Four User, 2.5 Gb/s, Spectrally Coded O-CDMA System Demonstration Using Low Power Nonlinear Processing

Z. Jiang, D.S. Seo*, S.-D. Yang, D.E. Leaird, and A.M. Weiner
Purdue University, 465 Northwestern Ave., West Lafayette, IN 47907-2035, USA
zjiang@purdue.edu, dseo@purdue.edu, shangda@purdue.edu, leaird@purdue.edu, amw@ecn.purdue.edu
******On leave from Dept. of Electronics, Myongji University, Yongin, Kyonggido, 449-728, Korea*

R.V. Roussev, C. Langrock, and M.M. Fejer
Edward L. Ginzton Laboratory, Stanford University, Stanford, CA 94305-4088, USA
rroussev@stanford.edu, langrock@stanford.edu, fejer@stanford.edu

Abstract: We demonstrate for the first time 2.5 Gb/s four user O-CDMA operation at ≤ 10^{-11} BER utilizing programmable spectral phase encoding, an ultrasensitive (< 0.4 pJ/bit) PPLN-waveguide nonlinear waveform discriminator and 10G Ethernet receiver.

OCIS codes: (060.2330) Fiber optics communications; (320.7160) Ultrafast technology

Optical code-division multiple-access (O-CDMA) is receiving increasing attention due to its potential for enhanced information security, simplified and decentralized network control, improved spectral efficiency, and increased flexibility in the granularity of bandwidth that can be provisioned. In O-CDMA, different users whose signals may be overlapped both in time and frequency share a common communications medium; multiple-access is achieved by assigning different, minimally interfering code sequences to different CDMA transmitters. In many O-CDMA approaches as shown schematically in Fig. 1A, input ultrashort pulses are time-spread during the encoding process into lower intensity noise-like signals [1-6]. In the receiver, data corresponding to a desired user is separated from multi-access interference via a matched filtering (decoding) operation, in which properly decoded signals are converted back to the original pulse-like signals, while improperly decoded signals remain low-intensity noise-like temporally broad waveforms. Since the energy in properly and improperly decoded signals is similar, and since the temporal duration of even improperly decoded signals is on the order of the bit period or below, both properly and improperly decoded signals will appear identical to an electronic receiver band-limited to the data rate. Consequently either very fast electronics or a nonlinear optical intensity discriminator play a critical role in separating properly decoded short pulses from improperly decoded multi-access interference. In previous work an AWG-based device was used for encoding/decoding of a single 10 Gb/s data stream; however, the crucial interference rejection function was not demonstrated [6]. Fiber grating encoders were used to demonstrate 2 simultaneous, frequency-overlapped 1.25 Gb/s users using fast electronics for waveform discrimination [5]. Fiber gratings were also used in a single-user 1.25 Gb/s experiment using a nonlinear fiber device for contrast enhancement; however, no testing with multiuser interference was reported [4]. An O-CDMA/WDM/TDM overlay experiment demonstrated very high aggregate bit rates, but relied on synchronous nonlinear gating in the receiver, with synchronism required down to ~1 ps [2]. A two-user experiment using spectral phase encoding-decoding demonstrated asynchronous interference rejection using nonlinear fiber optics, but operated at only ~50 Mb/s [5]. In this paper we discuss a 4-user spectral-phase-encoded O-CDMA demonstration at 2.5 Gb/s with strong nonlinear interference suppression. Compared to previous work, **the key points are the following: (1) full interference suppression with 4 users at Gb/s rates without the need for synchronous optical gating or ultrafast electronics; (2) the use of a novel, ultrasensitive nonlinear optical intensity discriminator** based on second harmonic generation (SHG) in a periodically-poled lithium niobate (PPLN) waveguide. Our discriminator permits a suppression as high as 20 dB at an operating pulse energy of less than 0.4 pJ (average power less than 1 mW), <u>approximately two orders of magnitude lower than previous discriminators</u> based on nonlinear fiber optics [2-4]. The ability to operate at low power per user will be critical for scaling O-CDMA to greater user numbers.

