OCDMA Over WDM PON—Solution Path to Gigabit-Symmetric FTTH

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

***Abstract*—It will be revealed that a myth of deploying low bit-rate uplink fiber-to-the-home (FTTH) services while providing a high bit-rate downlink is wrong. Therefore, for the future broadband FTTH services, the focus should be on the capability to provide gigabit- or even multigigabits-per-second both in up- and downlinks, namely gigabit symmetric systems. Optical code-division multiple access (OCDMA) now deserves a revisit as a powerful alternative to time-division multiple access and wavelength-division multiple (WDM) access in FTTH systems. In this paper, the authors will first highlight the OCDMA systems. The system architecture and its operation principle, code design, optical en/decoding, using a long superstructured fiber Bragg grating (SSFBG) en/decoder, and its system performance will be described. Next, an OCDMA over WDM passive optical network (PON) as a solution for the gigabit-symmetric FTTH systems will be proposed. The system architecture and the WDM interchannel crosstalk will be studied. It will be shown that by taking advantage of reflection spectrum notches of the SSFBG en/decoder, the WDM interchannel crosstalk can be suppressed and can enable OCDMA over WDM PON to simultaneously provide multigigabit-per-second up- and downlinks to a large number of users.**

***Index Terms*—Gigabit, optical code-division multiple access (OCDMA), passive optical network (PON), time-division multiplexing (TDM), wavelength-division multiplexing (WDM).**

I. Introduction

FIBER-TO-THE-HOME (FTTH) will resolve the first/last mile bottleneck in between the high-capacity metro networks and the customer premises of small-to-medium-sized businesses and residential users. From the viewpoint of the service provider or the carrier, the cost effectiveness as well as smooth service upgradeability with a negligible impact on the existing infrastructure are crucial for introducing the new FTTH system. Passive optical network (PON) will satisfy these criteria, to address the first/last mile of the communication infrastructure between the service-provider central office, head end or point-of-presence, and business or residential customer premises [1].

From the viewpoint of the customers' service demand, we will soon see a transition from a single play to triple play, such as high-speed Internet, IP telephony, and broadcasting video [2]. In the long run, the service demands will further progress toward high bit rate and customization. Eventually, it will be revealed that a myth of the uplink being of low bit rate while only the downlink being of high bit rate is wrong. This is because the peer-to-peer applications, such as exchanging the gigabyte files of uncompressed 1.2-Gb/s high-definition (HDTV) class or even 6-Gb/s super-high-definition (SHD) class digital movies [3] on a peer-to-peer basis as well as bidirectional medical applications of telediagnosis and surgery, are expected to become widespread. Customized services would be another demand for a wide variety of service options in the bit rate and QoS. Without an abundant bandwidth of uplink available either on demand or on an always-on basis, these applications could not be well supported and, consequently, ordinary nonpeer-to-peer users will be put in a disadvantageous position by being forced to share the limited bandwidth with a small number of bandwidth-hungry users. Therefore, in the upgrading scenario of the FTTH services in the near future, in order to meet the users' needs, a high bit-rate uplink is a requisite, leading to a novel-system concept of gigabit-symmetric FTTH [4], [5].

TDM PONs, such as asynchronous transfer mode (ATM) PON [1] and Ethernet PON (E-PON) [2], are currently being deployed. Current TDM PONs provide data rates ranging from 155 Mb/s to 1 Gb/s, shared among 8–32 users. However, in such TDM PONs, the time-sharing transmission in the uplink limits the bandwidth of the individual users. In the time-division multiple access (TDMA)-based PON system, it would be difficult to simultaneously provide all the customers with a gigabit-class bandwidth uplink, due to the nature of the time-slot-based multiple access protocol. It will also be difficult to provide the services to the users with different bit rates in the uplink. Therefore, TDM PON will not be a solution to the gigabit-symmetric FTTH system.

Wavelength-division multiple access (WDMA) is a natural approach to enhance the uplink capacity. WDM PON creates point-to-point links between the optical line terminal (OLT) and each user by uniquely assigning a wavelength to the user. A smooth migration to WDMA from TDM PONs is expected for the service providers in the near future if the mass production and the common specifications can reduce the cost of the optical network unit (ONU). Coarse WDM (CWDM) with the wavelength spacing of 20 nm in the spectral range from 1270 to 1610 nm has been linked with the PON architecture by International Telecommunication Union (ITU) G.694-2 [6]. However, the number of wavelengths is only 18, which may not be sufficient for the multiple access system, which accommodates even a moderate number of users.

Optical code-division multiple access (OCDMA) provides another dimension for multiple access, other than time- and optical frequency domains. Unfortunately, it has long remained

Manuscript received July 11, 2005; revised November 26, 2005.
K. Kitayama is with the Osaka University, 2-1, Yamadaoka, Suita, Osaka 565-0871, Japan (e-mail: kitayama@comm.eng.osaka-u.ac.jp).
X. Wang and N. Wada are with the National Institute of Information and Communication Technology, Tokyo, Japan (e-mail: xwang@nict.go.jp; wada@nict.go.jp).
Digital Object Identifier 10.1109/JLT.2006.871030

outside the main stream of optical communications R&D since its proposal in the mid-1970s [7] followed by experimental demonstrations in the 1980s [8]. This is mainly due to immaturity of optical devices, which are proprietary to OCDMA, such as optical en/decoder and optical thresholding device. Recently, a remarkable progress has been observed in device technologies for the optical en/decoder of the record-long sequence [9], [10] and optical thresholding devices [10]–[12].

The crosstalk between the different users sharing the common channel, known as the multiple access interference (MAI), and the signal-interference beat noise is the main source of bit errors. The reduction of the MAI and the beat noise are big challenges to make OCDMA a practical option for FTTH systems. Demonstrations of OCDMA-system test beds have also been conducted [13], [14]. Being encouraged by the progresses, OCDMA now deserves revisiting as a multiple-access technique for FTTH systems [15].

In this paper, we will first highlight the OCDMA systems and describe the system architecture as well as its operation principle, the code design, the optical en/decoding using a long superstructured fiber Bragg grating (SSFBG) en/decoder, and the system performance. Next, we will introduce the OCDMA over WDM PON as a solution for the gigabit-symmetric FTTH systems. We will analyze the system architecture and crosstalk between the WDM channels. It will be shown that, by taking advantage of the reflection spectrum notches of SSFBG en/decoder, the WDM interchannel crosstalk can be suppressed and, hence, OCDMA over WDM PON can simultaneously provide multigigabit-per-second up- and downlinks to a sufficient number of users.

