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A WDM-Based Future Optical Access Network and Support Technologies for Adapting the User Demands’ Diversity

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SUMMARY  We propose the network on demand concept to yield the optical access network system that well handles the diversity in user demands and support technologies such as module and devices configuration. In this proposal, the network accommodation equipment, such as OLT needed for each service, is installed ‘virtually’ using WDM, and the physical rate can adapt to the user-demanded service rate by using the WDM parallel transmission technique. It well handles the diversity in user demands/services and lowers system power consumption.

key words: access network, WDM, diversity, adaptive

1. Introduction

The recent spread of broadband access systems such as Fibre To The Home (FTTH) has been remarkable and will accelerate the increase in demands for higher speed and broadband services. The diffusion of FTTH will also further diversify user demands, for example, the used bandwidth for each user will expand to encompass a minimum of several kbps and a maximum exceeding 10 Gbps. On the other hand, with the recent emphasis on the environment, lowering the power consumption of communication systems has become increasingly important \cite{1}, \cite{2}. Accordingly, current research and development activities are mainly focused on ecological systems. Recently, the high efficient use of resources is researched actively from the viewpoint of ecology in various fields. In the field of power supply, the smart grid technology \cite{3} has been proposed and examined; this technique integrates the communication and control system into the physical power infrastructure; its goal is to fine tune the supply-demand tradeoff by connecting power generation facilities to the consumers, i.e. homes and factories. Accordingly, researchers in the optical communication system field should look beyond existing solutions to develop new paradigms and technologies that can significantly enhance power efficiencies. The need to support the diversification of user needs, which implies higher speeds and wider bandwidth, conflicts with the need to increase utilization efficiency and reduce system power consumption. To resolve these problems, we believe that the ideal access system is the adaptive optical access network (AAN), which autonomously optimizes itself to support the service demanded by the end user. Furthermore, we think that the ‘on demand type NW’ which provides just the bandwidth needed by the end user only when it is needed, is more effective than the conventional ‘static type NW’ which is always active even if traffic is very low. Together, these two technologies represent a new direction in system power reduction. We believe that wavelength division multiplexing (WDM) \cite{4} has the potential to significantly reduce system power consumption and promises the superior network flexibility needed to meet expected and unexpected user demands by offering rate extendibility as well as user and service multiplexing.

This paper proposes the network-on-demand (NoD) concept based on WDM as a future optical access network system, its network architecture, and support technologies. The proposed system well handles diversity in user demand, which is expected to continue to increase, and lowers system power consumption.

In next section, we predict the trends in optical communications; the services expected and the network systems to support the services. In Sect. 3, we propose the future optical access system, and introduce the network configuration and characteristics of our proposal. In Sect. 4, we propose the supporting technologies such as optical network unit (ONU) configuration, optical line terminal (OLT) configuration, and device technologies for realizing the proposed optical access system. In particular, we show the technologies needed to realize the ONU of the proposed network. Section 5 summarizes our proposal and details future work.

2. Trends in Optical Communications

This section shows the trends in communications services and the optical communication systems for supporting these services.

2.1 Services Trends

The spread of optical access systems will encourage the appearance of various services that have quite different characteristics. We predict that 2 types of services that strongly differ from mainstream services will emerge; one demand super wide bandwidth and low latency and the other needs only low bandwidth, latency is not important.

2.1.1 Super Wide Bandwidth Services

These provide high quality connections with bandwidths...
of more than 10–100 Gb/s and low transmission latency between end points. They are the target of many studies; typical services include high quality interactive video-conferencing with uncompressed high-definition video streams and Giga-byte-class digital file transfer between customers.

2.1.2 Super Low Bandwidth Services

Each of these accommodates an enormous number of terminals with very limited functions. Sensor nodes are the best examples of such terminals. These services will handle ‘event’ data from the terminals effectively at small cost. In the future, information and communication technology (ICT) will be applied to not only Internet contexts, but also various events in the real world. In next section, we describe the network requirements for supporting both types of services mentioned above.

2.2 Requirements of Optical Access Networks

To respond to the wide variety of customer requirements, an optical access network should be capable of providing a wide range of network services while efficiently utilizing resources which include equipment, energy, and wavelengths. One example of the efficient use of network resources in core networks is provided by SLICE (spectrum-sliced elastic optical path) [5]; end-to-end optical paths are allocated just the right size optical bandwidth by ‘slicing off’ the necessary spectral resources. We believe that future optical access networks must, considering cooperation with the core networks, meet the following requirements; (1) high-speed, wide bandwidth and low latency for large capacity service, i.e., super high quality communication systems, (2) support for a wide diversity of user needs, (3) lower overall power consumption.

