# Spectral phase encoding of ultra-short optical pulse in time domain for OCDMA application


**Xu Wang and Naoya Wada**

*Photonic Network Group, New Generation Network Research Center, National Institute of Information and Communication Technology (NICT), 4-2-1, Nukui-Kitamachi, Koganei-shi, Tokyo 184-8795 Japan*
xwang@nict.go.jp



**Abstract:** We propose a novel reconfigurable time domain spectral phase encoding (SPE) scheme for coherent optical code-division-multiple-access application. In the proposed scheme, the ultra-short optical pulse is stretched by dispersive device and the SPE is done in time domain using high speed phase modulator. The time domain SPE scheme is robust to wavelength drift of the light source and is very flexible and compatible with the fiber optical system. Proof-of-principle experiments of encoding with 16-chip, 20 GHz/chip binary-phase-shift-keying codes and 1.25 Gbps data transmission have been successfully demonstrated together with an arrayed-wave-guide decoder.





**OCIS codes:** (060.0600) Fiber optics and optical communications; (060.2630) Frequency modulation; (060.5060) Phase modulation; (060.4230) Multiplexing; (320.5540) Pulse shaping; (999.999) Encoding/decoding; (9999.999) Optical code division multiple access


## References and links


1. A. Stock and E. H. Sargent, "The role of optical CDMA in access networks," IEEE Communication Magazine **40**, 83- 87 (2002).
2. K. Kitayama, X. Wang, and H. Sotobayashi, "State of the art and applications of optical code division multiple access (Invited)," in European Cnference of Optical Communication (ECOC'04), (Stockholm, Sweden, 2004), Tu4.6.
3. X. Wang and K. Kitayama, "Analysis of beat noise in coherent and incoherent time-spreading OCDMA," J. Lightwave Technol **22,** 2226-2235, (2004).
4. T. H. Shake, "Confidentiality performance of spectral-phase-encoded optical CDMA," J. Lightwave Technol. **23**, 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. **41**, 817-819, (2005).
6. X. Wang, N. Wada, T. Miyazaki, and K. Kitayama, "Coherent OCDMA system using DPSK data format with balanced detection," IEEE Photon. Technol. Lett. **18**, 826-828, (2006).
7. H. Sotobayashi, W. Chujo and K. Kitayama, "1.6-b/s/Hz 6.4-Tb/s QPSK-OCDM/WDM (4 OCDM × 40 WDM × 40 Gb/s) transmission experiment using optical hard thresholding," IEEE Photon. Technol. Lett. **14**, 555-557 (2002).
8. S. Etemad, P. Toliver, R. Menendez, J. Young, T. Banwell, S. Galli, J. Jackel, P. Delfyett, C. Price, and T. Turpin, "Spectrally efficient optical CDMA using coherent phase-frequency coding," IEEE Photoni. Technol. Lett. **17**, 929-931, (2005).
9. Z. Jiang, D. Seo, S. 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 ~ 30 fJ/bit," IEEE Photon. Technol. Lett. **17**, 705-707, (2005).
10. R. P. Scott, W. Cong, K. Li, V. J. Hernandez, B. H. Kolner, J. P. Heritage, and S. J. Ben Yoo, "Demonstration of an error-free 4×10 Gb/s multiuser SPECTS O-CDMA network testbed," IEEE Photon. Technol. Lett. **16**, 2186-2188 (2004).
11. A. Agarwal, P. Toliver, R. Menendez, S. Etemad, J. Jackel, J. Young, T. Banwell, B. Little, S. Chu, J. Hryniewicz, W. Chen, W. Chen and P. Delfyett, "Fully-programmable ring resonator based integrated photonic circuit for phase coherent applications," in *Optical Fiber Communication Conference*, OFC 2005 Postdeadline Papers (OSA, Anaheim, 2005), paper PDP 6.
12. J. Cao, R. G. Broeke, N. K. Fontaine, C. Ji, Y. Du, N. Chubun, K. Aihara, A.-V. Pham, F. Olsson, S. Lourdudoss, and S. J. B. Yoo, "Demonstration of Spectral Phase O-CDMA encoding and decoding in monolithically integrated arrayed-waveguide-grating-based encoder," IEEE Photon. Technol. Lett. **18**, 2602-2604 (2006).
13. P. C. Teh, P. Petropoulos, M. Ibsen and D. J. Richardson, "A comparative study of the performance of seven-



