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Multi-user, 10 Gb/s spectrally phase coded O-CDMA system with hybrid chip and slot-level timing coordination

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Abstract: We demonstrate a multi-user, 10 Gb/s spectrally phase coded O-CDMA system with hybrid chip and slot-level timing coordination utilizing low power nonlinear processing. A new double Hadamard coding scheme is demonstrated to enable both chip-level timing coordination and full interference suppression without the need for synchronous detection.

Keywords: O-CDMA, timing coordination, nonlinear processing, low power

Classification: Photonics devices, circuits, and systems

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1 Introduction

Multiple access techniques are required to meet the demand for high speed and large capacity communications in optical networks, which allow multiple users to share the fiber bandwidth. Optical code division multiple access (O-CDMA) is receiving increased attention due to its potential for local area network application [1-8]. In O-CDMA, multiple access is achieved by assigning different, minimally interfering code sequences to different transmitters, which must subsequently be detected in the presence of multi-access interference (MAI) from other users. CDMA is well suited for bursty network environments, and the asynchronous nature of data transmission can simplify and decentralize network management and control. However, full asynchronism is difficult to implement for O-CDMA in practice while simultaneously maintaining sufficient MAI suppression. Therefore, some level of synchronism is built into many $\geq$ 2-user O-CDMA schemes. To suppress MAI effectively, many O-CDMA systems have relied on precise timing coordination at the transmitter and/or synchronous nonlinear gating at the receiver, with coordination/synchronism required at the level of the finest feature in the coded waveforms, equal to the duration of uncoded or properly decoded pulses, typically on the order of ~ps [5-8]. This is referred to as chip-level timing coordination. Prior work in our group demonstrated a 4-user, 10 Gb/s spectrally phase coded O-CDMA system with strong nonlinear interference suppression, without the need for chip-level timing coordination at the transmitter or synchronous optical gating with clock recovery at the receiver [4]. In our previous system, slot-level timing coordination was used to relax tim-

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ing constraints: each bit period was divided into multiple time slots (equal to or longer than the coded waveform duration, which is much longer than the chip duration), with each user assigned to a different time slot. System performance was degraded due to beat noise as the time-slot duration was decreased below the coded waveform duration [4]. In general, increasing timing coordination and synchronism can provide greater user counts and better performance, at the cost of greater complexity. In this paper, we discuss an O-CDMA system operating at 10 Gb/s with increased timing control at the transmitter but still without synchronous detection at the receiver. Two different schemes are implemented: (1) 3 overlapped users with chip-level timing coordination; (2) 4-users with hybrid chip- and slot-level timing coordination. Our result shows the potential of higher total user counts with both multiple users per slot and multiple slots.

Our experimental system relies on an ultrasensitive nonlinear optical intensity discriminator based on second harmonic generation (SHG) in a periodically-poled lithium niobate (PPLN) waveguide [9]. The nonlinear discriminator permits full MAI suppression at an operating energy of ~30 fJ/bit [4], as much as two orders lower than discriminators based on fiber optics [6]. The ability to operate at low power per user is critical for scaling O-CDMA to greater numbers of users. In multi-user 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].

2 Experiment

In a chip-level timing coordination scheme [5-7], all users are aligned precisely at the time scale of the uncoded short pulse (e.g. ~ps or better). Single Hadamard coding has been employed in prior O-CDMA systems [6, 7]; however, this coding scheme does not provide efficient MAI suppression in our SHG nonlinear discriminator. Considering the narrow band SHG process due to large group velocity mismatch in PPLN waveguide, one can control the SHG yield by changing the correlation properties of the applied spectral phase code; our group has previously demonstrated as much as 30 dB MAI suppression ratio using a double Hadamard code, showing potential for O-CDMA application [10]. In this scheme, the left half of the spectrum is coded (H_i) at the transmitter while the right half is coded at the receiver (H_j) to enable properly ($H_i = H_j$) or improperly ($H_i \neq H_j$) decoded operation; here we use H_i as a shorthand for a single Hadamard code sequence. In this paper we propose a modified double Hadamard coding scheme: at the transmitter each user is coded by a double Hadamard code ($H_1 : H_2$, $H_1 \neq H_2$) across the whole spectrum, and at receiver it is properly decoded back to a short pulse by the same code ($H_1 : H_2$) or improperly decoded by another code ($H_3 : H_4$). Double Hadamard coding requires spectral amplitude equalization, for which the SHG at the center wavelength becomes equal to the spectral correlation [10]. As a result, proper sets of double Hadamard codes

