, becomes more important. The guaranteed bandwidth per user is estimated to be more than 75 Mb/s in the near future, as shown in Table I.

While there have been several proposals for video broadcasting overlay over PON [2], [3], IP multicast technology is bandwidth efficient and has proven to be reliable and scalable. Furthermore, IP-based video delivery allows target advertisement (TA) by which advertisement is customized and the effect is enhanced. In addition, IP-based delivery of video content allows the time-shifted viewing services such as private video recording (PVR), VOD, and time-shifted TV. In the established

TABLE I
GUARANTEED BANDWIDTH PER USER REQUIRED
FOR TRIPLE-PLAY SERVICE

Services	Bandwidth [Mb/s]
Three HDTV Channels	60
Internet	10
Video Conference (Phone)	2
Telemetric / remote control	1
Total bandwidth	> 75

broadcasting industry, the value of a program has been determined not only by the content but also by the scheduling of time. The time-shifted viewing environment of TV programs eliminates the imposition of a schedule and creates additional value in the broadcasting. Therefore, IP-based video delivery is in a more favorable position for the convergence service of telecommunication and broadcasting than the video overlay over PON.

For the provisioning of the bandwidth required for TPS, the existing copper-based infrastructure such as a twisted pair and a hybrid fiber coaxial (HFC) network is not appropriate because of the limited bandwidth. FTTH network architectures can be divided into two main categories according to fiber distribution architecture [4]: one is the point-to-point star (also known as home run) architecture, and the other is the double-star architecture. In the home run architecture, the required number of fibers is the same as that of the subscribers, and it is expensive to install and handle the numerous fibers. Obviously, it is not appropriate for the massive deployment. In the double-star architecture, however, many subscribers share one fiber line through a remote node (RN) that performs one of active switching, passive power splitting, or wavelength (de)multiplexing functions. The RN is located between the subscribers and the central office (CO) and can be active or passive depending on whether the RN is electrically powered or not.

The double-star architecture with active RN is referred to the active optical network (AON), and the double-star architecture with passive RN is referred to as the passive optical network (PON). PON has advantages over AON in terms of installation, operation, and maintenance of network. PON can be divided into several categories according to multiple-access schemes such as subcarrier multiple access (SCMA), TDMA, and WDMA.

In SCMA, the baseband signal of a subscriber modulates a radio-frequency (RF) carrier with a unique frequency to the subscriber, which subsequently modulates a lightwave [5]. It needs high optical power as the number of subscribers increases because of the clipping-induced noise.

In TDMA, the collision of signals is avoided by the access control protocol, including ranging and cell allocation to each subscriber. TDMA has drawn interests from industries. ATM-PON was standardized by the International Telecommunications Union—Telecommunications Standardization Sector (ITU-T) [6], and Ethernet-PON (E-PON) is in the process of standardization [7]. TDMA has merits in that it can utilize the bandwidth of optical fiber effectively by the statistical

multiplexing of traffic for several subscribers. In TDMA, the downstream signals are broadcast, and optical signal power is split at the RN. The upstream signals of subscribers are combined at the RN. Therefore, security algorithms for downstream signals and collision-avoiding algorithms for upstream signals are required.

Even though TDMA has several advantages as an optical access network, it has several problems as well. Since the optical power splitter is used in the RN, the optical power loss of both direction signals increases as the number of optical network units (ONUs) increases. In addition, the splitting ratio is limited by the optical power of optical transmitters. The performance and speed of TDMA is restricted by the inherent characteristics of burst data transmission. First, the transmitter should turn off the signal power during transmission of other channels, because background light will degrade the signal-to-noise ratio (SNR). Therefore, the optical power of the transmitter cannot be controlled by measuring the average optical power. In addition, there exists turn-on delay before the data changes from low to high level. Second, the level of the optical signal varies depending on the distance from the ONUs. It increases the complexity of the optical transceiver. Therefore, the burst-mode transmission of TDM-PON makes it difficult to increase the speed high enough for TPS.

In WDMA, signal collision is avoided by allocating a dedicated wavelength for each subscriber. As WDM technology has matured during successful applications in backbone networks, there have been several suggestions for application of WDM to access network. The proposals can be classified as hybrid WDM-PON solution and WDM-PON. The former proposals attempt to take advantage of a combination of merits of WDM-PON and those of other technologies. TDMA-PON partially employs WDM to add additional services [6]. WDM/SCM PON was proposed to increase the utilization of bandwidth [8]. WDM-FTTC was proposed to use the existing copper lines and simplify the ONU [9]. However, the combination of technologies results in the combined effects of demerits as well as the merits.