#80494 - $15.00 USD Received 27 Feb 2007; revised 23 May 2007; accepted 30 May 2007; published 31 May 2007

and 63-chip optical code-division multiple-access encoders and decoders based on superstructured fiber Bragg gratings," J. Lightwave Technol. **19**, 1352-1365 (2001).
14. X. Wang, K. Matsushima, A. Nishiki, N. Wada, F. Kubota, and K. Kitayama, "High performance optical code generation and recognition using 511-chip 640Gchip/s phase-shifted superstructureed FBG," Opt. Lett. **30**, 355-357 (2005).
15. X. Wang, K. Matsushima, A. Nishiki, N. Wada, and K. Kitayama, "High reflectivity superstructured FBG for coherent optical code generation and recognition," Opt. Express. **12**, 5457-5468 (2004).
16. G. Cincotti, "Design of optical full encoders/decoders for code-based photonic routers," J. Lightwave Technol. **22**, 1642-1650 (2004).
17. X. Wang, N. Wada, T. Hamanaka, A. Nishiki and K. Kitayama, "10-user asynchronous OCDMA transmission experiment with 511-chip SSFBG and SC-based optical thresholder," in *Optical Fiber Communication Conference*, OFC 2005 Postdeadline Papers (OSA, Anaheim, 2005), paper PDP 33.
18. X. Wang, N. Wada, T. Miyazaki, G. Cincotti and K. Kitayama, "Field Trial of 3-WDM×10-OCDMA×10.71 Gbps, Truly-asynchronous, WDM/DPSK -OCDMA using Hybrid E/D without FEC and Optical Threshold," in *Optical Fiber Communication Conference*, OFC 2006 Postdeadline Papers (OSA, Anaheim, 2006), paper PDP 44.
19. A. M. Wiener, "Femtosecond pulse shaping using spatial light modulators," Rev. Sci. Instrum. **71**, 1929-1960, (2000).
20. N. Wada, F. Kutota, H. Watanabe, Y. Komai and K. Kodate, "160GHz to 20GHz Variable Rate RZ and CS-RZ Pulse Trains Generation by using Phase and Attenuation Tunable High-Resolution AWG, and its Application to Photonic Networks," in *Conference on Lasers and Electro-Optics in Europe (CLEO/Europe)*, Post-deadline, CEP-8-THU, (2003).
21. Z. Jiang, D. E. Leaird and A. M. Wiener, "Width and wavelength-tunable optical RZ pulse generation and RZ-to-NRZ format conversion at 10 GHz using spectral line-by-line control," IEEE Photonic Technol. Lett. **17**, 2733-2735 (2005).
22. P. C. Chou, H. A. Haus, and J. F. Brennan III, "Reconfigurable time-domain spectral shaping of an optical pulse stretched by a fiber Bragg grating," Opt. Lett. **25**, 524-526 (2000).
23. J. Azaña, N. K. Berger, B. Levit, and B. Fischer, "Reconfigurable generation of high-repetition-rate optical pulse sequences based on time-domain phase-only filtering," Opt. Lett. **30**, 3228-3230 (2005).
24. A. M. Weiner and J. P. Heritage, U.S. Patent No. 4,928,316

## 1. Introduction

Optical code division multiple access (OCDMA), where users share the same transmission medium by assigning unique pseudo-random optical code (OC), is attractive for next generation broadband access networks due to its features of allowing fully asynchronous transmission with low latency access, soft capacity on demand, protocol transparency, simplified network management as well as increased flexibility of QoS control [1~3]. In addition, since the data are encoded into pseudo-random OCs during transmission, it also has the potential to enhance the confidentiality in the network [4~6]. Figure 1 illustrates a basic architecture and working principle of an OCDMA passive optical network (PON) network. In the OCDMA-PON network, the data are encoded into pseudo random OC by the OCDMA encoder at the transmitter and multiple users share the same transmission media by assigning

