Compound Data Rate and Data-Rate-Flexible 622 Mb/s–10 Gb/s OCDMA Experiments Using 511-Chip SSFBG and Cascaded SHG-DFG-Based PPLN Waveguide Optical Thresholder

Taro Hamanaka, Xu Wang, *Senior Member, IEEE*, Naoya Wada, *Member, IEEE*, and Ken-ichi Kitayama, *Fellow, IEEE*

***Abstract*—Data-rate flexible optical code-division multiple access (OCDMA) system with 511-chip superstructured fiber Bragg grating encoder/decoders is investigated from 622 Mb/s to 0 Gb/s. A compound data-rate OCDMA system is experimentally demonstrated for the future multiple service provisioning on demand. A new optical thresholder based on cascaded second harmonic generation and difference in frequency generation in periodically poled lithium niobate waveguide is introduced and successfully applied in the system.**

***Index Terms*—Optical code-division multiple access (OCDMA), optical thresholder, superstructured fiber Bragg grating (SSFBG).**

I. Introduction

FIBER-to-the-home (FTTH) systems are now prevailing over digital subscriber loop (DSL) for providing broadband access services in Japan. The current FTTH system is based on time division multiple access (TDMA) passive optical network (PON) system. As the broadcasting or on-demand delivery of motion pictures as well as peer-to-peer applications, in addition to the Internet and IP telephony become main players in broadband services, demand for abundant bandwidths both for down- and uplinks is growing. The customer's needs are becoming diversified, and hence, a flexible provisioning of the data rate must be a critical issue. However, current TDMA-PON system cannot provide flexible data-rate service. While, wavelength division multiplexing PON (WDM-PON) has the capability due to the point-to-point architecture, its high cost remains to be reduced before being commercialized. Thus, optical code division multiple access (OCDMA) is one attractive solution, which can multiplex different data-rate signals on a single wavelength [1]. In time-spreading (TS) OCDMA, the short optical signal is spread in time by the encoders such as planar lightwave circuit (PLC) [2] and superstructured fiber Bragg grating (SSFBG) [3]. Generally, the multiple access interference (MAI) and the beat noise are the major noise sources that limit the capacity of the coherent TS-OCDMA system [4]. Using ultralong optical code generated by SSFBG encoders can effectively suppress MAI as well as beat noise in the TS-OCDMA system [3], [4]. However, the flexible data-rate OCDMA system will suffer from severe intersymbol interference (ISI) in a coherent TS-OCDMA system with SSFBG encoder/decoder because the adjacent bits of the encoded or decoded signals will overlap each other at high data rate [1].

Another key technique to suppress MAI noise in OCDMA system is optical thresholding. Various optical thresholding techniques have been demonstrated using nonlinear effect in dispersion-shifted fiber [5], supercontinuum generation in dispersion flattened fiber (DFF) [6], holey fiber [7], high nonlinear fiber (HNLF) [8], nonlinear optical loop mirror (NOLM) [9], and second harmonic generation (SHG) in periodically poled lithium niobate (PPLN) [10]. The fiber-based techniques have the advantage of polarization-independent performance; however, they are bulky and normally require high operation power. PPLN is more compact and can operate with relatively low optical power, which makes it an attractive device for the OCDMA system.

In this paper, we report two experiments demonstrating the data-rate that is flexible from 622-Mb/s up to 10-Gb/s OCDMA and the compound data-rate of 622 Mb/s–2.488 Gb/s OCDMA [11]. To overcome noises due to MAI and ISI, key enablers such as an optical thresholder based on cascaded SHG and difference frequency generation (DFG) in PPLN and a record-long 511-chip SSFBG are incorporated.

II. Key Components

A. 511-Chip SSFBG

An SSFBG can generate the bipolar optical code, which provides a good correlation property, due to a refractive index modulation profile inserting phase shifts (0 or π) between different segments. The phase of the chip pulses is determined by the pattern of the phase shifts. Moreover, the correlation property gets better with the longer code length. Using a holographic technique to fabricate SSFBGs enables them to be fabricated with a long code and variable code pattern [3]. In addition, they are independent of the polarization state of the input signal, and compact devices.

Manuscript received January 26, 2007; revised July 9, 2007.

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

X. Wang is with the School of Engineering and Physical Sciences, Heriot Watt University, Edinburg EH14 4AS, U.K. (e-mail: x.wang@hw.ac.uk).

