Experiments on High-Speed All-Optical Code-Division Multiplexing Systems Using All-Serial Encoders and Decoders for 2^n Prime Code

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***Abstract*— In this paper, 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 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 $\times$ 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. Furthermore, the use of AO-CDM systems can offer parallel communications over a common fiber channel, which in turn can support real-time computer interconnections for image and data communications.**

***Index Terms*— Optical code-division multiplexing, optical encoder and decoder, optical fiber communications, optical signal processing, optical transmission systems.**

I. Introduction

SINGLE-MODE optical fibers can provide an usable transmission bandwidth of 25 THz in the 1.55-μm wavelength window, which can support ultrahigh-speed data transmission and networking applications. However, the use of electronic signal processing ultimately limits the data throughput. To eliminate the throughput bottleneck, optical signal processing should be employed in ultrahigh-speed optical fiber systems where such functions as data sampling, multiplexing, transmission, amplification, and demultiplexing (also possibly including data regeneration) are performed completely in the optical domain. In doing so, this in turn can support ultrafast signal processing with a speed up to 100 Gb/s [1]–[3]. Therefore, future high-speed communication systems will be based on optically processed architectures.

In recent years, optical code-division multiplexing (CDM) techniques have been receiving considerable attention [1]–[9]. Experimental demonstrations of high-speed optical CDM systems have 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 (LAN's) because many users can simultaneously transmit data messages over a common fiber channel [2]. This characteristic of parallel communications can be substantially utilized to support real-time computer interconnections for high-speed image and data communications. As we know, using optical orthogonal codes (OOC's) with cross-correlation constraint λ_c of 1 and autocorrelation constraint λ_a of 1 can achieve better bit-error-rate (BER) performance than employing other address codes of $\lambda_c > 1$ 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 (i.e., the number of pulses per codeword). This characteristic can be utilized to significantly simplify the optical encoder and decoder by using an all-serial configuration shown in Fig. 1 [2], where only $n+1$ optical 2×2 couplers are required for generating or correlating any 2^n codeword. In contrast, an optical encoder (or decoder) with the parallel configuration comprises $\sum_{k=1}^{n} 2^k$ optical 1×2 couplers for a given code weight $w = 2^n$ (see Fig. 2), which is bulky and has a high power loss for a large value of w so that it may not be implementable (e.g., when w equals several tens or hundreds). In the ideal case, the total coding and decoding power loss for a 2^n code is equal to $6(n+1)$ dB if the encoder–decoder pair in Fig. 1 is used, while the total power loss is $12n$ dB if the encoder–decoder pair in Fig. 2 is employed. 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, as will be discussed subsequently. 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].

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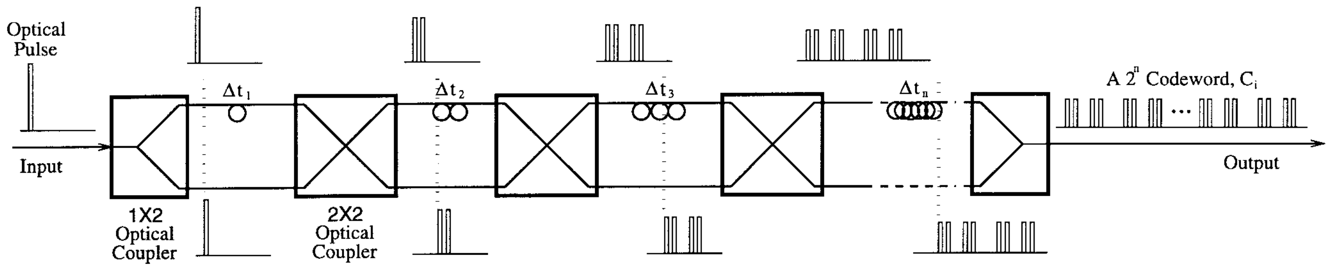


Fig. 1. All-serial configuration of an all-optical encoder or decoder.