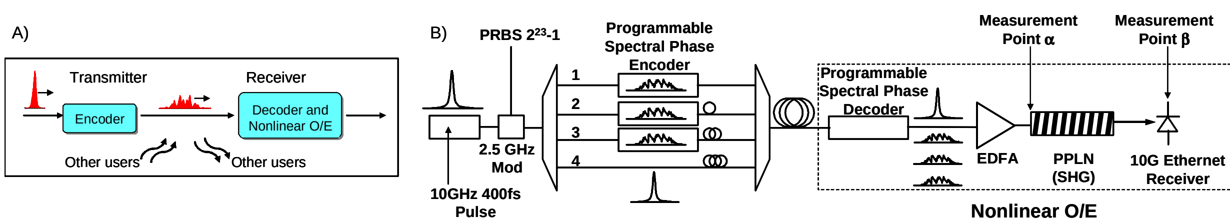

Fig. 1 A) Multiple user O-CDMA system scheme. B) Four user O-CDMA system testbed.

The power scaling issue can be understood as follows. For proper operation the self-gated nonlinear discriminator key to our scheme requires some threshold value U_{bit}, where U_{bit} in picojoules is the energy required per bit for a single properly decoded user. Since equal samples of each channel are seen by every O-CDMA receiver, the average power required at the nonlinear element is $0.5NBU_{bit}$, where N is the number of channels, B is the data rate, and the factor 0.5 comes from on-off keying. Previous demonstrations of O-CDMA nonlinear discriminators were based on nonlinear fiber optics, with typical values for U_{bit} ranging from 10-50 pJ [3-4]. For four 2.5 Gb/s channels, this gives an average power requirement of 17-24 dBm at each receiver. Scaling to significantly higher bit rates and channel numbers would require a very large optical amplifier at each receiver, which is highly undesirable for application to networks with large numbers of nodes. To address this scaling problem, it is critical to reduce U_{bit}. Our experiments using waveguide SHG generation achieve U_{bit} below 400 fJ, a reduction approaching two orders of magnitude.

A schematic diagram of the four user O-CDMA demonstration is shown in Fig. 1B. An actively mode-locked fiber laser followed by a dispersion decreasing fiber soliton compressor producing nearly transform-limited ~0.4 ps pulses at ~10 GHz centered near 1542 nm is used as the pulse source. A 2.5 Gb/s PRBS 2^{23}-1 data stream is impressed on the laser output with an intensity modulator and then a 1x4 passive splitter is used to generate the four separate users. For three users, the modulated ultrashort pulses are input into a fiber coupled Fourier Transform pulse shaper [7] which incorporates a 128 element liquid crystal modulator array to spectrally phase code the spectrum of the source laser. The fiber-to-fiber insertion loss of the pulse shapers are less than 5 dB. A fourth uncoded user path is also present as an additional interference channel. The output of each user path is connected through a fiber delay line to a 4x1 combiner and then connected to the transmission fiber consisting primarily of DCF used to compensate the dispersion of the user paths. The receiver consists of a fiber coupled Fourier Transform pulse shaper used to select the user channel to decode, an optical amplifier, a highly sensitive fiber pigtailed PPLN waveguide chip to perform the nonlinear discrimination function [8], and a 2.4 GHz bandwidth photoreceiver, adapted from 10 Gb/s Ethernet, operating at the second harmonic wavelength of 0.77 μm.

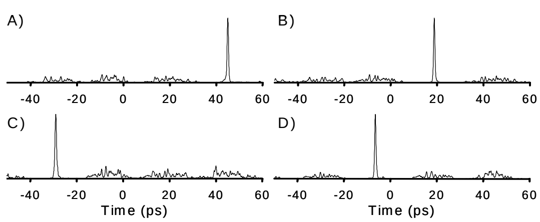

Fig. 2 Intensity cross-correlation measurements of properly decoded channels 1 to 4 (A to D respectively) demonstrating the ability to selectively decode any of the four user channels.