N. Wada is with the Department of Information and Network Systems, National Institute of Information and Communication Technology (e-mail: wada@nict.go.jp).

Digital Object Identifier 10.1109/JSTQE.2007.904082

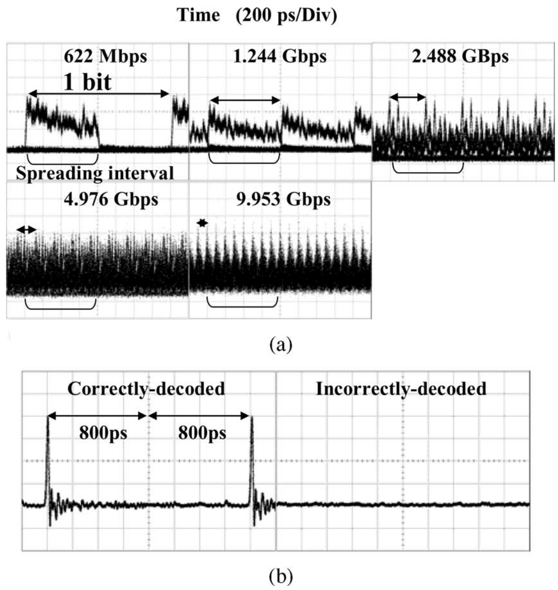


Fig. 1. Measured eye diagrams of encoded signals for different data rates, and the waveforms of correctly and incorrectly decoded signal in a 511-chip SSFBG.

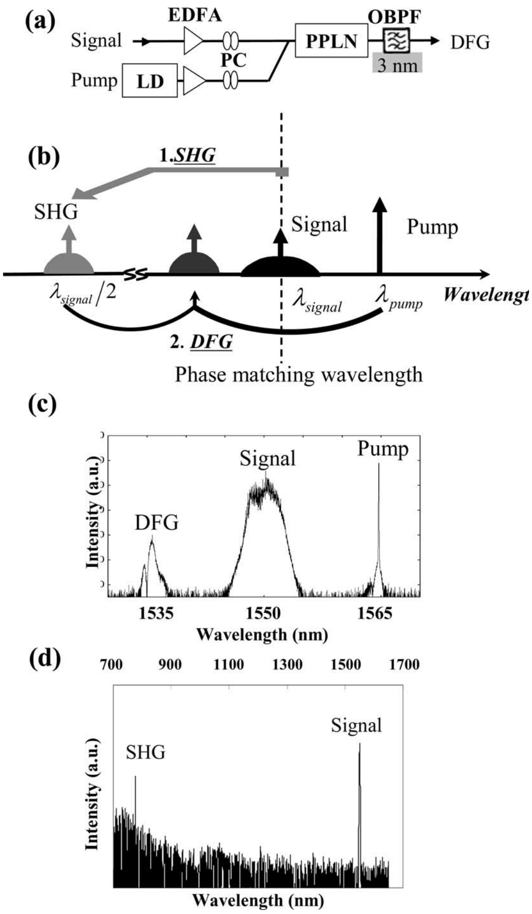


Fig. 2. (a) Setup of the optical thresholder. (b) Schematic diagram of cascaded SHG-DFG optical thresholder. (c) Measured spectrum of output from PPLN waveguide. (d) Spectrum of SHG in PPLN waveguide.

In this report, we use a record-long 511-chip SSFBG to effectively reduce the MAI and beat noise [4]. In encoding a signal, the pulses are spread over 800 ps. Fig. 1(a) shows the eye diagrams of encoded signals for different data-rate signals. Fig. 1(b) shows the waveforms of correctly and incorrectly decoded signal in the 511-chip SSFBG. As the temporal waveform of its autocorrelation (cross-correlation) is spread over the interval of 1600 ps, the intersymbol overlapping occurs in the encoded signal of more than 1.244 Gb/s. This results the arising of ISI noise and degradation of the system performance at high data-rate. Eventually, error-free (BER $< 10^{-9}$) transmission could hardly be achieved for 9.953 Gb/s signal [1].

B. Cascaded SHG-DFG-Based PPLN Waveguide Optical Thresholder

PPLN is a waveguide device of ferroelectric material, poled periodically by electric-field poling technique with a certain period, which decides the phase-matching condition [12].

