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Very-high-speed All-optical Code-division Multiplexing Systems Using a 2^n Prime Code

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Abstract

We demonstrate experimental all-optical code-division multiplexing (AO-CDM) systems using 64-ps optical pulses and a 2^n prime code of $n = 3$. A distinguishing feature of this experiment is that the modulation of an ultrashort optical clock stream by electrical data is realized without using any optical intensity modulator at each transmitter. Moreover, only low-cost optical 2×2 couplers and fiber delay lines are employed to implement all-serial encoders and decoders for a 2^n prime code.

Introduction

High-speed optical code-division multiplexing (CDM) systems have been recently demonstrated.[1–3] As known, using optical orthogonal codes (OOCs) with correlation constraints of 1, better bit-error-rate (BER) performance can be achieved than when using other address codes with cross-correlation constraint $\lambda_c > 1$ in AO-CDM systems.[4] Note that the value "1" is the minimum correlation constraint for incoherent optical signal processing.[4,5] However, the complexity of code generation/correlation and the power loss of an all-optical encoder/decoder must be also taken into account when we design AO-CDM systems. A recent study

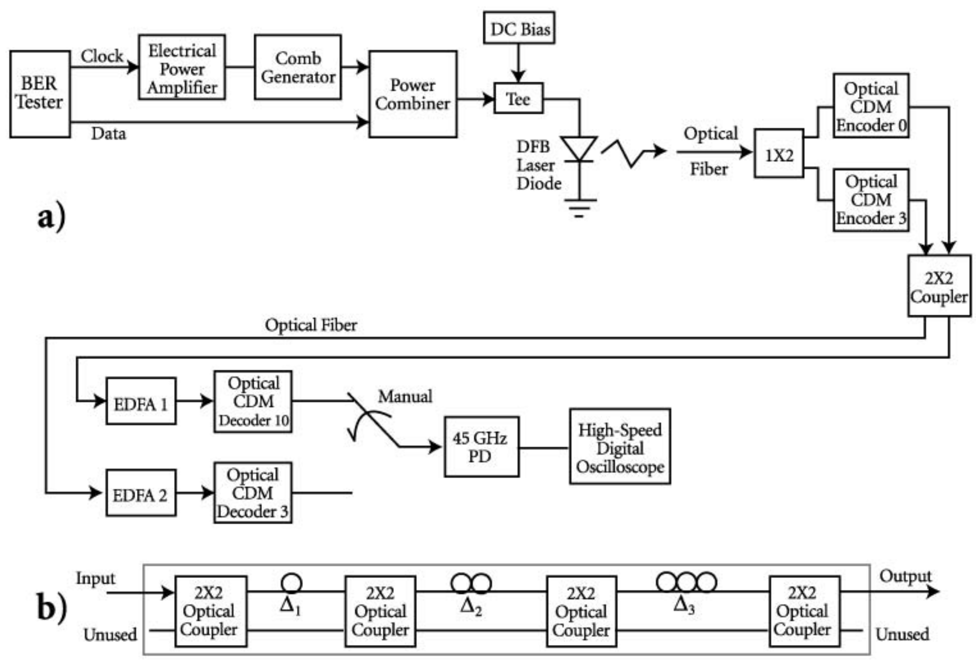

Figure 1. A two-user AO-CDM experiment. (a) Experimental setup. EDFA: erbium-doped fiber amplifier. (b) All-serial encoder or decoder.

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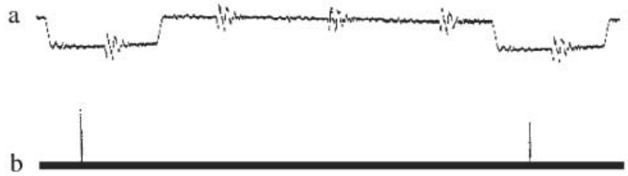


Figure 2. (a) Non-return-to-zero electrical data bits "10001" (with ECL logic). (b) The resulting optical bit pattern "10001" from a gain-switched laser diode. Timebase: 5.2 ns/div.

has shown that using 2^n codes in AO-CDM systems can result in a simple encoder and decoder using an all-serial structure, which requires a far smaller number of optical components and has lower optical power loss than using a conventional all-parallel encoder/decoder.[1] This is because the second half of the 2^k pulses in any 2^k codeword is just the delayed replica of the 2^{k-1} pulses in the first half of this codeword, where $2 \leq k \leq n$ and 2^n is the code weight. Moreover, the all-serial structure can be implemented by using a silica-based planar lightwave circuit to further reduce the power loss and to guarantee a precise time delay. In particular, the 2^n prime codes derived from original prime codes are very attractive to AO-CDM applications, because their encoding/decoding algorithms are very simple (*i.e.*, modulo multiplication).[6,7] This note reports a new experiment on very-high-speed AO-CDM systems using 2^n prime code.