II. Optical Code-Division Multiple Access (OCDMA) Passive Optical Network (PON)

A. System Architecture and Its Operation Principle

OCDMA provides another dimension for multiple access, other than the time- and optical frequency domains. Fig. 1(a) shows a basic architecture of a $1 \times N$ OCDMA access network. An OLT located in the end office and a number of ONU installed in the users' homes are connected via a $1 \times N$ coupler. The number of transmitters and the receivers equals the number of users' OLT. Moreover, a transmitter and a receiver are put in each ONU. The transmitters and receivers have optical encoders and decoders, respectively. Note that the optical encoding and decoding are performed solely in the optical domain. In the time-spread OCDMA system, each bit is divided up into chip time periods, and each chip is represented by a temporal waveform that is a so-called optical code sequence, as shown in Fig. 1(b). The encoder of each transmitter represents each "1" bit by sending the optical code, while a binary "0" bit is not encoded and is represented using an all-zero sequence. A unique optical code sequence is assigned to each decoder so that the decoder can restore only the intended signal out of composite received waveform.

The most attractive property of OCDMA for FTTH services is an asynchronous nature of OCDMA. OCDMA can support a fully asynchronous transmission in the uplink, which allows all the users to access on demand without contention. It is noteworthy that TDMA requires a tight control on synchronization, and WDMA needs a tight control on wavelength. There is a time-slotted operation of OCDMA in which users are assigned a time slot in addition to the code [11], [12]. Although the time-slotted OCDMA can mitigate the beat noise, this synchronous approach sacrifices the most desirable characteristic of asynchronism. Moreover, the use of time-slot significantly lowers the bandwidth efficiency of the system, and it requires the delivery of timing clock signal to all the users. Therefore, our choice will be asynchronous OCDMA. As the optical encoding and decoding are performed in the optical domain, the low latency of data transmission is guaranteed, and the transmitter, as well as the receiver, does not require any complex electrical equipment. OCDMA is also provided with the feature of soft capacity on demand, in that the users can be added on demand to the network by assigning new optical codes. It provides for the network fairness [15] in that all the users in the network have access to an equal portion of the shared bandwidth as many active users share the bandwidth of a fiber.

The performance of OCDMA system is evaluated bt the signal-to-noise power ratio. Let us look at the signal-to-noise power ratio at the receiver. In Fig. 1(b), the receiver block diagram is shown. It consists of the optical correlator and photodetector; between those two devices are the time-gate and/or optical thresholder. Note that the optical decoder plays the role of a correlator. In the time-spread OCDM system, the optical correlator time despreads the encoded signal, reconstructing the original short pulse, producing low-peak side lobes if the codes between the encoder and decoder match. On the other hand, the unmatched codes remain randomly spread over T after the decoding. For K users, each user's decoder processes a composite received waveform containing the desired signal of power S and $(K-1)$ interference signals. Thus, the signal-to-noise ratio is given by

$$\mathrm{SNR} = \frac{S}{(K-1)S + \sigma^2} = \frac{1}{(K-1) + \frac{\sigma^2}{S}} \tag{1}$$

where σ^2 is the variance of additive noise power [16]. It is assumed that the signal powers of the channels are equal. The additive noise includes the MAI noise, shot noise, and thermal noise of the receiver. The beat noise between the desired signal and the interference signals could become dominant over the MAI noise [17]. The beat noise is generated by the square-law detection of the photodetector, if a coherent light source having its coherence time longer than the chip duration $\Delta\tau$ is used. On the other hand, the incoherent OCDMA is MAI noise limited. SNR in (1) is obtained by the data-rate detection, in which the desired signal and interference signals are converted into the photocurrent by square-law detection, and the current is integrated over a bit duration time T.

B. Time Gating and Optical Thresholding

The key to improve the system performance is the chip-rate detection. The chip-rate detection is performed by time gating the optical correlator output, as shown in Fig. 1(b). This is exactly equivalent to the narrowbandpass filtering in wireless

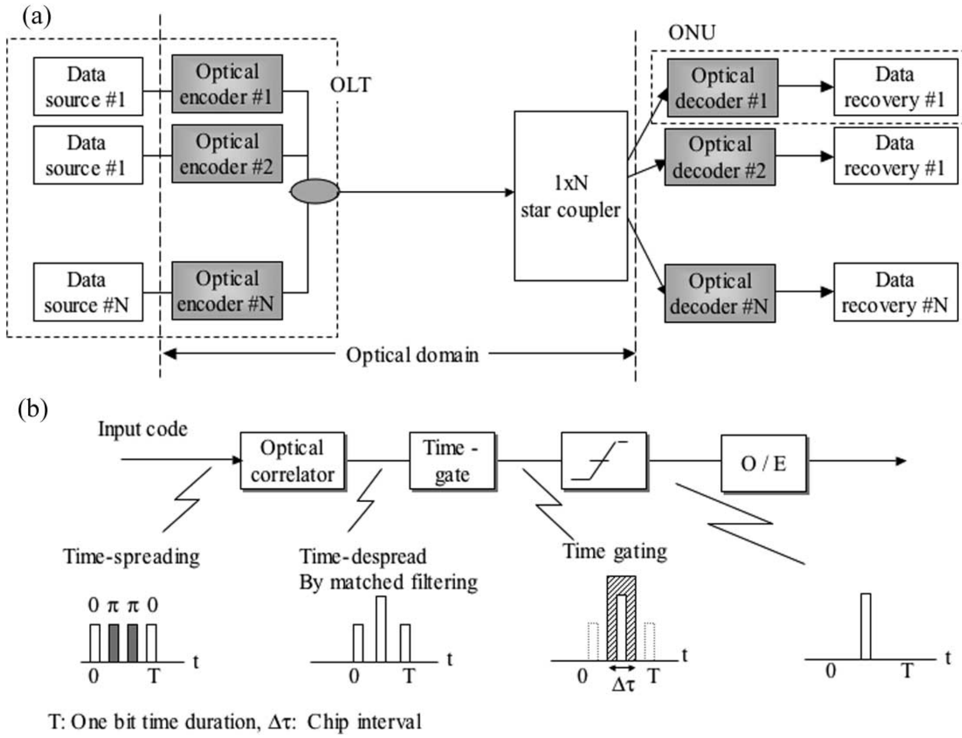


Fig. 1. (a) Basic $1 \times N$ OCDMA architecture. (b) Operation principle of time-spread OCDMA.

spread-spectrum system [16]. Time gating can dramatically reduce the MAI noise by eliminating the noises outside the time window, but the beat noise remains because the peak of the correlation waveform accompanies the beat noise. The processing gain G is expressed as the ratio of one bit time duration T to the time window $\sim \Delta\tau$ of the time gating, which is nominally set equal to or slightly longer than the chip duration $\Delta\tau$. The bit energy-to-interference density ratio E_{b}/N_0 [18] after time gating is obtained as

$$\frac{E_b}{N_0} = \frac{S}{(K-1)S\left(\frac{\Delta\tau}{T}\right) + \sigma^2\left(\frac{\Delta\tau}{T}\right)} = \frac{G}{(K-1) + \frac{\sigma^2}{S}}$$
$$G = \frac{T}{\Delta\tau}. \tag{2}$$

Comparing with (1), the bit energy-to-interference density ratio is enhanced by a factor of the processing gain G. From (2), the larger G becomes, the better the discrimination is obtained, or in other word, the more users can be accommodated. Although time gating has been demonstrated by using an injection-locked laser diode [19] and fiber-optic nonlinear loop mirror [20], it requires the chip-level synchronization and, for this reason, it will diminish the asynchronous access without precoordination, which is one of the advantages over TDMA.