In WDM-PON, the optical line terminal (OLT) in the CO and optical network terminal (ONT) of each subscriber are virtually point-to-point connected through the dedicated wavelength. WDM-PON has inherent advantages over TDMA-PON in terms of bandwidth, protocol transparency, security, and simplicity in electronics, etc. In addition, the splitting ratio is not limited by splitting loss at the RN. However, the bandwidth for the dedicated wavelength is not fully utilized. While several schemes of WDM-PON have been proposed, the cost of the system has been of main concern. Even though distributed feedback laser diode (DFB-LD) has been dominantly used in the long-haul WDM transmission, it is not appropriate to be used in access network. One of the problems is that it is not easy to manage the wavelength of DFB-LDs in each subscriber's premise. Management of the wavelength of the optical transmitters in the subscribers' side is a significant burden for network operators. The other problem is that the cost reduction is limited due to the low production yield.

Several approaches have been proposed to solve the problems. Spectrum slicing using a broad-band incoherent light

source such as a light-emitting diode (LED) or an ASE of the erbium-doped fiber amplifier (EDFA) have gained great attention [10]–[12]. The broad-band light sources are used as transmitters and the wavelength for each subscriber was allocated by spectrum slicing at the arrayed-waveguide grating (AWG). The LED can be fabricated at a low cost and modulated directly. However, its output power is insufficient to accommodate many channels by spectrum slicing. The spectrally sliced ASE light source provides much higher output power compared with the LED. Unfortunately, it requires an expensive external modulator. The PON employing a spectrally sliced FP superluminescent laser diode (SLD) was proposed [13]. However, its performance is inherently limited by the intensity noise induced by the mode partition and/or the mode fluctuation [14], [15]. The F-P SLD can be converted to a single-mode laser by injection locking with an extra stable single-mode coherent light source [16], [17], but it is not cost effective, since we need a stable coherent source. A reflective semiconductor optical amplifier (R-SOA) was used to modulate and amplify the spectrum-sliced broad-band noncoherent light source and coherent laser light source [18], [19]. A strained quantum-well structure is employed to obtain high quantum efficiency and to alleviate polarization dependency; however, the cost reduction of the R-SOA is limited.

Recently, a novel scheme of ASE-injected FP-LD was proposed for WDM-PON. [1] Since it is expected to be economical and practical, the scheme was employed to implement a WDM-PON system, which will be described in detail in the following sections.

One of the key devices for WDM-PON is a (de)multiplexing device. There are many candidate devices, such as fiber type, thin-film type, and planar lightwave circuit (PLC) type. AWG is most favorable for (de)multiplexing a great number of wavelengths, since it can be manufactured by silica-based PLC technology. In addition, temperature-insensitive AWG was developed, and it seems quite reliable [20]. It eliminates the necessity for monitoring the wavelength shift of AWG, which is to be placed outdoors. The temperature dependency results from the positive thermal coefficient of silica, and the position of focusing by the interference of lightwaves from the waveguide arrays shifts as temperature changes. The temperature independency can be achieved in two ways: 1) the refractive index change of silica waveguide arrays are compensated by inserting the material, which has a negative thermal coefficient [21], or 2) the portion of waveguides for the demultiplexed lights are separated from the main part and devised to move mechanically following the focus. [22]

III. WDM-PON SYSTEM BASED ON ASE-INJECTED FP-LD SCHEME

It was shown that the wavelength of the FP-LD can be locked to externally injected spectrally sliced ASE or broad-band light source (BLS) [1]. Fig. 1 shows the experimental setup to demonstrate the operating principle of the wavelength-locked FP-LD. It consists of an FP-LD that was modulated by a 155-Mb/s pseudorandom bit stream (PRBS) data. The broad-band light source generated by pumped erbium-doped fiber (EDF) was