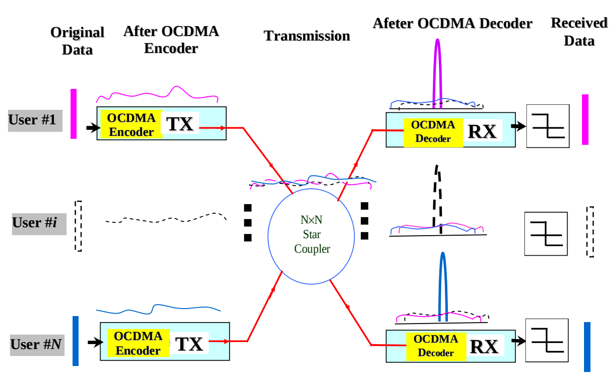


Fig. 1. Working principle of an OCDMA network

#80494 - $15.00 USD Received 27 Feb 2007; revised 23 May 2007; accepted 30 May 2007; published 31 May 2007

different OCs to different users. At the receiver, the OCDMA decoder recognizes the OCs by performing matched filtering, where the auto-correlation for target OC produces high level output, while the cross-correlation for undesired OC produces low level output. Finally, the original data can be recovered after electrical thresholding.

Recently, coherent OCDMA technique with ultra-short optical pulses is receiving much attention for the overall superior performance over incoherent OCDMA and the development of compact and reliable en/decoders (E/D) [7~15]. In coherent OCDMA, encoding and decoding are performed either in time domain or in spectral domain based on the phase and amplitude of optical field instead of its intensity.

Figure 2(a) shows the working principle of the coherent time spreading (TS) OCDMA, where the encoding/decoding are performed in time domain. In such a system, the encoding is to spread a short optical pulse in time with a phase shift pattern representing a specific OC. The decoding is to perform the convolution to the incoming OC using a decoder, which has an inversed phase shift pattern as the encoder and generates high level auto-correlation and low level cross-correlations. Planar lightwave circuit (PLC) [7], superstructured fiber Bragg grating (SSFBG) [13~15], and multi-port E/D with waveguide grating configuration [15] can be used as the en/decoder for this scheme. High capacity coherent TS-OCDMA have been demonstrated by different en/decoders [17~18]. One drawback is that the auto-correlation has not only a high level peak but also low level sidelobes as shown in Fig. 2(a) [15].

