

Recent Progresses in OCDMA

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ABSTRACT

In this paper, the recent progresses in optical code division multiple access (OCDMA) are reviewed including WDM/OCDMA system, high capacity multi-user field trials, and new coding techniques.

Keywords: Fiber optics communication; Wavelength division multiplexing, Optical code division multiple access; Modulation format; Field trial.

1. BACKGROUND

Passive optical network (PON) provides a solution for the first/last mile bottleneck in telecommunications infrastructure between the service provider central office, head-end or point-of-presence, and business or residential customer premises. The rapid traffic growth in access network driving by triple play services (such as high-speed internet, IP telephony, and broadcasting video) creates the demand for abundant uplink bandwidth. In the upgrading scenario in the near future, therefore, in order to meet the bandwidth requirements, a high bit rate uplink is a requisite, leading to a proposal of the system concept of Gigabit-symmetric FTTH [1].

Optical code division multiple access (OCDMA) technique, which allows multiple users share the same transmission media by assigning different optical codes (OCs) to different users, is an attractive candidate for next generation broadband access networks due to its unique features of allowing fully asynchronous transmission with low latency access, as well as enhanced confidentiality [1~3]. In addition, since the data are encoded using pseudo-random optical codes (OCs) during transmission, it also has the potential to enhance the confidentiality in the network [4~6]. In the OCDMA-PON network, data is encoded into OCs by the OCDMA encoder at the transmitter, and multiple users share the same transmission media by using power splitter/combiner. At the receiver, the OCDMA decoder recognizes the OCs by performing matched filtering, and the auto-correlation for target OC produces high level output, while the cross-correlations for undesired OCs produce low-level outputs. Finally, the original data is recovered after electrical thresholding.

Recently, coherent OCDMA technique, where encoding and decoding are based on the phase and amplitude of optical field instead of its intensity, is receiving much attention for the overall superior performance over incoherent OCDMA and the development of compact and reliable en/decoders (E/D) [7~14] like spatial light phase modulator (SLPM), superstructured fiber Bragg grating (SSFBG) and multi-port array waveguide grating (AWG)-type E/D. In coherent OCDMA systems, an ultra-short optical pulse is either spectrally encoded time-spread (SPECTS) by high resolution phase E/D [8] or spatial light phase modulator (SLPM) [9~10], or directly time-spread encoded by superstructured fiber Bragg grating (SSFBG) [11~13] or multi-port E/D with a waveguide grating configuration [14~15].

In this paper, we will discuss several recent progresses in OCDMA.

2. KEY TECHNIQUES

2.1 Coding techniques

Superstructured fiber Bragg grating (SSFBG) encoder/decoder exhibits advantages such as the capability to generate ultra-long optical code with ultra-high chip rate, polarization independent performance, low and code-length independent insertion loss, inherent compatibility with fibre-optic system, high compactness as well as low cost [11-13]. The phase-shifted SSFBG encoder/decoder can be fabricated with a single short phase mask by continuous grating writing or holographic techniques, which provide a high flexibility in producing different ultra-long optical code and high-precision phase control enabling fabrication of multiple phase level OCs.

Recently, 16-chip, 16-level phase-shifted SSFBG encoder/decoders have been developed with central wavelength of 1551 nm and chip length ~ 0.52 mm [16]. The 16 phase levels are generated by shifting the chip grating by a step of $\pm \lambda/8$. Figure 1 shows the photo of the SSFBGs, the encoding waveform, auto-correlation and cross-correlation. 10 Gbps multi-user OCDMA system has been demonstrated using hybrid multi-port encoder/SSFBG decoder.