2.2.1 High-Speed, Wide Bandwidth and Low Latency

The current growth in broadband access applications is demanding network system configurations that provide wider bandwidth, higher flexibility and better economy. In Japan, the gigabit Ether passive optical network (GE-PON) [6], which is based on time division multiplexing (TDM), is being introduced extensively. Furthermore, research and development of 10G-EPON [7] and standardization activities are underway to yield an attractive high-speed GE-PON. As shown in Fig. 1, we think that the optical access system will be based on TDM until the limit of electrical devices is reached, which may be about 10 Gb/s. WDM technology will be necessary for realizing high-speed networks beyond 10 Gb/s, because WDM-based systems allow the physical rate in each channel to be lowered compared to a TDM-based equivalent to the point that we can eliminate compensation techniques such as optical amplifiers; a significant cost saving.
it adapts to the diversity of user demands with low network system power consumption.

3. Future Optical Access Network System

In this section, we introduce the concept of the future optical access network system, its system configuration and characteristics.

3.1 Concept of Future Optical Access Network

Our solution to satisfying the network requirements above mentioned is the NoD, which is a novel optical access network architecture. AAN is one key network configurations for realizing the NoD concept as shown in Fig. 3. When an end user starts using some service in the network, the network autonomously optimizes itself for the service. To realize AAN, we believe that the access system must first pass through two phases as shown in Fig. 3. We call the first phase the ‘wide band and low latency NW.’ The second phase is the ‘flexible NW.’ While this second phase cannot, by itself yield the AAN, it has sufficient flexibility to support new service demands such as higher transmission speeds and new service applications. Furthermore, we assume 2 scenarios to elucidate the development of future optical access networks, see Fig. 4. Scenario 1 demonstrates high-speed and wide bandwidth and is basically the conventional trend. Scenario 2 is the new direction; it covers network ecology. For scenario 1, we think that the network bandwidth has already exceeded the bandwidth needed for introducing applications which average user uses, and may exceed the processing power of individual machines used for computer-to-computer communication in the near future, we expect that it will be about several hundreds Gb/s considering progress of devices technologies as shown in Fig. 4. We think that bandwidth extension is not so important, so we paid attention to scenario 2 and researched the key technologies for realizing scenario 2. Furthermore, we think the network will gradually change from ‘static type’ to ‘on demand type.’ The ‘static type NW’ is always active even if traffic is very low. On the other hand, the ‘on demand type NW’ provides just the bandwidth needed by the user when needed, so system power consumption can be reduced dramatically.

3.2 Configuration of Future Optical Access Network

We think that it is necessary to reconsider network design theory if we are to radically reduce system power consumption. From the viewpoint of ecological networking, the most effective area to address is the access networks because there will be tens of millions of nodes such as OLTS and ONUs, all of which are now permanently “hot.” Our research target is building an AAN that is ‘energy scalable’; i.e. provides just the bandwidth that the user actually needs. In addition, the AAN will be able to accommodate access lines at virtually any point in the core network. Figure 5 shows the NoD architecture based on WDM. In the conventional network shown in Fig. 5(a), all services are terminated at the OLT. Figure 5(b) shows that the proposed network has two OLT modes; one is the termination mode (same as conventional OLT), the other is the pass-through mode, which uses WDM techniques to forward the data to the next OLT. In the example shown in Fig. 5(b), services (#A_p2, #A_p3) pass through OLTS #1 and #2, and are terminated at OLT #3. Service #A_p1 is terminated at OLTs #1 and #2. Such OLTS are called ‘elastic’ and employ a wavelength SW to realize termination or pass-through. Furthermore, for improving network flexibility, the elastic OLT has wavelength conversion. The proposed network can provide the responsive network that reforms itself to more efficiently support each user.

3.3 Characteristics of Proposed Network

The proposed network system can assign just the number of wavelengths needed when needed, which is very effective from the viewpoint of reducing system power consumption and the efficient use of wavelength resources. It well supports user and service applications by offering rate extensibility; instantaneous demand changes can be satisfied by combining control in the time and wavelength domains.

