

10 Gb/s-Based PON Over OCDMA Uplink Burst Transmission Using SSFBG Encoder/Multi-Port Decoder and Burst-Mode Receiver

Satoshi Yoshima, Naoki Nakagawa, Nobuyuki Kataoka, *Member, IEEE*, Naoki Suzuki, Masaki Noda, Masamichi Nogami, Junichi Nakagawa, and Ken-Ichi Kitayama, *Fellow, IEEE*

Abstract—In this paper, we propose a novel 10 Gb/s-based passive optical network (PON) over optical code division multiple access (OCDMA) system to realize the new generation full capacity optical access network which is easily upgraded from existing time division multiplexing PON (TDM-PON) without sacrificing the currently uplink bandwidth assigned to the individual user. 16-ONU (4-OCDMA x 4-packet) uplink burst transmission, an upgrade scenario by a factor of four of conventional 10 Gb/s-based PON, is experimentally demonstrated by using multi-level phase-shift-keying (PSK) super-structured fiber Bragg grating (SSFBG) encoder/multi-port decoder and burst-mode receiver. In the discussions, it will be shown that 32 users can be accommodated in 10 Gb/s-based PON over OCDMA system, and a key is newly introduced multi-level phase-shifted en/decoding, of which auto-correlation waveform can be preferably adopted in the burst-mode reception at 10 Gb/s.

Index Terms—Burst-mode transmission, code shift keying, optical code division multiple access (OCDMA), 10 Gb/s-based passive optical network.

I. INTRODUCTION

THE progress of a time division multiplexing passive optical network (TDM-PON) system stimulates the growth of commercial fiber-to-the-home (FTTH) services due to the user-shared cost-effective facilities. Especially, the 1 Gb/s-based PON systems such as 1 Gigabit Ethernet PON (1G-EPON) has been widely spread because of a high

1.25 Gbit/s bit-rate, a 32-user shared low-cost system, and a long 20-km transmission line. Due to explosive growth of 1G-EPON systems, standardization activities for 10 Gb/s-based PON systems [1], [2] are underway. Researches on optical burst-mode transmitter [3], [4], receiver [5], and clock and data recovery (CDR) [6], [7] for 10 Gb/s-based PON system have been strongly pursued. 10 Gb/s-based PON system is able to achieve only the bandwidth of about 300 Mb/s per user when the data rate of 10 Gb/s is shared among 32-user. In the future, optical access network of more total capacity will be required to provide “symmetric gigabit-bandwidth” of up/down link for the peer-to-peer applications [8]. However, it is very difficult to realize this network by adapting only TDM-PON because of many development problems of optical/electrical devices. For that reasons, over 40 Gb/s wavelength division multiplexing (WDM)/TDM-PON systems has been proposed [9], but this system has a problem of the wavelength allocation due to the lack of usable wavelength windows when new systems co-exist with 1 Gb/s and 10 Gb/s—based PON systems [10].

On the other hand, optical code division multiple access (OCDMA) can multiplex a number of channels on a single wavelength and same time slot. In addition, OCDMA has unique characteristics of low signal processing latency and asynchronous transmission. In recent years, the coherent OCDMA systems are making remarkable progresses over incoherent OCDMA because of its excellent correlation property and frequency efficiency. Note that the coherent time-spreading (TS)-OCDMA system is realized by only applying compact optical passive devices such as super-structured fiber Bragg grating (SSFBG) [11] and multi-port optical encoder/decoder in the arrayed waveguide grating (AWG) configuration [12]. Therefore, the network capacity is able to upgrade easily for new generation full capacity optical access network by combining OCDMA technique and existing TDM-PON systems. We have proposed the 1G-EPON over OCDMA system having tell-and-go multiple access capability without sacrificing link capacity and successfully demonstrated its uplink burst transmission using SSFBG encoder/decoder adapting bipolar phase-shifted encoding scheme and optical burst-mode receiver for 1G-EPON [13]. However, the 10 Gb/s-based PON over OCDMA system with considering the phase-shifted encoding scheme remains a challenge since bipolar phase-shifted encoding auto-correlation signal is hard to receive due to a few picoseconds pulse width.

In this paper, we propose a novel 10 Gb/s-based PON over OCDMA system which multiplexes the 10 Gb/s-based PON

Manuscript received May 30, 2009; revised September 04, 2009. First published October 09, 2009; current version published February 01, 2010. This work was supported in part by SCOPE (Strategic Information and Communications R&D Promotion Programme) project of Ministry of Internal Affairs and Communications of Japan.

S. Yoshima, N. Suzuki, M. Noda, M. Nogami, and J. Nakagawa are with the Information Technology R&D Center, Mitsubishi Electric Corporation, 5-1-1 Ofuna, Kamakura, Kanagawa 247-8501, Japan (e-mail: Yoshima.Satoshi@aj.MitsubishiElectric.co.jp; Suzuki.Naoki@dy.MitsubishiElectric.co.jp; Noda.Masaki@eb.MitsubishiElectric.co.jp; Nogami.Masamichi@eb.MitsubishiElectric.co.jp; Nakagawa.Junichi@ay.MitsubishiElectric.co.jp).