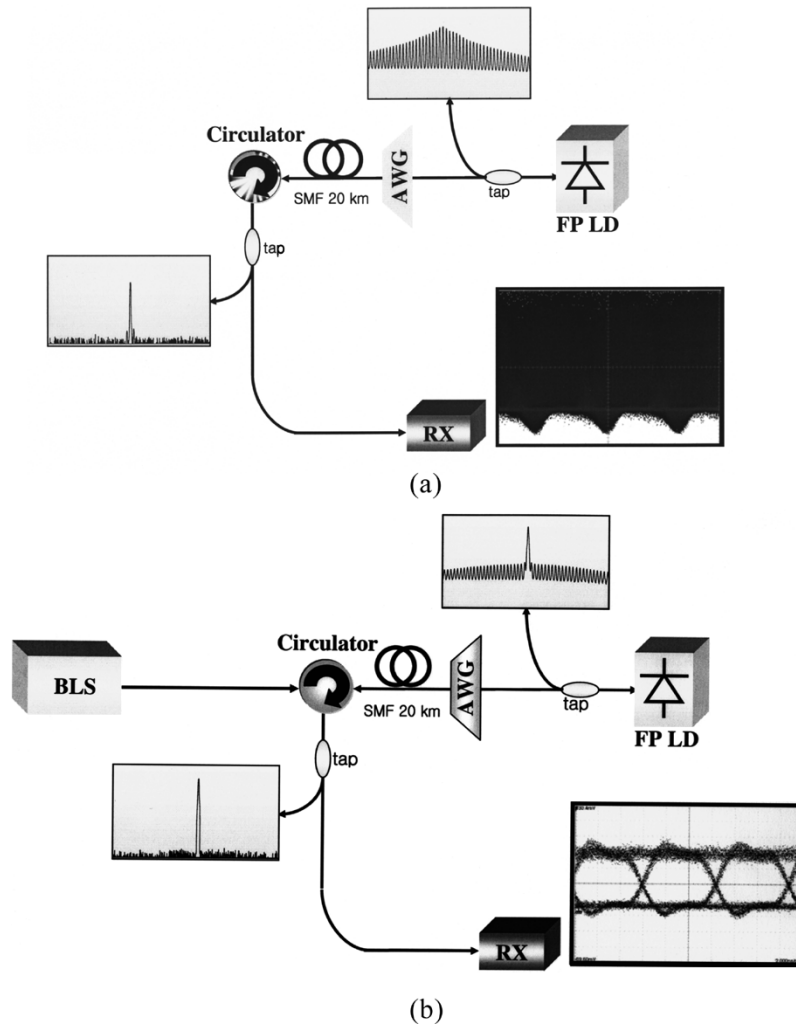


Fig. 1. Operation principles of ASE-injected FP-LD. Experimental setup for measurements of BER and spectrum of the FP-LD (a) without ASE injection and (b) with ASE injection.

transmitted through the transmission fiber before spectrum slicing. We used an AWG with wavelength spacing of 100 GHz for spectrum slicing. Then, the spectrum-sliced light was injected into the FP-LD. The light output from the laser was filtered by the AWG and transmitted through the transmission fiber. The wavelength-multiplexed signal can be demultiplexed by using another AWG after the optical circulator that separates signals from the injected ASE. Then, the bit-error rate (BER) and eye pattern were measured.

When we do not inject the ASE into the laser, the FP-LD laser shows multimode output as shown in Fig. 1(a). After the modulated multimode light is filtered by the AWG, we can observe a single-mode peak in the spectrum analyzer. However, we cannot transmit data successfully, since the power of particular mode fluctuates randomly with time. The origin of the fluctuation is randomness of the spontaneous emission coupled to each mode [14]. The eye diagram in Fig. 1(a) is the measured result, and it is completely closed. Thus, it is difficult to use the FP-LD as a WDM source by spectrum slicing of a single mode among the multimode output. However, the laser output becomes almost a single mode when we injected the spectrum-sliced broad-band light source (BLS) into the laser as shown in Fig. 1(b). The spectral power density and 3-dB bandwidth of the injected ASE

were -16 dBm/0.2 nm (-12 dBm total power) and 0.4 nm, respectively. The typical side-mode suppression is about 30 dB. We can see very clear opening of the eye. The measured BER curves show the error floor at 10^{-3} for the case of no injection as in Fig. 1(a) and error free in Fig. 1(b) with the injection. The measured sensitivity at a BER of 10^{-9} was about -38 dBm. By attaching an FP-LD at each output port of the AWG, we can generate a WDM signal. To increase the injection efficiency, we may need the antireflection coating on the front facet of the laser. In addition, the cavity length can be increased to have at least one lasing mode within the bandwidth of the injected ASE. We used an FP-LD chip with 600 μ m of cavity length and 1% of front facet reflectivity. The reflectivity was reduced to increase the injection efficiency and output power of the LD.

We measured the BER and optical power gain, defined as the ratio of emitted signal power to injected BLS power estimated in front of the FP-LD. When the injection wavelength is matched with the lasing wavelength, we achieved maximum 5-dB gain. The gain decreases about 2 dB, when we detune the injection wavelength for ± 20 nm from the envelope peak of the free-running laser. If the injection wavelength is between the two lasing modes of the laser, the gain decreases about 5 dB. We have -2 -dB minimum gain, when the detuning is ± 20