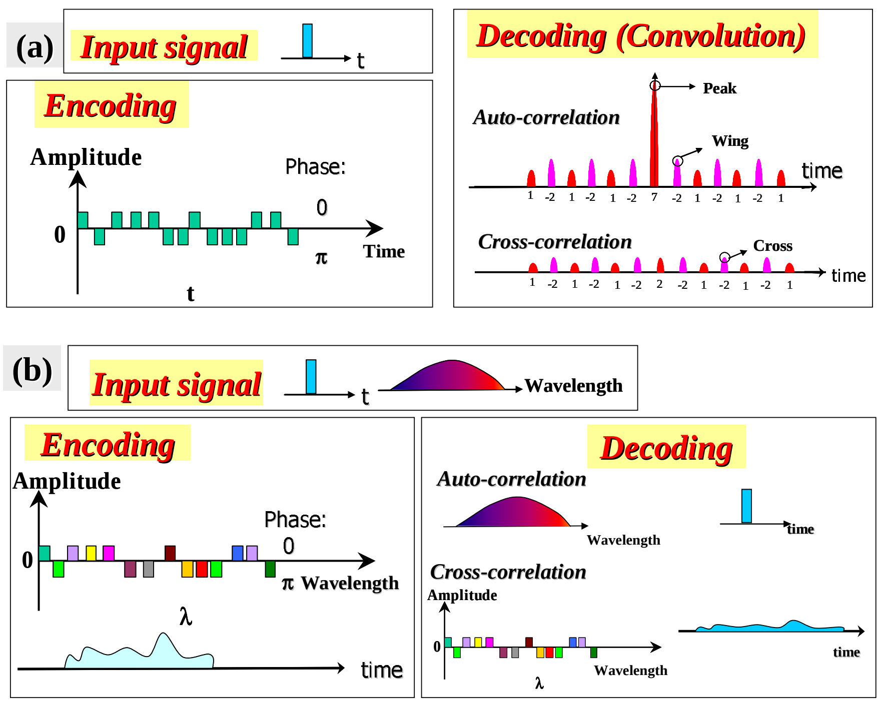


Fig. 2. Working principles of coherent OCDMA (a) TS OCDMA (b) SPETS OCDMA

On the other hand, the spectrally phase encoding time spread (SPECTS) OCDMA system performs the en/decoding in spectral domain [8~12]. Figure 2(b) shows the working principle of the SPECTS-OCDMA. In such a system, the encoding is done to the broad spectrum of the ultra-short optical pulse and different spectral component has different phase shift. This also results the spreading of the short pulse in time domain. The decoding is to give inverted phase changes to different spectral components by the proper decoder with a complementary phase

#80494 - $15.00 USD Received 27 Feb 2007; revised 23 May 2007; accepted 30 May 2007; published 31 May 2007

shift pattern compared to encoder. Therefore, the auto-correlation for the proper code can recover the spectrum as well as the temporal shape of the original pulse, while the cross-correlation still spread in time similar as the encoded signals. The spectral phase encoding (SPE) scheme can also be applied in pulse shaping as well for applications such as high-repetition-rate pulse burst generation [19~20], RZ-to-NRZ converting [21] and etc. The SPECTS en/decoders include spatial lightwave phase modulator (SLPM) [9~10], high resolution phase encoder/decoder [8], micro-ring-resonator (MRR) [11] or monolithically integrated en/decoders including AWG and phase shifters [12]. Generally, in the SPECTS-OCDMA system, high spectral resolution is always desirable for the sake of the spectral efficiency [8]. As a limit, the resolution of each chip should equal to the mode spacing, or the repetition rate of the optical pulses [8, 21]. Therefore, the wavelength stability requirement for laser source and encoder/decoder is very stringent, which appears an issue for this system. Another issue is the compatibility of the encoder/decoders with the fiber optic system because the most of them are based on free-space optics. The third issue is the relatively high loss with these encoder/decoders.

Recently, spectral shaping to be done in time domain by stretching short pulse with dispersive components has also been proposed and demonstrated [22~24]. This time domain spectral shaping technique can be much flexible and compatible with fiber optic system. In this paper, we propose and demonstrate a novel reconfigurable time domain SPE scheme for coherent OCDMA application.

## 2. Proposed SPE scheme

Figure 3 shows schematic diagram of the proposed reconfigurable time domain SPE scheme. The pulse generator generates ultra-short optical pulses, which have broadband spectrum. The SPE section is composed of a pair of dispersive devices with opposite dispersion values (–D and +D) and a high speed phase modulator (PM). The first dispersive device with dispersion value of D is to stretch the pulse in time domain, so that different spectral components of the signal spread at different positions in one bit duration. The PM is driven by OC patterns to modulate the phases of different spectral components. The second dispersive component with dispersion value of +D (opposite to the first one) is to compress the encoded signal and generate SPE signal. The SPE signal generated in this way can be decoded by conventional spectral phase decoders generating auto-/cross-correlations for proper or improper OCs.