N. Nakagawa is with the Department of Electrical, Electronic and Information Engineering, Osaka University, Osaka 565-0871, Japan. He is now with the Nippon Telegraph and Telephone West Corporation, Osaka 540-8511, Japan, (e-mail: naoki@pn.comm.eng.osaka-u.ac.jp).

N. Kataoka is with the Photonic Network Group, Research Department 1, New Generation Network Research Center, National Institute of Information and Communications Technology, Tokyo 184-8795, Japan. (e-mail: n_kataoka@nict.go.jp).

K. Kitayama is with the Department of Electrical, Electronic and Information Engineering, Osaka University, Osaka 565-0871, Japan. (e-mail: kitayama@comm.eng.osaka-u.ac.jp).

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Digital Object Identifier 10.1109/JLT.2009.2033820

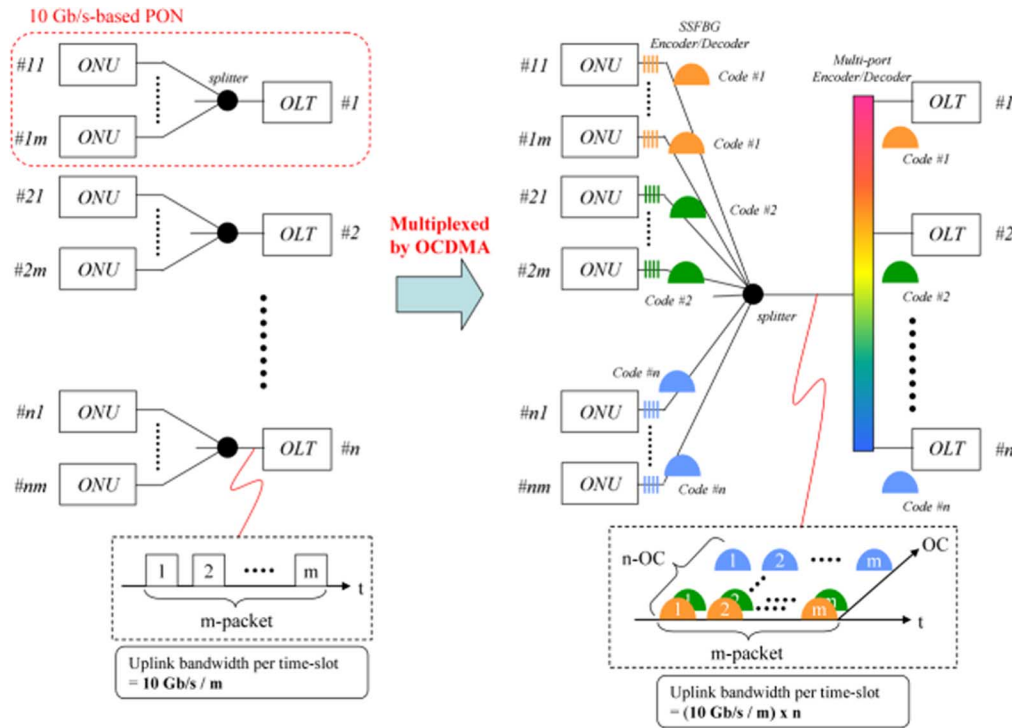


Fig. 1. Architectures of scalable 10 Gb/s-based PON system upgrade by using OCDMA approach.

systems by using OCDMA technique. The proposed system is able to increase the total capacity without sacrificing currently uplink bandwidth assigned to the individual optical network unit (ONU). 16-ONU (4-OCDMA \times 4-packet) uplink burst transmission, an upgrade scenario by a factor of four of conventional 10 Gb/s-based PON is experimentally demonstrated for the first time by using hybrid 16-chip (200 Gchip/s), 16-phase-shifted SSFBG encoder/multi-port decoder [14] and burst-mode receiver [15] along with a forward-error correction (FEC). Finally, we will discuss that 32-user can be accommodated in 10 Gb/s-based PON over OCDMA system, and a key to an unprecedented symmetric uplink bandwidth is a newly introduced multi-level phase-shifted en/decoding, of which auto-correlation waveform can be preferably adopted in the burst-mode reception at 10 Gb/s.