Without the time gating, an optical thresholder could mitigate the MAI noise [21]–[23]. Here, we use an optical thresholding technique based on supercontinuum generation in dispersion-flattened fiber (DFF) [24]. The principle is illustrated in Fig. 2. It consists of an erbium-doped fiber amplifier (EDFA), a 2-km-long DFF and a 5-nm bandpass filter (BPF). The operation principle is as follows. The EDFA boosts the decoded optical signal, then only if the correctly decoded pulse, which have a well defined shape with $\sim$ 2-ps pulsewidth and high peak power, will be able to generate supercontinuum (SC) in the DFF. While, on the contrary, the incorrectly decoded signals, which is the MAI noise, will spread over a large time span with very low peak power so that the SC cannot be generated. The BPF only allows the SC signal passing through and rejects the original signal. Therefore, after BPF, the correctly decoded signal can be recovered without MAI noise. It exhibits an excellent discrimination between a desired signal and interference signals with features of pulse reshaping, low insertion loss, polarization independence, as well as a moderate operation power. In Fig. 3, the measured power transfer function is plotted as a function of input optical power. It shows a sharp thresholding property despite a hump in the middle.

C. Optical Code Design

The only solution to the beat-noise issue in coherent OCDMA systems is to use optical code sequences as long as possible for a given bit rate [10]. Various code sequences used for wireless CDMA communications, such as M sequence, gold codes, Kasami code [25], have been adopted as the optical codes. These code sequences are designed to have good periodic auto/cross correlation properties. However, it is still difficult to obtain a large number of available codes with good aperiodic correlation property in the code theory. A simple approach for our application is to select several code subsets from the original code set, e.g., gold code, so that some specific aperiodic auto/cross correlation criteria can be guaranteed. To quantitatively measure the aperiodic correlation property of optical code in coherent time-spread schemes, we introduce two parameters in this paper: one is the autocorrelation intensity

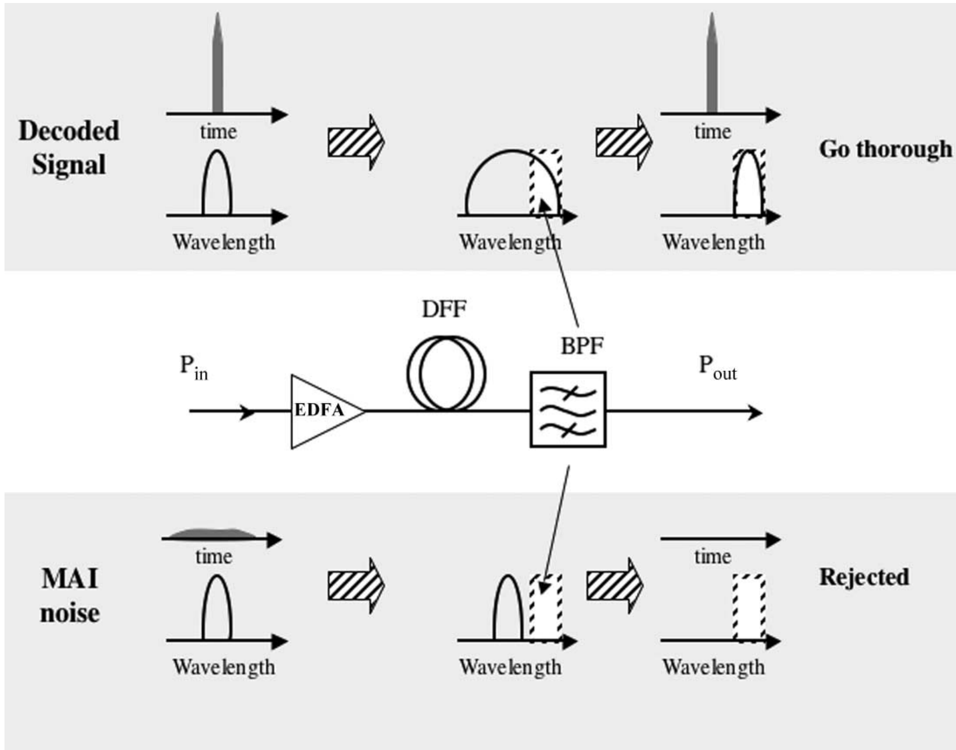


Fig. 2. Principle of DFF-based optical thresholding.

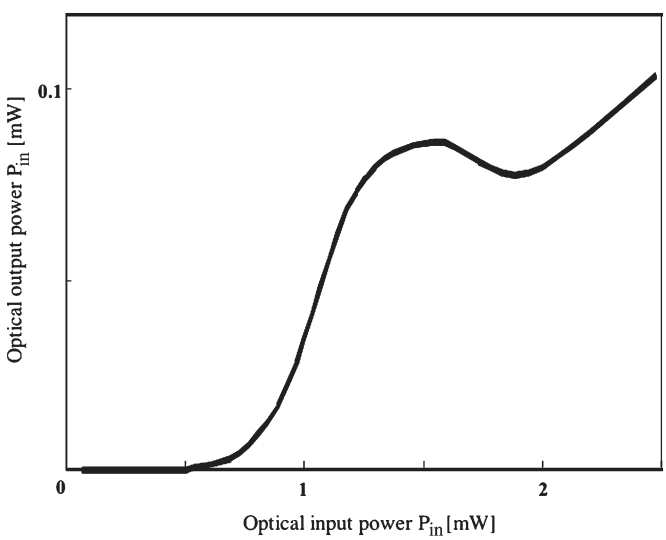


Fig. 3. Power transfer function of the SC-based optical thresholder.

peak to the maximum wing level ratio, so-called P/W ratio, and the other is the autocorrelation intensity peak to the maximum cross correlation level ratio, so-called P/C ratio [26]. Table I lists, as an example, 127-chip and 511-chip gold codes for different correlation criteria to illustrate this approach. The number of codes that satisfies these rather stringent criteria is severely limited.