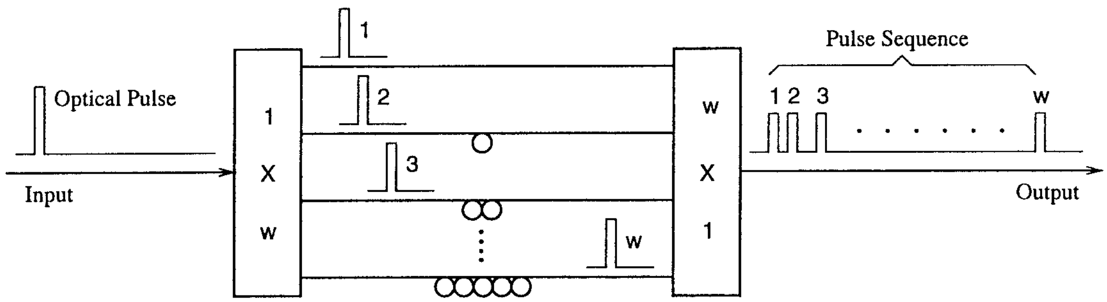


Fig. 2. All-parallel configuration of an AO-CDM encoder or decoder.

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 at each transmitter to gate the ultrashort optical clock pulses by electrical data. 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. Therefore, this new system is more cost- and power-effective than a conventional AO-CDM system.

II. 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]

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

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

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

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

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

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

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

Using (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 section, we demonstrate two-user AO-CDM systems. In the experiment, the used codewords are the zeroth codeword and the third codeword of the 2^n prime code with $P = 11$ and $n = 3$ (i.e., code weight 8)

$$\begin{aligned} C_0 = (&00000000000 \quad 00000000000 \quad 10000000000 \\ &10\,000\,000\,000 \quad 10\,000\,000\,000 \quad 10\,000\,000\,000 \\ &10\,000\,000\,000 \quad 10\,000\,000\,000 \quad 10\,000\,000\,000 \\ &10\,000\,000\,000 \quad 00\,000\,000\,000) \end{aligned}$$

and

$$\begin{aligned} C_3 = (&00\,000\,000\,000 \quad 00\,000\,000\,000 \quad 00\,000\,010\,000 \\ &00\,000\,000\,010 \quad 01\,000\,000\,000 \quad 00\,001\,000\,000 \\ &00\,000\,001\,000 \quad 00\,000\,000\,001 \quad 00\,100\,000\,000 \\ &00\,000\,100\,000 \quad 00\,000\,000\,000). \end{aligned}$$

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). This data rate has been adopted by the data-communication standards, such as *Fiber Distributed Data Interface* (FDDI) and *fast ethernet*, to support computer interconnections for data and image communications.

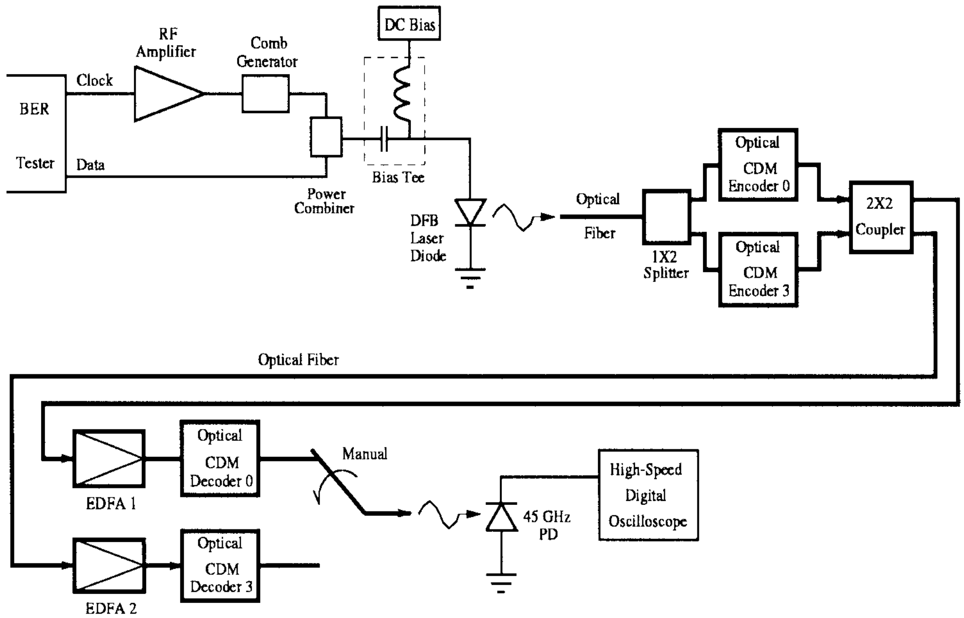


Fig. 3. Experimental setup for simulating two-user AO-CDM communication systems.