II. 10 GB/S-BASED PON OVER OCDMA SYSTEM

Fig. 1 shows an upgrade scenario of a single 10 Gb/s-based PON to $n \times 10$ Gb/s-based PON systems over OCDMA. When n conventional 10 Gb/s-based PON systems including $m \times$ ONUs are accommodated, the bandwidth per user is reduced by a factor of n due to the nature of time division multiple access (TDMA), resulting in the bandwidth reduction factor of $m \times n$, that is, $10 \text{ Gb/s}/m/n$ per ONU. On the contrary, 10 Gb/s-based PON over OCDMA system can maintain the bandwidth reduction factor of only the number of ONUs ($=m$) by assigning different optical codes (OCs), OCs #1 \sim # n , to an individual 10 Gb/s-based PON system. For example, OC #1 is shared with #11 \sim #1 m ONUs where uplink signals #11 \sim #1 m in a group are time-aligned without a contention. As a result, uplink bandwidth per user can be increased by a factor of n , that is, $10 \text{ Gb/s}/m$. Unlike WDM-PON, it is unnecessary to reallocate the

wavelength channel of an individual 10 Gb/s-based PON system due to the nature of OCDMA, for example, by adapting same uplink and downlink wavelength channels of 10 G-EPON [1]. From the view point of the upgrade cost of 10 Gb/s-based PON system, the cost of our proposed system increases by adding the OCDMA-specific components. Additional components of PON over OCDMA to conventional PON systems would include the encoder/decoder as well as a special class of short pulsed laser. However, the costs of multi-port decoder as well as that of the short pulsed laser can be shared with the numbers of ONUs, and the SSFBG type of encoder could become inexpensive if it's mass-produced.

For 10 Gb/s-based PON over OCDMA system, a single multi-port OCDMA encoder/decoder [12] is located at optical line terminal (OLT), which can generate n different OCs, while, on the other hand, at each ONU uses a multi-level phase-shifted SSFBG. The multi-port encoder/decoder can improve the loss budget due to the simultaneous processing of the multiple OCs without splitters. In addition, it has a cost-effective capability because the cost can be shared by all ONUs. While, SSFBG has the ability of the processing of the ultra-long OC, polarization-independent operation, compact structure as well as low-cost capability for mass production [11]. Therefore, it is most appropriate to allocate the multi-port encoder/decoder to the OLT and the SSFBG encoder/decoder to the ONUs, respectively. A crucial challenge of 10 Gb/s-based PON over OCDMA system is the detection of uplink optical "burst" signals, decoded after the transmission. To study the feasibility of the 10 Gb/s-based PON over OCDMA systems, we developed the 10 Gb/s burst-mode receiver which consists of avalanche photodiode (APD)-preamplifier module and a limiting amplifier. This burst-mode receiver can realize the high-sensitivity by adapting

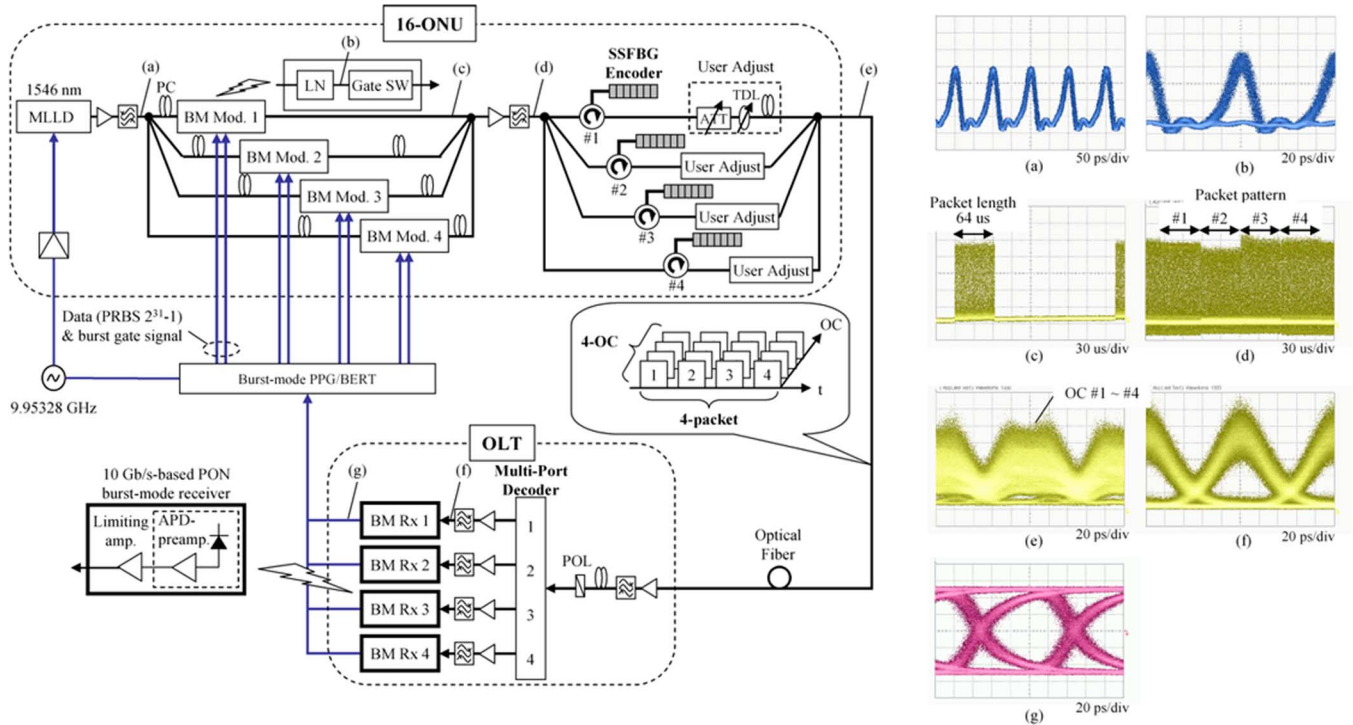


Fig. 2. Experimental setup of 16-ONU 10 Gb/s-based PON over OCDMA uplink transmission.

the Mitsubishi's APD, which has large gain-bandwidth products [16], and the low-noise preamplifier.