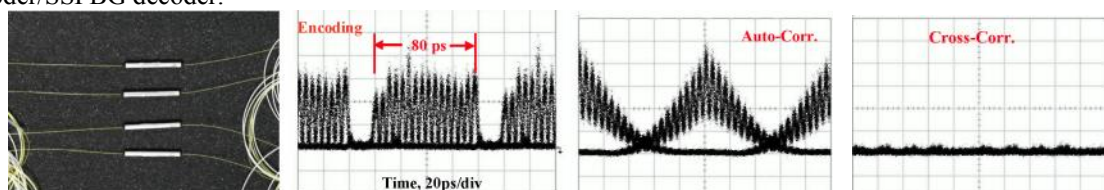


Figure 1. 16-chip, 16-phase level SSFBG encoder/decoder.

The AWG-based multi-port OCDMA encoder/decoder is able to simultaneously generate and recognize a set of time-spread OC with single device [14]. The unique capability of simultaneously processing multiple optical codes with one device makes the AWG encoder/decoder a cost effective device for OCDMA networks to be used in the central office to reduce the number of coding devices. Another attractive feature is the very high power contrast ratio (PCR) between auto- and cross-correlation signals compared to other coding devices. The 50×50 port E/D that can generate 50 coherent time-spreading OCs with 50 chips and 500 Gchip/s has been developed and applied in high capacity WDM/OCDMA demonstration [17].

The reconfigurable time domain spectral phase encoding/decoding (SPE/D) scheme uses dispersive components to stretch/compress the ultra-short optical pulse in time domain and modulate the phases of different frequency components according to a code pattern. It provides a novel flexible coding scheme for OCDMA and secured communication applications [18, 19].

Electronic transversal filters at 18 Gchips/s have also been demonstrated for OCDMA encoding/decoding providing an alternative for gigabit data rates access applications [20].

2.2 Modulation formats

Coherent OCDMA with differential phase-shift keying (DPSK) modulation format and balanced detection (DPSK-OCDMA) is superior over the OOK-OCDMA with advantages of improved receiver sensitivity, better tolerance to beat noise and multiple-access-interference (MAI) noise without optical threshold, and no need for dynamic Threshold level setting [6]. High capacity WDM/OCDMA systems have been demonstrated with DPSK data modulation [16, 21, 22].

For further enhancing the spectral efficiency, differential quaternary phase shift keying (DQPSK)-OCDMA has been demonstrated in synchronous condition together with FEC and polarization multiplexing [23]. Total spectral efficiency reached 0.87 bit/s/Hz.

Code-shift-keying (CSK)-OCDMA with balanced detection can also improve multi-user capability with respect to OOK-OCDMA. The requirement for real-time number of active user estimation and dynamic threshold level setting are relaxed in CSK-OCDMA scheme, in the same way as in the DPSK-OCDMA with balanced detection. And more importantly, the security can be significantly improved in the CSK-OCDMA system because an eavesdropper could not decipher the signal without knowing the OCs [24]. Figure 2 shows the improvement of CSK-OCDMA as compared to OOK-OCDMA against an eavesdropper with data-rate power detection.

M-ary CSK-OCDMA could further enhance the spectral efficiency by carrying multiple bits with a pulse [25]. The security could also been improved by M-ary CSK modulation [26].

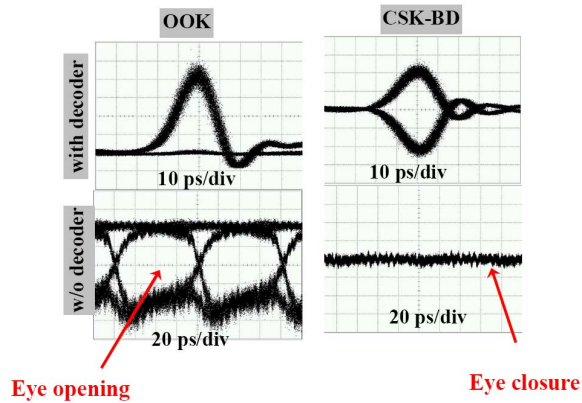


Figure 2. Security improvement in CSK-OCDMA.