Experimental demonstration

Figure 1a (see first page) shows the experimental setup for simulating two-user AO-CDM communication systems. The used codewords are the 0th codeword (C_0) and the 3rd codeword (C_3) of a 2^n prime code with $P = 11$, $\lambda_c = 2$, $n = 3$ (code weight = 8), and length $L = 121$, *i.e.*, C_0 = (00000000000 00000000000 10000000000 10000000000 10000000000 10000000000 10000000000 10000000000 10000000000 10000000000 00000000000) and C_3 = (00000000000 00000000000 00000010000 00000000010 01000000000 00001000000 00000001000 00000000001 00100000000 00000100000 00000000000). In the experiment, the data bit rate f_d of users is set to 100 Mbit/s. The slot width (*i.e.*, unit delay), τ, is then equal to $1/f_d L = 82.6$ ps.

At the transmitting end, a 100-MHz electrical clock signal from a BER tester is amplified first to drive a 100-MHz HP comb generator of which the output signal is added to the 100-Mbit/s electrical data at a power combiner (see Fig. 1a). A DFB laser diode (LD) at the 1.55-μm wavelength is then driven by a current signal containing three components (*i.e.*, a DC prebias, a data current pulse, and a clock pulse). By correctly setting the prebias and data currents, the DFB LD is biased just below a threshold at which the gain switching occurs. The LD is gain switched if both a data and clock pulse are simultaneously present, making the carrier concentration above the threshold.[8] Thus, an ultrashort optical clock signal is effectively modulated by electrical data bits at the LD, without using any optical intensity modulator. The resulting optical pulse is then fed into an all-optical encoder, i, to generate the codeword C_i ($i = 0$ and 3). For a 2^n codeword of $n = 3$, the all-serial encoder (or decoder) comprises only $n + 1 = 4$ passive optical 2×2 couplers that are serially connected with each other as shown in Figure 1b,[1] where $\{\Delta_1 = 909.1\ ps, \Delta_2 = 1818.2\ ps,$

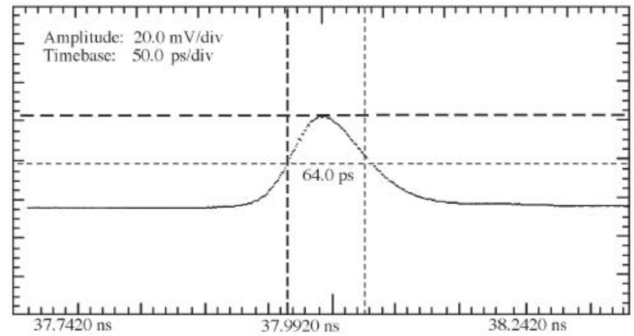


Figure 3. Optical pulse from a gain-switched DFB LD.

$\Delta_3 = 3636.4\ ps\}$ for C_0 and $\{\Delta_1 = 1157.0\ ps, \Delta_2 = 1405.0\ ps, \Delta_3 = 3719.0\ ps\}$ for C_3. Here optical fiber delay lines and reference fibers (assuming 0 delay) are the only pigtail fibers commercially available with 2×2 optical couplers. In contrast, a 2^n-code encoder (or decoder) of $n = 3$, if using an all-parallel structure,[1] requires 14 optical 1×2 couplers, 7 optical fiber delay-lines, and 1 reference fiber. It is clear that using the all-serial structure can efficiently reduce cost, complexity, and power loss for optical encoders/decoders, especially for a large value of n.

By using an HP high-speed digital oscilloscope, the non-return-to-zero electrical data bits "10001" are measured from a BER tester (with ECL logic) and are shown as the upper trace in Figure 2. The resulting optical pulses from the gain-switched LD (see Fig. 1a) are directly measured at the output of a 45-GHz photodetector (PD), and illustrated as the lower trace in Figure 2. The width of gain-switching optical pulses is then measured to be 64 ps (see Fig. 3). The timing jitter and frequency chirping of a gain-switched DFB LD can be reduced by injecting a narrow linewidth cw light from an external tunable optical source. The generated optical short pulse is then fed into two encoders (see Fig. 1a). The corresponding codewords C_0 and C_3 at the outputs of both encoders are shown in Figures 4a and 4b, respectively. Although commercially available low-cost 2×2 optical couplers (with splitting ratios of 2.8 dB/3.2 dB and 2.9 dB/3.1 dB) are used in the encoders and decoders, the optical pulse sequence of nearly constant amplitude is obtained for C_0 by using couplers of splitting ratio 2.9 dB/3.1 dB and carefully fusing pigtail fibers between two couplers in series. In

