Four-User 10-Gb/s Spectrally Phase-Coded O-CDMA System Operating at ∼30 fJ/bit

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Abstract—**We demonstrate a four-user 10-Gb/s spectrally phase-coded optical code-division multiple-access system via nonlinear processing with ultralow power (∼30 fJ/bit). Full interference suppression is achieved in a time-slotted scheme without the need for chip-level coordination and synchronous detection. Performance degradation caused by pulse overlap between users is investigated.**

Index Terms—**Lightwave communications, multiplexing, nonlinear processing, optical code-division multiple access (O-CDMA), pulse shaping.**

OPTICAL code-division multiple access (O-CDMA) is receiving increased 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, multiple access is achieved by assigning different, minimally interfering code sequences to different CDMA transmitters. In many O-CDMA approaches, input ultrashort pulses are time-spread during the encoding process into lower intensity noise-like signals [1]–[8], [13]. In the receiver, data corresponding to a desired user are separated from multiaccess interference (MAI) 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 broadened 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 MAI.

In previous work, we have demonstrated a four-user 2.5-Gb/s spectrally phase-coded O-CDMA system with low power per user [3], [13]. In other work, an O-CDMA/wavelength-division-multiplexing (WDM)/time-division-multiplexing overlay experiment demonstrated record high spectral efficiency as well as very high aggregate bit rates using a time domain encoding scheme, but relied on chip level timing coordination at the transmitter and synchronous nonlinear gating at the receiver, with synchronism required down to ∼1 ps at both transmitter and receiver [4], [5]. Recently, hyperfine spectral phase coding, compatible with traditional WDM systems, was demonstrated also using chip level timing coordination and synchronous gating [6]. A four-user 10-Gb/s system has also been recently demonstrated using spectral phase coding and an asynchronous highly nonlinear-fiber discriminator for MAI suppression [7]. This experiment required coordination of transmitted signals with chip level timing requirements as well as high powers at the nonlinear discriminator. In our group, we have also recently published a four-user 10-Gb/s O-CDMA demonstration based on chip level timing control [12]. In the current letter, we discuss a four-user spectrally phase-coded O-CDMA demonstration at 10 Gb/s with strong nonlinear interference suppression, without the need for chip-level coordination at the transmitter or synchronous optical gating with clock recovery at the receiver. Our experiments rely on an ultrasensitive nonlinear optical intensity discriminator based on second-harmonic generation (SHG) in a periodically poled lithium niobate (PPLN) waveguide [9]. We previously demonstrated the operation of this discriminator technology in our four-user 2.5-Gb/s system experiment [3], [13] and in experiments at 10 GHz for a single user without data modulation (periodic pulse train) and without MAI [9]. Here we demonstrate the use of this discriminator for full MAI suppression in four-user 10-Gb/s system experiments at an energy level of only ∼30 fJ/bit, as much as one order of magnitude lower than our previous four-user 2.5-Gb/s system [3], [13], two orders lower than discriminators based on highly nonlinear fiber [7], and three orders lower than discriminators based on traditional dispersion-shifted fiber [2]. The ability to operate at low power per user is critical for scaling O-CDMA to greater numbers of users. In multiuser networking, each receiver will see a sample of each of the multiple-access signals; therefore, the required amplifier saturation power scales with the number of users (as well as bit rate) [2], [3], [13].

A schematic diagram of the four-user 10-Gb/s O-CDMA demonstration is shown in Fig. 1, which is similar to our previous work [3], [13] except that now a 10-Gb/s pseudorandom binary sequence $2^{23}-1$ data stream is impressed on the ∼0.4-ps 10-GHz mode-locked fiber laser output. For three users, the modulated ultrashort pulses are input into a fiber

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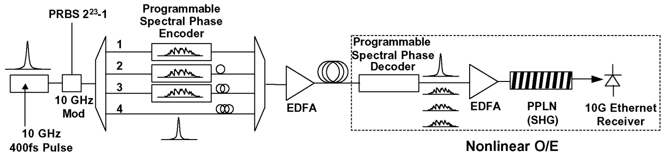

Fig. 1. Experimental apparatus.

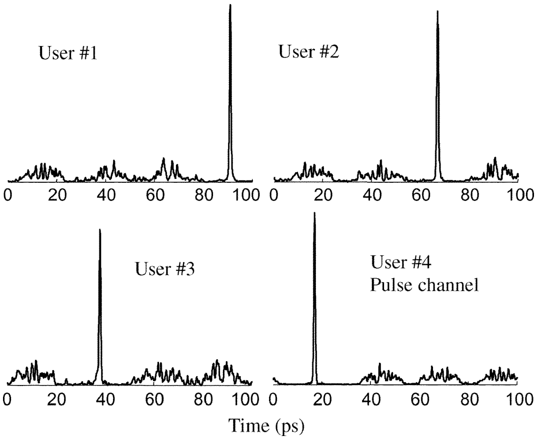

Fig. 2. Intensity cross-correlation measurements of properly decoded Users 1–4, demonstrating the ability to selectively decode any of the four users.

