ELectronics EXpress

IEICE Electronics Express, Vol.5, No.4, 157–162

A wide range, over 9.6 ns, skew compensation LSI for a flexible optical access system

Yoshihito Sakai[1a)], **Hideaki Kimura**[1], **Yusuke Ohtomo**[2], **and Makoto Tsubokawa**[1]

[1] *NTT Access Network Service Systems Laboratories, NTT Corporation, 1–6 Nakase, Mihama-ku, Chiba-shi, Chiba 261–0023 Japan*

[2] *NTT Microsystem Integration Laboratories, NTT Corporation, 3–1 Morinosato, Wakamiya, Atsugi-shi, Kanagawa 243–0198 Japan*

a) *sakai.yoshihito@ansl.ntt.co.jp*

Abstract:

In order to realize flexible bandwidth allocation in access networks with bit rates of 10 Gb/s or more, transmitting data by parallel streams with different wavelengths is an attractive approach. In such systems, the timing skew induced by fiber dispersion is the critical problem. This paper proposes a skew compensation LSI for an optical access system based on power splitter based wavelength division multiplexing passive optical network (PS-WDM-PON). The LSI can compensate timing skew of more than 9.6 ns with 82 ps resolution; experiments show that transmission distance of 24 km are possible if the bit rate of each wavelength is 2.5 Gbit/s and all wavelengths lie within 20 nm.

Keywords: skew compensation, flexible optical access system

Classification: Photonics devices, circuits, and systems

References

[1] T. Tatsuta, N. Oota, N. Miki, and K. Kumozaki, "Design philosophy and performance of a GE-PON system for mass deployment," *J. Opt. Netw.*, vol. 6, no. 6, pp. 689–700, June 2007.

[2] K. Iwatsuki, J. Kani, H. Suzuki, and M. Fujiwara, "Access and metro networks based on WDM technologies," *J. Lightwave Technol.*, vol. 22, no. 11, pp. 2623–2630, Nov. 2004.

[3] H. Kimura and Y. Sakai, "A Construction Technology of Flexible Optical Access Network System —An Examination for High-speed Techniques Based on WDM in Access Network—," *Proc. of the 2007 IEICE General Conf.*, Nagoya, Japan, B-8–9, March 2007. (In Japanese)

[4] S. Shen and A. M. Weiner, "Demonstration of Timing Skew Compensation for Bit-Parallel WDM Data Transmission with Picosecond Precision," *IEEE Photon. Technol. Lett.*, vol. 11, no. 5, pp. 566–568, May 1999.

[5] G. Jeong and J. W. Goodman, "Long-distance parallel data link using WDM transmission with bit-skew compensation," *J. Lightwave Technol.*, vol. 14, no. 5, pp. 655–670, May 1996.

DOI: 10.1587/elex.5.157
Received December 26, 2007
Accepted January 17, 2008
Published February 25, 2007

[6] O. H. Adamczyk, M. C. Cardakli, J.-X. Cai, M. I. Hayee, C. Kim, and A. E. Willner, "Coarse and Fine Bit Synchronization for WDM Interconnections Using Two Subcarrier-Multiplexed Control Pilot Tones," *IEEE Photon. Technol. Lett.*, vol. 11, no. 8, pp. 1057–1059, Aug. 1999.
[7] K. Takiguchi, T. Shibata, and M. Itoh, "Integrated-Optic Timing Tuner for High-Speed WDM Signals," *IEEE Photon. Technol. Lett.*, vol. 15, no. 7, pp. 948–950, July 2003.
[8] M. E. Vieira Segatto, F. N. Timofeev, R. Kashyap, R. Wyatt, I. Lealman, R. Harmon, and J. R. Taylor, "Bit skew and dispersion compensation in 10 Gb/s-channel bit parallel WDM systems," *in Proc. LEOS 2000*, Rio Grande, Puerto Rico, WZ2, pp. 619–620, Nov. 2000.

1 Introduction

The number of broadband access network users continues to increase. Given this increase, various services that require large bandwidth will appear and bandwidth requirements will explode. In Japan, there are about ten million optical access network subscribers, and most use the Ethernet passive optical network (EPON) defined in IEEE 802.3 [1]. The bit rate of the EPON is currently 1 Gbit/s, and may exceed 10 Gbit/s in the near future.

EPON multiplexes the data frames for each user in the time domain and transmits them at the same wavelength. Time division multiplexing (TDM) makes it possible to reduce equipment cost because few optical components are needed. However, receiver sensitivity falls as the transmission speed rises and the minimum sensitivity of existing p-i-n photodiodes (PIN-PDs) is a barrier to raising the bit rate. Using avalanche photodiodes (APDs) or optical amplifiers will solve this problem, but these components are expensive. Moreover, higher data rates require dispersion compensation and high speed analog circuits.