Fig. 3  Adaptive optical access system.

Fig. 4  Directions for network development.
3.3.1 Improvement of Accommodation Efficiency

The proposed system improves the accommodation efficiency by changing the termination-OLT according to the service; low rate services will be terminated at the far side OLT and high rate services at the near side OLT. This is done because the network’s transmission performance is dependent on the physical rate; low rate services can be provided with long distance transmission. As an example, the improvement of receiver sensitivity of about 10 dB can be achieved if the low physical rate was assumed to 1/10 of high physical rate, which corresponds to the transmission length improvement about 20 km. This shows that the improvement of accommodation efficiency and the high efficient use of resources such as network equipment can be realized by FTTH service area expansion, and so it leads to construct the optical access systems economically.

3.3.2 Improvement of Power Consumption

Proposed system based on WDM can introduce the optical access system with drastic low power consumption because it is possible to make the physical rate closely match the service rate. As an example, Fig. 6 shows the power consumption of ONU, which is calculated by circuit simulator. In proposal, the operation rate of each wavelength was assumed to $f_{\text{max}}/M$; where $f_{\text{max}}$ is maximum operation rate in TDM-based system and $M$ is the number of wavelengths used in proposed system. As shown in Fig. 6, it is clear that proposal is effective compared to TDM-based system from the viewpoint of power consumption. And it is observed that the power consumption of proposal is larger than that of TDM-based system at operation rate $f_{\text{max}}$, which is caused by the additional circuit such as MUX which multiplexes the signals of each wavelength. These results show that proposal is effective when the average rate of user used is smaller than $f_{\text{max}}$ and there is the diversification of user used bandwidths.

In the next section, we propose the fundamental devices technologies needed for realizing the proposed optical access network.

4. Support Technologies

This section proposes the support technologies for realizing proposed network. In particular, this section focuses on the devices technologies which are necessary for realizing ONU.

4.1 Technologies for Realizing Proposed Network

If the proposed network is to offer the above mentioned performance attributes, such as high-speed, wide dynamic range, flexibility and low power consumption, the WDM parallel transmission technique is a key technology. In the next section, we describe the configurations of key devices such as OLT and ONU.

4.2 Equipment Configuration for Proposed Network

In this section, we show the technologies that offer network flexibility with economy.

4.2.1 Techniques for Wide Bandwidth and Flexibility

We think that parallel transmission techniques based on WDM are very effective, because they can decrease the physical rate in each channel to the point that no loss compensation techniques are needed. The basic physical line rate in each channel is the maximum physical rate that can be transmitted within the loss budget of 29 dB as defined in NTT’s GE-PON optical access system without optical
power compensation techniques such as OAMP or high-sensitivity APDs. In the proposed system, multiple wavelengths are offered to the user and the user selects the wavelengths needed to enjoy the service desired. This system makes it easy to increase bandwidth by increasing the number of wavelengths. The next subsection describes the ONU and OLT configurations that can support the proposed system.

4.2.2 ONU Configuration

As shown in Fig. 7(a), the optical receiver module used in the proposed network includes WDM filter, Pin-PDs, transimpedance amplifiers (TIAs), auto gain control amplifier (AGC), deskew LSI, flexible multiplexer (FMUX) and fixed 4:1 multiplexer LSI, switching circuit (SW) and rate control circuit. The transmitter includes WDM filter, LDs, LD drivers, demultiplexer (DEMUX), SW and rate control circuit as shown in Fig. 7(b). FMUX includes a clock data recovery (CDR), data selector and flexible parallel/serial (P/S) converter. The rate control circuit changes the operation mode such as line rate. Optical receiver and transmitter module are modularized in units of 4 channels (wavelengths) as shown in Fig. 7. Overall power consumption is reduced because each module operates independently.

4.2.3 OLT Configuration

As shown in Fig. 7, OLT has two modes (termination and pass-through). System 1 has the fixed type configuration in which the wavelengths that are terminated and those that are passed-through are fixed. System 2, our final OLT configuration target, is flexible since the wavelengths terminated and passed-through can be varied. This final OLT mounts a MEMS-based wavelength selector. This makes it possible to change the equipment used to suit the service; it leads to continuous improvements in equipment application efficiency and power efficiency. In next section, we propose the technologies that can realize the elastic ONU.