The SHG-based PPLN optical thresholder has been reported that can operate at optical power as low as $\sim$30 fJ/bit [10]. However, since the generated signal is at the second-harmonic wavelength of about 750 nm, it is not suitable for further optical processing and detection. Here, we propose a new optical thresholding scheme by using the cascaded SHG-DCF in PPLN to suppress the MAI and ISI.

Fig. 2(a) shows the setup of the proposed optical thresholder. It is composed of erbium-doped fiber amplifiers (EDFAs), tunable laser diode (LD), polarization controllers (PCs), PPLN, and optical bandpass filter (OBPF) with 3-nm bandwidth. Fig. 2(b) shows the schematic diagram of the operation principle of the cascaded SHG-DFG optical thresholder. The phase-matching wavelength of the PPLN is chosen to be the same as the central wavelength of signal ($\lambda_{\mathrm{signal}}$). Therefore, a high-power optical signal will generate SHG at $\lambda_{\mathrm{signal}}/2$, whose intensity is proportional to the square of the signal $\propto (I_{\mathrm{signal}})^2$. With simultaneous injection of the pump light at λ_{pump}, the DFG signal between SHG and pump signal will be generated at a wavelength of $2\lambda_{\mathrm{signal}} - \lambda_{\mathrm{pump}}$. By adjusting the wavelength of the pump signal, the DFG wavelength can be flexibly generated at the wavelength of interest. This flexibility is significantly different from other schemes. The intensity of DFG signal I_{DFG} is proportional to $[(I_{\mathrm{signal}})^2 I_{\mathrm{pump}}]$. The output signal from the optical thresholder is much broader in time domain than the original signal because the bandwidth of the converted DFG signal is down to about 1nm from 5 nm of the original signal limited by the width of the PPLN phase-matching window. This can be further improved by applying special PPLN waveguide with large phase-matching window of about 100 nm, which is capable to convert 160-Gb/s return-to-zero signals [13].

In the experiment, the amplified signal ($\lambda_{\mathrm{signal}} = 1550$ nm) and a pump light ($\lambda_{\mathrm{pump}} = 1565$ nm) with an average power of about 25 mW from a tunable laser diode (continuous wave) is injected into the PPLN, to generate a DFG ($\lambda = 1535$ nm) as shown in Fig. 2(c). Then, the SHG is also generated at $\lambda = 775$ nm as shown in Fig. 2(d). The conversion efficiency $[P_{\mathrm{SHG}}/(P_{\mathrm{input}})^2]$ of the PPLN in this experiment is $\sim$450% where P_{SHG} and P_{input} are defined as the average power of the

