Error-free spectral encoding and decoding operation of InP O-CDMA encoder

J. Cao, R.G.Broeke, N. Fontaine, W. Cong, C. Ji, Y.Du, N.Chubun, K.Aihara, Anh-Vu Pham and S. J. B. Yoo
Department of Electrical and Computer Engineering, University of California, Davis, CA 95616, USA
Email: yoo@ece.ucdavis.edu
F. Olsson, S. Lourdudoss
Department of Microelectronics and Information Technology, Royal Institute of Technology, KTH-Electrum 229, S-16440 Kista, Sweden
P. L. Stephan
Lawrence Livermore National Laboratory, Livermore, CA 94550, USA

Abstract: We report error-free spectral encoding and decoding operation of an InP monolithic, ultra-compact optical-CDMA encoder/decoder photonic chip pair. The experimental results demonstrate the strong potential for realizing high performance O-CDMA networks with InP micro-systems.

OCIS codes: 060.4510 Optical communications, 230.3120 Integrated optics devices

1. Introduction

The Optical Code Division Multiple Access (O-CDMA) technology utilizes optical codes to achieve truly flexible access to large network capacity instead of wavelength channels or time slots. Reconfigurable code assignment at the local node (end user) makes O-CDMA attractive for agile next generation all-optical local area networks [1, 2]. In our implementation of O-CDMA, spectral phase encoded time spreading (SPECTS)-OCDMA the spectral phase of ultra-short pulses are encoded for data transmission [3]. The encoded pulse is spread in time. The decoder applies a code to the phase of the encoded signal. If the encoder and decoder codes match a short pulse is reconstructed, otherwise the pulse remains spread in time. Non-linear thresholding differentiates properly encoded users from incorrectly decoded users by differences in peak optical power. Also, in our chosen code set, the time domain pulse has a null at t=0 allowing us to improve sensitivity to multi-users by using a non-linear optical loop mirror (NOLM) based time gate. While the SPECTS-OCDMA system has been demonstrated in free space bulk optics [4], monolithic chip-scale integration and miniaturization are essential for reliable, low-cost, and large-scale deployment of O-CDMA systems. InP arrayed waveguide gratings (AWGs) are promising candidates for the SPECTS encoder due to its on-chip integratibility with phase modulators which have been demonstrated as a spectral encoder and decoder for O-CDMA [5]. We previously demonstrated an AWG based encoder in InP [6], incorporating an electro-optic phase shifter array for rapid code reconfigurations with negligible power consumption. This paper presents error-free spectral O-CDMA encoding and decoding operation on monolithic InP O-CDMA encoder/decoder chips in tandem. This is an important first step towards realizing highly integrated O-CDMA micro-photonic systems such as O-CDMA transceivers.

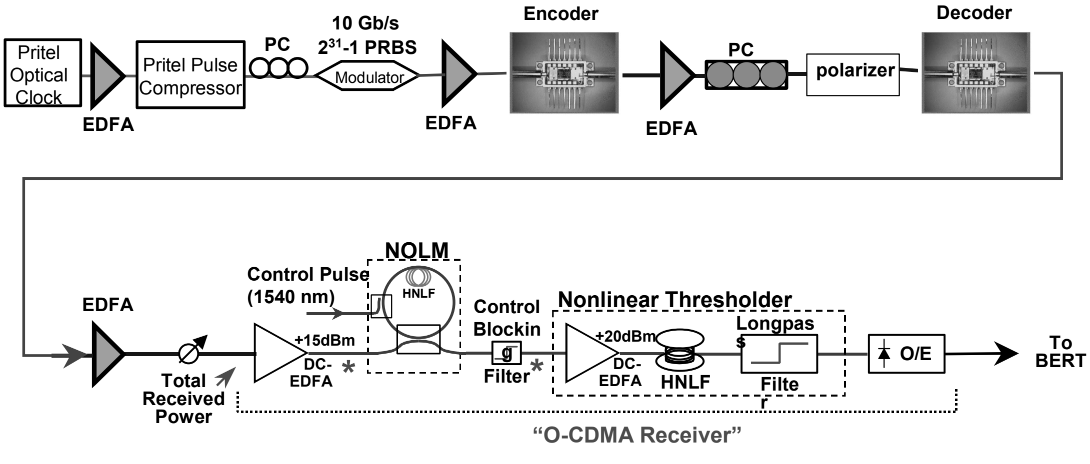

Fig. 1 Experimental setup for spectral encoding and decoding of an InP encoder and decoder

2. Experiment description

Fig.1 shows a schematic of the testbed. A fiber-based mode-locked laser generates 500 fs pulses at 10 GHz repetition rate. Next, a $LiNbO_3$ modulator modulates the pulse train with a 10 Gb/s 2^{31}-1 pseudo-random bit sequence (PRBS). The signal passes through the InP encoder-decoder pair. Upstream to each chip, an erbium doped fiber amplifier (EDFA) and a polarization controller supply 21dBm of transverse electric (TE) polarized light. At the receiver side, a nonlinear optical loop mirror (NOLM) provides time gating, and a highly nonlinear fiber (HNLF) provides peak power thresholding. The combination of the NOLM and the HNLF based peak-power detection allows necessary detection of the correctly decoded pulses while suppressing the detection of incorrectly decoded pulses. More details can be found in [4], where basically the same testbed is used, but here it employs the InP chips instead of a free-space spatial-light modulator (SLM).