III. BURST-MODE UPLINK TRANSMISSION EXPERIMENT OF 16-ONU 10 GB/S-BASED PON OVER OCDMA

Fig. 2 shows the experimental setup for 16-ONU 10 Gb/s-based PON over OCDMA uplink burst-mode transmission. The capacity of 16-ONU was realized by the 4-packet 10 Gb/s-based PON over 4-OC OCDMA. The 1.8 ps pulse train was generated by a mode-locked laser diode (MLLD) as shown in Fig. 2(a). The center wavelength was 1546 nm and the repetition rate was 9.95328 GHz. The output of the MLLD was modulated to 4 packets by the optical burst-mode modulators which were constructed by the LiNbO_3 (LN) intensity modulator and acousto-optic modulator (AOM) as a burst-mode gate switch. The switching speed and the extinction ratio of the burst-mode gate switch were about 100 ns and over 40 dB, respectively. Therefore, the optical burst-mode modulators could realize the fast burst turn-on/off time and sufficient power suppression during idle period simultaneously. Fig. 2(b) shows the LN intensity modulator output data with $2^{31} - 1$ pseudo random bit sequence (PRBS). Each packet length was 64 us which includes 10 us overhead as shown in Fig. 2(c). Fig. 2(d) shows the packet pattern which guard time was 0 ns. This guard time was set to cope with the most severe condition for a fast response of the burst-mode receiver. These packets were encoded by 4 different 16-chip, 16-phase-shifted SSFBGs. In the SSFBG encoder, the input optical pulse is time-spread into 16 pulses so called chip pulse with 5 ps interval. These chip pulses have the relative phase shift with respect to each code. The design parameters of the SSFBG encoder are; the center wavelength is 1546 nm, chip length is ~ 0.52 mm, total length

of grating is 8.32 mm, and the 16 phase levels are generated by shifting the chip grating by a step of $\pm\lambda/8$. These encoded signals were time-multiplexed into TDM over OCDM signal. Tunable optical attenuator (ATT), tunable delay line (TDL) and polarization controller (PC) were inserted in the each path to investigate the system performance in the worst scenario that the interference becomes most serious as shown in Fig. 2(e).

At the OLT side, the received signal was decoded by a 16-chip with 5 ps interval (200 Gchip/s), 16-phase-shifted multi-port decoder which could process the 16-OC simultaneously. In the decoding process, each chip pulse is time-spread again into 16 pulses and suffers a relative phase shift with respect to the combination of in- and out-put ports. The frequency deviation (channel spacing) between neighboring ports of 16×16 port decoder is 12.5 GHz. Fig. 2(f) shows the decoded signal of OC #1, showing the high-peaked auto-correlation waveform with multiple access interference (MAI) noise skirt. Each decoded signals were processed at our own developed 10 Gb/s burst-mode receiver. The 10 Gb/s-based PON burst-mode receiver could provide a high-sensitive burst-mode 2R function with the optimal multiplication factor M of the APD ($M = 8.0$). Fig. 2(g) shows the good electrical eye opening from the decoded signal despite the MAI noise because of the adequate bandwidth of the burst-mode receiver, which was more than 6.0 GHz, for 10 Gb/s-based PON over OCDMA systems. In this experiment, erbium doped fiber amplifiers (EDFAs) were inserted to compensate the optical loss of each component such as SSFBG encoders and multi-port decoder.

Fig. 3 shows the measured bit error rate (BER) performances about all 16-ONU of 4-OC \times 4-packet and those of back-to-back non-en/decoded signal, respectively. All packets can realize error-free ($\text{BER} < 10^{-3}$) operation with the FEC as