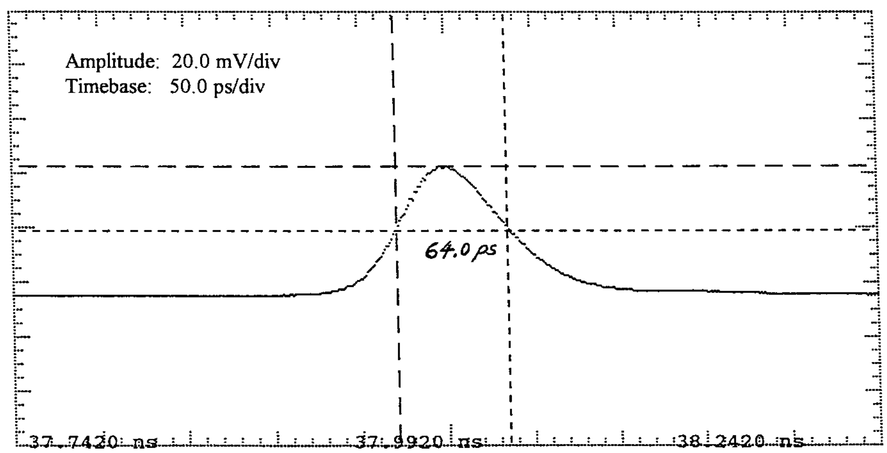


Fig. 4. Optical pulse from a gain-switched DFB LD.

Fig. 3 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-Mb/s electrical data at a power combiner. Then a DFB laser diode (LD) at the 1.55-μm wavelength is driven by a current signal containing three components (see Fig. 3), 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. Thus, 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. In doing so, it not only can reduce the complexity and cost of an AO-CDM transmitter, but also can eliminate the insertion power loss associated with using an optical intensity modulator (e.g., about several dB). Consequently, cost-effective AO-CDM transmitters can be realized by using this scheme, whereas the conventional AO-CDM transmitter must use an optical intensity modulator to on–off modulate the optical clock pulse stream [2]–[6]. 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* (assumed to have 0 delay) as shown in Fig. 1 [2], 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. Note that both delay-line and reference fibers are only pigtail optical fibers of commercially available 2×2 optical couplers. In contrast, a 2^n-code encoder (or decoder), if using an