TABLE I
127- AND 511-CHIP GOLD CODE SEQUENCE AND ITS CRITERIA

127-chip Gold code (Total 129 codes)	P/C >	17.9					20.5		
	P/W >	17.9	30	35	38	42	35	38	42
	Number of codes	129	110	82	48	29	33	22	17
511-chip Gold code (Total 513 codes)	P/C >	70					75	77	
	P/W >	70	100	120	130	140	130	130	140
	Number of codes	513	430	211	107	76	63	58	46

D. Optical En/Decoding

A number of optical en/decoding techniques have been proposed and demonstrated. They are classified into three categories: one dimensional (1-D) either in time domain [4], [5], [8]–[10], [13] or optical frequency domain [11], [12], [27], and two dimensional (2-D) both in time and optical frequency domain, simultaneously [28]. Another classification can be made in terms of the coherency of the light source. Encoding of coherent OCDMA, which employs a phase-shift-keying (PSK) optical code, is superior in terms of the overall system performance to the incoherent OCDMA, which uses an intensity-modulated optical code because it provides better correlation property than the intensity-modulated optical code.

The optical en/decoding technique used to obtain a long optical code is the key to realize practical coherent OCDMA systems. Devices that have been used as the optical en/decoder for coherent OCDMA include planar lightwave circuits (PLC) [4], [5], SSFBG [9], [10], [29], spatial light modulators, arrayed-waveguide-gratings (AWG) [27], and micro-electro-mechanical-system (MEMS) mirrors [30]. The reconfigurability in encoding is desirable, and all the above devices have the reconfiguration capability. Coherent time-spread OCDMA has

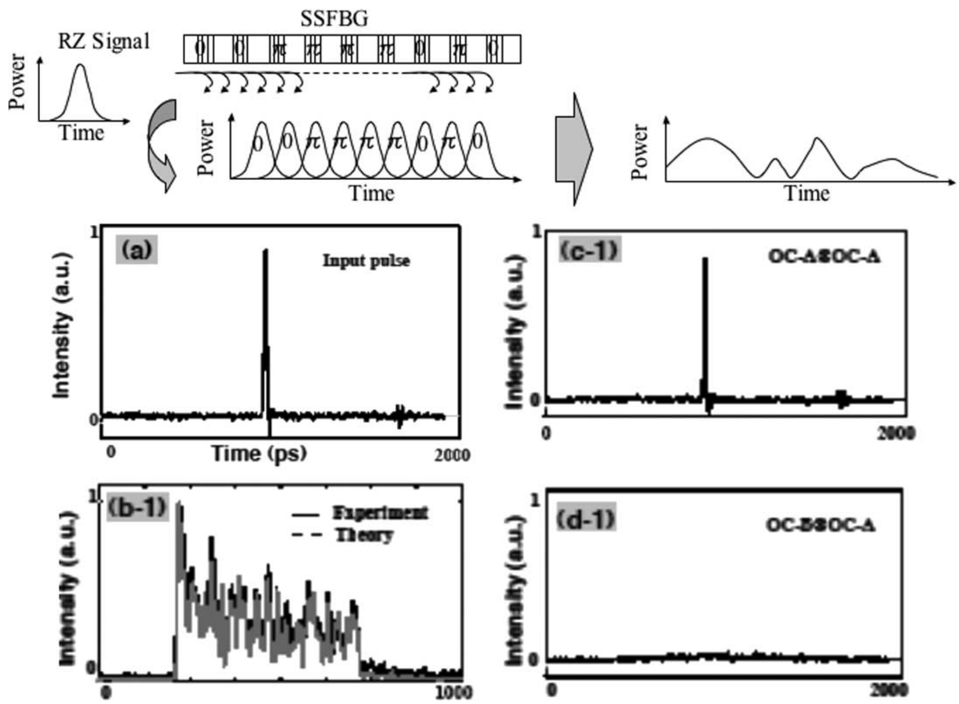


Fig. 4. Superstructured SSFBG and generation of bipolar optical code. (a) Input pulse. (b-1) Encoded signal. (c-1) Autocorrelation. (d-1) Cross correlation.

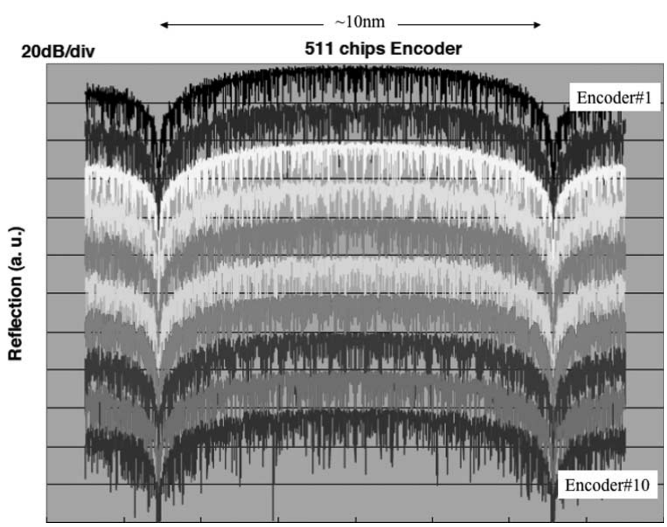


Fig. 5. Measured transmission spectra of 511-chip SSFBG encoders.

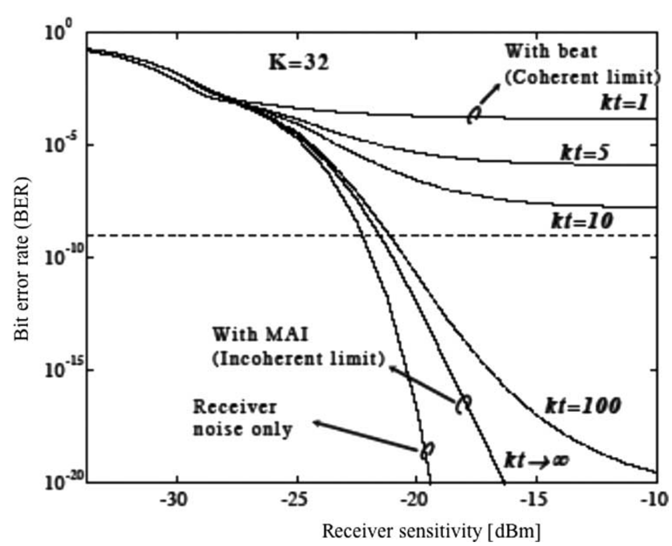


Fig. 6. Influence of the different noise sources and the coherent ratio kt on the BER performance of time-spread OCDMA with 32 active users.

been demonstrated by PLC and SSFBG. Up to 16 chips PLC have been experimentally demonstrated, but the scalability in code length might be a problem in the case of PLC due to the size constraint of the substrate and the insertion loss caused by power splitting.