One solution to this problem is the wavelength division multiplexing (WDM) approach. The common WDM-PON [2] uses a wavelength splitter (WS) instead of the power splitter of the EPON, and each user and service is assigned a different wavelength. This keeps the bit rate of each wavelength low, and enables transceivers to use inexpensive components. However, there are two problems. The first is that it is difficult to use the existing PON infrastructure; constructing a new fiber network for each system requires huge cost. The second is that allocating wavelengths to users and services makes the required number of wavelengths at least equal to the number of users; higher wavelength stability is required as the number of wavelengths increases. To overcome these problems, the power-splitter-based WDM-PON (PS-WDM-PON) is effective. The PS-WDM-PON can coexist with existing systems on the same fiber network, and can decrease the number of wavelengths by sharing all wavelengths among users and services. In [3], we proposed a flexible optical access system based on the PS-WDM-PON that uses multiple wavelengths for each data frame and realizes efficient bandwidth allocation by jointly using the time axis and the wavelength axis.

DOI: 10.1587/elex.5.157
Received December 26, 2007
Accepted January 17, 2008
Published February 25, 2007

IEICE Electronics Express, Vol.5, No.4, 157–162

In this paper, we propose a wide range skew compensation LSI, an essential component of our system. Moreover, we describe the experiment conducted to confirm that the LSI has enough compensation range and resolution for our system.

2 Flexible optical access system

The architecture of the system is shown in Fig. 1. The key point of the system is that the data frames are transmitted in parallel streams and flexible bandwidth allocation is achieved by coordinating time and wavelength domains.

In downstream transmission, the serial-to-parallel (S/P) converter in the optical line terminal (OLT) converts an incoming data frame into multiple data streams, each of which modulates a different transmitting laser diode (LD). The optical network unit (ONU) specified as the destination of the frame uses PIN-PDs to receive the transmitted signals and a skew compensator to adjust the timing of each stream; the original data frame is reconstructed by performing parallel-to-serial (P/S) conversion. For upstream data frames, the transmission procedure is almost the same except that the skew compensator is placed at the transmitter side and the transmission time and the wavelengths are allocated by the OLT. The reason why it is in the transmitter is that the amount of timing skew of each wavelength is detected by the ONU side. The skew compensator in the transmitter applies the appropriate delay for each port so that all frames reach the receiver at the same time.

Flexible bandwidth allocation and management of the quality of each user/service are achieved by controlling both time domain and wavelength domain settings. Data frames are transmitted at various wavelengths in free time periods. An example of flexible bandwidth allocation is illustrated

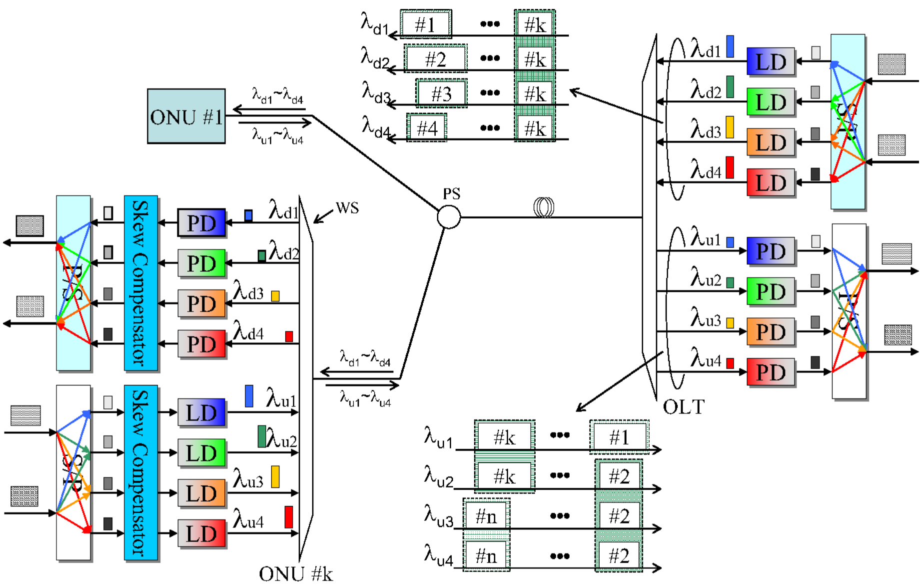


Fig. 1. Block diagram of the flexible optical access system

DOI: 10.1587/elex.5.157
Received December 26, 2007
Accepted January 17, 2008
Published February 25, 2007

IEICE Electronics Express, Vol.5, No.4, 157–162

in Fig. 1. Moreover, to allow the use of a coarse WDM (CWDM) filter to isolate our system from existing services, and thus realize coexistence, all wavelengths used for downstream and upstream transmission must lie within 20 nm. Even without APDs or optical amplifiers, this system provides 10 Gbit/s by using four wavelengths whose bit rate is 2.5 Gbit/s with 29 dB loss budget (EPON specification).