3. FIELD TRIALS OF MULTI-USER WDM/OCDMA

The field trials for multi-user WDM/DPSK-OCDMA were carried out on an optical testbed of JGNII (Japan Gigabit Network II). JGN II is a nationwide open testbed network operated by NICT as a ultra-high-speed testbed networks for R&D collaboration between industry, academia, government. The fiber used in the experiments is installed in the field between the laboratory in Koganei city and downtown Tokyo in a loop-back configuration as shown in Fig. 3. The total length is about 100 km.

The first field trial involves 16×16 ports, 200 Gchip/s multiport encoder/decoder and DPSK modulation format [21]. The data rate is 10.7 Gbps, WDM channel spacing is 400 GHz. Signals of 3-WDM, 10-OCDMA have been transmitted over the field fibre with BER < 10⁻⁹. The spectral efficiency (SE) is about 0.32 and 0.27 bit/s/Hz for B-to-B and field transmission, respectively.

With a large scale (50×50 ports, 500 Gchip/s) multi-port encoder/decoder and FEC, terabit payload capacity (1.24 Tb/s) asynchronous WDM/DPSK-OCDMA transmission field trial has been successfully demonstrated [17]. Payloads of 5 wavelengths (600GHz spacing)×25-OCDMA users at 9.95328 Gbps/user have been successfully transmitted over 100 km field fibre with BER < 10⁻⁹ and SE is ~0.41 bit/s/Hz for payload.

Very recently, an OCDMA prototype has been developed by hybrid using multi-port and SSFBG en/decoders [22]. It includes 10GbE interface OCDM transmitter (Tx) and receiver (Rx). Figure 4 shows the configurations

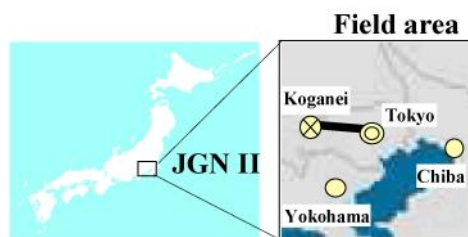


Figure 3. Field trial on JGNII.

and photos of OCDMA prototype. The OCDM Tx consists of mode-locked laser diode (MLLD), LiNbO₃ phase modulator (LN-PM), and OCDM Tx board, which convert the inputted 10GbE signal into 10.3125 Gbps serial data with DPSK precoding and clock recovery. The MLLD generates ~ 1.8 ps pulses at repetition rate of 10.3125 GHz. The signal was modulated with DPSK format by LN-PM. The OCDM Tx is 19-inch $\times$ 3U sized rack and independently driven by the inputted 10GbE signal without the external synthesizer allowing full-asynchronous operation. OCDM Rx consists of an interferometer, dual-pin photo detector (PD), and OCDM Rx board, which converts the DPSK detected signal into 10GbE signal. At the ONU side, OCDM Rx includes the SSFBG decoder and is in 19-inch $\times$ 1U sized rack. The package of the SSFBG is 45 mm $\times$ 3 mm in size without temperature control.

Duplex, fully-asynchronous, 10Gbps, 8-user DPSK-OCDMA field trial has been successfully demonstrated on this prototype [22].

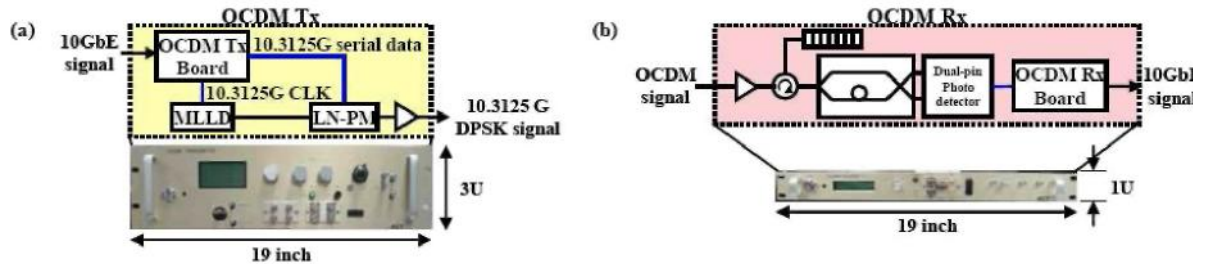


Figure 4. Configurations and photographs of OCDMA prototype: (a) OCDM Tx and (b) OCDM Rx.