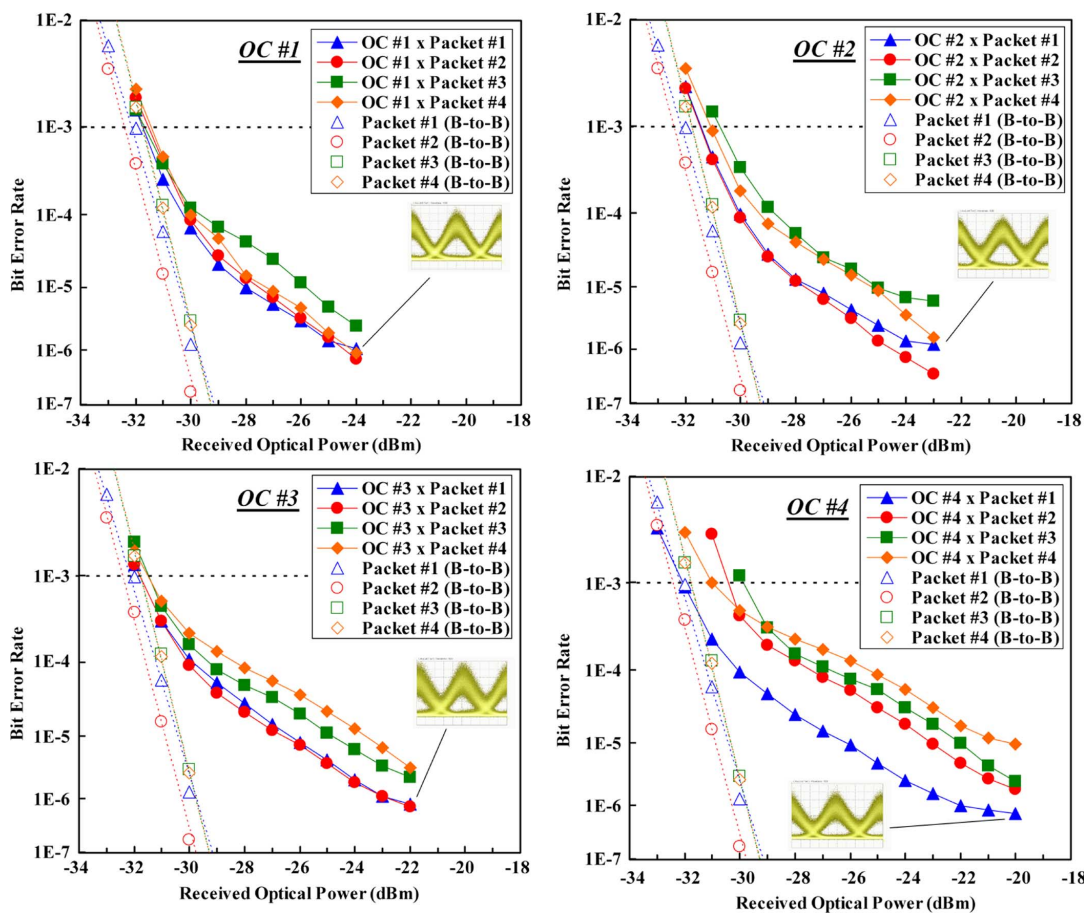


Fig. 3. Measured bit error rate performances of all 16-ONU.

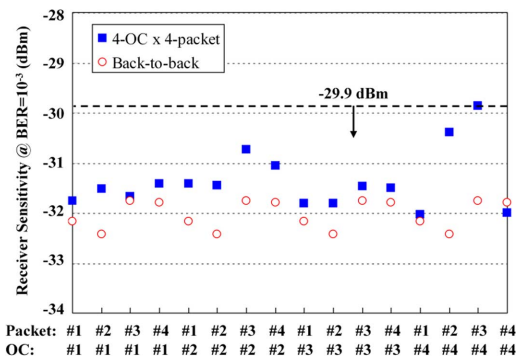


Fig. 4. Measured receiver sensitivity of all data at BER = 10⁻³.

Reed–Solomon (RS) (255, 223). In the 4-OC multiplexed case, BER of less than 10⁻⁷ could not be measured due to the MAI noise. However, the feasibility of the 10 Gb/s-based PON over OCDMA system could be shown because the 10 Gb/s-based PON system is operated with the FEC. We obtained good eye openings for all four decoded signals of OC #1–#4, as are evidenced by the BER measurements in Fig. 3. This fact confirms that the uplink bandwidth is equal to 10 Gb/s/4 that is four time larger than the conventional 10 Gb/s-based PON, 10 Gb/s/16. Fig. 4 shows the receiver sensitivity at BER = 10⁻³ for all 16-ONU uplink data. The receiver sensitivity of less than -29.9 dBm was successfully achieved by adapting the high-

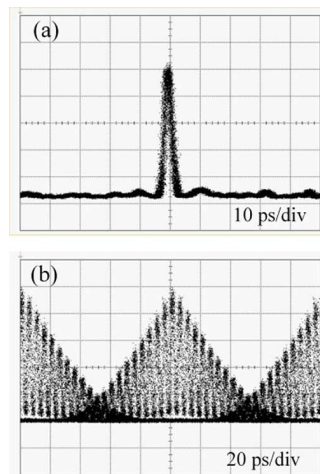


Fig. 5. The auto-correlation waveforms of (a) bipolar and (b) 16-level phase-shifted encoding.

sensitive burst-mode receiver and the power penalties between 4-OC x 4-packet and back-to-back were less than 2.0 dB which were caused by the degradation of optical signal-to-noise ratio (OSNR) due to the amplified spontaneous emission (ASE) and MAI noise. The small deviation of receiver sensitivities was caused by the characteristic mismatch of optical components such as burst-mode modulators and SSFBG encoders.