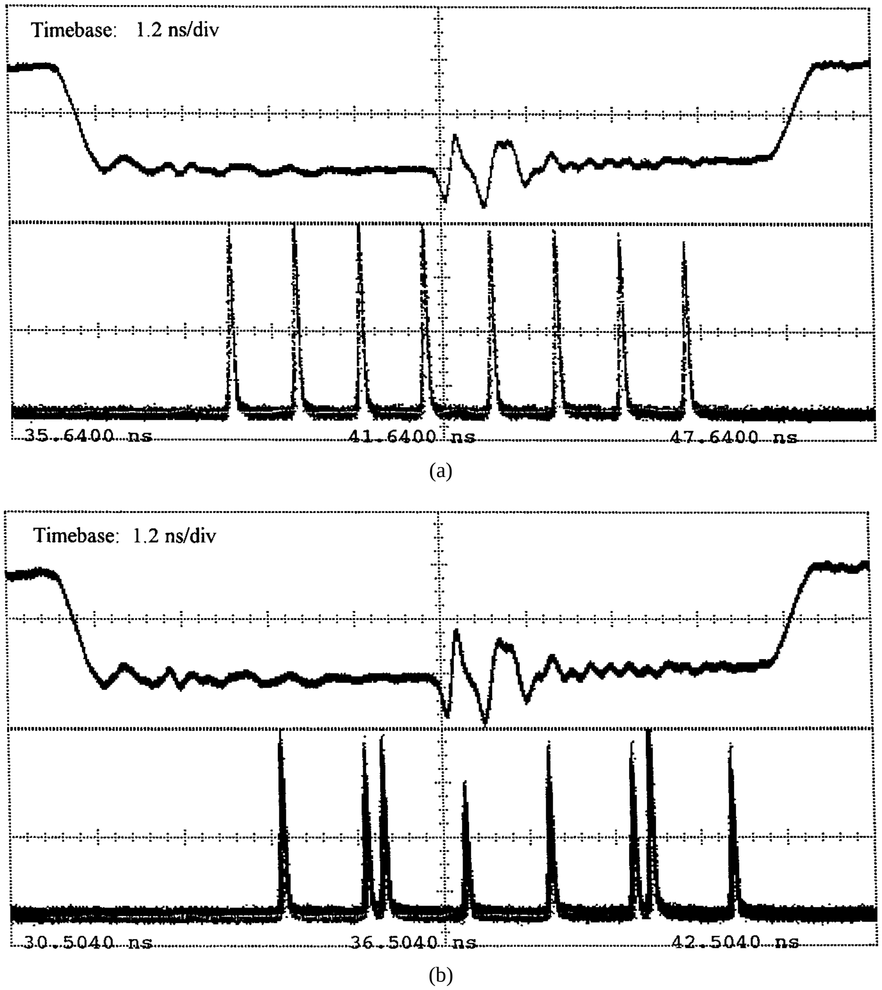


Fig. 5. (a) Electrical data bit “1” (with ECL logic) and the optical pulse sequence encoded with C_0. (b) Electrical data bit “1” and the optical pulse sequence encoded with C_3.

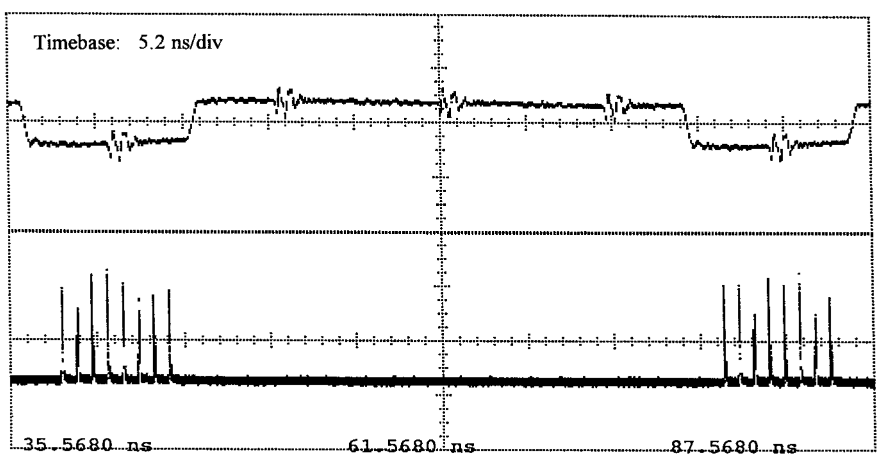


Fig. 6. Electrical bit stream “10 001” (with ECL logic) and the resulting pulse sequences encoded with C_0.

all-parallel structure [2], requires 14 optical 1×2 couplers, 7 *delay-line* and 1 *reference* fibers, as shown in Fig. 2. 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. Furthermore, the use of integrated optics can allow us to feasibly implement power-efficient, waveguide-integrable all-serial encoders and decoders. This in turn can facilitate applications of AO-CDM systems.

