Experiments on High-Speed All-Optical Code-Division Multiplexing (CDM) 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-picosecond optical pulses and a 2^n prime code of $n = 3$. A distinguishing feature of this experiment is that the modulation of ultrashort optical clock stream by electrical data is realized without using any optical intensity modulator at each transmitter. Moreover, only low-cost standard optical 2×2 couplers and fiber delay lines are employed to implement all-serial encoders and decoders for a 2^n prime code. As a result, this new system is more cost- and power-effective than a conventional AO-CDM system.

1. Introduction

Today's single-mode optical fibers can offer an usable bandwidth up to 25,000 GHz (25 THz) in the 1.5-μm wavelength window, which can support ultra-high-speed data transmission and networking. However, the use of electronic signal processing ultimately limits the data throughput. To eliminate the throughput bottleneck, optical signal processing techniques should be employed in such systems. This in turn can provide an ultrafast processing speed up to 100 Gbit/s [1]-[3]. Therefore, future high-speed communication systems will be based on optically-processed architectures.

Recently, optical code-division multiplexing (CDM) techniques have been receiving considerable attention [1]-[9]. Experimental demonstration of high-speed optical CDM systems has been also reported [2]-[6]. Optical CDM, as an alternative to optical time-division and wavelength-division multiplexing, is attractive for high-speed local-area networks [2]. As we know, using optical orthogonal codes (OOC's) with cross-correlation constraint $\lambda_c = 1$ and autocorrelation constraint $\lambda_a = 1$ can achieve better bit-error-rate (BER) performance than employing other address codes with $\lambda_c > 1$ in all-optical CDM (AO-CDM) systems [7]. Note that the value "1" is the minimum correlation constraint for incoherent optical signal processing [3][7]. However, the complexity of code generation/correlation and the power loss of all-optical encoder/decoder must be also taken into account when we design AO-CDM systems.

A recent study has shown that employing 2^n codes in AO-CDM systems can result in 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 conventional all-parallel encoder/decoder [2]. 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. This characteristic can greatly simplify the structures of optical encoders and decoders by using an all-serial structure as shown in Figure 1 [2], which requires only $n+1$ optical 2×2 couplers for generating or correlating any 2^n codeword. Furthermore, 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, those 2^n codes derived from prime codes are very attractive to AO-CDM applications, because their encoding/decoding algorithms are systematical and are very simple (i.e., modulo multiplication) [8][9].

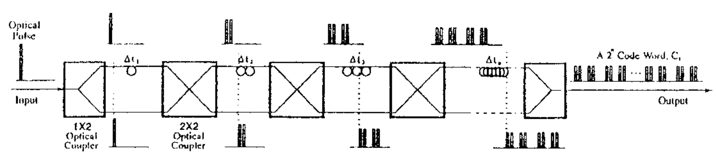

Figure 1: All-serial configuration of an all-optical encoder or decoder.

In this paper, we report a new experiment on high-speed AO-CDM systems using 2^n prime code. Unlike conventional AO-CDM systems [2]-[6], in our experiment no any optical intensity modulator is used to gate the ultrashort optical clock pulses by electrical data at each transmitter. Moreover, optical-injection locking is employed to reduce the timing jitter of a gain-switched laser diode in our experimental system.

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2. Principle and Experimental Set-Up

Let P be a prime number. A prime code of length $L = P^2$ and weight P is derived from a set of prime sequences $S_i = \{s_{i0}, \cdots, s_{ij}, \cdots, s_{i(P-1)}\}$, where $i \in GF(P)$–Galois field, and $s_{ij} = \{i \cdot j\}$ modulo P [3]. A prime code with P distinct codewords, $C_i = (c_{i0}, c_{i1}, \cdots, c_{ik}, \cdots, c_{i(L-1)})$ for $k = 0, 1, 2, \cdots, L-1$, are thus constructed by [3]

$$c_{ik} = \begin{cases} 1 & k = s_{ij} + jP \text{ and } j \in GF(P) \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