In this experiment, it was not shown that the dynamic range dependence between packets and guard time dependence due to the lack of the burst-mode optical amplifier [19]. However, the system feasibility can be demonstrated by using this burst-mode receiver which can process the 10 Gb/s uplink packets with different optical power [15].

IV. DISCUSSIONS

A. Bipolar versus Multi-Level Phase-Shifted Correlation Performances for 10 Gb/s Burst-Mode Reception

A burst-mode reception is a “must” for PON system, which has never been realized at 10 Gb/s for any OCDMA systems. This is because the auto-correlation waveform in the optical decoding has a sharp peak, which requires tens of gigahertz bandwidth of the burst-mode receiver at 10 Gb/s. This requirement will be tolerated by narrowing the bandwidth of the decoded signal, and we will take this approach. Two different phase-shifted encoding schemes for coherent TS-OCDMA have been proposed and demonstrated [17]. One is the bipolar phase-shifted encoding ($0, \pi$) by using SSFBG [11]. The other is multi-level phase-shifted encoding by using multi-port encoder/decoder [12]. Figs. 5(a) and (b) compare the auto-correlation waveforms of bipolar and 16-level phase-shifted encoding used in the transmission experiment, respectively. The pulsewidth of auto-correlation signal of bipolar phase-shifted code (63 chip and 640 Gchip/s) is a few picoseconds due to the suppression of side-lobe. On the other hand, the envelope width of 16-level phase-shifted auto-correlation signal is about 80 ps (=16 chip/200 Gchip/s). The difference in the pulsewidth is a key to successful burst-mode reception at 10 Gb/s. For 1G-EPON over OCDMA [13], the bipolar phase-shifted encoding has been adapted for the burst-mode reception, however, this narrow pulsewidth was a stumbling block at 10 Gb/s. This is because that it is difficult to receive the bipolar phase-shifted auto-correlation signal without OSNR degradation, and the high bandwidth receiver (tens of gigahertz) is required. Currently, it won't be feasible to realize both high-bandwidth and high-gain burst-mode reception under the condition that the gain-bandwidth product remains constant. In addition, bipolar phase-shifted encoding has another problem of using long-OC. As longer the code length becomes for a high data rate, the narrower the auto-correlation waveform becomes. This feature indicates that the bipolar phase-shifted encoding is inadequate for the proposed systems. This is why we employed the multi-level phase-shift encoder, having the broader and smoother auto-correlation temporal waveform. It is noteworthy that the multi-level phase-shifted encoding can generate more codes than bipolar phase-shifted encoding with the same number of chips. In perspective of inter-symbol interference (ISI), the spreading duration of 63-chip bipolar (640 Gchip/s) and 16-chip multi-level (200 Gchip/s) are 200 and 160 ps, respectively. Therefore, 16-chip multi-level phase-shifted code can suppress the influence of ISI than 63-chip bipolar code. In addition, the multi-level phase-shifted code has better power contrast ratio (PCR) characteristic than bipolar code [21]. It can suppress coherent beat noise and MAI. Therefore, the multi-level phase-shifted encoding is the best solution for 10 Gb/s-based over OCDMA uplink burst transmission because

higher bandwidth of burst-mode receiver is not required in order to process the multi-level phase-shifted auto-correlation signal.

B. Uplink Performances

The uplink performances of the proposed system are also discussed. Fig. 6 shows the uplink burst frame model. If data payload is fully loaded, uplink bandwidth per user can be written as

$$BW = BR \times \frac{GP - (m \times OH_{PMD})}{GP} \times \frac{100 - OH_{FEC}}{100} \times \frac{n}{m} \quad (1)$$

where BW is the bandwidth per user, BR is the bit rate of the system, GP is the grant period which is equal to the optical burst frame length, m is the number of ONUs belonging to a 10 Gb/s-based PON system, OH_{PMD} is PMD overhead which consists of burst-mode turn-on/off and sync time, OH_{FEC} is the FEC overhead ratio after the FEC frame mapping, n is the number of multiplexed systems by using OCDMA technique. Table I shows the parameters of throughput calculation of the proposed system. For this calculation, we assume that OH_{PMD} includes the burst-mode CDR lock time because burst-mode CDR can realize a quick burst-mode data recovery [7]. In addition, OH_{FEC} and GT are 12.9% [18] and 1 ms, respectively. Other parameters are based on the experimental conditions.

Fig. 7 shows the calculation results of uplink bandwidth per user. Here, the number of the users is equal to $n \times m$. The uplink bandwidth per user of conventional 10 Gb/s-based PON systems is given by the (1) with $n = 1$. The proposed system capacity realizes more than four times larger than conventional 10 Gb/s-based PON systems. Therefore, the uplink bandwidth per user is achieved about 1 Gb/s even if the system accommodates 32-user and all users can use symmetric gigabit-bandwidth applications by applying OCDMA technique. On the other hand, the increase in network capacity by using OCDMA technique is able to be adapted to the rise of the subscribers. For example, the number of users of this system can be added up to 128-user without throughput degradation while, on the other hand, a 10 Gb/s-based PON system accommodates 32-user.