Fig. 2 demonstrates the ability to properly decode any of the four user channels by the correct selection of decoder spectral phase code – here a length 31 M-sequence code. The figure shows intensity cross correlation measurements of the non-data-modulated stream measured at 'measurement point α' (just before the nonlinear processor) shown in Fig. 1B. The necessity of a nonlinear pulse discriminator is dramatically demonstrated in Fig. 3, where we use a 1.5 μm photo-detector optimized for the 2.5 Gb/s data rate to detect the decoder output prior to entering the nonlinear processor. Fig. 3 shows the temporal profile of both properly decoded (A - short pulse) and improperly decoded (B - temporally broadened) signals, using a length 31 M-sequence code as seen on a sampling scope. Other than the very small amplitude difference due to slightly different coding loss in the pulse shapers, there is no noticeable difference between the signals. This clearly illustrates the main issue in O-CDMA with ultrashort pulses: <u>properly decoded and improperly decoded waveforms have fundamentally the same energy, which means they produce the same output from a relatively slow electronic detector, even though they can show strong differences in temporal structure and peak intensity on an ultrafast time scale</u> (as per Fig. 2). Further, in a system environment, the signals from all users will be superimposed when viewed by a conventional photoreceiver with bandwidth optimized for the data rate. Figures 3C and 3D show cases of 2 and 4 overlapping users; the eyes are completely closed.

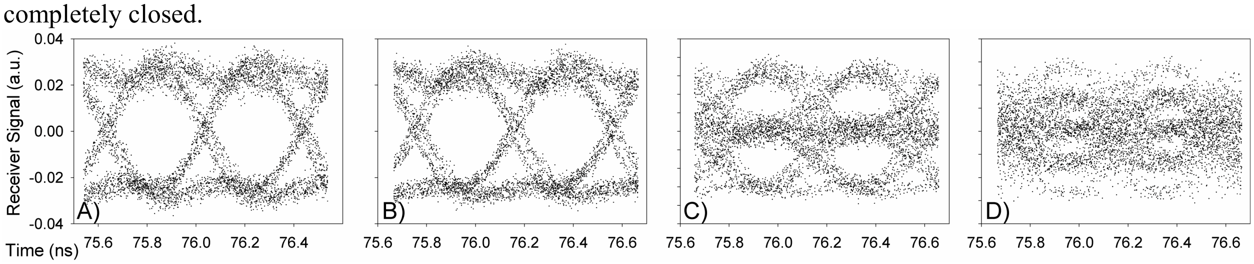

Fig. 3 Eye diagrams prior to nonlinear processing (measurement point α in Fig. 1B). Single user properly decoded (A), improperly decoded (B), two user (C), and four user (D). A & B demonstrate that both properly decoded and improperly decoded single user channels look essentially identical on a linear detector. C & D demonstrate that multiple users can not be adequately separated using linear detection.

Nonlinear processing enables us to separate these temporally overlapped signals thereby permitting a multi-user system. Figures 4A to 4D respectively show the output of the receiver (measurement point β in Fig. 1B), for a single properly decoded user, a single improperly decoded user, two users (channel 1 properly decoded), and four users (channel 4 properly decoded) at a power in the nonlinear processing element of -3 dBm per user. The clean eye diagrams clearly demonstrate the ability to properly decode the desired channel, and separate it from the interference channels. Figures 5(A,B) show bit error rate curves for 1, 2, and 4 users plotted vs. power at the photoreceiver ('measurement point β'), with either channel 1 or 2 decoded. In all cases we were able to measure BERs down to less than 10^{-11}. There is a power penalty of roughly 1.5 dB per interfering user (similar for both decoded channels) which we attribute to the finite interference suppression ratio of the nonlinear discriminator. Figure 5C shows the same BER data as in Fig. 5A, but replotted against the total power in the nonlinear discriminator ('measurement point α'). The key point is that we are able to run the four-user experiment at under 1 mW per user in the nonlinear element, which provides substantial margin for scaling to higher bit rates and user counts while provisioning only a moderately sized optical amplifier to each receiver node.