3 Skew compensation LSI

In the flexible 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.

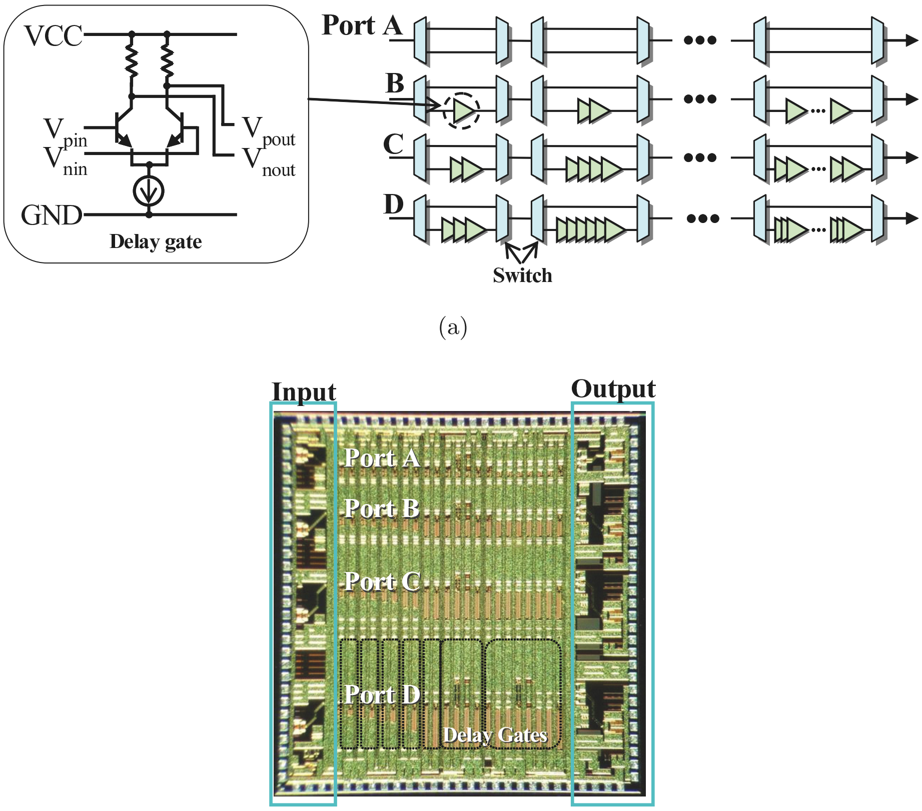
Previously proposed skew compensation techniques include dispersion compensating fiber (DCF) [4], bit realignment with shift registers [5], both are capable of fine and coarse synchronization [6], optical delay lines integrated with arrayed waveguide gratings [7], and fiber Bragg gratings [8]. In the 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. 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).

3.1 LSI design

To meet all the above requirements with a compact and low-cost device, we designed a skew compensation LSI. 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. 2 (a). 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. By using the gate delay characteristics, the resolution can be decreased to the gate delay time.

The LSI was fabricated using the SiGe 0.25 μm BiCMOS process. Fig. 2 (b)

DOI: 10.1587/elex.5.157
Received December 26, 2007
Accepted January 17, 2008
Published February 25, 2007



(a)

(b)

Fig. 2. (a) Configuration, and (b) photograph of the fabricated LSI.

shows a photograph of our skew compensation LSI; its chip size is 4.5 mm × 4.7 mm.

3.2 Experimental result

We measured the skew compensation range and resolution of the fabricated LSI at various temperatures (0 °C, 25 °C, 50 °C, and 75 °C). The measured delay of each port is shown in Fig. 3 (a). The maximum delay at each temperature was 9.6 ns, 9.8 ns, 10.1 ns, and 10.4 ns, and the resolution of port D was 76 ps, 77 ps, 79 ps, and 82 ps, respectively. Moreover, the least-squares-better (LSB) of integral nonlinearity (INL) and differential nonlinearity (DNL) were calculated to be ± 0.29 and ± 0.34, respectively. Compared with the design values, the obtained maximum delay and its temperature dependency show good agreement. In order to cancel this temperature dependency, skew detection and feedback schemes [6, 5] will be necessary.

The waveforms before and after skew compensation are shown in Fig. 3 (b) and (c), respectively. The skew at the input port is about 9.6 ns, and the output has synchronized. We also measured the RMS (root mean square) timing jitters at the input and output of the LSI, and obtained 6.3 ps and 14.9 ps, respectively. Timing jitter degradation is estimated to be about 8.6 ps. Power consumption of this LSI during the measurements was about 1.85 W. These results confirm that the fabricated LSI successfully compensates the target skew of over 8 ns in temperature range from 0 °C to 75 °C.