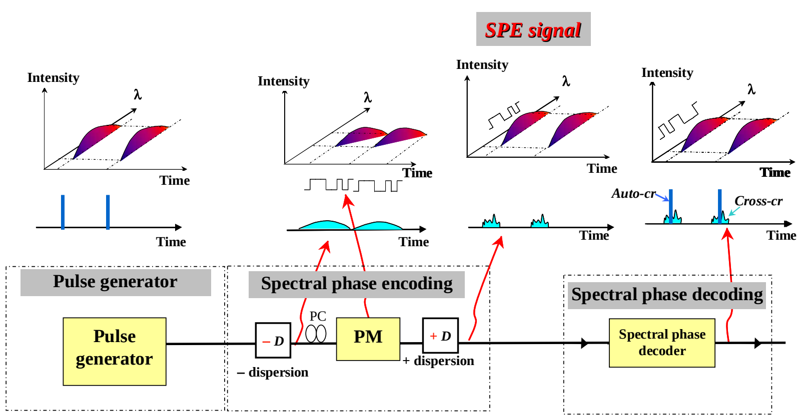


Fig. 3. Proposed SPE scheme

The dispersive components can use single mode fibers (SMF) and dispersion compensation fibers (DCF), or long chirped fiber Bragg gratings (LCFBG). Conventional high speed PM can generate OC at 40 Gchip/s chip-rate. The potential advantages of the proposed SPE scheme

#80494 - $15.00 USD Received 27 Feb 2007; revised 23 May 2007; accepted 30 May 2007; published 31 May 2007

include: 1. Good flexibility. This scheme offers fast (bit-by-bit) OC reconfigurable capability, which is unique compared to conventional techniques. 2. Relaxed wavelength alignment requirement. The wavelength alignment for laser and encoder is done in time domain, the requirement is much lower compared to conventional schemes. 3. Simple configuration and good compatible with fiber optic system. This scheme can even be simplified by combining the SPE and data modulation with a single modulator. 4. Low loss and low cost. One probable issue of this scheme is that the data rate of the system is limited by the speed of the PM and the length of the OC. For a system with data-rate higher than 1 Gbps, the length of OC will have to be lower than 40-chip. But it should be enough for many OCDMA applications.

## 3. Encoding/decoding experiments

Figure 4 shows the setup of the proof-of-principle experiment for the proposed scheme. The 1.5 ps optical pulse train with central wavelength of about 1552.52 nm was generated @1.25 GHz repetition rate using a mode-locked laser diode (MLLD) and an intensity modulator (IM). Figures 5 (a) and 5(b) are the spectrum and auto-correlation trace of this pulse, respectively. Then, this pulse was stretched in time domain by a piece of reverse dispersion fiber (RDF) and modulated with a 20 GHz phase modulator (PM) driven by 16-chip, 50 ps/chip (20 Gchip/s) binary phase shift keying (BPSK) code patterns with repetition rate of 1.25 GHz. Figures 5(c) and 5(d) are the spectrum and waveform of the stretched SPE signal. The stretched signal has temporal profile same as its spectrum, each narrow pulse in the stretched signal corresponds to one longitudinal mode. The total dispersion of the RDF is -312.5 ps/nm, therefore one bit duration of 800 ps covers 2.56 nm (320 GHz) spectral range. By properly adjusting the delay of the input signal, the BPSK code patterns can be precisely modulated onto this spectral range to perform the SPE. After PM, a span of SMF with +312.5 ps/nm dispersion was used for pulse compressing and finally generated the SPE signal. The proposed scheme is very robust to the wavelength drift of the light source because every 1 GHz optical frequency change can be compensated by accordingly changing the delay for 2.5 ps, which is very easy to be achieved either optically or electrically. The requirement for the synchronization between optical and electrical signals is also not very strict, there was no obvious change of the en/decoded signal in the experiment if the optical and electrical signal shifted several pico-second with each other.