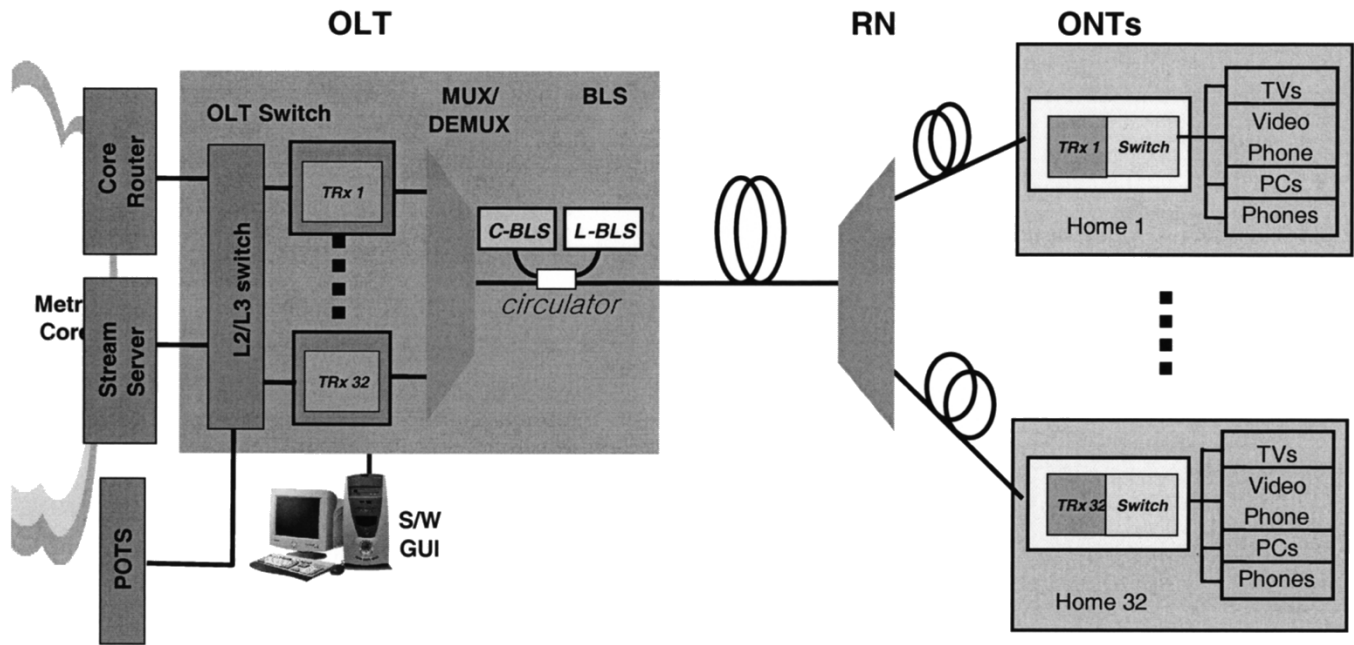


Fig. 2. Architecture of WDM-PON network employing the ASE-injected FP-LD. The TRx consists of an FP-LD, a p-i-n PD, and a thin-film filter. C-BLS and L-BLS represent the *C*-band EDFA for upstream signals and the *L*-band EDFA for downstream signals and are coupled into the optical fiber via the optical circulator.

nm and the injection wavelength is located between two modes. In other words, the minimum output power is -14 dBm. If the receiver sensitivity is -35 dBm, we have about a 21-dB link budget. The measured BER curve shows error-free characteristics whether the injection wavelength is matched with lasing wavelength or not. However, there exists a maximum 1-dB penalty due to detuning of injection wavelength from the lasing wavelength. Thus, a single FP laser can be used for a WDM source within the ± 20 -nm range.

The operating range can be increased further by using a broad-band FP-LD that has modified quantum well in the active region [23]. Since we can use a single FP-LD for all subscribers and communication wavelength is determined by the passive component (i.e., the AWG), it is possible to have a single type of transmitter/receiver, regardless of communication wavelength.

The WDM-PON system based on the proposed light source is shown in Fig. 2. We have a transmitter and receivers at the CO. In addition, an AWG and two BLSs are located at the CO. The AWG is used for spectrum slicing and multiplexing for the downstream signal. It demultiplexes the upstream signal. Two different bands of BLSs are used for bidirectional transmission over a single fiber. *C*-band and *L*-band EDFAs are used for upstream and downstream transmission, respectively. *C* band is used for upstream due to the fact that the optical loss is minimum in the *C* band. We take advantage of periodic property of the AWG for the simultaneous usage of AWG for the *C* band and the *L* band. Therefore, the center wavelength in the *L* band is off the ITU grid, while those of *C* band fits into the ITU-frequency grids. The different band signals are separated by a thin-film filter in the transmitter/receiver module. It may be realized by a bidirectional module that consists of a laser, a thin-film filter, a photodiode (PD), and a transimpedance amplifier.

The RN consists of an AWG. We may need athermal AWG for operation over a wide temperature range. At the subscriber side, each subscriber has a transmitter and receiver module to receive downstream data and to send upstream data. The transmitter and receiver module also contains the thin-film filter to separate the two different bands.