An SSFBG is a promising device for a long PSK optical code because of the low insertion loss and low cost. Recently, a record long 511-chip SSFBG en/decoder has been demonstrated [10]. The chip length of the grating and the total length are 0.156 and 80 mm, respectively, which corresponds to the chip rate of 640 Gchip/s with the duration of the generated optical code of about 800 ps. Fig. 4 shows the temporal waveforms of input pulse, encoded signal, auto- and cross correlations. They show well-defined autocorrelation peaks and very low level cross correlations. The measured spectra of ten tested 511-chip 640-Gchip/s SSFBG encoders are shown in Fig. 5. The first notch appears 640 GHz (= 5 nm) apart from the central peak. The peak reflectivity is measured to be about 92%, which is the highest to date. Note that these characteristics are insensitive to the polarization state of the input signal, which shows that our fabrication progress has guaranteed good cylindrical symmetry in the SSFBG.

E. System Performance

The effects of the MAI noise and the beat noise on the bit-error rate (BER) performance versus the receiver sensitivity of

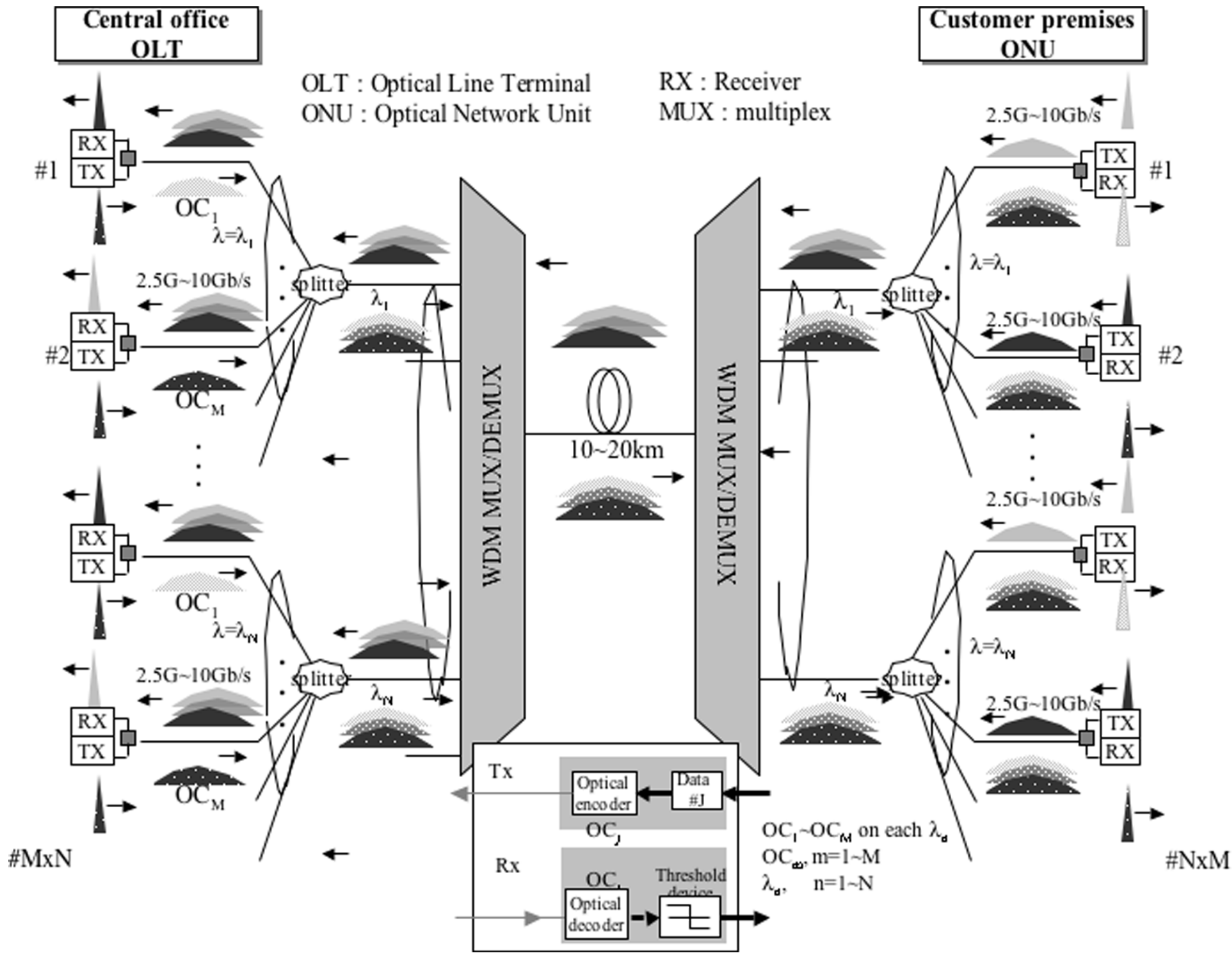


Fig. 7. Architecture of OCDM over WDM.

OCDMA system are illustrated in Fig. 6. For example, 32 active users are assumed. Here, kt is defined as the coherent ratio, and $\mathrm{kt} = 1$ and $\mathrm{kt} \to \infty$ correspond to the coherent and incoherent limits, respectively. The lowest solid curve is the one with the receiver noise only; the middle is that of an incoherent OCDMA with the receiver noise plus MAI noise, and the highest one is that of coherent OCDMA with the beat noise. It is clear that in coherent OCDMAs, the beat noise could become dominant, while, on the other hand, the incoherent OCDMA is MAI-noise limited. Note that the comparisons between the coherent and incoherent limits are based on a simple assumption that they are with same P/C ratio to emphasize the impact of the beat noise. However, in incoherent OCDMA, a much longer optical code will be needed to achieve the same P/C as in coherent OCDMA. The beat-noise suppression is a must in coherent OCDMA systems. As described in Section III-B, the only way to mitigate it is to adopt a long optical code sequence. For example, in order to support ten active users with chip-rate detection, the interference level should be lower than -27 dB. That means the code length should be longer than 500 chips. An encouraging fact is the recent experiment using a 511-chip long SSFBG encoder/decoder to provide a 10-user truly asynchronous 1.24-Gb/s coherent OCDMA [14].

III. Gigabit-Symmetric OCDMA Over WDM PON

A. System Architecture

A solution path to the gigabit-symmetric FTTH system would be OCDMA over WDM PON, as shown in Fig. 7. OCDMA channels can be overlaid on WDM grids. On each WDM grid λ_n $(n = 1, \ldots, N)$, M users can be accommodated by individually assigning each user with a different OC_m $(m = 1, \ldots, M)$. Note that the same code sequence OC_m can be reused on all the WDM channels. The total number of users that can be accommodated in the PON becomes $N \times M$. OCDMA over WDM might be viewed in a way that a WDM channel is shared with M users by equally dividing the bandwidth into channels. A clear differentiation from a conventional TDMA is that this channel division can be realized in an asynchronous manner without using time slots.