We have not investigated the chose of suitable codes at this stage. In the experiment, we have tried with five different BPSK code patterns to demonstrate the feasibility of the proposed scheme: two of them are from 15-chip M-sequences and other 3 are randomly selected. The

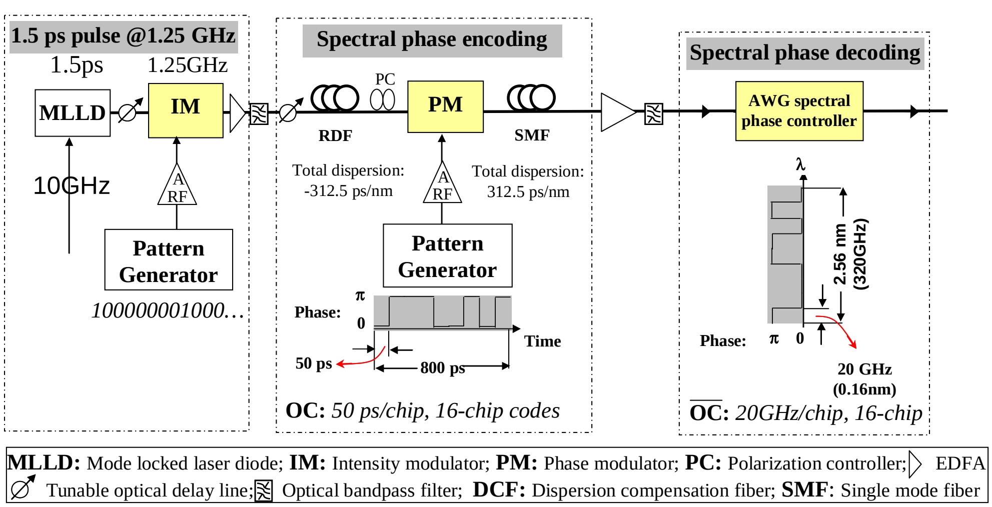


Fig. 4. Experimental setup of the proposed encoding/decoding scheme

#80494 - $15.00 USD Received 27 Feb 2007; revised 23 May 2007; accepted 30 May 2007; published 31 May 2007