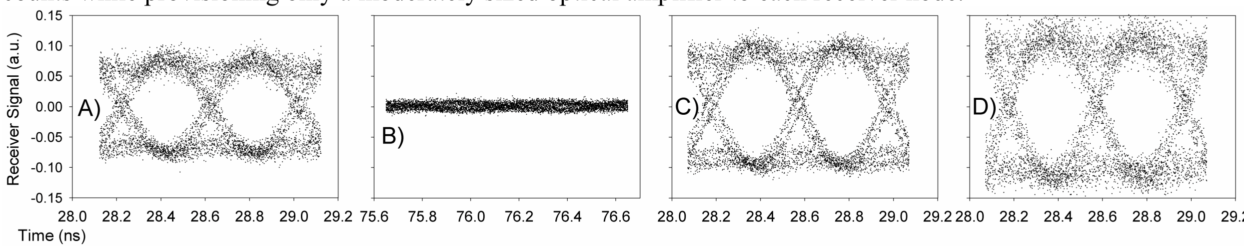

Fig. 4 Eye-diagrams after nonlinear processing (measurement point β in Fig. 1B), at -3dBm per user. (A) Properly decoded channel 1, single user. B) Improperly decoded channel 1, single user. C) Two user system, properly decode channel 1. D) Four user system, properly decode channel 4. A&B demonstrate the large contrast between a properly and improperly decoded single user channel. C&D demonstrate clear decoding of the desired user in a multiple user system via nonlinear processing.

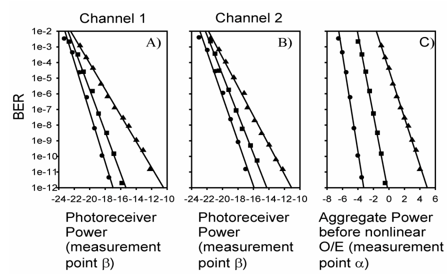

Fig. 5 Bit Error Rate measurements for single user (circles), 2 user (squares), 4 users (triangles). A) decode channel 1, B) decode channel 2, C) same as (A) but now power refers to value in nonlinear waveguide. System is operated at less than 1mW per user.

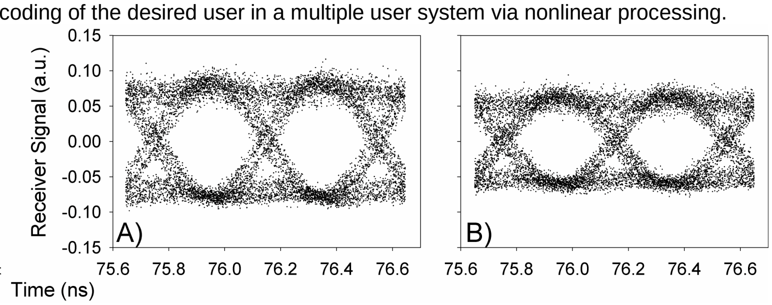

Fig. 6 Eye diagrams for properly decoded channel using alternative code families: A) quaternary code, B) Quadratic Residue code. These data demonstrate substantial flexibility in code choice.

Finally, it is important to note that the programmable spectral phase coding scheme we employ permits us to easily investigate multiple code families with little additional effort. As an example of this capability, Fig. 6A and 6B shows eye diagrams obtained by coding and decoding with a quaternary code and a length 31 Quadratic Residue code respectively.

In summary, we have demonstrated for the first time a multi-user O-CDMA system operating at 2.5 Gb/s requiring less than 400 fJ per user due to the novel nonlinear processing element based on SHG in a PPLN waveguide.

This material is based upon work supported by DARPA under grant MDA972-03-1-0014 and the Air Force under grant F49620-02-1-0240. D.S. Seo is supported in part by KOSEF (under grant R1-2003-000-10444-0) and Inha University (ERC).

References

1. J.A. Salehi, A.M. Weiner, and J.P. Heritage, J. Lightwave Technol., **8**, 478-491 (1990).
2. H. Sotobayashi, W. Chujo., and K. Kitayama, IEEE Photon. Technol. Lett., **14**, 555-557 (2002).
3. H.P. Sardesai, C.C. Chang, and A.M. Weiner, J. Lightwave Technol., **16**, 1953-1964 (1998).
4. J.H. Lee, P.C. Teh., Z. Yusoff, M. Ibsen, et. al., IEEE Photon. Technol. Lett., **14**, 876-878 (2002).
5. P.C. Teh., M. Ibsen, J.H. Lee, P. Petropoulos, and D.J. Richardson, IEEE Photon. Technol. Lett., **14**, 227-229(2002).
6. H. Tsuda, H. Takenouchi, T. Ishii, K. Okamoto, et. al.," Electron. Lett., **35**, 1186-1188 (1999).
7. A.M. Weiner, Rev. Sci. Instr., **71**, pp. 1919-1960 (2000).
8. Z. Zheng, A. M. Weiner, K. R. Parameswaran, et. al., IEEE Photon. Technol. Lett., **13**, 376-378 (2001).