A 2^n prime code with cross-correlation constraint $\lambda_c = 2$ is obtained from the prime code of P, by selecting only the 2^n pulses (per codeword) that satisfy the specific delay-distribution constraint: For any C_i and any integers x, y, z, and m, such that $x \neq y$, $x \in [0, 2^n - 2]$, $y \in [0, 2^n - 2]$, and $z \in [1, n-1]$, if x and y are divisible by 2^z, then we have [8]

$$t_{x \oplus (2^{z-1}-1) \oplus m} = t_{y \oplus (2^{z-1}-1) \oplus m} \tag{2}$$

for a given integer $m \in [0, 2^n - 1]$, where the "$\oplus$" in eqn. (2) denotes modulo-2^n addition, and the adjacent relative cyclic delays t_j's are defined as [8]

$$t_j = \begin{cases} s_{i,(j+z_j \bmod P)} - s_{ij} + z_j P, \\ \quad \text{for } j = 0, 1, \ldots, P-2 \\ s_{i,z_j - 1} - s_{ij} + z_j P, \quad \text{for } j = P-1 \end{cases} \tag{3}$$

where $z_j \in [1, P-1]$ is an integer and $i \in \mathrm{GF}(P)$.

For all $k = \{0, 1, \ldots, n-2\}$ and $u = \{0, 1, \ldots, P - 2^n\}$, the valid codeword C_i of a 2^n prime code is obtained from S_0, S_i and S_{P-i} satisfying [8]

$$\frac{2(P-u)\left(2^k - 1\right)}{2^n - 2^{n-k} + 1} \leq i \leq \frac{(P-u)\left(2^{k+1} - 1\right)}{2^n - 2^{n-k-1} - 1} \tag{4}$$

where $i = \{1, 2, \ldots, (P-1)/2\}$.

Using eqn. (4), we can find that all the codewords of the prime code with $P = 11$ can be modified to form a 2^n prime code with $n = 3$, code length $L = 121$, and code size 11 (i.e., the total number of users).

In this paper, we demonstrate two-user AO-CDM systems. In the experiment, the used codewords are the 0th codeword and the 3rd codeword of the 2^n prime code with $P = 11$ and $n = 3$ (code weight 8), 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)

We assume that the data rate f_d of users is equal to 100 Mbit/s. The slot width (i.e., unit delay) τ is then equal to $1/f_d L = 82.6$ picoseconds (ps).

Figure 2 shows the experimental set-up for simulating two-user AO-CDM communication systems. At the transmitting end, 100-MHz electrical clock signal from a BER tester is amplified first, so that it can 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. Then a DFB laser diode (LD) at 1.55 μm is driven by a current signal containing three components (see Figure 2), namely, a DC prebias, a data current pulse, and a clock pulse. By correctly setting prebias and data currents, the DFB LD is biased just below a threshold at which the gain switching occurs, whereas the LD is gain switched only if a data pulse and a clock pulse are simultaneously present to make the carrier concentration above the threshold [10]. In this way, ultrashort optical clock signal is effectively modulated by electrical data bits at the LD, without using any optical intensity modulator. Then the resulting optical pulse is fed into all-optical encoder i to generate 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 by 3 *fiber delay lines* and 3 *reference fibers* (assuming 0 delay) [2], as shown in Figure 1, where $\{\Delta t_1 = 909.1\,ps, \Delta t_2 = 1818.2\,ps, \Delta t_3 = 3636.4\,ps\}$ for C_0 and $\{\Delta t_1 = 1157.0\,ps, \Delta t_2 = 1405.0\,ps, \Delta t_3 = 3719.0\,ps\}$ for C_3.

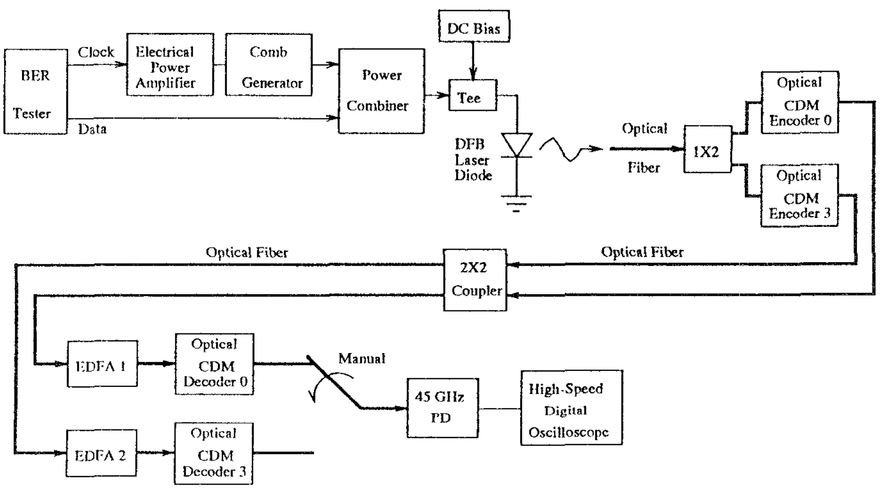

Figure 2: Experimental set-up for simulating two-user AO-CDM communication systems.