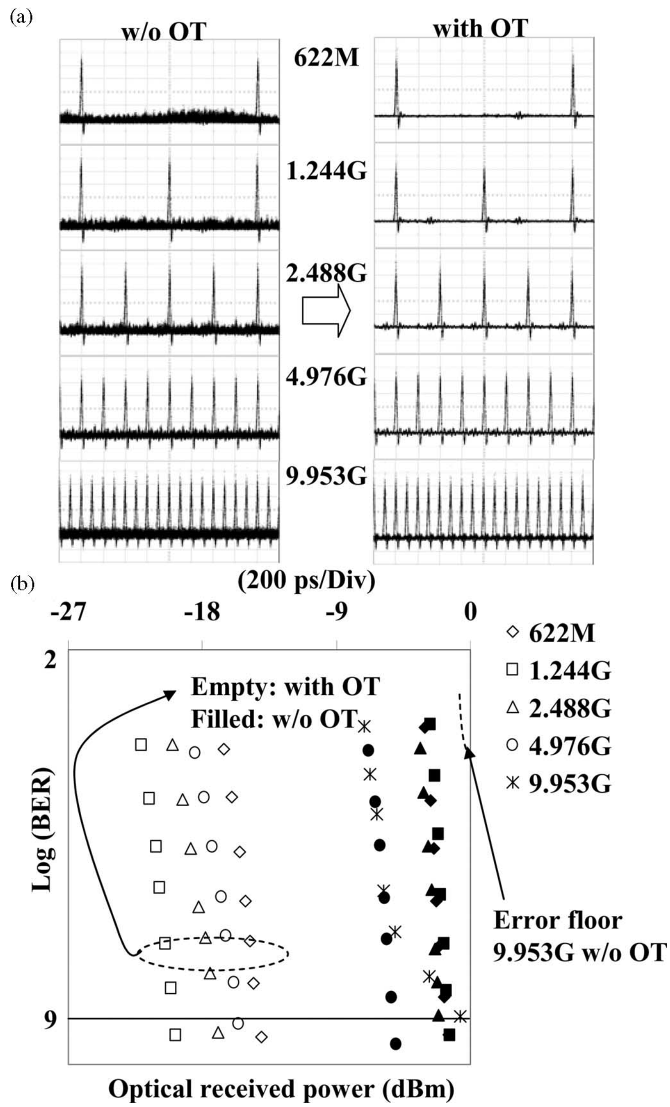


Fig. 3. (a) Measured eye diagrams of the signal and (b) measured BER with and without optical thresholder for different data rates.

SHG and the input signal. Fig. 3(a) shows the measured eye diagrams of signals with and without the optical thresholder for different data rates. It is observed that dominant noises are suppressed effectively. Measured BERs corresponding to these signals are shown in Fig. 3(b). In 10-Gb/s measurement without optical thresholder, the error-free transmission could not be measured. A large power penalty was recorded between the measurements with and without optical thresholder. Fig. 4 shows the measured transfer function of this optical thresholder ($P_{\rm in}$ *versus* $P_{\rm out}$). The average operation power is about 6 mW for 1.25 Gb/s, which means that the peak power is about 30 W (60 pJ/bit). With a two-times increasing data rate, the operation power is increasing with 3 dBm theoretically, while it was $\sim$2.5 dBm in the experimental measurement.

III. Data-Rate Flexible OCDMA

We measured the maximum number of active users K that could be accommodated with BER $< 10^{-9}$ for different data

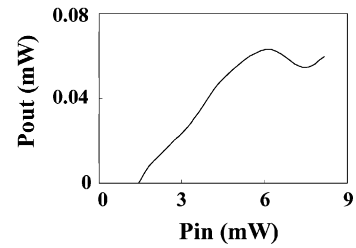


Fig. 4. Transfer function of cascaded SHG-DFG optical thresholder.

rates in an OCDMA system with 511-chip, 640-Gchip/s SSFBG encoder/decoders. Fig. 5(a) shows the experimental setup. A 9.953-GHz optical pulse train with a central wavelength of 1550 nm was modulated by $2^{23} - 1$ pseudorandom bit sequence (PRBS) at each different data rate (622 Mb/s–9.953 Gb/s). The amplified signal was split into ten branches, and encoded by ten different 511-chip SSFBG encoders. In the setup, the "phase adjust" segment, which consisted of a fixed fiber delay line with different lengths, tunable optical delay line (TODL), tunable optical attenuator (ATT) with switch and PC, was used to balance the power level from each branch and adjust the K value [5]. In this experiment, we measured by emulating random access, and the polarization states of all the signals are aligned.

The multiplexed K encoded signals were amplified by an EDFA and then decoded by SSFBG decoder. Fig. 5(b) shows the eye diagrams of the multiuser encoded signals at different data rates and with different K. Fig. 5(c) shows the eye diagrams of the signals after the SSFBG decoder while Fig. 5(d) shows those after the PPLN optical thresholder based on cascaded SHG-DFG. Finally, the optical signal was detected by the photodetector (PD), and the BER was measured by error detector (ED). In 10-Gb/s measurement, an error-free transmission was achieved due to the optical thresholder. Fig. 6(a) shows the measured maximum K with BER $< 10^{-9}$ *versus* data rate together with the theoretical calculation [1], [4]. Fig. 6(b) shows the measured and calculated power penalty versus K for two different data rates for 2.448 and 1.244 Gb/s. The deviations between the experimental and theoretical results shown in Fig. 6 are mainly due to the slight unevenness in the wings around the autocorrelation and the nonidea performance of the practical optical thresholder.