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are fully orthogonal and ideally give zero crosstalk between orthogonal codes and full MAI suppression. Note that a single length-N Hadamard code family comprises N distinct orthogonal codes. For our double Hadamard coding scheme with a length-N Hadamard code on each half spectrum, there are N^2 different codes. One can divide these N^2 codes into N groups, where any code in one group is orthogonal to any code in a different group. However, any code in one group can perfectly decode any other code in that same group! Consequently, only N distinct code words (one selected from each distinct group) are supported.

Our experimental setup is similar to the system used in our prior work [3, 4]. A 10 Gb/s PRBS 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 coupled Fourier Transform pulse shaper [11] which incorporates a 2 × 128 pixel liquid crystal modulator (LCM) array to spectrally phase code and amplitude equalize the spectrum of the source laser. A fourth uncoded user path is also present as an additional interference channel [3]. 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 (CW) and 170%/pJ for ultrashort pulses. Compared to [3, 4], three important changes in the current work are: (1) spectral amplitude equalization, (2) chip-level timing control, and (3) introduction of the double-Hadamard coding scheme.

Fig. 1 (a) shows the optical spectrum before amplitude equalization. Fig. 1 (b) shows the equalized spectrum without spectral phase coding, for which the 9 nm bandwidth covers 64 pixels of the LCM. Fig. 1 (c) shows one typical double Hadamard code. We use a length-16 Hadamard code (16 code elements) on each half of the spectrum with 2 pixels per code-element. Note that the code-element order is reversed on each half of the spectrum.

Fig. 2 shows the O-CDMA system results with chip-level timing coordination. All users are aligned at the chip-level time scale with ~ps accuracy.

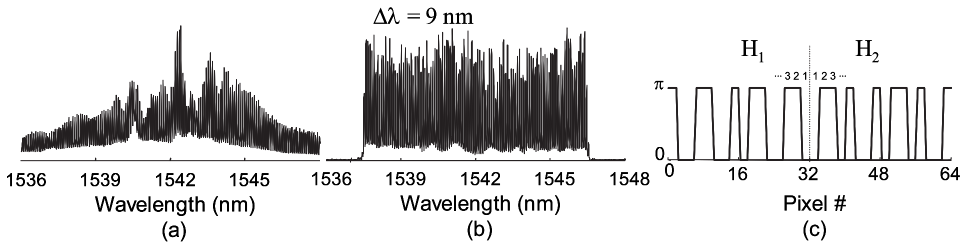

Fig. 1. (a) Spectrum before amplitude equalization. (b) Spectrum after amplitude equalization. (c) Double Hadamard code, consisting of 16 code elements on each half of the spectrum.

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Fig. 2 (a) shows intensity cross correlation measurements in which the pulse user is properly decoded, for 1 user, 2 users and 3 users respectively. Approximately a 5-ps wide minimum occurs at the center of the interference user waveforms where the properly decoded short pulse is located, enhancing the MAI rejection. Double length-16 Hadamard coding is used resulting in an interference user waveform broadened to ~25 ps. Fig. 2 (b) and (c) shows corresponding eye diagrams and bit error rate (BER) curves as a function of power *at the nonlinear discriminator*. To increase from 1 user to 2 users, the ~3.5 dB power differences between BER curves at BER $= 10^{-9}$ implies 0.5 dB power penalty due to MAI, since 3 dB arises from doubling of the number of users. Similarly, with 3 users a total of ~1.2 dB power penalty caused by MAI is observed at BER $= 10^{-9}$. Fig. 2 (d) shows the BER curves for another properly decoded user. There is ~2.7 dB power difference compared with the pulse user shown in (c), mostly caused by coding degradation and coding loss [2]. This is larger than our previous results [3, 4] due to the higher resolution used in our current pulse shapers (2 pixels/code-element vs. 4 pixels/code-element). Nevertheless, BER curves (c) and (d) show essentially similar behavior except for the power difference.