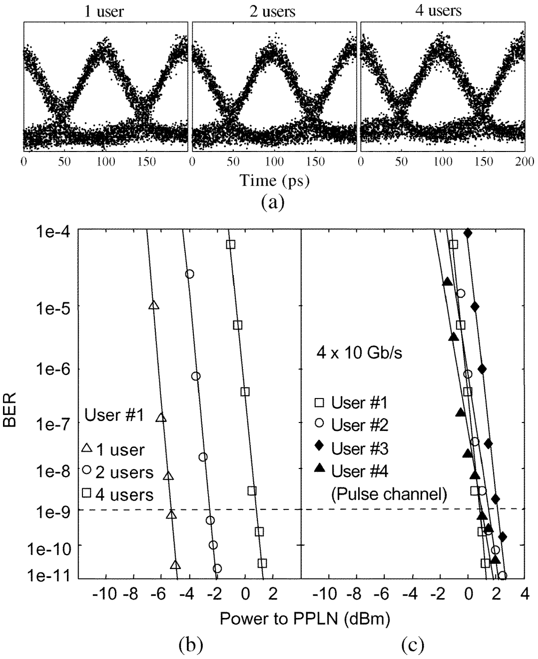

Fig. 3. Performance measurement of the 4 × 10 Gb/s O-CDMA system. (a) Eye diagram of properly decoded User 1 for one user, two users, and four users. (b) BER measurements of User 1 corresponding to (a). (c) BER measurement of all four users. Powers refer to the values in the PPLN nonlinear discriminator.

coupled Fourier transform pulse shaper [10] which incorporates a 128-element liquid crystal modulator array to spectrally phase code the spectrum of the source laser. A fourth uncoded user path is also present as an additional interference channel [3], [13]. 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 [9], and a 10-Gb/s Ethernet photoreceiver (3-dB bandwidth of 7.5 GHz), operating at the second-harmonic wavelength of 0.77 μm. The measured internal SHG conversion efficiency of the PPLN waveguide is 3100%/W for continuous wave and 170%/pJ for ultrashort pulses.

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. Fig. 2 shows intensity cross correlation measurements of the nondata-modulated stream measured before the nonlinear processor. In our experiment, the pulses from each user are roughly separated by ~25 ps in a time-slotted O-CDMA scheme [3], [13]. There is no need for precise chip-level control of the time offsets. Nonlinear processing enables us to separate the desired user from MAI, thereby permitting a multiuser system. As shown clearly in our previous work [3], [9], [13], communication is not possible without a nonlinear discriminator since the receiver is too slow to resolve the small timing shifts between slots. Fig. 3(a) shows the eye diagrams of properly decoded User 1 for one user, two users, and four users, respectively. The clean eye diagrams clearly demonstrate the ability to properly decode the desired user, and separate it from the MAI. Fig. 3(b) shows corresponding bit-error-rate (BER) curves for User 1 plotted versus the total power in the nonlinear discriminator. The ~3-dB power differences between BER curves are simply due to the doubling of the number of users. This implies almost negligible power penalty induced by MAI. The key point is that we can operate with one user at BER $= 10^{-9}$ at a power level of less than -5.5 dBm (28.2 fJ/bit), and four users at less than 1 dBm (31.5 fJ/bit), showing significant improvement compared with other approaches utilizing optical fiber nonlinearities. Fig. 3(c) shows BER curves for all four users. Even the worst channel, in which we attribute the degradation to the finite interference suppression of the nonlinear discriminator, still operates at BER $=$ 10^{-9} with a four-user power of 2 dBm (39.6 fJ/bit). From a system point of view, it is important to run all four users successfully since MAI may exhibit distinct suppression characteristics for each specific desired user. In our system, the ~30-fJ/bit requirement provides substantial margin for scaling to higher bit rates and user counts while provisioning only a moderately sized optical amplifier to each receiver node.