IV. Compound Data-Rate OCDMA

In another experiment, we demonstrated a compound data-rate (622 Mb/s + 2.488 Gb/s) OCDMA system for the provision of diversified service applications. Fig. 7 shows the experimental setup. The 10-GHz optical pulses from MLLD were split into two arms and modulated by PRBS data at 622 Mb/s and 2.488 Gb/s for different services, respectively. The 622-Mb/s and 2.488-Gb/s signals were split into eight and two branches, respectively. Signals in different branches were encoded by different 511-chip SSFBG encoders. We used totally ten different encoders in the experiment, i.e., code 1–code 10 [6]. Encoder code 1 and code 9 were used for the 2.44-Gb/s signal; the other encoders were for the 622-Mb/s signal. The "user adjust"

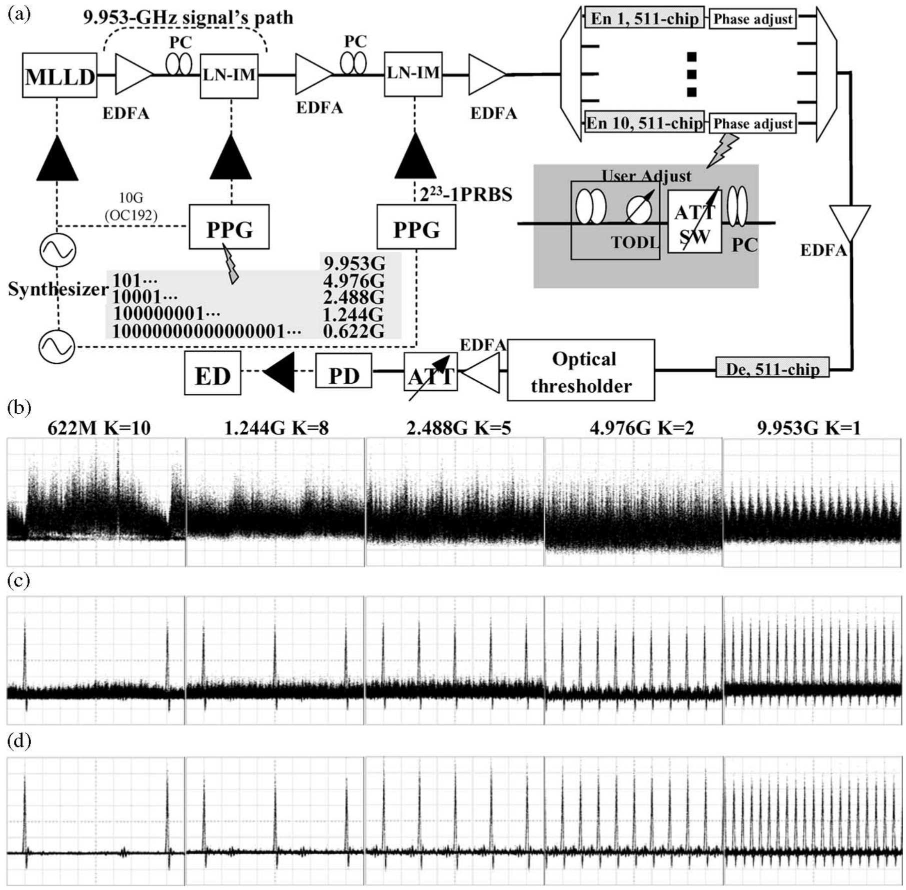


Fig. 5. (a) Experimental setup of flexible data-rate OCDMA. (b) Eye diagrams of the multiuser encoded signals. (c) Signals after 511-chip SSFBG decoder. (d) Signals after PPLN optical thresholder at different data rates with different K.

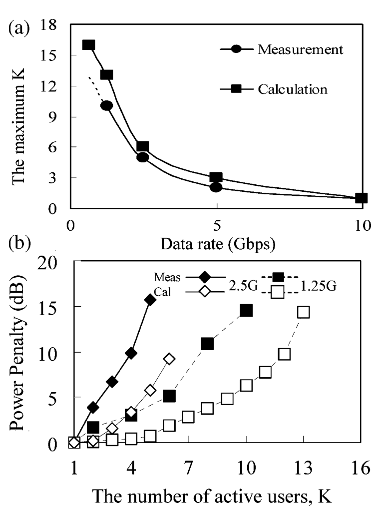


Fig. 6. (a) Maximum K *versus* the data rate and (b) the power penalty *versus* K for 2.488 Gb/s and 1.244 Gb/s.