The broad-band light from the *C*-band BLS was coupled into transmission fiber via the optical circulator and sent to the AWG located at the RN. ASE is spectrally sliced by the AWG and injected into the FP-LD at the ONT of each subscriber. The upstream transmission wavelength of each subscriber is determined by the wavelength of the injected light. Hence, we can use a common type of FP-LD for upstream data transmission of all the subscribers, and the ONT is "colorless." The upstream data is multiplexed by the AWG located at the RN. The multiplexed data is transmitted through the transmission fiber. At the CO, the received data is demultiplexed by using the AWG located at the CO. Then, the receiver recovers the transmitted data.

For downstream data transmission, the *L*-band BLS is coupled into the AWG located in the CO. It is spectrally sliced and injected into the FP-LD. The lasers are modulated with the downstream data. The modulated signals are multiplexed by the AWG located at the CO. Then, it was transmitted through the transmission fiber, demultiplexed by the AWG located at the RN, and sent to the receiver located at the customer premises.

Since we allocate each wavelength for downstream and upstream, the customer can communicate with the CO regardless of the status of the other customers. In other words, the system supports dedicated connectivity between the CO and the customers.

We developed a 32-channel WDM-PON system based on the proposed scheme. We used *C* band for the upstream signal and *L* band for the downstream signal. The channel spacing is 100

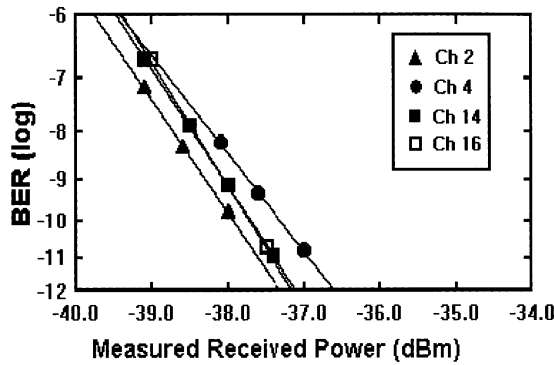


Fig. 3. Measured BER of four channels among 32 channels for transmission of 155 Mb/s over 20 km by the WDM-PON system.

GHz for *C* band. The transmission length between the ONT to the CO is 20 km. The minimum injection power into the laser is -16 dBm/0.2 nm at peak. The measured BER curves show error free for transmission over the 20 km of transmission fiber. The measured sensitivity at BER of 10^{-9} was about -38 dBm at 155 Mb/s. Fig. 3 shows the measured BER curves. No penalty was observed after transmission of 20 km.

IV. SYSTEM ARCHITECTURE

A WDM-PON system was proposed utilizing the ASE-injected FP-LD, which was described in the previous section. The system was designed to support TPS, including Internet access, voice by both of POTS and VoIP, HDTV broadcasting, and video communication. In this section, the protocols used in the system, quality of service (QoS) functions for voice and video communications service, IP-based HDTV broadcasting, and the system architecture are described in detail.

The protocol stack used in the system is shown in Fig. 4. The OLT is placed in the CO and connected to the ONT through optical fiber. In the optical PMD layer, the OLT and ONT are linked through WDM, opening point-to-point connections with a speed of 125 Mb/s. Since there is no signal collision in WDM-PON, WDM-PON MAC simply conducts the media-converting functions, which lowers the overall system complexity.

Ethernet is adopted in layer 2, where Ethernet adaptation and switching is performed. Ethernet is the most widespread technology and low cost. In addition, it provides a practical way of combining data, voice, and video for TPS through class of service (CoS) and virtual local area network (VLAN) features offered in Ethernet protocol. Layer 3 of the OLT performs routing, subnetting, DHCP server functions and serves as a V5.2 gateway for POTS. Fig. 5(a) describes functions for supporting the POTS over the Ethernet. OLT exchanges E1 voice data with the V5.2 gateway by the V5.2 protocol. For the ingress voice data, OLT terminates the V5.2 protocol and drops the E1 signal into the DS0E signals. Then, they are cross-connected to an appropriate destination. The DS0E signals are encapsulated into Ethernet frames with the highest priority and transmitted to the ONT, where the Ethernet headers are stripped out and the recovered DS0E signals are converted into analog voice. Fig. 5(b) shows the network architecture supporting VoIP service. In this case, the ONT acts as a transparent pipe

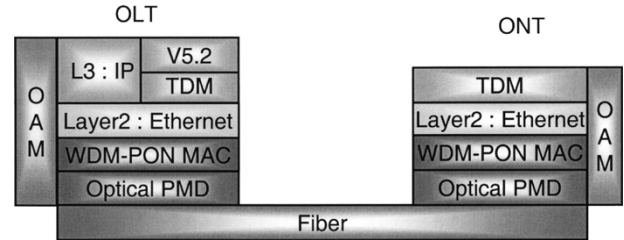


Fig. 4. Protocol stack used in the WDM-PON system.

for VoIP packets, which are passed to the IP phone through RJ45 port. VoIP packets coming through RJ45 are prioritized for scheduling with the highest priority. For voice service either by POTS or VoIP, QoS is of primary concern. In both cases, the Ethernet layer should support priority queuing, fast scheduling, and packet classification.