4.3 Devices Technologies

The proposed optical access system is based on WDM; the basic physical rate is 2.5 Gb/s in each wavelength. Because the optical access system must be constructed economically, it is important to keep GE-PON loss budget to within 29 dB without amplifier devices. The physical rate of 2.5 Gb/s is reasonable to satisfy its requirement. In general, TDM-based systems have simple and low cost module configurations because additional optical devices such as WDM filters are not necessary. Unfortunately, receiver sensitivity degrades as the physical rate increases due to the thermal noise created by the transimpedance of the preamplifier. In the case of a PON system that uses a PS, it is necessary to compensate the optical power loss by following technologies; (1) decreasing the splitting ratio of the PS, (2) using high sensitivity APDs in place of Pin-PDs, and (3) installing an OAMP (optical amplifier) between OLT and ONUs. All of these approaches will increase total system cost, particularly at over 10 Gb/s. To overcome these problems, parallel transmission scheme using wavelength multiplexing are very effective, because they can decrease the physical rate in each channel compared to TDM systems, so no compensation techniques are needed.

On the other hand, WDM parallel transmission scheme have some issues. The next subsection introduces our solutions.

4.3.1 Skew Compensation Technique

In the proposed optical access system, to reconstruct the original data frame accurately, the different wavelength streams must reach the P/S converter in the receiver at virtually the same time. However, because of fiber dispersion, signals transmitted at different wavelengths will not be received at the same time even if they were transmitted simultaneously. This timing difference, called timing skew, must be compensated. Previously proposed skew compensation techniques include dispersion compensating fiber (DCF), bit realignment with shift registers, both are capable of fine and coarse synchronization, optical delay lines integrated with arrayed waveguides gratings, and fiber Bragg gratings [8]–[10]. In the optical access network, it is preferable to put the skew compensator in the ONU because each ONU lies at a different length from the OLT, so the compensator must be small, wide range, and flexible.

A. Requirements

The required skew compensator specifications for our system are as follows; (1) the range of skew compensation should be at least 8 ns (all wavelengths lie within 20 nm), the maximum fiber length between OLT and ONU is 20 km in NTT’s network and the C-band dispersion parameter is...
about 20 ps/nm/km), (2) handle four input streams simultaneously, and (3) the resolution should be better than 200 ps (each data stream is transmitted at 2.5 Gbit/s, and the maximum permissible timing deviation at the following circuit is one half of one-bit period).

B. Circuit configuration

To meet all the above requirements with a compact and low-cost device, we designed a skew compensation LSI (deskew LSI) [11]. It has four input/output ports and sets the desired delay values for each port by driving the delay gates as appropriate. The configuration of our LSI and its delay gate structure are shown in Fig. 8. In the LSI, each port consists of some sets of unit structures. Each unit structure has delay gate(s) in only one arm with switching elements at both ends; for each channel, each unit structure has twice as many delay gates as its upstream neighbor. Ideally, the timing skews of the streams are proportional because the wavelength interval of our system is uniform. Therefore, port C and D have two and three times as many delay gates as port B, respectively. In order to achieve delays of more than 8 ns, each port has seven units.

C. Performances

We fabricated the LSI using the SiGe 0.25 μm BiCMOS process. Figure 9 shows a photograph of our skew compensation LSI; the chip size is 4.5 mm × 4.7 mm.

Figure 10 shows the temperature (25, 50, 70°C) dependencies of deskew range in port B, C and D based on port A as shown in Fig. 7 and least squares better (LSB) of integral nonlinearity (INL) and differential nonlinearity (DNL) as deskew performance metrics. As shown in Fig. 10(a), the proposed electrical deskew circuit has a wide range, over 9.6 nsec, and good temperature stability. Its delay resolution is about 25 psec and its pulse width fluctuation is less than 10%. Furthermore, power consumption is very low at less than 1.85 W. Figure 10(b) shows the signal waveforms before and after 9.6 nsec deskew. Timing jitter is 27.8 psec and 33.3 psec before- and after-deskew, respectively. Timing jitter degradation of the deskew circuit is very small at about 5.5 psec.

4.3.2 Flexible Multiplexing Technique

In this subsection, we describe the circuit functions of the FMUX LSI, a key device for realizing bandwidth flexibility in the WDM scheme.