segments were inserted in all these branches to investigate the system performance in the worst case scenario withsynchronous bits and aligned polarization state [6]. At the receiver, the multiplexed compound data-rate OCDMA signals were decoded by the SSFBG decoders: code 1 for 2.488 G and code 4 for 622 M. The PPLN optical thresholder based on cascaded SHG-DFG was used to remove the MAI and ISI noise. The operation power is almost the same as the data-rate flexible OCDMA experiment. Finally, the decoded signal is photodetected by PD, followed by a 5.2-GHz lowpass filter (LPF) used to perform data-rate detection for the signal. With 8-channel 622-Mb/s and 2-channel 2.488-Gb/s OCDMA signal multiplexing, BERs were around 10^{-3} for both 622-Mb/s and 2.488-Gb/s signals in the worst case. Fig. 8(a) (left column) shows the eye diagrams of the output from LPF. The BER could easily achieve lower than 10^{-9} by adjusting the TODL for the best case, i.e., slot-level timing coordination—synchronous case (Syn). The BERs are shown in Fig. 8(b) marked by "Syn," and the right column in Fig. 8(a) shows the corresponding eye diagrams. With up to 3-channel 622-Mb/s and 2-channel 2.488-Gb/s compound OCDMA signals, BER $< 10^{-9}$ could be achieved in both these data rates under the worst case scenario for asynchronous operation. The BERs are shown in Fig. 8(b) marked by "Asy," and the eye diagrams are shown in the middle column of Fig. 8(a).

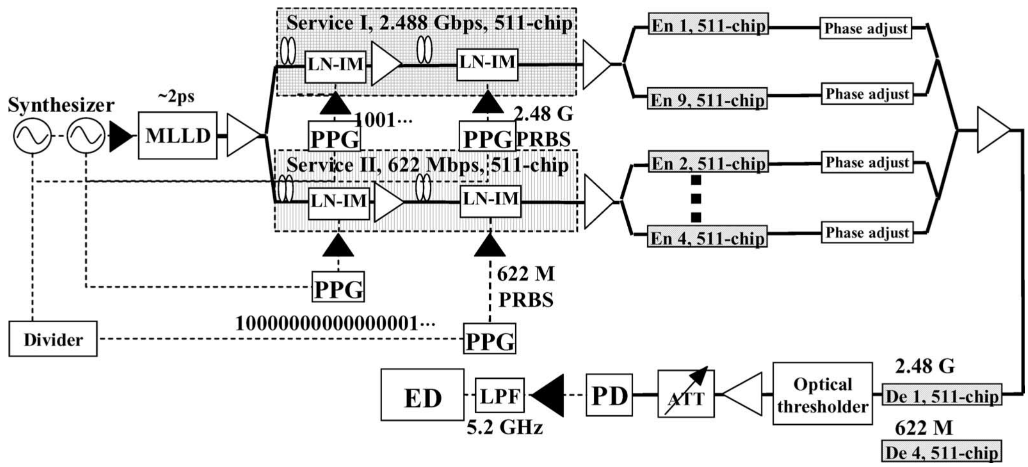


Fig. 7. Experimental setup of compound data-rate OCDMA.

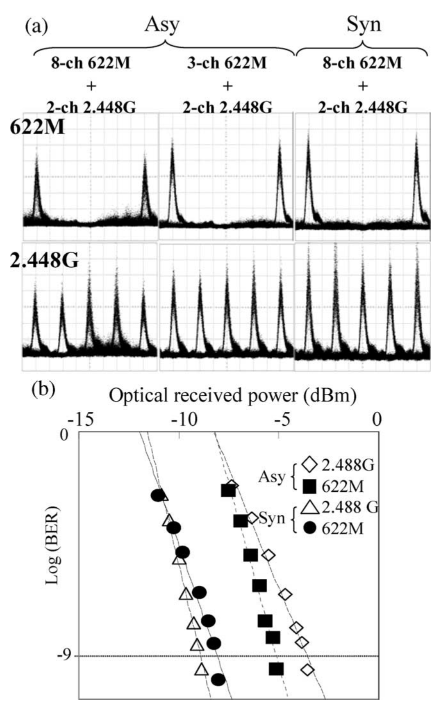


Fig. 8. (a) Eye diagrams of the output from LPF and (b) measured BERs for different cases.

V. Conclusion

We have experimentally investigated the data-rate flexibility of the OCDMA system with a 511-chip SSFBG and optical thresholder, and demonstrated the compound data-rate OCDMA system for the future multiple service provisioning on demand. We have proposed a new optical thresholder by using cascaded SHG-DFG in PPLN waveguide to reduce MAI and ISI noises. This new optical thresholder can be flexibly operated in C-band with reasonable low power, allowing further optical processing and easy detection.