By using a *HP* high-speed digital oscilloscope, the 64-ps width of gain-switching optical clock pulses is directly measured at the output of a 45-GHz photodetector, as shown in Fig. 4. Normally, a gain-switched laser diode suffers both

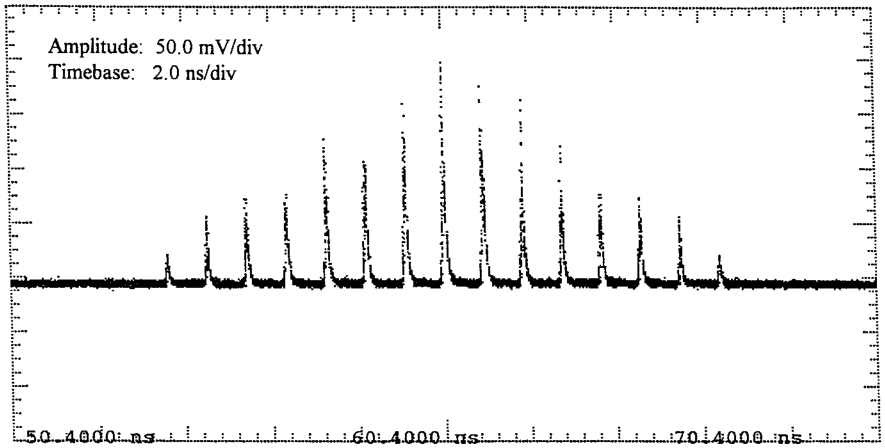
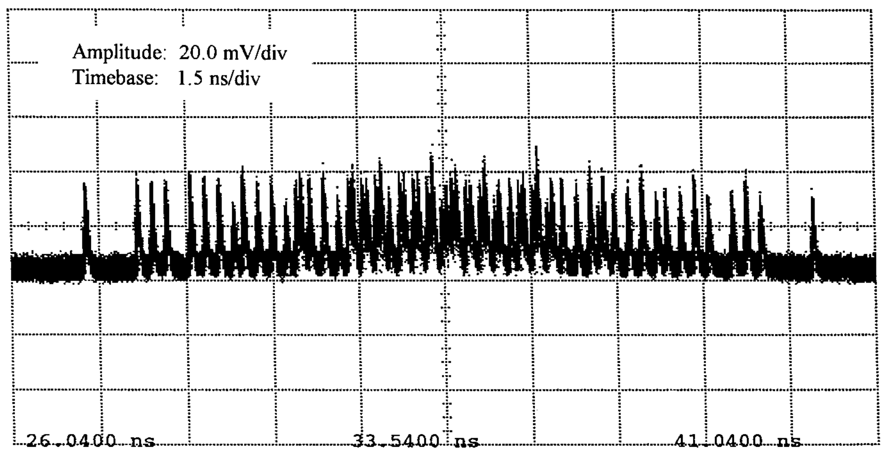
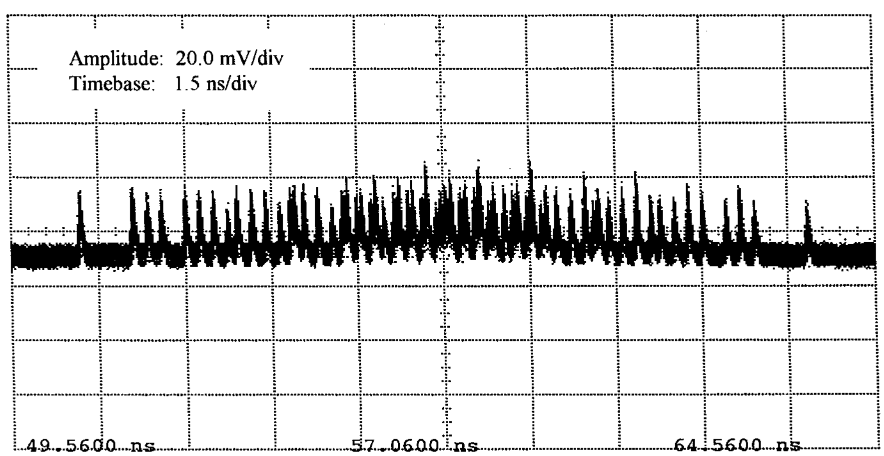


Fig. 7. Measured autocorrelation of C_0.



(a)



(b)

Fig. 8. (a) Measured cross correlation of C_0 with C_3. (b) Measured cross correlation of C_3 with C_0.

timing jitter and frequency chirping, but they can be reduced by injecting a narrow linewidth continuous-wave (CW) light into the gain-switched laser diode. The CW light of narrow linewidth can be obtained from an external tunable optical source.