Note that both delay-line and reference fibers are only pigtail optical fibers of commercial 2×2 couplers. In contrast, a 2^n-code encoder (or decoder), if using an all-parallel structure [2], requires 14 optical 1×2 couplers, 7 *delay-line* and 1 *reference* fibers, as shown in Figure 3. It is clear that using the all-serial structure can efficiently reduce cost, complexity and power loss of optical encoders/decoders, especially for a large value of n.

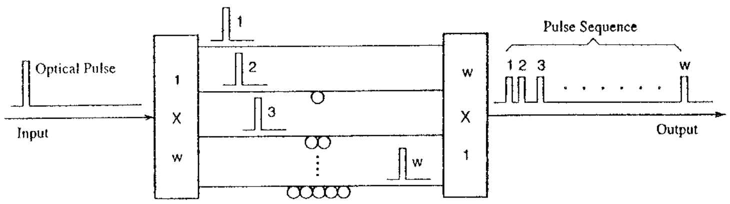

Figure 3: All-parallel configuration of an AO-CDM encoder or decoder.

By using a *HP* high-speed digital oscilloscope, the 64-ps with of gain-switching optical clock pulses is directly measured at the output of a 45-GHz photodetector, as shown in Figure 4. Although a gain-switched DFB LD suffers both timing jitter and frequency chirping, they can be reduced by injecting a narrow linewidth CW light (from an external tunable source) into the gain-switched LD. In our experiment, the timing jitter is reduced from 7.2 ps to 3.7 ps, as measured from the *HP* high-speed digital oscilloscope, by using this optical-injection locking scheme with the injection power of 155 μw at the 1.55 μm wavelength.

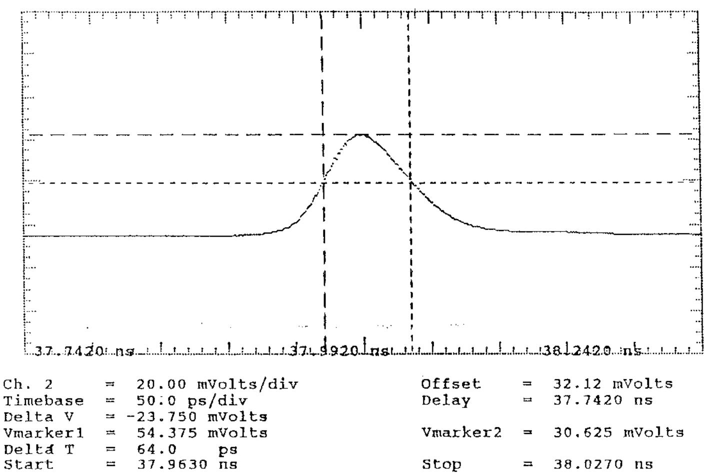

Figure 4: Optical pulse from a gain-switched DFB LD.

An electrical NRZ data bit "1" (with ECL logic) from the BER tester is illustrated as the upper traces in Figures 5 and 6, respectively. The corresponding codewords C_0 and C_3 from two optical encoders are then shown as the lower traces in Figures 5 and 6, respectively. Figure 7 shows the complete electrical data bits "10001" at the input of a gain-switched LD (upper trace) and the resulting