Acknowledgment

The authors would like to thank H. Furukawa and Y. Tomiyama of the National Institute of Information and Communication Technology for their valuable support.

References

[1] X. Wang, N. Wada, and K. Kitayama, “Inter-symbol interference and beat noise in flexible data-rate coherent OCDMA and the BER improvement by using optical thresholding,” *Opt. Express*, vol. 13, pp. 10469–10474, 2006.

[2] K. Kitayama, X. Wang, and H. Sotobayashi, “State of the art and applications of optical code division multiple access,” presented at the ECOC, Stockholm, Sweden, Sep. 2004, Paper Tu4.6.1.

[3] X. Wang, K. Matsushima, K. Kitayama, A. Nishiki, N. Wada, and F. Kubota, “High-performance optical code generation and recognition by use of a 511-chip, 640-Gchip/s phase-shifted superstructured fiber Bragg grating,” *Opt. Lett.*, vol. 30, no. 4, pp. 355–357, Feb. 2005.

[4] X. Wang and K. Kitayama, “Analysis of beat noise in coherent and incoherent time-spreading OCDMA,” *J. Lightw. Technol.*, vol. 22, no. 10, pp. 2226–2235, Oct. 2004.

[5] H. P. Sardesai and A. M. Weiner, “Nonlinear fibre-optic receiver for ultrashort pulse code division multiple access communications,” *Electron. Lett.*, vol. 33, pp. 610–611, 1997.

[6] X. Wang, N. Wada, T. Hamanaka, K. Kitayama, and A. Nishiki, “10-user truly-asynchronous OCDMA experiment with 511-chip SSFBG en/decoder and SC-based optical thresholder,” presented at the Opt. Fiber Commun. Conf., Anaheim, CA, Mar. 2005, Paper PDP33.

[7] J. H. Lee, P. C. Teh, Z. Yusoff, M. Ibsen, W. Belardi, T. M. Monro, and D. J. Richardson, “A holey fiber-based nonlinear thresholding device for optical CDMA receiver performance enhancement,” *IEEE Photon. Technol. Lett.*, vol. 14, no. 6, pp. 876–878, Jun. 2002.

[8] K. Li, W. Cong, V. J. Hernandez, R. P. Scott, J. Cao, Y. Du, J. P. Heritage, B. H. Kolner, and S. J. Ben Yoo, “10 Gbit/s optical CDMA encoder-decoder BER performance using HNLF thresholder,” presented at the Opt. Fiber Commun. Conf., Anaheim, CA, Mar. 2004, Paper MF87.

[9] J. H. Lee, P. C. Teh, P. Petropoulos, M. Ibsen, and D. J. Richardson, “A grating-based OCDMA coding-decoding system incorporating a nonlinear optical loop mirror for improved code recognition and noise reduction,” *J. Lightw. Technol.*, vol. 20, no. 1, pp. 36–46, Jan. 2002.

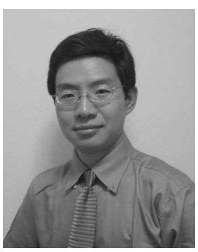
[10] Z. Jiang, D. S. Seo, S. D. Yang, D. E. Leaird, R. V. Roussev, C. Langrock, M. M. Fejer, and A. M. Weiner, “Four user 10 Gb/s spectrally phase-coded O-CDMA system operating at $\sim$30 fj/bit,” *IEEE Photon. Technol. Lett.*, vol. 17, no. 3, pp. 705–707, Mar. 2005.

[11] T. Hamanaka, X. Wang, N. Wada, and K. Kitayama, “511-chip SSFBG and DFG-based optical thresholder enabled compound data rate (10Gbps–622Mbps) OCDMA experiment for multiple service provisioning platform,” presented at the Opt. Fiber Commun. Conf., Anaheim, CA, Mar. 2006, Paper OThT4.

[12] L. E. Myers, R. C. Eckardt, M. M. Fejer, R. L. Byer, W. R. Bosenberg, and J. W. Pierce, "Quasi-phase-matched optical parametric oscillator in bulk periodically poled LiNbO3," *J. Opt. Soc. Am. B*, vol. 12, pp. 2102–2116, 1995.