In Fig. 8, the CWDM grids of 18 counts under ITU-T G.694.2 along with the filter response are illustrated. There

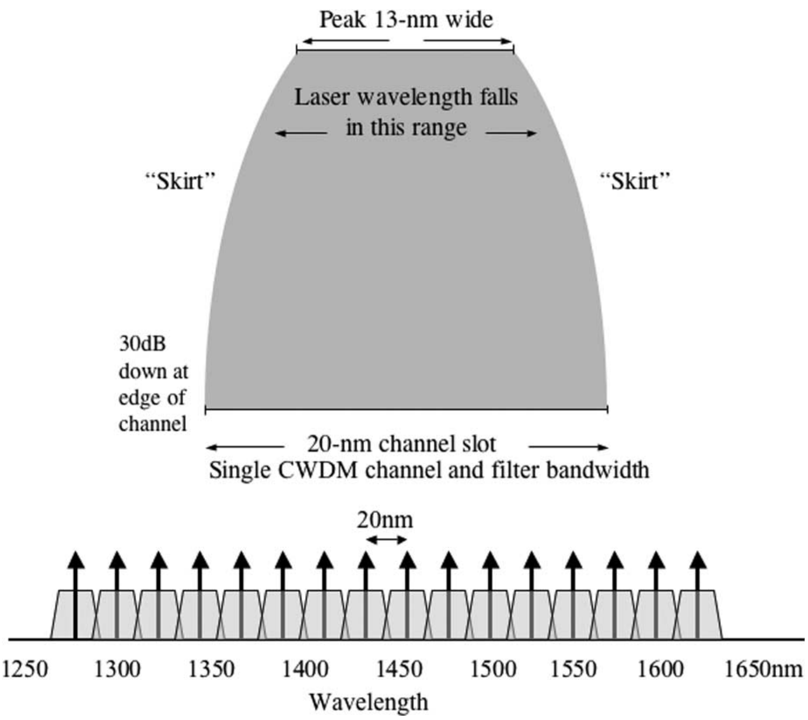


Fig. 8. CDWM-grid allocation over the spectral range from 1270 to 1630 nm under ITU-T G.694.2 along with the filter bandwidth.

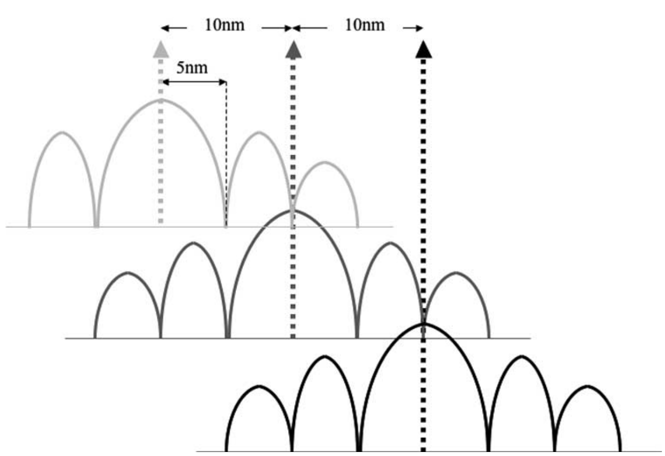


Fig. 9. Channel allocation of OCDMA over CWDM using SSFBG encoder.

are 16 wavelengths available, spaced 20 nm apart over the spectral range from 1310 to 1610 nm. In Fig. 9, for example, spectra of OCDMA channels on the WDM grid of 10 nm apart are shown in the case with 640 Gchip/s 511-chip SSFBG in Fig. 5. Note that the first notch appears about 5 nm (= 640 GHz) apart from the central peak. By taking advantage of the pseudoperiodic nature of the SSFBG en/decoder reflection spectrum, the spectral efficiency OCDMA over WDM can be increased. The neighboring WDM grids can be allocated at the spectrum notch and, hence, the desired signal on the grid is almost free from the WDM interchannel crosstalk from the neighboring grids. This fact will be confirmed by the numerical analysis described in Section III-B.

Let us consider the target total number of channels in OCDMA over WDM. Our preliminary experiments of 1.24-Gb/s OCDMA have verified that at least ten active users can be accommodated in a truly asynchronous manner on a single WDM grid by using the SSFBG en/decoder [14], and further increase of users is expected. Assuming that 16 users can be accommodated on a single WDM channel, the projected total number of channels for four typical cases are the following:

Case 1)

a) 256 channels : 16 active users on 16 CDWM grids with the interval of 20 nm from 1310 to 1610 nm;
b) 512 channels: 16 active users on 32 WDM grids of 10 nm with the interval of 10 nm from 1310 to 1610 nm;

Case 2)

a) 80 channels: 16 active users on 5 CDWM grids with the interval of 20 nm in C- and L-bands;
b) 160 channels: 16 active users on ten CDWM grids with the interval of 10 nm in C- and L-bands.

From the economical viewpoint, OCDMA over WDM PON is currently considered to be not viable. However, the FBG en/decoder is a passive device, and it should be potentially of low cost. The ultrashort pulse laser is an expensive mode-locked laser diode. A loop-back scheme implemented by placing a single ultrashort pulse laser in OLT will allow a number of users to share the light source for the uplink. This will drive down the system cost while improving the system reliability.

B. Interchannel Crosstalk

We theoretically analyze the interchannel crosstalk of OCDMA over WDM. In Fig. 10, the numerical average peak

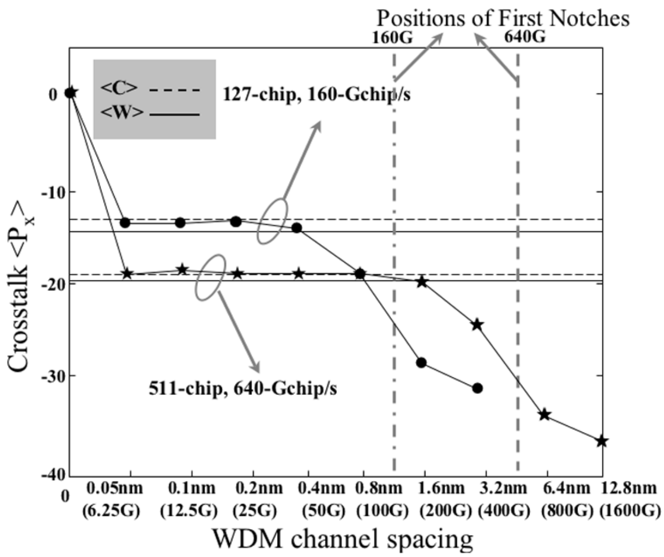


Fig. 10. Average peak power of interchannel crosstalk versus WDM channel interval for 127-chip and 511-chip SSFBG en/decoders.