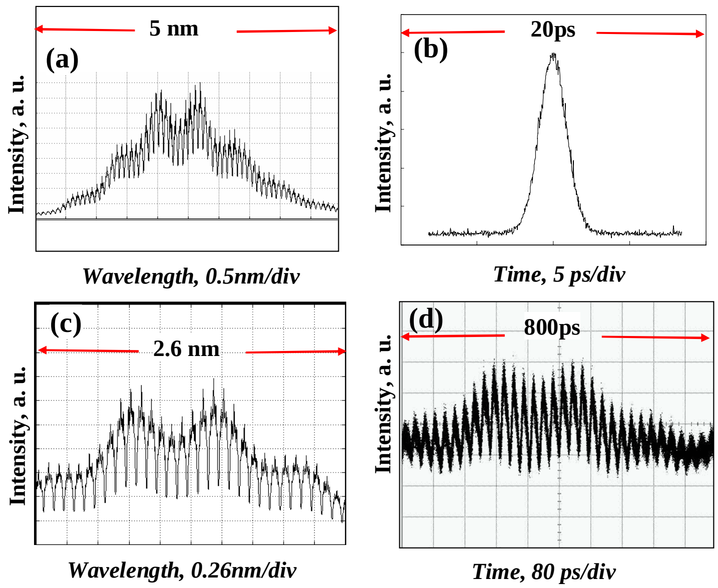


Fig. 5. Spectra and waveform of the (a)&(b) input and (c)&(d) stretched pulses

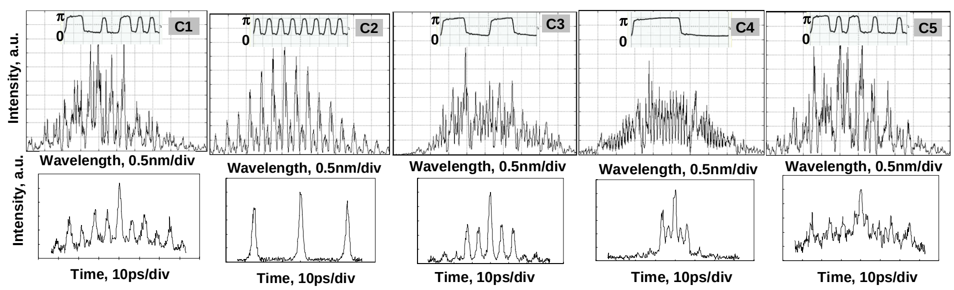


Fig. 6. Spectra and waveform of the SPE signals

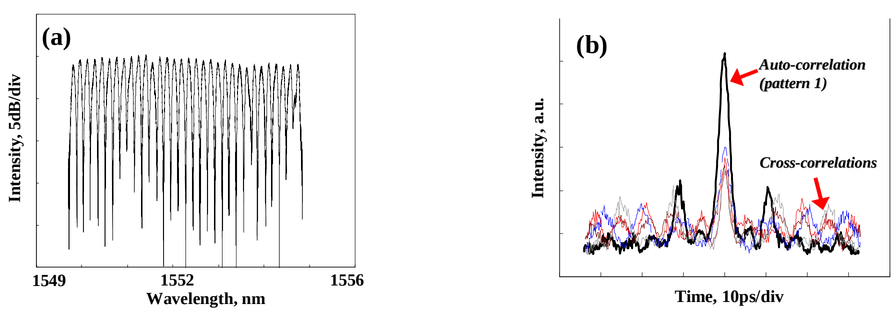


Fig. 7. (a). Spectrum of AWG spectral phase decoder (b). Waveforms of auto-/cross-correlations.

cross-correlations are not very good in fact. The patterns used in our experiments are: C1 (1110001001101010) is a 15-chip M-sequence plus one zero. C2 is (1010101010101010), C3 is (1111000011110000), C4 is (1111111100000000) and C5 (1110101100100010) is another 15-chip M-sequence plus a zero. Figure 6 shows the spectra and waveforms of the SPE pulses with these codes. Finally, we used an AWG spectral phase controller as the spectral phase decoder. The AWG device has 32 channels, which matches to the ITU grid, centered at 1552.51

#80494 - $15.00 USD Received 27 Feb 2007; revised 23 May 2007; accepted 30 May 2007; published 31 May 2007

nm with 20 GHz channel spacing. Figure 7(a) shows the spectrum of this device. It can control the phase, as well as the amplitude, of each channel individually [20] to perform spectral phase decoding. Figure 7(b) shows the measured auto- (thick dark line) and cross-correlations (thin color lines). The peak ratios between auto- /cross-correlation is around 2, the discrimination of different codes can be done by proper thresholding [7~10]. However, peak ratio is not very high so far. This is mainly due to the existing of notches in the spectral response of the AWG decoder, which could be improved by using decoders with much smooth spectral response [19].

## 4. Transmission experiment

We have also carried out transmission experiment with the proposed scheme. The setup is shown in Fig. 8(a). The 1.25 Gbps, $2^{23-1}$ pseudo random bit sequence (PRBS) was modulated by an IM before SPE. Two different code patterns (C1&2) were used for SPE. The dispersion of the transmission system was managed globally: the 19.5 km transmission fiber functions for pulse compression as well and ~545 m RDF was used in the receiver to compensate dispersion mismatch. The AWG decoder was also configured to decode the two codes, the decoded signals were detected by a photo-detector (PD) followed by a 2.5 GHz low-pass-filter (LPF). The measured bit-error-rate (BER) performances were shown in Fig. 8(b) with the open marks together with the eye diagrams. Error free has been reached in both cases. With this setup, the data modulation was done before the SPE. To simplify the system, both data modulation and SPE can be done with a single modulator—either a hybrid modulator for OOK or a single PM for DPSK modulation. To investigate this, we moved the IM after the PM. The BERs were shown in Fig. 8(b) with the filled marks as well as the eye diagrams. Compared to previous case