[13] H. Furukawa, A. Nirmalathas, N. Wada, S. Shinada, H. Tsuboya, and T. Miyazaki, "Tunable all-optical wavelength conversion of 160 Gbit/s RZ signals based on cascaded SFG-DFG in PPLN waveguide," presented at the Opt. Fiber Commun. Conf. Expo., Mar. 2006, Paper OWW5.

Taro Hamanaka received the B.E. and M.E. degrees from the Department of Electrical, Electronic and Information Engineering, Osaka University, Osaka, Japan, in 2005 and 2007, respectively.



Xu Wang (S'91–M'98–SM'06) received the B.S. degree in physics from the Zhejiang University, Hangzhou, China, in 1989, the M.S. degree in electronics engineering from the University of Electronics Science and Technology of China (UESTC), Chengdu, China, in 1992, and the Ph.D. degree in electronics engineering from the Chinese University of Hong Kong (CUHK), Hong Kong, in 2001.

From 1992 to 1997, he was a Lecturer in National Key Laboratory of Fiber Optic Broad-band Transmission and Communication Networks, UESTC. From 2001 to 2002, he was a Postdoctoral Research Fellow in the Department of Electronic Engineering, CUHK. From 2002 to 2004, he was a Telecommunications Advancement Organization (TAO) Research Fellow with the Department of Electronic and Information Systems, Osaka University, Osaka, Japan. He joined the Ultra-Fast Photonic Network Group, Department of Information and Network Systems, National Institute of Communication and Information Technology, Tokyo, Japan, as an Expert Researcher in April 2004. He joined the School of Engineering and Physical Sciences, Heriot Watt University, Edinburgh, U.K., as a Senior Lecturer in July 2007. He is also an Adjunct Professor with a couple of universities in China. His research interests include fiber optic communication networks, optical code-division multiplexing, optical packet switching, semiconductor laser, application of fiber gratings, and fiber optic signal processing. He has filed 3 patents and authored more than 70 technical papers published in several journals and conference proceedings.

Dr. Wang was awarded the Telecommunications Advancement Research Fellowship by the TAO of Japan in 2002 and 2003.

Naoya Wada (M'97) received the B.E., M.E., and Dr. Eng. degrees in electronics from Hokkaido University, Sapporo, Japan, in 1991, 1993, and 1996, respectively.

In 1996, he joined the Communications Research Laboratory, Ministry of Posts and Telecommunications, Tokyo, Japan. He is currently a Senior Researcher with the National Institute of Information and Communications Technology, Tokyo, Japan, where he has been a Project Reader of Photonic Node Project and Research Manager with the Ultra-Fast Photonic Network Group, Department of Information and Network Systems, since April 2006. His current research interests include photonic networks and optical communication technologies, particularly optical packet switching network, optical processing, and optical code-division multiple access system. He has authored more than 200 papers published in several journals and conference proceedings.

Dr. Wada is a member of the IEEE Communications Society, the IEEE Lasers and Electro-Optics Society, the Institute of Electronics, Information and Communication Engineers, the Japan Society of Applied Physics, and the Optical Society of Japan. He received the 1999 Young Engineer Award from the Institute of Electronics, Information and Communication Engineers of Japan, and the 2005 Young Researcher Award from the Ministry of Education, Culture, Sports, Science and Technology.

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, Kanagawa, Japan. From 1982 to 1983, he was a Research Fellow with the University of California, Berkeley. He joined the Communications Research Laboratory (now called the National Institute of Information and Communications Technology), Tokyo, Japan, in 1995. Since 1999, he has been the Professor of the Department of Electrical, Electronic and Information Engineering, Graduate School of Engineering, Osaka University. He is an Associate Editor of *Optical Switching and Networking*. His research interests include photonic networks, optical signal processings, OCDMA systems, and radio-over-fiber communications. He has authored over 210 papers published in refereed journals, two book chapters, and translated one book. He is the holder of more than 30 patents.

Prof. Kitayama is a Fellow of the Institute of Electronics, Information and Communication Engineers (IEICE) of Japan. He is on the Editorial Boards of the IEEE PHOTONICS TECHNOLOGY LETTERS and the IEEE TRANSACTIONS ON COMMUNICATIONS. He received the 1980 Young Engineer Award from IEICE, the 1985 Paper Award of Optics from the Japan Society of Applied Physics, the 2004 Achievement Award of the of Japan, and the 2007 Shida Rinzaburoh Award.