From the view point of the number of users, the maximum number of users could be increased more than 32-user for a 10 Gb/s-based PON over OCDMA system because the optical power ratio between the burst signal and idle period is more than 40 dB. According to the theoretical analysis of the maximum number in this coherent OCDMA system [22], provided that the en/decoding are properly performed, 32 users and more can be accommodated at any bit rate, and the number of active users depends on the coherency of the light source. As the coherence goes higher, the beat noise becomes dominant rather than the MAI noise.

V. CONCLUSION

An upgrade scenario of a single 10 Gb/s-based PON to $n \times 10$ Gb/s-based PON systems has been studied, based upon a novel 10 Gb/s-based PON over OCDMA system without sacrificing currently assigned uplink bandwidth per user. The uplink burst-data transmission of 4×10 Gb/s-based PON systems over $4 \times OC$ has been demonstrated for the first time by using 16-chip (200 Gchip/s) and 16-level phase-shifted SSFBG encoder at ONUs and a single multi-port decoder at OLT.

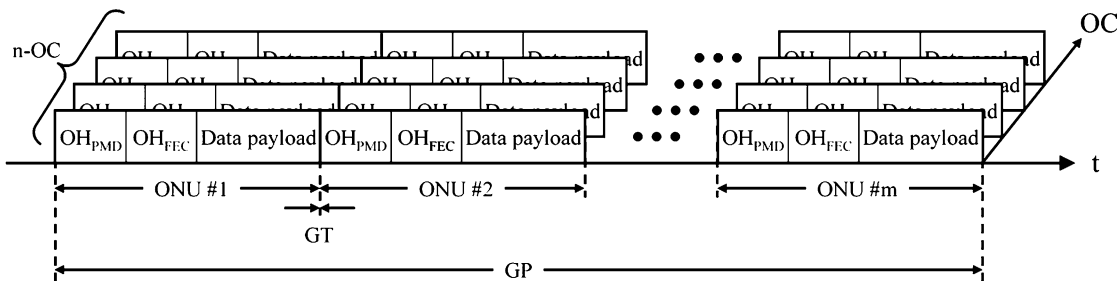


Fig. 6. Uplink transmission optical burst frame model.

TABLE I
PARAMETERS OF THROUGHPUT CALCULATION

Quantity	Symbol	Unit	Parameter values
Bit rate	BR	Gb/s	9.95328
PMD overhead	OH_{PMD}	us	10
FEC overhead	OH_{FEC}	%	12.9
Guard time	GT	ns	0
Grant period	GP	ms	1
Optical code	n		4

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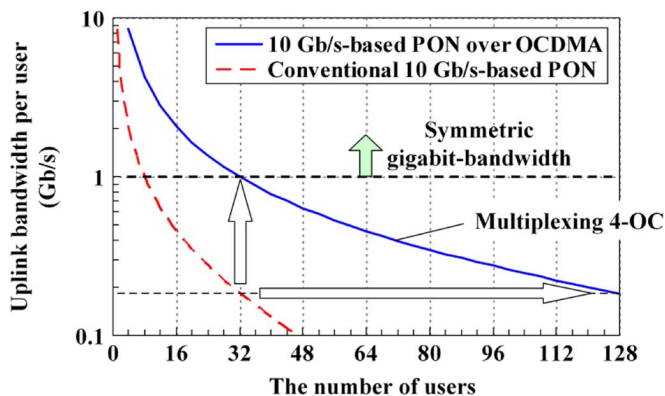


Fig. 7. 10 Gb/s-based PON over OCDMA uplink bandwidth calculation result.

With the assistance of the FEC, error-free operation could be achieved in all 16-ONU of 10 Gb/s-based PON over OCDMA, having four times larger total capacity than the conventional 10 Gb/s-based PON. Finally, we have shown that 32-user can be accommodated by being provided with the up/down link of symmetric gigabit-bandwidth in 10 Gb/s-based PON over OCDMA system, and a key to an unprecedented symmetric uplink bandwidth is a newly introduced 16-level phase-shifted en/decoding, of which auto-correlation waveform can be preferably adopted in the burst-mode reception at 10 Gb/s.

ACKNOWLEDGMENT

The authors would like to thank N. Wada and T. Miyazaki of the National Institute of Information and Communications Technology (NICT), G. Cincotti of the University Roma Tre, X. Wang of the Heriot Watt University, H. Fujinuma of NTT Electronics Corporation, and A. Sakamoto and Y. Terada of the Fujikura Corporation for their supports of this experiment.

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Satoshi Yoshima received the B.E. and M.E. degree in communication engineering from Osaka University, Osaka, Japan, in 2004 and 2006, respectively.

In 2006, he joined the Information Technology R&D Center, Mitsubishi Electric Corporation, Kanagawa Japan, where he has been engaged in research on optical access systems. His research interests include fully integrated optical transceivers and OCDMA systems.