An electrical NRZ data bit "1" (with ECL logic) from the BER tester is illustrated as the upper traces in Fig. 5(a) and (b), respectively. The corresponding codewords C_0 and C_3 from two optical encoders are then shown as the lower traces in Fig. 5(a) and (b), respectively. Fig. 6 shows the complete electrical data bits "10 001" (upper trace) at the input of a gain-switched LD and the resulting pulse sequences for C_0 (lower trace). Although commercially available low-cost 2×2 optical couplers (with splitting ratios of 2.8 dB/3.2 dB and 2.9

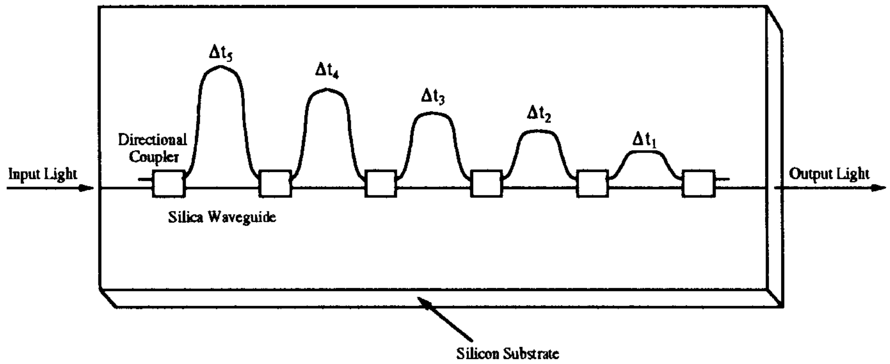


Fig. 9. Schematic diagram of a proposed AO-CDM encoder (or decoder) using silica-based PLC [14].

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 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 Fig. 5(b)], because optical 2×2 couplers with worse ratio (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, as will be discussed subsequently. 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 Fig. 7, because C_0 is of a repetition code. The cross correlation of C_0 with C_3 is shown in Fig. 8(a). There is no surprise to observe that the cross correlation of C_3 with C_0, shown in Fig. 8(b), is the same as that of C_0 with C_3. These are also confirmed by the computed cross correlations.

III. Design Consideration

The use of discrete optical 2×2 couplers and fiber delay lines can implement AO-CDM encoders and decoders as described in the above. This simple approach, however, has some disadvantages. For example, the resulting encoder and decoder normally have a relatively large size and low reproducibility. To fabricate them, special attentions are paid to fiber alignment, length adjustment/control, and fiber splicing, which in turn lead to the unavoidable splice power loss and time-delay error in the manufacture process. Moreover, the achievable precision in control of fiber lengths may prevent such encoders and decoders from ultrahigh-speed operations. To overcome these difficulties, monolithic integration of optical passive couplers with delay lines is highly required.

As known, integrated optics or planar waveguide technology has played an important role in the fabrication of lightwave circuits due to the reasons of manufacturability and economy.

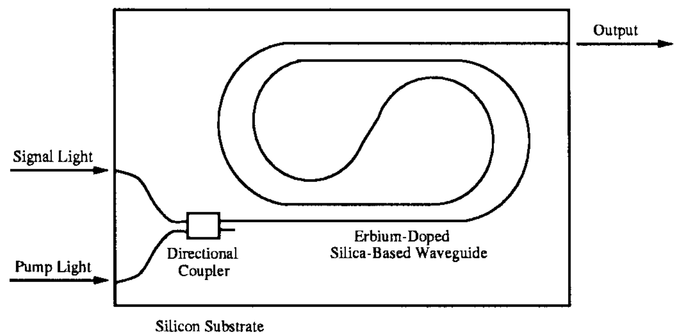


Fig. 10. Schematic diagram of an erbium-doped silica-based planar waveguide amplifier [17].

With this technology, integrated-optic components can be implemented lithographically, resulting in the potential of low cost for mass production. Planar waveguides are light paths that are carefully fabricated as a region of increased refractive index within some low-loss transparent substrate material or upon such a substrate [11]. In particular, silica-on-silicon technique is very promising for integrated optics. This is because: 1) the fabrication process is cheap and compatible with that used for silicon-based microelectronics; 2) the connection to single-mode optical fibers may be achieved with low loss and cost; 3) a wide range of low-loss passive components may be easily fabricated on large substrates; and 4) some active devices such as optical amplifiers can be constructed [12].