4. CONCLUSIONS

The recent advances in OCDMA encoding/decoding techniques include multi-phase-level SSFBG encoder that is compatible to the AWG-based en/decoder, large scale (50 $\times$ 50) multiport en/decoder, reconfigurable time domain SPE/D and high speed electronic transversal filters. These are one branch of the key technologies towards the flexible, high capacity and secured OCDMA network. New signal modulation formats in OCDMA including DPSK, DQPSK, CSK and M-ary CSK are another branch of the key technologies. Field trials of high capacity WDM/OCDMA system have been demonstrated using these technologies. Further investigation could be focused on the flexibility and security of the network.

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REFERENCES

- [1] K. Kitayama, X. Wang and N. Wada: OCDMA over WDM PON -A Solution Path to Gigabit-Symmetric FTTH-?, *IEEE/OSA J. Lightwave Technol.* vol.24, pp.1654-1662, April, 2006.
- [2] A. Stock and E. H. Sargent: The role of optical CDMA in access networks, *IEEE Communication Magazine*, vol.40, pp. 83- 87 (2002).
- [3] X. Wang and K. Kitayama: Analysis of beat noise in coherent and incoherent time-spreading OCDMA, *IEEE/OSA J. Lightwave Technol.* 22, 2226-2235, 2004.
- [4] T. H. Shake: Confidentiality performance of spectral-phase-encoded optical CDMA, *IEEE/OSA J. Lightwave Technol.*, vol. 23, pp. 1652-1663, 2005.
- [5] D. E. Leaird, Z. Jiang, and A. M. Weiner: Experimental investigation of security issues in OCDMA: a code-switching scheme, *Electron. Lett.*, vol. 41, pp.817-819, July 2005.
- [6] X. Wang, N. Wada, T. Miyazaki, and K. Kitayama: Coherent OCDMA system using DPSK data format with balanced detection, *IEEE Photonic Technol. Lett.*, vol. 18, pp.826-828, April, 2006.
- [7] H. Sotobayashi, W. Chujo and K. Kitayama: 1.6-b/s/Hz 6.4-Tb/s QPSK-OCDM/WDM (4 OCDM $\times$ 40 WDM $\times$ 40 Gb/s) transmission experiment using optical hard thresholding, *IEEE Photon. Tech. Lett.*, vol. 14, pp. 555-557 (2002).
- [8] S. Etemad, *et al.*: Spectrally Efficient Optical CDMA Using Coherent Phase-Frequency Coding, *IEEE Photonic Technol. Lett.*, vol. 17, pp. 929-931, 2005.
- [9] Z. Jiang, *et al.*: Four-user 10-Gb/s spectrally phase-coded O-CDMA system operating at ~ 30 fJ/bit, *IEEE*