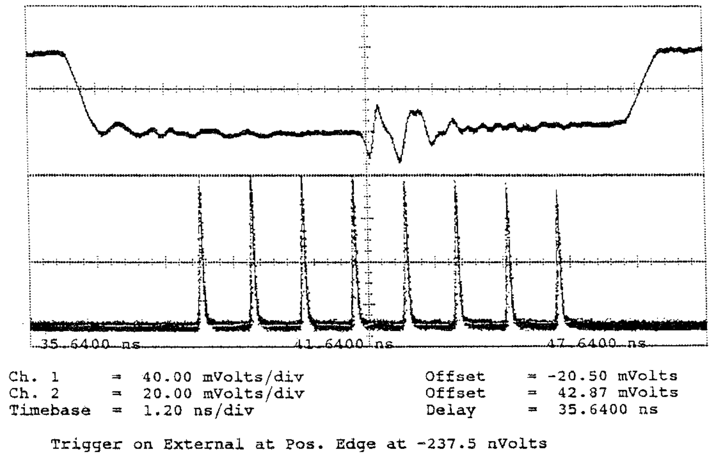

Figure 5: Electrical data bit and the optical pulse sequence encoded with C_0.

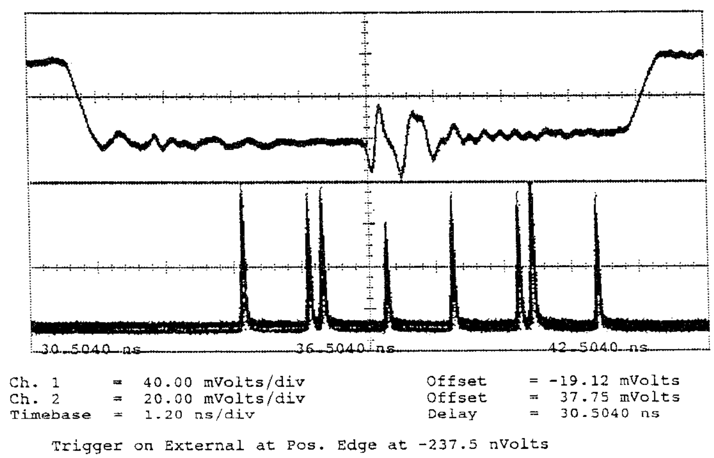

Figure 6: Electrical data bit and the optical pulse sequence encoded with C_3.

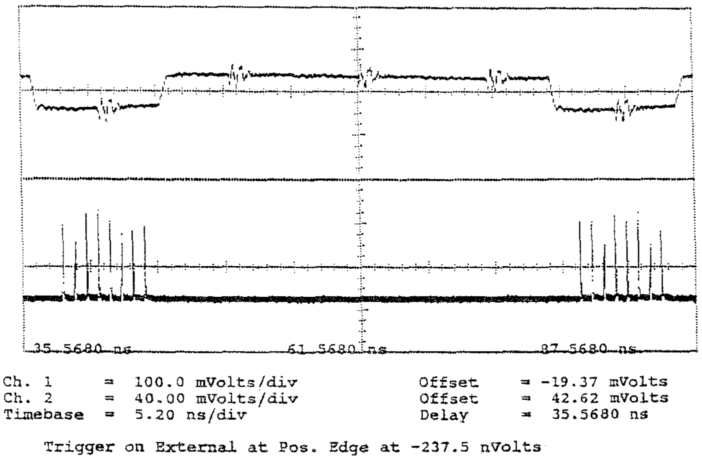

Figure 7: Electrical bit stream "10001" and the resulting pulse sequences encoded with C_0.

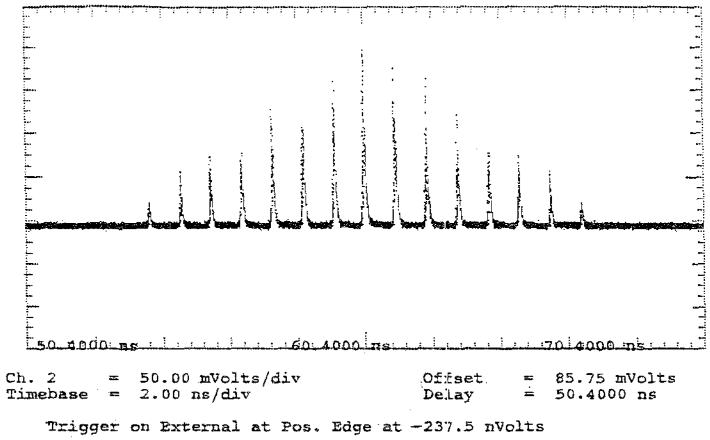

Figure 8: The measured autocorrelation of C_0.