Silica-based planar lightwave circuits (PLC's) are very suitable for integrated AO-CDM encoders and decoders because of low loss (e.g., less than 0.1 dB/cm [11]) and compactness. Moreover, they can have high reproducibility and low coupling loss to optical fibers (e.g., 0.05 dB) [12], [13]. Silica-based PLC's have been already employed as an ultrahigh-speed time multiplexer in all-optical time-division multiplexing (AO-TDM) systems with a speed up to or beyond 100 Gb/s [14]–[16]. Here we can use a similar structure, i.e., a Mach–Zehnder interferometer (MZI) chain, to design an AO-CDM encoder (or decoder) with silica-based PLC, as shown in Fig. 9. The device comprises low-loss silica waveguides and directional couplers on a silicon substrate. The difference between the proposed encoder (decoder) and the reported time multiplexer is only due to the selections of different delay times for a MZI chain. This is achieved by carefully choosing a specific length difference between two arms in each MZI.

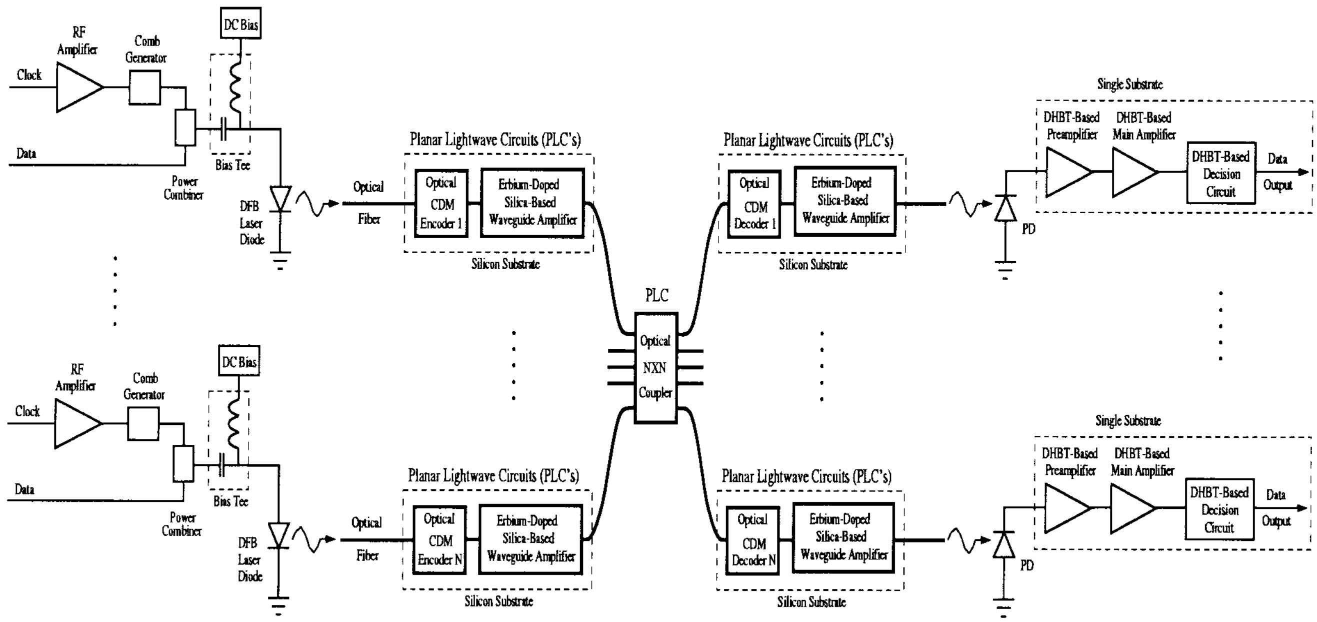


Fig. 11. Configuration of a proposed AO-CDM system using integrated optics and optoelectronic integrated circuits.