- Photonics Technol. Lett.*, vol. 17, 705-707, 2005.
- [10] R. P. Scott, *et al.*: Demonstration of an error-free 4×10 Gb/s multiuser SPECTS O-CDMA network testbed, *IEEE Photonics Technol. Lett.*, vol. 16, pp.2186-2188, 2004.
 - [11] P. C. Teh, P. Petropoulos, M. Ibsen and D. J. Richardson: A comparative study of the performance of seven- and 63-chip optical code-division multiple-access encoders and decoders based on superstructured fiber Bragg gratings, *J. Lightwave Technol.* 19, pp. 1352-1365 (2001).
 - [12] X. Wang, *et al.*: High reflectivity superstructured FBG for coherent optical code generation and recognition, *OSA Optics Express*, vol. 2, no. 22, pp. 5457-5468, Nov.1, 2004.
 - [13] X. Wang, *et al.*: High performance optical code generation and recognition using 511-chip 640Gchip/s phase-shifted superstructured FBG, *Optics Lett.*, 30, pp. 355-357 (2005).
 - [14] G. Cincotti: Design of optical full encoders/decoders for code-based photonic routers, *J. Lightwave Technol.*, vol. 22, pp. 1642-1650, 2004.
 - [15] X. Wang, N. Wada, G. Cincotti, T. Miyazaki, and K. Kitayama: Demonstration of Over 128-Gb/s-Capacity (12-User 10.71-Gb/s/User) Asynchronous OCDMA Using FEC and AWG-Based Multiport Optical Encoder/Decoders, *IEEE Photonics Technol. Lett.*, vol. 18, 1603-1605, 2006.
 - [16] X. Wang, N. Kataoka, N. Wada, G. Cincotti and K. Kitayama: Flexible 10 Gbps, 8-user DPSK-OCDMA System with 16×16 Ports Encoder and 16-level Phase-shifted SSFBG Decoders, *OFC'08*, OMR2, San Diego, CA USA, February, 2008.
 - [17] X. Wang, N. Wada, N. Kataoka, T. Miyazaki, G. Cincotti and K. Kitayama: 100 km Field Trial of 1.24 Tbit/s, Spectral Efficient Asynchronous 5 WDM×25 DPSK-OCDMA using One Set of 50×50 Ports Large Scale En/Decoder, *OFC'07 post-deadline*, PDP 14, Anaheim, CA., USA, Mar., 2007.
 - [18] X. Wang and N. Wada: Spectral Phase Encoding of Ultra-short Optical Pulse in Time Domain for OCDMA Application, *OSA Optics Express*, vol. 15, pp. 7319-7326, June, 2007.
 - [19] X. Wang, and N. Wada: Novel Synchronous Time-domain Spectral Phase Encoding/Decoding Scheme for Secured Optical Communication, *CLEO/Europe -IQEC2007*, CI3-5-Tue, Munich, Germany, June, 2007.
 - [20] J. B. Rosas-Fernandez, J. Ingham, R. Penty, I. White: 18 Gchips/s Electronically-Processed OCDMA Spread Spectrum for Access Networks, *OFC'08 postdeadline*, PDP30, San Diego, CA USA, Feb. 2008.
 - [21] X. Wang, N. Wada, T. Miyazaki, G. Cincotti and K. Kitayama: Field Trial of Asynchronous WDM/DPSK-OCDMA Using Hybrid E/D, *J. Lightwave Technol.* Vol.25, pp. 207~215, Jan. 2007.
 - [22] N. Kataoka, N. Wada, X. Wang, G. Cincotti, A. Sakamoto, Y. Terada, T. Miyazaki and K. Kitayama: Duplex, Fully-Asynchronous, 10Gbps x 8-User DPSK-OCDMA Field Trial Using a Multi-Port En/Decoder and SSFBG En/Decoders, *OFC'08 postdeadline*, PDP27, San Diego, CA USA, 2008.
 - [23] P. Toliver, A. Angarwal, T. Banwell, R. Menezes, J. Jackel and S. Etemad: Demonstration of high spectral efficiency coherent OCDM using DQPSK, FEC and integrated ring resonator-based spectral phase encoder/decoder, *OFC'07 postdeadline*, PDP7, 2007.
 - [24] X. Wang, N. Wada, T. Miyazaki, G. Cincotti, and K. Kitayama: Asynchronous Multi-user Coherent OCDMA System with Code-Shift-Keying and Balanced Detection, *IEEE J. Sel. Topics Quantum Electron.*, vol. 13, no. 5, pp. 1463-1470, Sep./Oct. 2007.
 - [25] R. Menendez, A. Agarwal, P. Toliver, J. Jackel, and S. Etemad, "Direct optical processing of M-ary code-shift keyed OCDMA using integrated passive optical phase decoders", *ECOC'06*, P165, 2006.
 - [26] N. Nakagawa, *et al.*: Experimental demonstration of 16-ary, 2.5Gbit/s OCDMA using single multi-port en/decoder, submitted to *ECOC 2008*.