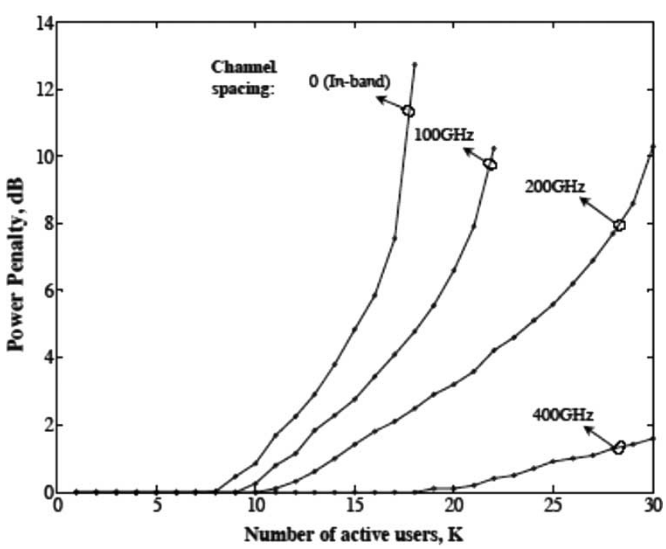


Fig. 11. Power penalty versus number of active users K for 511-chip SSFBG with different WDM channel intervals.

powers of the crosstalk $\langle P_x \rangle$ from the same optical code are plotted as a function of WDM channel spacing. The adjacent wavelength channels for 127-chip 160 G-chip/s and 511-chip 640-Gchip/s SSFBGs are shown by filled circles and stars, respectively. Note that the first notches of 127- and 511-chip SSFBGs are located at 160 and 640 GHz apart from the central peaks, respectively. $\langle C \rangle$ and $\langle W \rangle$ represent the average powers of maximum intrachannel cross correlations and autocorrelation wings, normalized by their autocorrelation peaks. A criterion of the WDM channel spacing for the tolerable interchannel crosstalk is set so that $\langle P_x \rangle$ be equal or lower than the values of $\langle C \rangle$ and $\langle W \rangle$. For the 127-chip SSFBG, $\langle C \rangle \sim -14$ dB and $\langle W \rangle \sim -14.8$ dB, while for 511-chip SSFBG, $\langle C \rangle$ and $\langle W \rangle$ are reduced to -18.8 and -19.4 dB, respectively. For the 127-chip SSFBG, therefore, the channel spacing can be reduced to 50 GHz, while, for the 511-chip SSFBG, it has to be 200 GHz or larger. In Fig. 11, the power penalty for $\mathrm{BER} = 10^{-9}$ is plotted as a function of the number of active users K for the 511-chip 640-Gchip/s SSFBG with different WDM channel spacing. For $K = 16$, the power penalty is 2 dB in the case of 200-GHz interval, but it can be made negligible for 400-GHz interval. It is also confirmed that, with the channel interval of 200 GHz, the interchannel crosstalks have smaller impact on the BER than the intrachannel MAI.

IV. Conclusion

A focus has been put on the future-proof PON system having gigabit symmetry in bandwidth between the up- and downlinks. It has been shown that OCDMA is capable of providing a gigabit- or even multigigabit-per-second for each user both in the up- and downlinks, and OCDMA over WDM PON could be one of the most promising system architectures that can break through the last/first mile bottleneck. The theoretical analysis of the interchannel crosstalk between the neighboring WDM channels of OCDMA over the WDM system using SSFBG en/decoder has shown a good spectral efficiency. In the case of WDM channel intervals of 200 and 400 GHz, the interchannel crosstalk can be negligible. Recent experimental results of truly synchronous gigabit OCDMA system using the record-long 511-chip 640-Gchip/s optical en/decoder are encouraging to support the feasibility of its practical system implementation.

Acknowledgment

The authors would like to thank F. Kubota and H. Sotobayashi of the National Institute of Information and Communication Technology (NICT), Tokyo, Japan, A. Nishiki of the New Energy and Industrial Technology Development Organization (NEDO), Kawasaki, Japan, and Prof. S. Oshiba of Kyoto Institute of Technology for their invaluable discussions.

References

[1] P. Green, "Paving the last mile with glass," *IEEE Spectrum*, vol. 39, no. 12, pp. 13–14, Dec. 2002.
[2] H. Shinohara, "FTTH development in Japan and its enabling technologies," presented at the Broadband Europe 2005, Bordeaux, France, Dec. 2005, Mo2.
[3] T. Fujii, K. Shirakawa, M. Nomura, and T. Yamaguchi, "Cinema-class digital content distribution via optical networks (Invited)," in *Proc. OpNeTec*, Pisa, Italy, Oct. 2004, pp. 11–18.
[4] K. Kitayama, X. Wang, and H. Sotobayashi, "State of the art and applications of optical code division multiple access (Invited)," presented at the Eur. Conf. Optical Communication (ECOC), Stockholm, Sweden, Sep. 2004, Paper Tu4.6.1.
[5] ——, "Multi-gigabit symmetric FTTH—OCDMA over WDM PON," in *Proc. ONDM*, Milano, Italy, Feb. 2005, pp. 273–281.
[6] D. K. Mynbaev, "PON performance improves with multiplexing," *WDM Solut.*, pp. 18–20, Jan. 2003.
[7] C. Delisle and P. Cielo, "Application de la modulation spectrale a la transmission de I'information (in French)," *Can. J. Phys.*, vol. 53, pp. 1047–1053, 1975. (Note that this might not be OCDMA in a strict definition.)
[8] P. R. Prucnal, M. A. Santoro, and T. R. Fan, "Spread spectrum fiber-optic local area network using optical processing," *J. Lightw. Technol.*, vol. LT-4, no. 5, pp. 547–554, May 1986.
[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] X. Wang, K. Matsushima, A. Nishiki, N. Wada, F. Kubota, and K.-I. Kitayama, "Experimental demonstration of 511-chip 640 Gchip/s superstructured FBG for high performance optical code processing," presented at the Eur. Conf. Optical Communication (ECOC), Stockholm, Sweden, Sep. 2004, Paper Tu1.3.7.

[11] 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, 2.5-Gb/s, spectrally coded OCDMA system demonstration using low-power nonlinear processing," *J. Lightw. Technol.*, vol. 23, no. 1, pp. 143–158, Jan. 2005.

[12] R. P. Scott, W. Cong, K. Li, V. J. Hernandez, B. H. Kolner, J. P. Heritage, and S. J. B. Yoo, "Demonstration of an error-free 4×10 Gb/s multiuser SPECTS O-CDMA network testbed," *IEEE Photon. Technol. Lett.*, vol. 16, no. 9, pp. 2186–2188, Sep. 2004.