pulse sequences for C_0 (lower trace). Although commercially available low-cost 2×2 optical couplers (with splitting ratios of 2.8dB/3.2dB and 2.9dB/3.1dB) 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 2.9dB/3.1dB and carefully fusing pigtail fibers between two couplers in series. In the experiment, we can control the delay-time error of fiber delay lines within 17 ps as measured for C_0, only by carefully cutting and fusing the pigtail fibers of couplers. For the pulse sequence of C_3, unequal pulse amplitudes are visible (see the lower trace in Figure 6), because optical 2×2 couplers with worse ratio (2.8dB/3.2dB) 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 (PLC) 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, where $i = 0$ and 3.

The autocorrelation of C_0 is measured at the output of decoder 0, which has a main peak of 8 (i.e., code weight 8) and the highest sidelobe of 7 as shown in Figure 8, because C_0 is of a repetition code. The cross-correlation of C_0 with C_3 is shown in Figure 9. There is no surprise to observe that the cross-correlation of C_3 with C_0, shown in Figure 10, is the same as that of C_0 with C_3. These are also confirmed by the computed cross-correlations.

3. Conclusion

New AO-CDM systems using 64-ps optical pulses and a 2^n prime code of $n = 3$ have been reported in this paper. In principle, 11 users can be accommodated with data rate up to 129 Mbit/s if we assume that the slot width is equal to 64 ps. Since no any 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. Furthermore, the lossless encoder (or decoder) of $n = 4$ can be imple-

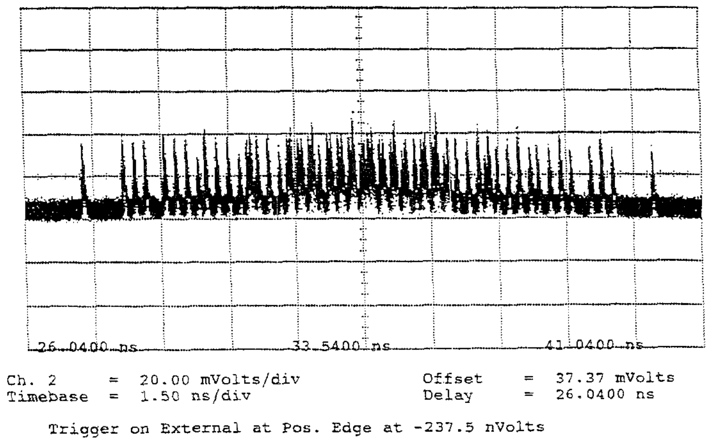

Figure 9: The measured cross-correlation of C_0 with C_3.

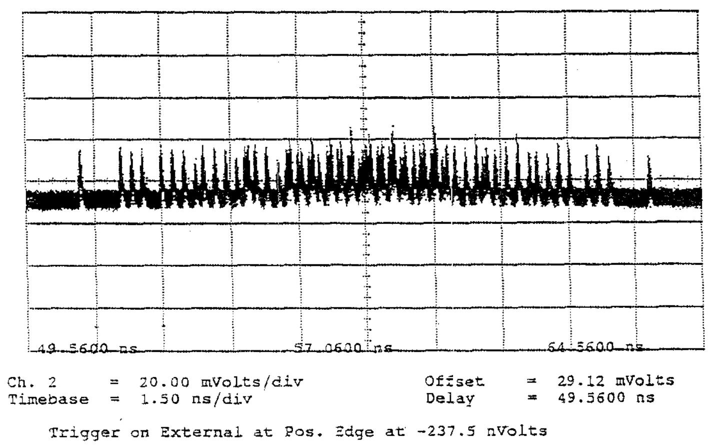

Figure 10: The measured cross-correlation of C_3 with C_0.

mented by using the silica-based PLC integrated with an Er-doped silica waveguide amplifier of $\sim$ 15dB gain [11].

The proposed AO-CDM systems use a 2^n prime code with the cross-correlation constraint $\lambda_c = 2$. To improve their BER performance, we can pad $P-1$ zeros in each subsequence of codewords in the original 2^n prime code to reduce the value of λ_c from 2 to 1. Therefore, we obtain a new family of 2^n codes, called 2^n extended prime codes of $\lambda_c = 1$, which will be reported in our another paper [12].

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