A. Requirements

The required FMUX specifications for our proposed system are as follows; (1) extract necessary signal from two or more parallel input signals which are transmitted from OLT at each time slot, (2) the operation bit rate range is 2.5 Gb/s to 10 Gb/s, and (3) mounts voltage control oscillator (VCO) and phased locked loop (PLL) circuits on the same LSI for enhanced network system economy.

B. Circuit configuration

We have designed a FMUX LSI with 4 physical input ports, in which 2.5 Gb/s data signals are input to each physical port. FMUX converts the 2.5 Gb/s × 4 parallel data signals sent from OLT to the physical rate desired by the user in each time slot and outputs the results to any pre-selected port. A 10 GHz clock signal for clock and data recovery (CDR) is extracted from the 2.5 Gb/s data signal, one of the 4 parallel data signals. Figure 11 shows a block diagram of the proposed FMUX LSI with 10 GHz on-chip PLL circuit. As shown in Fig. 11, the FMUX LSI includes flexible parallel-to-serial (P/S) converter, VCO, PLL circuit [12] and data selector (Sa, Sb, Sc, Sd) for deciding multiplexing number. The FMUX LSI outputs 1:1, 2:1, 3:1 and 4:1
multiplexed signals as determined by the data selector to the pre-selected physical port; maximum output signal rate is 10 Gb/s in the case of 4:1 multiplexing. The free running frequency of VCO can be adjusted by a frequency setting signal (SEL1, 2) and offset voltage.

C. Performances

We fabricated a FMUX LSI with on-chip PLL circuit using the 0.25 μm SiGe Bi-CMOS process in accordance with simulation results for package and module substrate. The cut-off frequency of the transistor at the typical condition is 90 GHz. Figure 12 shows a photograph of the fabricated FMUX LSI.

LSI power consumption remains at about 1.32 W at the temperatures of 25°C, 50°C, and 75°C. LSI power consumption varies with supply voltage as follows: 1.13 W at 2.97 V (V_0 − 10%), 1.32 W at 3.3 V (V_0), and 1.52 W at 3.63 V (V_0 + 10%). Chip size is about 4.7 × 4.5 mm^2, so the economical and miniature BCC package can be used. Experimental free running frequency of VCO is 0.2 GHz lower than that of back annotation results, but the offset voltage dependence of frequency matches the results of circuit simulations. Figure 13 shows the FMUX waveforms measured using a 2^31 − 1 PRBS optical input data signal; the upper side shows extracted 10 GHz clock and lower side shows output signals. Figures 13(a), (b), and (c) show the waveforms at the bit rates of 2.5 Gb/s, 5 Gb/s, and 10 Gb/s, respectively.

These results show the validity of proposed LSI for realizing the proposed optical access system with bandwidth flexibility. In the next section, we propose a power reduction technique that uses module level operation switching, the maximum bit rate of over 40 Gb/s is achieved with low power consumption.

4.4 Key Technique for Power Reduction

Reducing system power consumption will become more and more important in the future. Unfortunately, conventional systems based on TDM tend to suffer high power consumption rates because TDM multiplexes low rate (service rate) to high rate (line rate) in the time domain. In this section, we propose the service rate matching technique to reduce module power consumption.

4.4.1 Concept of Service Rate Matching

One power-saving measure is maximize the use of the sleep mode, but the power reduction effect of ONU used in NTT’s existing GE-PON system is about 50–80% at most. Here, we compare the power consumption per ONU used in TDM system with that of WDM system in which it was assumed that the power consumption is proportional to the bandwidth. When the average used bandwidth for each user was assumed to be B_0, the maximum transmission bandwidth in TDM system becomes N × B_0 for B_0 in WDM system in which wavelength is allocated to each user. So, in a TDM system, average power consumption per ONU is about P_{TDM} = (1 + (N − 1)α)P_0, where N is the number of ONUs, α is the ratio of the power consumption in sleep mode to that in the active mode, and P_0 is power consumption in the active mode. Average power consumption per ONU of a WDM system, which use wavelengths for user multiplexing; i.e. a
point-to-point system, is about $P_{\text{WDM}}=P_0$. As an example, if $N$ is 32 and $\alpha$ is 0.5, $P_{\text{TDM}}$ per ONU is about 16.5$P_0$. Of course, if $\alpha$ could become 0 in TDM system, $P_{\text{TDM}}$ per ONU becomes $P_0$ which is equal to the average power consumption per ONU $P_{\text{WDM}}$ of a WDM system. This result shows that WDM point-to-point systems, in which the service rate closely approaches the line rate, are very effective in decreasing the power consumption. We propose here a service rate matching module whose operation frequency is switched to match the service rate. As a result, power consumption of network systems can be reduced.