[13] V. Baby, I. Glesk, R. J. Runser, R. Fischer, Y.-K. Huang, C.-S. Bres, W. C. Kwong, T. H. Curtis, and P. R. Prucnal, "Experimental demonstration and scalability analysis of a four-node 102-Gchip/s fast frequency-hopping time-spreading optical CDMA network," *IEEE Photon. Technol. Lett.*, vol. 17, no. 1, pp. 253–255, Jan. 2005.

[14] 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 Optical Fiber Communication (OFC) Conf., Anaheim, CA, Mar. 2005, Postdeadline Paper, PDP33.

[15] A. Stok and E. H. Sargent, "The role of optical CDMA in access networks," *IEEE Commun. Mag.*, vol. 40, no. 9, pp. 83–87, Sep. 2002.

[16] K. Kitayama, H. Sotobayashi, and N. Wada, "Optical code division multiplexing (OCDM) and its applications to photonic networks," *IEICE Trans. Fundam. Electron. Commun. Comput. Sci.*, vol. E82-A, no. 12, pp. 2616–2626, Dec. 1999.

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

[18] K. S. Gilhousen, I. M. Jacobs, R. Padovani, A. J. Viterbi, L. A. Weaver, and C. E. Wheatley, "On the capacity of a cellular CDMA system," *IEEE Trans. Veh. Technol.*, vol. 40, no. 2, pp. 303–312, May 1991.

[19] H. Kurita, H. Y. Hashimoto, and H. Yokoyama, "All-optical signal processing at over 100 Gb/s with nonlinear effects in semiconductor lasers," in *Proc. CPT*, Sendai, Japan, 1999, pp. 217–218. Pc-14-1.

[20] H. Sotobayashi, W. Chujo, and K. Kitayama, "Highly spectral efficient optical code division multiplexing transmission system," *IEEE J. Sel. Topics Quantum Electron.*, vol. 10, no. 2, pp. 250–258, Mar./Apr. 2004.

[21] H. P. Sardesai and A. M. Weiner, "Nonlinear fiber-optic receiver for ultrashort pulse code division multiple access communication," *Electron. Lett.*, vol. 33, no. 7, pp. 610–611, Mar. 1997.

[22] 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.

[23] K. Li, W. Cong, V. J. Hernandez, R. P. Scott, J. Cao, Y. Du, J. P. Heritage, B. H. Kolner, and S. J. B. Yoo, "10 Gb/s optical CDMA encoder-decoder BER performance using HNLF thresholder," presented at the Optical Fiber Communication (OFC), Los Angeles, CA, Feb. 2004, Paper MF87.

[24] X. Wang, T. Hamanaka, N. Wada, and K. Kitayama, "Optical thresholder based on SC generation in DFF for multiple-access-interference suppression in OCDMA system," *Opt. Express*, vol. 13, no. 14, pp. 5499–5505, 2005.

[25] E. H. Dinan and B. Jabbari, "Spreading codes for direct sequence CDMA and wideband CDMA cellular networks," *IEEE Commun. Mag.*, vol. 36, no. 9, pp. 48–54, Sep. 1998.

[26] X. Wang, K. Matsushima, A. Nishiki, N. Wada, and K. Kitayama, "High reflectivity superstructured FBG for coherent optical code generation and recognition," *Opt. Express*, vol. 12, no. 22, pp. 5457–5468, Nov. 2004.

[27] H. Tsuda, H. Takenouchi, T. Ishii, K. Okamoto, T. Gosh, and C. Amano, "Photonic spectral encoder/decoder using an AWG for coherent optical code division multiplexing," in *Proc. OFC*, San Diego, CA, 1999, pp. PD32/1–PD32/3.

[28] H. Fathallah, L. A. Rusch, and S. LaRochelle, "Passive optical fast frequency-hop CDMA communications system," *J. Lightw. Technol.*, vol. 17, no. 3, pp. 397–405, Mar. 1999.

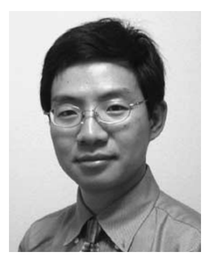
[29] M. R. Mokhtar, M. Ibsen, P. C. Teh, and D. J. Richardson, "Reconfigurable multi-level phase shift keying encoder–decoder for all-optical networks," *IEEE Photon. Technol. Lett.*, vol. 15, no. 3, pp. 431–433, Mar. 2003.

[30] P. Ebrahimi, M. Kargar, M. Hamer, A. E. Willner, K. Yu, and O. Solgaard, "A 10-μs-tuning MEMS-actuated Gires-Tournois filter for use as a tunable wavelength demultiplexer and a tunable OCDMA encoder/decoder," presented at the Optical Fiber Communication (OFC), Los Angeles, CA, Feb. 2004, Paper ThQ2.

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 Nippon Telegraph and Telephone Corporation (NTT) Electrical Communication Laboratory. In 1982–1983, he spent a year as the 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 of Osaka University. His research interests are in photonic networks and radio-on-fiber communications. He has published over 200 papers in refereed journals, has written two book chapters, and has translated one book. He holds more than 30 patents.

Dr. Kitayama currently serves on the Editorial Boards of the IEEE PHOTONONICS TECHNOLOGY LETTERS and IEEE TRANSACTIONS ON COMMUNICATIONS, *Optical Switching*, and *Networking* as the Associate Editor. He 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, and 2004 Achievement Award of Institute of Electronic and Communication Engineers (IEICE) of Japan. He is a Fellow of IEICE of Japan.



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

From 1992 to 1997, he was a Faculty Member and Lecturer in the National Key Laboratory of Fiber Optic Broad-Band Transmission and Communication Networks of UESTC. From 2001 to 2002, he was a Postdoctoral Research Fellow in the Department of Electronic Engineering of CUHK. He subsequently worked in the Department of Electronic and Information Systems of Osaka University, Osaka, Japan as a Telecommunications Advancement Organization of Japan (TAO) Research Fellow. In April 2004, he joined the Ultra-fast Photonic Network Group of Information and Network Systems Department, National Institute of Communication and Information Technology (NICT), Tokyo, Japan, as an Expert Researcher. His research interests include fiber-optic communication networks, optical-code-division multiplexing (OCDM), optical-packet switching, semiconductor lasers, application of fiber gratings, and fiber-optic signal processing. He has authored approximately 40 technical papers in refereed journals and conferences.

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 (CRL), Ministry of Posts and Telecommunications, Tokyo, Japan. He is currently a Senior Researcher of National Institute of Information and Communications Technology (NICT), Tokyo, Japan. His current research interests are in the area of photonic networks and optical communication technologies, such as optical-packet routing, optical processing, and optical OCDM.

Dr. Wada received the 1991 Shimizu-Matsumoto Award from Hokkaido University and the 1999 Young Engineer Award from IEICE of Japan. He is a member of IEICE, the Japan Society of Applied Physics (JSAP), and the Optical Society of Japan (OSJ).