Mr. Yoshima is a member of the Institute of Electronics, Information and Communication Engineers (IEICE) of Japan. He was the recipient of the 2008 Young Researcher's Award from the Institute of Electronics, Information and Communication Engineers of Japan.



Nobuyuki Kataoka (S'03–M'06) received the B.E., M.E., and Dr. Eng. degrees from Osaka University, Osaka, Japan, in 2001, 2003, and 2006, respectively.

In 2006, he joined the National Institute of Information and Communications Technology (NICT), Tokyo Japan. His research interests are in the area of photonic networks such as optical packet switching, optical add/drop multiplexing, and optical code division multiple access.

He is a member of the IEEE and the Institute of Electronics, Information and Communication

Engineers (IEICE) of Japan.

Naoki Suzuki was born in Chiba, Japan, on February 14, 1973. He received the B.S. degree from Sophia University, Tokyo, in 1996 and M.S. degree from University of Tokyo, Tokyo, Japan, in 1998.

In 1998, he joined the Mitsubishi Electric Corporation, Kanagawa, Japan, where he has been engaged in research and development on optical components for optical communication systems.

Mr. Suzuki is a member of the Institute of Electronics, Information and Communication Engineers (IEICE) of Japan. He was the recipient of the 2005 Young Researcher's Award from the Institute of Electronics, Information and Communication Engineers of Japan.

Masaki Noda was born in Fukuoka, Japan, on June 27, 1971. He received the B.S. and M.S. degrees from Tokyo University, Tokyo, Japan, in 1994 and 1996, respectively.

In 1996, he joined the Mitsubishi Electric Corporation, Kanagawa, Japan, where he has been engaged in research and development on optical components for optical communication system.

Mr. Noda is a member of the Institute of Electronics, Information and Communication Engineers (IEICE) of Japan.

Masamichi Nogami was born in Wakayama, Japan, in January 1966. He graduated from the Toin Technical College, Kanagawa, Japan, in 1986.

In 1986, he joined the Information Technology R&D Center, Mitsubishi Electric Corporation, Kanagawa, Japan, where he has been engaged in research and development on fully integrated optical transceivers.

Mr. Nogami is a member of the Institute of Electronics, Information, and Communication Engineers (IEICE) of Japan.

Junichi Nakagawa received the B.E., M.E., and Dr. Eng. Degrees from University of Tokyo, Tokyo, Japan.

In 1994, he joined the Information Technology R&D Center, Mitsubishi Electric Corporation, Kanagawa Japan. He was engaged in 10 Gb/s integrated transceivers, submarine cable systems, and DWDM systems. In 1999–2001, he researched optical 3R repeaters in Stanford University as a visiting scholar. His current interests are in the area of lightwave transceivers and transmission technologies for optical access systems.



Ken-Ichi Kitayama (S'75–M'76–SM'89–F'03) received the B.E., M.E., and Dr. Eng. degrees in communication engineering from Osaka University, Osaka, Japan, in 1974, 1976, and 1981, respectively. In 1976 he joined the NTT Electrical Communication Laboratory in 1976. In 1982–1983, he spent a year as a Research Fellow at the University of California, Berkeley. In 1995, he joined the Communications Research Laboratory (Presently, National Institute of Information and Communications Technology, NICT), Tokyo. Since 1999, he has been the Professor

of the Department of Electrical, Electronic and Information Engineering, Graduate School of Engineering, Osaka University.

His research interests are in photonic networks, optical signal processings, optical code division multiple access (OCDMA) systems, and radio-over-fiber systems. He has published over 240 papers in refereed journals and holds more than 30 patents.

He currently serves on the Editorial Boards of the *IEEE/OSA JOURNAL OF LIGHTWAVE TECHNOLOGY*, *IEEE TRANSACTIONS ON COMMUNICATIONS*, and *Optical Switching and Networking* as the Associate Editor. He served as Guest Editors for special issues, including the *Journal of the Optical Society of America B* on "Innovative Physical Approaches to the Temporal or Spectral Control of Optical Signals" in 2002, *IEEE JOURNAL OF SELECTED TOPICS IN QUANTUM ELECTRONICS* on "Optical Code in Optical Communications and Networks" in 2007, *IEEE/OSA JOURNAL OF LIGHTWAVE TECHNOLOGY* on "Convergence of optical wireless networks," in 2007, *IEEE JOURNAL OF SELECTED AREAS OF COMMUNICATIONS* on "Role of optical and electronic technologies for large capacity switches and routers" in 2008, and *IEEE/OSA JOURNAL OF LIGHTWAVE TECHNOLOGY* on "Converged Optical Network Infrastructures in Support of Future Internet and Grid Services" in 2008.

Dr. Kitayama received the 1980 Young Engineer Award from the Institute of Electronic and Communication Engineers of Japan, the 1985 Paper Award of Optics from the Japan Society of Applied Physics, 2004 Achievement Award of IEICE of Japan, and 2007 the Shida Rinzaburoh Award. He is a Fellow of IEICE of Japan.