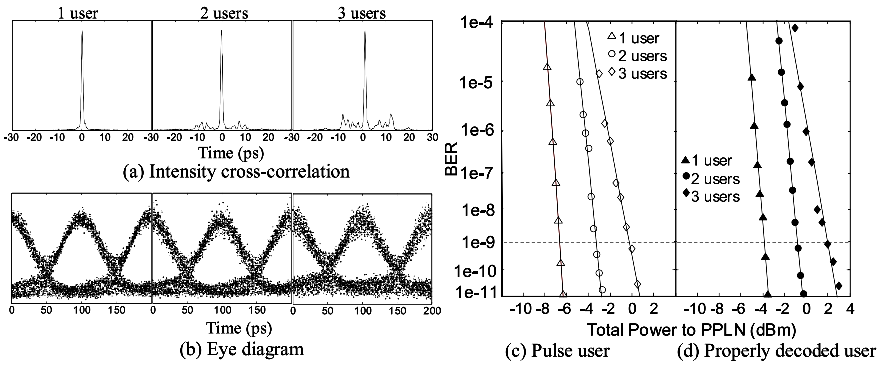

Fig. 2. Performance measurement of 10 Gb/s O-CDMA system with chip-level timing coordination. (a) Intensity cross-correlation of 1, 2 and 3 users with pulse user properly decoded. (b) Eye diagram and (c) BER measurement corresponding to (a). (d) BER measurement of one other properly decoded user.

Fig. 3 shows the 4-user O-CDMA system results with hybrid chip and slot-level timing coordination with the pulse user properly decoded. Fig. 3 (a) shows intensity cross correlation measurements of 4 combinations: A) 4 users separated in a time-slotted configuration; B) overlap 3 MAI users, separate 1 desired user; C) separate 2 pairs of overlapping users; D) overlap 3 users including the desired user, separate 1 MAI user. Fig. 3 (b) and (c) shows corresponding eye diagrams and BER curves, all operating at less than 3 dBm for 4 users (~50 fJ/bit) at BER $= 10^{-9}$.

Considering the ~25 ps slot occupied by each user, there are 4 available slots for the 100 ps bit duration at 10 Gb/s. This implies the potential of a

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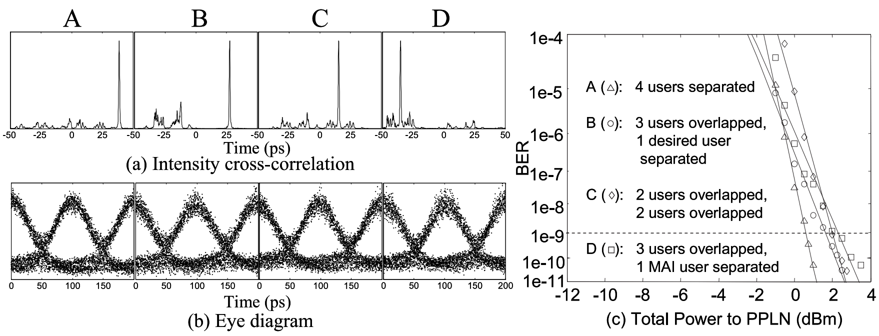

Fig. 3. Performance measurement of 4 × 10 Gb/s O-CDMA system with hybrid chip and slot-level timing coordination. (a) Intensity cross-correlation of 4 users with pulse user properly decoded. (b) Eye diagram and (c) BER measurement corresponding to (a). A: separate 4 users; B: overlap 3 MAI users, separate 1 desired user; C: separate 2 pairs of overlapping users; D: overlap 3 users including desired user, separate 1 MAI user.

12-user O-CDMA system if there are 3 users with chip-level timing coordination within each of the 4 slots. In our system, the low power 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, operating at practical power levels compatible with traditional optical communication systems. Although chip and slot-level timing coordination is required in this scheme, fully asynchronous detection is achieved through the asynchronous nonlinear optical processing technique.

3 Conclusion

In summary, based on a modified double Hadamard coding scheme, we have demonstrated 3 overlapped users with chip-level timing coordination, and 4-users with hybrid chip and slot-level timing coordination, in an O-CDMA system operating at 10 Gb/s with low power per user.

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