Although both the current 10-Gb/s and the previous 2.5-Gb/s [3], [13] experiments utilized the same 10-GHz mode-locked laser source and 10-Gb/s Ethernet receiver, the current 10-Gb/s experiments require ten times lower energy per bit and lower overall power in the nonlinear discriminator. We attribute this substantial improvement to several sources. First, in the current 10-Gb/s experiment, all the energy per bit is in a single pulse, which is more efficient in driving the nonlinear discriminator than a 2.5-Gb/s data stream with four pulses per bit and correspondingly reduced peak power. Second, there is receiver sensitivity improvement for return-to-zero versus nonreturn-to-zero signaling [11]. Finally, we put significant effort in optimizing system performance, including encoder–decoder pair matching, PPLN waveguide phase matching temperature tuning, dispersion compensation, etc. The overall result of all these factors is to yield the ~10-dB improvement in the energy requirement per user while increasing the data rate by four times.

We emphasize that our scheme only requires slot level timing coordination, and nonlinear processing and detection is fully asynchronous. In the experiments, we intentionally separated

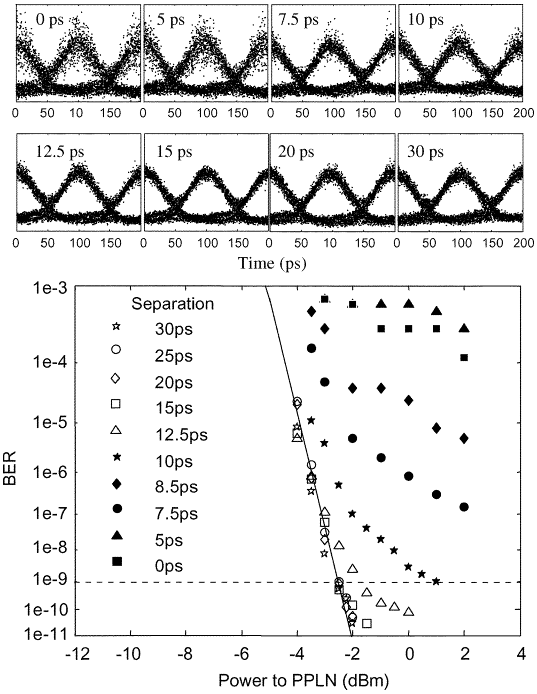

Fig. 4. BER measurements and eye diagrams of properly decoded User 1 with one interference user while tuning the user separation. Performance is degraded when two users overlap.

the four users in the time domain (Fig. 2). The system performance is degraded as pulses overlap between users. Fig. 4 shows the eye diagrams and corresponding BER measurement for a two-user experiment while tuning the separation between the users. Length-31 M-sequence coding is still used such that the interference user is broadened to an $\sim$20-ps pseudonoise waveform. Negligible degradation is observed when the two users separation is $>$15 ps. At 12.5-ps separation, the BER can still be pushed down to 10^{-10}, which shows the possibility to run eight slotted 10-Gb/s users distributed in the 100-ps bit duration. When the user separation is $<$10 ps, performance is seriously degraded and depends on the precise relative timing and phase of the overlapping users. In general, performance is better when the desired user (properly decoded short pulse) is located at a dip rather than at a spike of the interference waveform. This explains why BER performance at 7.5-ps separation is slightly better than that at 8.5-ps separation. Finally, BER is degraded to $10^{-4} \sim 10^{-3}$ within a 5-ps separation range. Such degradation is a kind of beat noise between the desired user and interference. The effect of beat noise in ultrashort pulse O-CDMA has been fully analyzed when an ideal thresholder is used at the receiver [1], but further analysis is needed when practical, asynchronous nonlinear optical processing devices are placed before the optical-to-electrical conversion which of course will depend strongly on the detailed mechanism of the particular nonlinear optical processing device. Degradation caused by overlap is a universal problem for multiuser O-CDMA systems. In addition to our slot-level coordination scheme, other proposed remedies include synchronous optical gating at the receiver [4]–[6], [8] and/or chip level timing coordination at the transmitter [4]–[7]. In general, increasing timing coordination and synchronism can provide greater user counts and better performance, at the cost of greater complexity. We point out that although our scheme requires relatively relaxed timing control, both slot and chip level timing coordination sacrifice the benefit of asynchronous operation in a CDMA system. The coherent beat noise existing in many multiuser O-CDMA systems also limits the user counts with specified BER performance, and therefore, imposes limitation on the spectral efficiency in these systems.

In summary, we have demonstrated a four-user O-CDMA system operating at 10 Gb/s requiring $\sim$30 fJ/bit due to an ultrasensitive nonlinear optical processing element based on SHG in a PPLN waveguide. The low power requirement enables a multiuser O-CDMA system to operate at practical power levels compatible with traditional optical communication systems. Our scheme only requires slot level timing coordination and achieves fully asynchronous detection, which significantly simplifies system control.

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