### 4.4.2 Module Configuration and Operation Process

Proposed optical receiver module includes WDM filter, Pin-PDs, TIAs, AGC, deskew LSI, FMUX LSI and fixed 4:1 multiplexer LSI, SW and rate control circuit as shown in Fig. 14. FMUX LSI includes a CDR, data selector and flexible P/S converter. CDR extracts a 10 GHz clock from the 2.5 Gb/s downstream signal. FMUX can output different physical rates (2.5, 5, and 10 Gb/s) from any preselected port. The fixed 4:1 multiplexer includes CDR and P/S converter, which multiplexes 10 Gb/s streams to 40 Gb/s. The rate control circuit changes the operation mode such as line rate (2.5, 5, 10, or 40 Gb/s). The optical receiver module is built in units of 4 channels (wavelengths) as shown in Fig. 14. Each block includes 4 PDs, 4 TIAs, 4 GCAs, 1 deskew and 1 FMUX.

Proposed module operates as follows:

- **Case 1:** user demand rate is less than 2.5 Gb/s, only 1 PD, TIA and GCA operate in each block, (note: currently deskew and FMUX LSI have no sleep mode operation but this is a future research topic)
- **Case 2:** user demand rate is less than 10 Gb/s, only 1 of 4 blocks operates, other blocks and 4:1 multiplexer are quiescent as directed by the control circuit.
- **Case 3:** user demand rate is over 10 Gb/s, 4 blocks and 4:1 multiplexer operate.

### 4.4.3 Performances

Figures 15(a)–(c) show the receiver output waveforms measured with a PRBS optical input data signal. Figure 15(a) shows the waveforms at the bit rate of 2.5 Gb/s, i.e. 1:1 multiplexing by FMUX LSI. This is the output waveform of the comparator. Figures 15(b) and (c) shows the waveforms at the bit rates of 10 Gb/s and 40 Gb/s, respectively; the upper side shows the 40 Gb/s data signal which is demultiplexed to 2.5 Gb/s × 16 parallel data streams at the OLT side, middle side shows the output signal and lower side shows the extracted 40 GHz clock data signal. The eye opening of the output data is wide as shown in Fig. 15. These experimental results confirm the effectiveness of the proposed module in proposed optical access systems. The proposed module can instantaneously switch from the average bit rate per user of 1 Gb/s to the maximum bit rate of over 40 Gb/s using 2.5 Gb/s × 16 wavelengths, and so can meet user demand for immediate increases in line rate. Now in case of operation rate of 2.5 Gb/s, the power consumption using proposed technique becomes about 1/3 compared with the conventional receiver in which the operation rate is 40 Gb/s even if the service rate was 2.5 Gb/s. But there is a possibility of more power reduction, because all of ports in deskew, FMUX LSI are active though one port operation is ideal now. In future work, we are going to improve their subject. Furthermore, this is the first report of a high speed PON system that offers the maximum bit rate of over 40 Gb/s while meeting the GE-PON loss budget of 29 dB without using loss compensation techniques such as OAMPs or APDs. We expect that proposed rate matching optical receiver module will yield optical access systems that offer flexibility, extendibility and economy with low power consumption.

## 5. Conclusions

In this paper, we emphasized the superiority of the dynamic NW over the conventional static NW. We introduced the
novel NoD concept, its architecture, and support key technologies based on WDM parallel transmission scheme. As the key to realizing the NoD concept, we proposed the novel ‘elastic OLT’; the devices needed for each service are installed ‘virtually.’ To resolve the issues posed by the WDM parallel transmission scheme, we proposed a deskew LSI and examined its performance. To realize the bandwidth flexibility needed, we proposed the FMUX LSI and confirmed its feasibility. Furthermore, to reduce power consumption, we proposed the module level switching architecture and realized a service rate matching receiver module that offers the maximum bit rate of over 40 Gb/s with low power consumption. It well handles diversity expected in user demand and lowers overall system power consumption. We expect that our proposal will become accepted for constructing future optical access systems. Finally, we note the cooperation of wired and wireless networks will become increasingly important. So we will research OLT configurations and devices technologies for realizing the future optical network that subsumes wired and wireless system.

Acknowledgments

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References

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