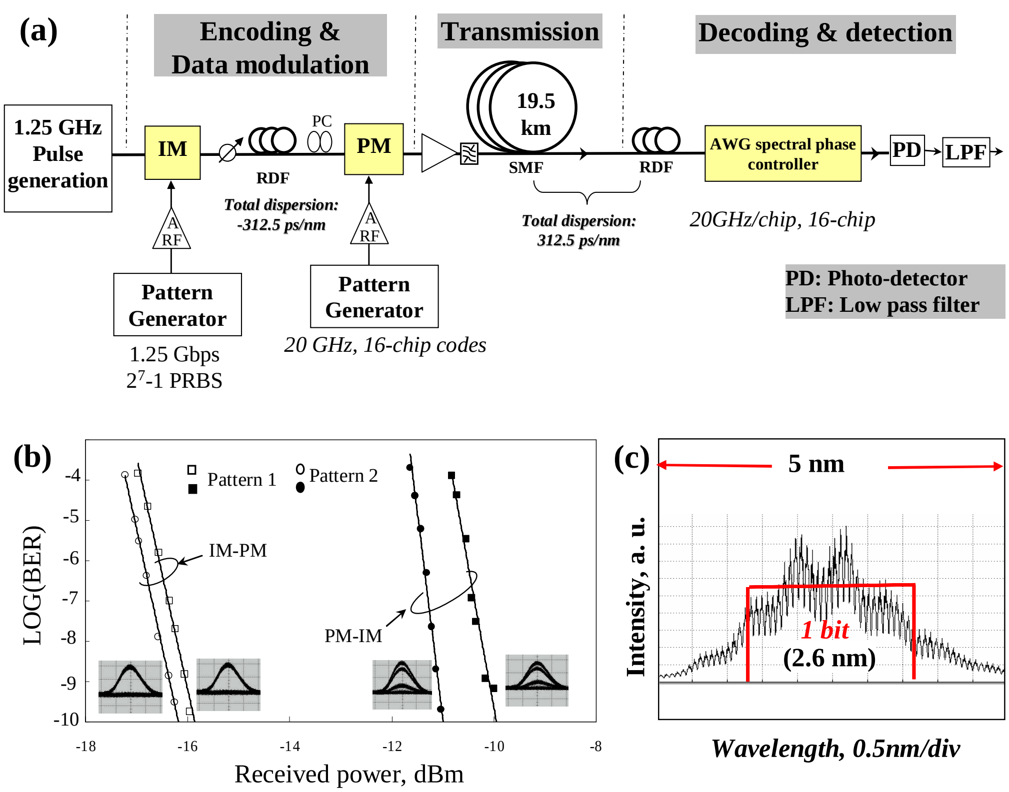


Fig. 8. Transmission experiment (a) setup (b) BER performances (c) Spectral range of the signal that is to the correctly modulated

#80494 - $15.00 USD Received 27 Feb 2007; revised 23 May 2007; accepted 30 May 2007; published 31 May 2007

the power penalties are 5.9 and 5.3 dB respectively for the two patterns. As it can be seen from the eye diagrams, this degradation is mainly due to that the duration of the stretched SPE signal exceeds one bit duration, resulting in the non-ideal modulation. Figure 8(c) shows the spectrum of the optical signal in 5 nm span. Only the central part with about 2.6 nm bandwidth is correctly modulated by the data, the rest part outside this range, which is not negligible, will result the performance degradation. This issue can be further solved by using a proper optical filter to block the unwanted spectral part or enlarging the spectral chip to reduce the total dispersion requirement.

## 5. Conclusion

In conclusion, we have proposed a reconfigurable time domain SPE scheme for coherent OCDMA application. The proof-of-principle experiments were demonstrated with 5 different 16-chip, 20 GHz/chip BPSK codes and 1.25 Gbps data rate. Compared to conventional SPE schemes, the wavelength alignment requirement for laser source and encoder can be relaxed in the proposed scheme, so it is very robust to the wavelength drift of the light source. It is very flexible and compatible with the fiber optical system. It also has the potential to be simplified by combining the SPE and data modulation with a single modulator.


## Acknowledgments

The authors would like to thank for Y. Tomiyama and Sumimoto of NICT for their technical support in the experiment.


#80494 - $15.00 USD Received 27 Feb 2007; revised 23 May 2007; accepted 30 May 2007; published 31 May 2007