IP video service can be provided in Ethernet frame format using IP multicasting protocol, and we need L2/L3 QoS functions, such as packet classification, 802.1p, Diffserv, VLAN and tagging. Fig. 6 shows how QoS informations of L2 and those of L3 are inter-related.

Layer 3 supports multicast service protocol to increase the bandwidth efficiency. Protocol-independent multicast-sparse mode (PIM-SM) and Internet group management protocol (IGMP) are used for the multicast protocol in OLT and IGMP snooping in ONT. In case that the backbone network does not support any QoS scheme for multicast service, the rendezvous point should be placed as near as possible to the access network, and a unified multicast protocol, like IGMP, could be supported. Table II summarizes the protocols used in the WDM-PON system.

The video services by the WDM-PON can be divided into a unicast and a multicast service. In the unicast service like VoD, users decide when and what contents are to be delivered; in the multicast service, users are served with the scheduled contents of the broadcast service providers. The elements for video service include video head end, which broadcasts video contents and operates as a user/content administration and authentication agency, video data transmission networks, and set top box (STB). Each connection for VOD and each channel for multicasting forms a service-based VLAN.

Fig. 7 describes the overall video service network employing the WDM-PON system. Video channels from the broadcast head end are transmitted to the rendezvous point placed in the CO by either satellite network or dedicated optical network for broadcasting. Each channel is encapsulated into the IP stream and sent to the rendezvous point, which is a high-speed L3 switch. If a subscriber of WDM-PON requests a certain channel, an IGMP join message is sent to the IGMP server. During the transmission of the join message, the node tossing that message to the server looks into data base to decide whether the requested channel matches with that already in multicast, and, if yes, the node replicates and transmits the channel to the user who has requested it. In the scenario, QoS must be provided such that the multicast traffic flow is not affected by other traffic of lower priority, and the zapping time is minimized. Therefore, the rendezvous point is placed to the access network as near as possible. The back-end office is placed in the main

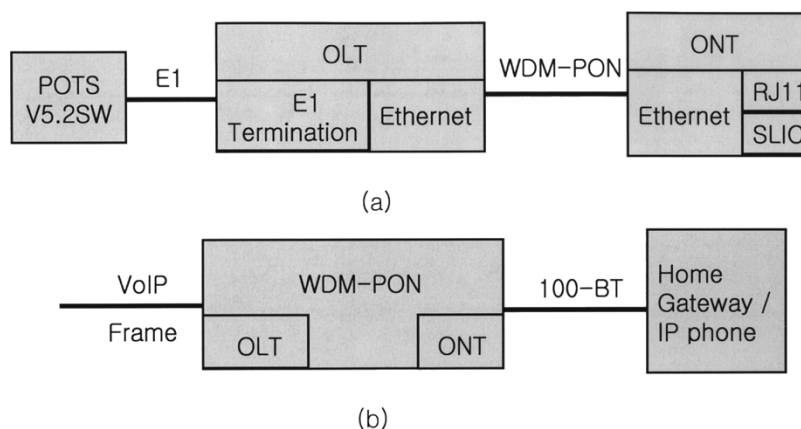


Fig. 5. Architecture of network for voice service by (a) the V5.2 protocol and (b) VoIP.

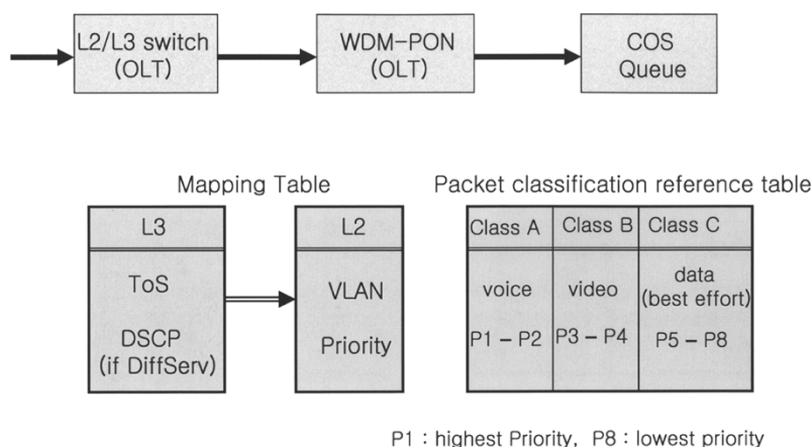


Fig. 6. Packet classification and queuing in the WDM-PON system.