DOI: 10.1587/elex.5.157
Received December 26, 2007
Accepted January 17, 2008
Published February 25, 2007

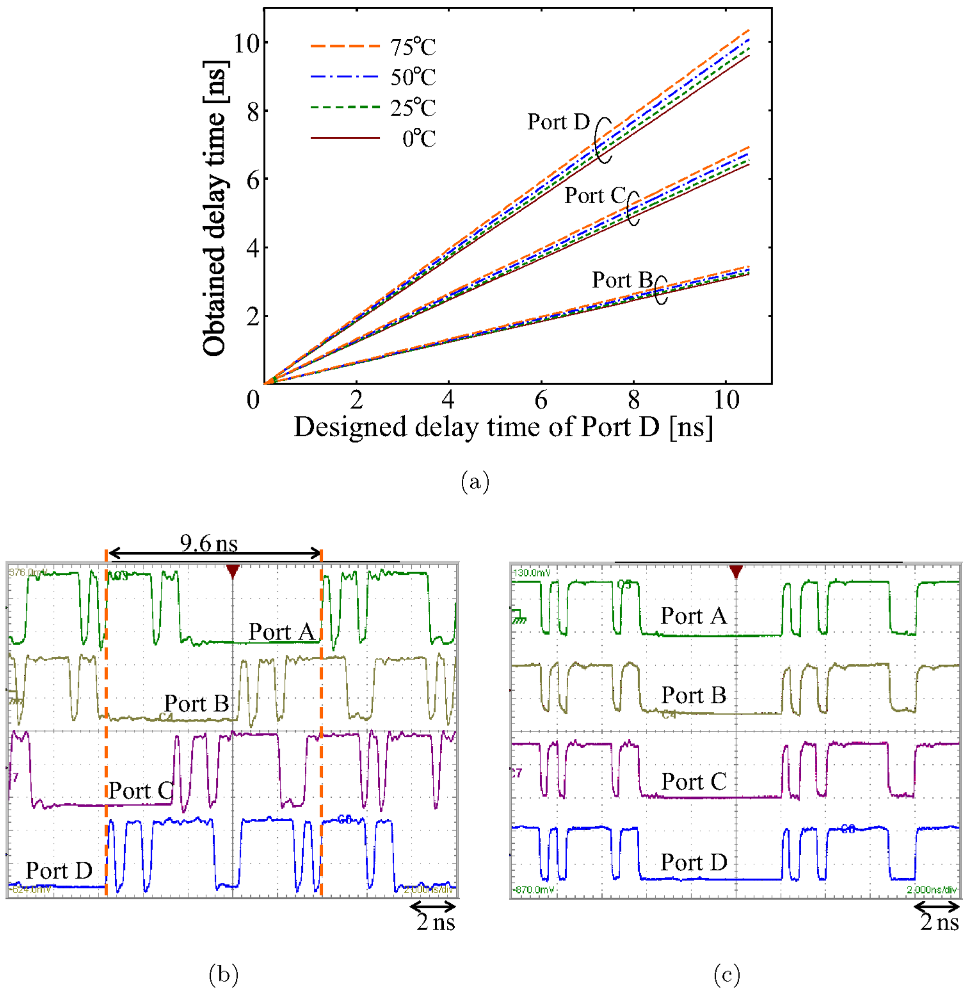


Fig. 3. (a) Measured relative delay against port A, and waveforms (b) before and (c) after the circuit.

The remaining problem is fine tuning of delay at each port. In the current design, it is assumed that the wavelength interval is the same. However, the wavelength tolerance of LDs, which is of the order of 0.1 nm to several-nm, causes about 1 ns difference from the ideal case because the wavelength dependency of the timing skew is about 400 ps/nm for dispersion of 20 ps/nm/km and fiber length of 20 km. Therefore, we should add a fine tuning structure into the LSI.

4 Conclusion

In this paper, we proposed a wide range and high resolution skew compensation LSI for the optical access system based on the PS-WDM-PON. An LSI capable of four channel operation was fabricated using the SiGe 0.25 μm BiCMOS process; its maximum skew compensation was found to be over 9.6 ns, which corresponds to over 24 bits at the bit rate of 2.5 Gbit/s. This supports propagation lengths of over 24 km if the transmission wavelengths are within 20 nm and the optical fiber's dispersion parameter is 20 ps/nm/km. Our work shows that our optical access system together with the LSI can provide 10 Gbit/s and over 20 km transmission on the PON network by using four wavelengths.

DOI: 10.1587/elex.5.157
Received December 26, 2007
Accepted January 17, 2008
Published February 25, 2007