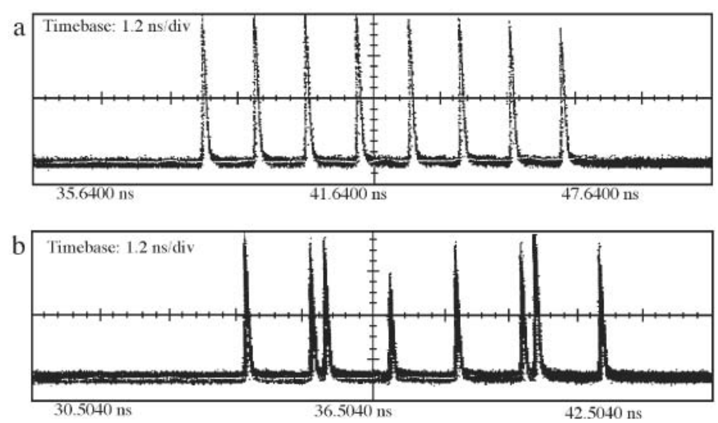
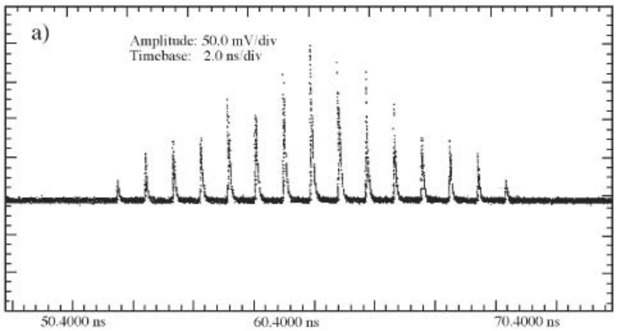


Figure 4. (a) Optical pulse sequence encoded with C_0 and (b) with C_3.



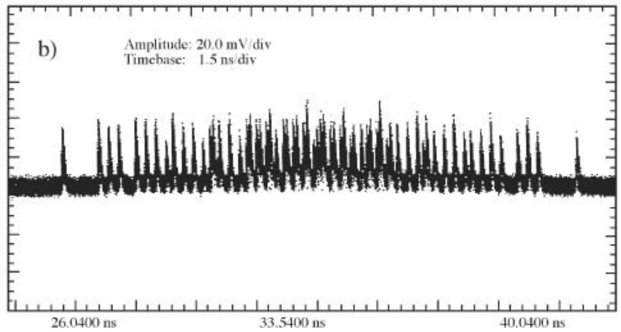


Figure 5. (a) The measured autocorrelation function of C_0. (b) The measured cross-correlation function of C_0 with C_3.

the experiment, we can control the delay-time error of fiber delay lines within 17 ps as measured, only by carefully cutting and fusing the pigtail fibers of optical couplers. For the pulse sequence of C_3, unequal pulse amplitudes are visible (see Fig. 4b), because optical 2×2 couplers with worse ratios (2.8 dB/ 3.2 dB) are used at this encoder such that the accumulated amplitude error is more severe. This also suggests that using a silica-based planar lightwave circuit should achieve the low-power loss, uniform splitting ratio, and very precise time delay for all-serial encoders/decoders. Because of symmetric pulse distribution in each 2^n codeword, decoder i is the same as encoder i for the codeword C_i. The autocorrelation function of C_0 is measured at the output of decoder 0, which has a main peak of eight and the highest sidelobe of seven (see Fig. 5a), because C_0 is of a repetition code. The cross-correlation function of C_0 with C_3 is shown in Figure 5b, which is also the same as the cross-correlation function of C_3 with C_0. Moreover, all the peaks of both cross-correlation functions are limited to be 1 ($< \lambda_c = 2$) for the specific code-words C_0 and C_3. These are confirmed by the computed cross-correlation functions. Note that Figures 5a and 5b have different amplitude scales, *i.e.*, 50 mV/division in Figure 5a while 20 mV/division in Figure 5b.

In conclusion, new AO-CDM systems using 64-ps optical pulses and a 2^n prime code of $n = 3$ have been reported. In principle, 11 users can be accommodated with a data bit rate up to 129 Mbit/s if we assume that the slot width is equal to 64 ps. Since there is no optical intensity modulator is required at each transmitter, and low-cost optical 2×2 couplers are used at the all-serial encoder/decoder, both cost- and power-effective AO-CDM systems can be realized.

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Tunability in the Terahertz Regime: Charge-Carrier Wavepacket Manipulation in Quantum Wells

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Abstract

A convenient method for generating upshifted and harmonically-generated terahertz transients via the creation of highly anisotropic electron-hole wavepackets in quantum wells is described. Our results are in agreement with experimental measurements.

Recent progress in the generation and detection of ultrashort (less than a ps) lasers in various regimes of the electromagnetic (EM) spectrum has given rise to the creation of innovative methods for research on materials, modern optoelectronics, and time-domain transient electrodynamics. However, due to the absence of convenient and reliable sources, the terahertz (THz) regime remains largely unexplored. Nevertheless, with the advancement of free-electron lasers (FELs) as well as THz solid-state emitters, THz physics and related technology is currently coming out of its infancy. Further, two-color techniques (optical and THz) applied to mesoscopic semiconductors have also been developed. Consequently, the dynamics of charge carriers after excitation with short light pulses and THz fields in semiconductor heterostructures have been receiving an upsurge of attention in the last few years. Besides being of fundamental interest, the investigation of interplaying THz and optical fields is also relevant in the operation of high-speed electronic and optoelectronic devices such as photodetectors, modulators, and switches.[1] Terahertz pulses have, moreover, proven useful for a wide variety of applications, including FIR/time-domain spectroscopy, study and control of Rydberg atoms,[2] and T-ray imaging of optical materials. Regrettably, using solid-state sources, a common limitation to the generation of THz transients is the lack of tunability.