TABLE II
PROTOCOLS ADOPTED IN THE WDM-PON SYSTEM

	OLT	ONT
L2	MAC Table maintenance capability Up to 4096 VLANs are supported STP(802.1d) Link aggregation(802.1ad)	MAC Table maintenance capability Up to 8 VLANs are supported
L3	Static Routing DHCP server : > 1000 IP Default Gateway : > 2	DHCP relay
QoS	Diffserv 802.1p Packet classification and marking Traffic management	802.1p Packet classification and marking Traffic management
Multicasting functions	PIM-SM IGMP server IGMP snooping	IGMP snooping
Voice	V5.2	VoIP, POTS

CO for it is shared among several access networks and QoS is not an issue between the back end and the rendezvous point.

The OLT of the proposed WDM-PON system consists of several function units.

- 1) The main control unit (MCU) controls all of the operations and management (OAM) features of the OLT and ONTs and offers administration capabilities through the element management system (EMS).
- 2) The switching unit (SWU) provides Gigabit Ethernet interface ports, switches receiving Ethernet frames to the destination port.
- 3) The TDM interface unit (TIU) processes V5.2 gateway functions and adapts receiving TDM traffic into the Ethernet frames (TDM over Ethernet), and vice versa.
- 4) The WDM-PON interface unit (WIU) transmits and receives Ethernet frames to/from the ONT connected through WDM.

The internal functions of the ONT consists of optical transceiver, Ethernet switch, and user interface with RJ11 port for POTS and RJ45 port for data, video, and VoIP.

V. DEMONSTRATION OF TRIPLE-PLAY SERVICE BY WDM-PON

The FTTH can deliver TPS including several new services such as high-definition (HD) VoD, broadcasting of HDTV, private video recording (PVR), and time-shifted TV. We implemented the WDM-PON system and performed a laboratory trial of the services, such as the HDTV broadcasting, VoD, and VoIP based on session initiation protocol (SIP), and video telephony.

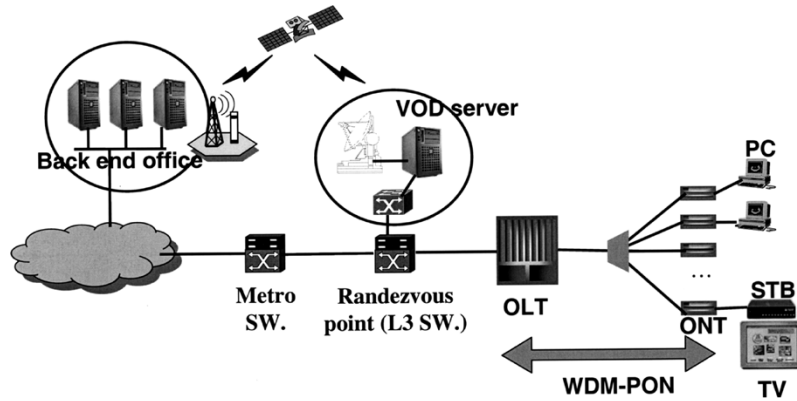


Fig. 7. IP-based delivery of video service by the WDM-PON. Each channel is delivered via either satellite network or optical network consisting of Ethernet switches.