The encoder and decoder each consist of an identical pair of 8-channel AWGs with 180 GHz channel spacing and a free spectral range (FSR) of 12-channel spacings. The total wavelength span provided by the 8 channels is approximately 1.4 THz, which is sufficient for encoding sub-picosecond pulses. The on-chip phase shifter array provides the spectral phase coding. The AWGs are slightly polarization sensitive, with responses at the two polarization states shifted by approximately 220 GHz. Only TE polarization responses of the O-CDMA encoder and decoder pair have been investigated.

3. Experimental results and discussions

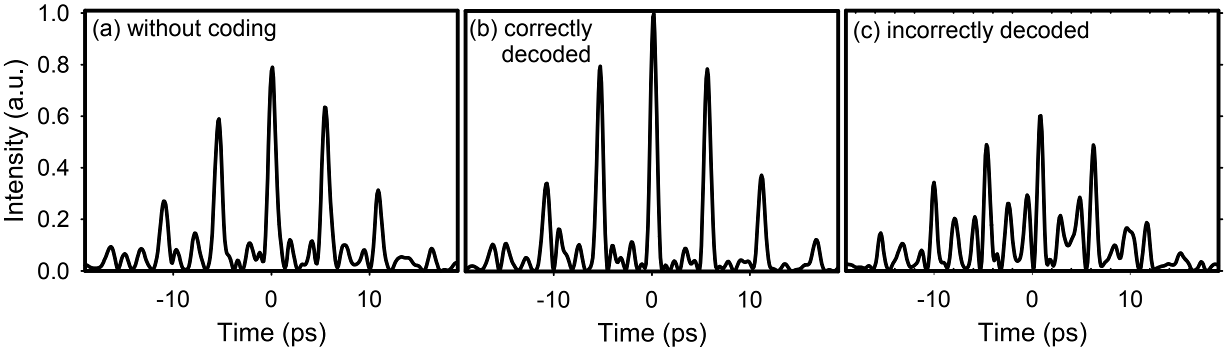

Fig. 2. The time domain response of the signal after encoder-decoder pair for (a) correctly decoded output without phase error correction (b) with phase error correction. (c) incorrectly decoded output. All pulses are normalized to their average power.

The coding performance of the InP encoder and decoder is characterized with cross-correlation frequency-resolved optical gating (XFROG). XFROG, unlike the cross-correlation and spectrum, completely characterizes the electric field of an optical pulse in both phase and intensity. By measuring the spectral phase of a pulse before and after transmission through an encoder, the phase shift in channel is retrieved. All XFROG traces are binned on a 256x256 grid over 100 ps to because of the large time spreading of the pulses. Typically, retrieval errors are less than 0.005 (0.5%) indicating successful retrieval. Additional cross-correlation traces and measured spectra matched the retrieved XFROG result verifying its consistency. Fig. 2 (a) shows the pulse intensity after the encoder-decoder pair without phase error compensation. The ringing peaks at 5.5ps intervals are due to the AWG's comb-shaped spectral filtering. Note that time-gating around t=0ps with a narrow window (<3 psec) removes any ringing peaks, at expense of signal power. Fig. 2(b) shows the improved signal to noise ratio of the reconstructed pulse with phase correction to remove built-in phase errors in the O-CDMA chip. Fig. 2 (c) shows the intensity of the incorrectly decoded signal with [00011110] coding on the encoder. The figure shows a clear reduction in peak power with a null at t = 0 ps, as expected.

Fig. 3 shows BER measurement results of the decoded signal. The BER measurement was conducted downstream to the O-CDMA receiver at the input to the "OCDMA receiver" consisting of the NOLM and the HNLF based nonlinear thresholder as illustrated in Fig. 1. The back-to-back measurements denoted as circles ('○' symbols) are taken with the O-CDMA encoder and decoder pair bypassed and the signal fed directly into the 'O-CDMA receiver". The correctly decoded measurements ('◊' symbols) and incorrectly decoded measurements ('□' symbols) are taken with the encoder and decoder pair inserted with correct or incorrect decoding codes. The received power in all BER curves is defined as the total average power input to the "O-CDMA receiver" marked in Fig 1. For the correctly decoded signal, error-free operation was achieved. The power penalty between the correctly decoded signal and back-to-back signal is 7.4 dB at BER = 10^{-9}, mainly due to power in the ringing peaks (outside the time-gate) of the corrected decoded signal and also due to the degraded signal-to-noise ratio after insertion loss and EDFA amplification. The incorrectly decoded signal reached an error floor at 10^{-6} instead of 0.5, primarily because incorrect decoding code of [00011110] is not sufficiently orthogonal to the Walsh code used. In addition, the short (8 bit) code length used in this experiment did not allow sufficient pulse spread in time to open wide enough a null window at t=0 ps to accommodate the NOLM time gate window. Therefore, the ~3 ps NOLM gate window still transmits considerable power from this incorrectly decoded signal. A narrower time gate window would improve the NOLM's discrimination capability of the incorrectly decoded signals against the correctly decoded signals.