Since the use of integrated silica-based waveguides can guarantee a high precision in length control, this makes waveguide delay lines not only compact but also have a more accurate delay time compared with using their fiber-optic counterpart. For example, silica-based PLC's have achieved an accuracy of delay time being better than 15 fs [16]. This in turn can support ultrafast signal processing above 1 Tb/s. Moreover, the coupling ratios of the couplers in each MZI can be controlled by thin-film heaters [14]. In doing so, it can guarantee uniform splitting ratios for couplers, and therefore, constant-amplitude optical pulse stream can be generated. As reported in [15], the 50-Gb/s time-multiplexed optical pulse stream has been generated by using a silica-based PLC, having almost equal pulse amplitude and accurate time interval between optical pulses.

Recently, an erbium-doped silica-based planar waveguide amplifier has been demonstrated with a net gain of 27 dB, and it has been integrated with a directional coupler to multiplex the signal and pump lights [17]. In the waveguide amplifier, erbium-doped silica-based waveguides were fabricated on a silicon substrate by flame hydrolysis deposition and reactive ion etching [17], [18], as shown in Fig. 10. Moreover, with planar waveguide technology, such an erbium-doped waveguide amplifier can be further integrated with a passive AO-CDM encoder or decoder (see Fig. 9) on the same silicon substrate to make the encoder or decoder subsystem more compact and suitable for mass reproduction at low cost. Monolithic integration can also eliminate the coupling loss at each fiber-device interface. For practical applications, the input and output fibers must be connected to such silica-based PLC's in order to make the system work. Moreover, it is highly desirable that fiber-to-PLC connection should have a low cost and allow mass production. To achieve this aim, V-grooves can be used to efficiently connect PLC's to optical fibers with the potential low cost, by preferential etching and direct implementation on the silicon-supported integrated optic components [19]. It is also advantageous if the waveguide and alignment features are fabricated on a common substrate [12]. For example, fiber-to-PLC connection can be implemented by using V-grooves on the silicon substrate.

As shown in Fig. 3, all the electronic circuits at an optical transmitter can be implemented by employing mature IC techniques that have been already used in radio and wireless communications. It is because, compared with optical pulses of a few tens of picoseconds, the electrical signal which is used to gain switch the laser diode normally has a much larger pulsewidth (e.g., a few hundred picoseconds or even larger). Moreover, a laser diode can be monolithically integrated with a V-groove to enable passive alignment with the optical fiber [20]. The use of this monolithic approach can result in the reduction of assembly time and size required for pigtailed lasers. On the other hand, InP–InGaAs double-heterojunction bipolar transistors (DHBT's) can be monolithically integrated with p-i-n photodetectors to realize wide-band optical receivers that can support a transmission speed up to 40 Gb/s [21]. It is expected that either monolithic integration or hybrid integration can be applied to fabricate a high-speed optical CDM receiver containing the DHBT-based decision circuit [22]. Therefore, the configuration of the proposed AO-CDM system using integrated optics and optoelectronic integrated circuits (OEIC's) is illustrated in Fig. 11.

IV. Conclusion

In this paper, we have reported the design of new AO-CDM systems using 64-ps optical pulses and a 2^n prime code of $n = 3$. In principle, 11 users can be accommodated with data rate up to 129 Mb/s if we assume that the slot width is equal to 64 ps. This data rate can support FDDI and fast ethernet applications. Since no optical intensity modulator is required at each transmitter and only low-cost optical 2×2 couplers are used to implement the all-serial encoder–decoder, both cost- and power-effective AO-CDM systems can be realized. Furthermore, the lossless AO-CDM encoder (and decoder) can be implemented by using the silica-based PLC integrated with an erbium-doped silica waveguide amplifier of 27-dB gain [17]. This can make encoders and decoders compact. For practical applications, the input and output fibers must be connected to such silica-based PLC's. To achieve this aim, V-grooves can be used to efficiently connect PLC's to optical fibers. We have also discussed the feasibility of using integrated optics and OEIC's to implement the proposed systems. Since the use of AO-CDM systems can offer parallel communications over a common fiber channel, this in turn can support real-time computer interconnections for image and data communications.

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