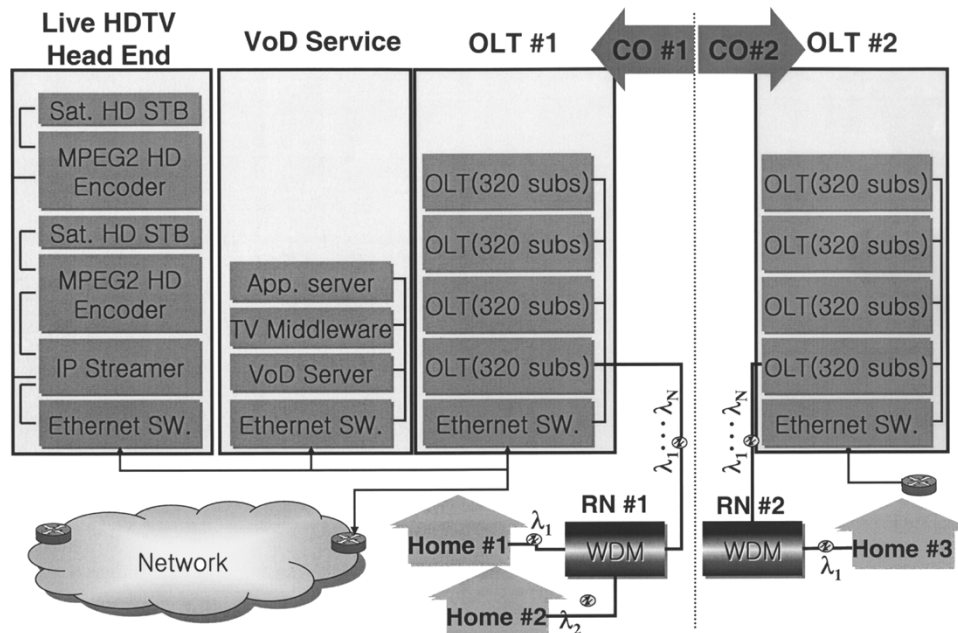


Fig. 8. Network configuration for the demonstration of TPS. Home 1 and 2 are connected to OLT 1, and home 3 is connected to OLT 2. OLT 1 and 2 are connected by the Ethernet.

Fig. 8 shows the configuration of a network for demonstration of the services. The network consists of two sets of WDM-PONs. OLT 1 serves home 1 and home 2, and OLT 2 serves home 3. OLT 1 and OLT 2 are connected by Ethernet switches. The system supports Internet access, HD IP TV, HD and standard definition (SD) VoD, VoIP, and video telephony. Table III summarizes services provided in the demonstration. We implemented an IP-based HDTV broadcasting system. The HDTV content is provided from a satellite TV provider and encoded into a 4:2:2 profile and level, 1080i resolution, and constant bit rate (CBR) and variable bit rate (VBR) format by an HD encoder. The streamer is for encapsulation of data into the IP packet, which is multicast to subscribers through WDM-PON. For HDTV MPEG 2 decoding and generation of analog video signal, we developed HD IP STB, which includes a hardware HD decoder and runs Linux. For the implementation of video telephony, we employed the video compression in digital video (DV) format, which is similar to motion JPEG and the IEEE 1394 interface for exchanging a digital video stream. DV/RTP (real-time transport protocol) was implemented for the assur-

ance of interoperability. The system successfully supported the services indicated in Table III. Even though the number of subscribers was limited, the trial showed the possibility of the HD-grade TPS by WDM-PON.

VI. CONCLUSION

Facing the challenges of creating new business models, network providers are seeking the optimal way of innovating the existing network infrastructure. TPS is expected to improve as a social benefit as well as create a new business chance for network providers. Voice, data, and video communications can be integrated into TPS and delivered through a converged network. The estimated required bandwidth for TPS in the near future is greater than 75 Mb/s per subscriber. Since the copper-based infrastructure cannot support the required bandwidth, the network providers are required to opticalize their access network. The authors of this paper believe that FTTH is in a more favorable position than the partial opticalization, such as FTTC, considering the upgrade cost and the required bandwidth in the near fu-

TABLE III
SERVICES OFFERED FOR EACH HOME IN THE DEMONSTRATION

Home (bandwidth)	STB	Equipments at home	Services
Home#1 (34Mbps)	IP HD STB 2 IP SD STB 1	ONT, L2 SW Notebook	1. HD VOD and SD VOD 2. Internet access by PC
Home#2 (47Mbps)	IP HD STB 3	ONT, L2 SW Camera 1, VoIP(SIP) 1	1. Video telephone 2. Internet access by TV 3. VoIP based on SIP
Home#3 (87Mbps)	IP HD STB 4 IP HD STB 1	ONT, L2 SW Camera 2, VoIP(SIP) 2 Notebook	1. Video telephone 2. Real time HD IP Multicasting 3. HD VOD 4. VoIP based on SIP 5. Internet access by PC

ture. Even though WDM-PON has several prestigious features compared with other schemes such as TDMA-PON, it has little success in commercialization, the reason being that there has been no practical and low-cost solution for a WDM light source. Recently, the ASE-injected FP-LD scheme was proposed, and it turned out to be low cost and practical. Furthermore, WDM technologies have matured enough to be applied in the access network. For example, athermal AWG has achieved reliability and has been commercialized. The authors of this paper have proposed and implemented a WDM-PON system that employs the ASE-injected FP-LD scheme. It was shown that the FP-LD can function as a WDM light source with the operation wavelength range of 40 nm. The system has 32 channels with wavelength spacing of 100 GHz. Athermal AWG was used as an RN. *C* band was used for upstream, and *L* band was used for downstream signals. Both upstream and downstream signals use the common AWG in the RN and OLT and are separated by a thin-film filter in the ONU and OLT. The measured sensitivity at BER of 10^{-9} was about -38 dBm at 155 Mb/s. The Ethernet was adopted as layer 2 of the system. The Ethernet protocol has features of multicast and VLAN, which are effective in implementing IP broadcasts and combining several services, such as voice, data, and video. In this paper, HDTV broadcasting, VOD, VoIP, and video telephony services by the proposed WDM-PON system were successfully demonstrated.

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