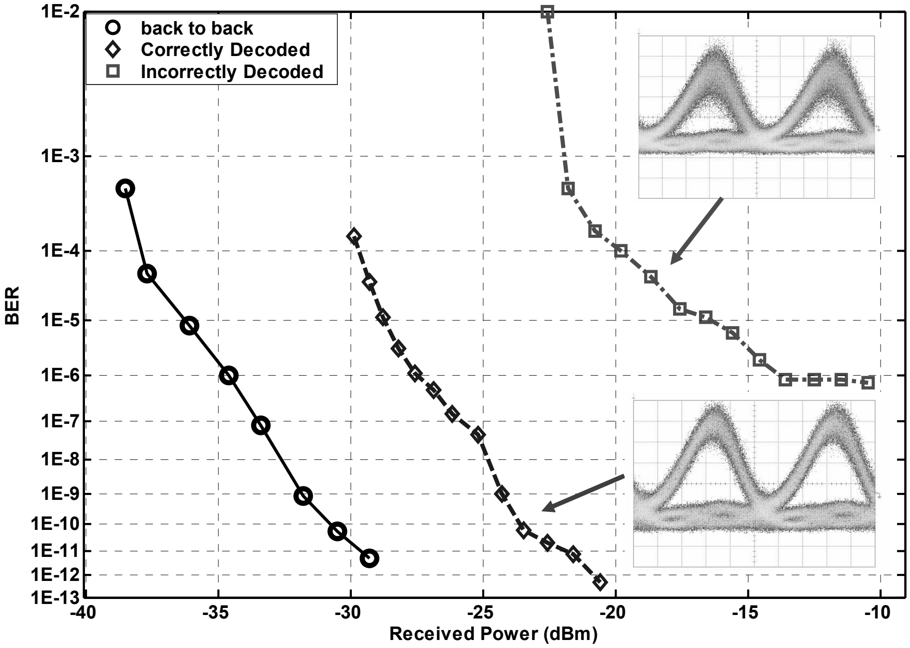

Fig. 3. BER measurement and eye-diagrams for correctly decoded user, '◊', and incorrectly decoded user, '□'

4. Summary

We successfully demonstrated the spectral encoding and decoding of sub-picosecond pulses using a pair of monolithic optical-CDMA encoder/decoder InP chips. The experiments showed error-free operation, which indicates the feasibility of realizing highly integrated InP O-CDMA micro-photonic systems.

5. Reference:

[1] J. A. Salehi, A. M. Weiner, and a. J. P. Heritage, "Coherent ultrashort light pulse code-division multiple access communication systems," *J. Lightwave Technol.*, vol. 8 (3), pp. 478-91, 1990.

[2] H. P. Sardesai, C. C. Chang, and A. M. Weiner, "A femtosecond code-division multiple-access communication system test bed," *J. Lightwave Techonol.*, vol. 16 (11), pp. 1953-1964, 1998.

[3] J. P. Heritage, A. M. Weiner, and R. N. Thurston, "Picosecond pulse shaping by spectral phase and amplitude manipulation," *Optics Letters*, vol. 10 (12), pp. 609-611, 1985.

[4] W. Cong, V. J. Hernandez, R. P. Scott, J. P. Heritage, B. H. Kolner, and a. S. J. B. Yoo, "An Eight-User Time-Slotted SPECTS O-CDMA Network Testbed Incorporating a NOLM Time Gate," *in Proc. of Conference on Lasers and Electro-Optics (CLEO'2005), Washington, D.C., paper CTuFF2*, 2005.

[5] H. Tsuda, H. Takenouchi, T. Ishii, K. Okamoto, T. Goh, K. Sato, A. Hirano, T. Kurokawa, and C. Amano, "Spectral encoding and decoding of 10 Gbit/s femtosecond pulses using high resolution arrayed-waveguid grating," *IEE Electron. Lett.*, vol. 35(14), pp. 1186-8, 1999.

[6] J. Cao, R. G. Broeke, C. Ji, Y. Du, N. Chubun, P. Bjeletich, F. Olsson, S. Lourdudoss, P. L. Stephan, and a. S. J. B. Yoo, "A Monolithic Ultra-compact InP O-CDMA Encoder with Planarization by HVPE Regrowth," *in Proc. OFC'2005,paper OFL6*, 2005.

This work was supported in part by DARPA and SPAWAR under agreement number N66001-02-1-8937.