Demonstration of Over 128-Gb/s-Capacity (12-User × 10.71-Gb/s/User) Asynchronous OCDMA Using FEC and AWG-Based Multiport Optical Encoder/Decoders

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***Abstract*—For the first time, an arrayed-waveguide-grating (AWG)-based multiport optical encoder/decoder (E/D) and forward-error-correction (FEC) technique are applied in an optical code-division multiple-access (OCDMA) system. The AWG-based OCDMA E/D with high power contrast ratio between auto-/cross-correlation can significantly suppress the interference noises in an asynchronous OCDMA system without using ultra-long optical codes and optical thresholder. A 12-user 10.71-Gb/s asynchronous OCDMA experiment has been successfully demonstrated to transmit ITU-T G.709 OTN frames including FEC.**

***Index Terms*—Arrayed waveguide grating (AWG), beat noise, fiber-optics communication, forward-error correction (FEC), multiple access interference (MAI), optical code-division multiple-access (OCDMA).**

I. INTRODUCTION

THE OPTICAL code-division multiple-access (OCDMA) technique is attractive for next-generation broadband access networks [1]–[3]. Recently, the coherent OCDMA technique is receiving increasing attention for the overall superior performance over incoherent OCDMA and the progress on the compact and reliable encoder/decoders (E/Ds) [4]–[7]. In these coherent OCDMA systems, an ultrashort optical pulse is either spectrally encoded time-spread by high resolution phase E/D [4] and spatial light phase modulator (SLPM) [5], [6] or directly time-spread encoded by superstructured fiber Bragg grating (SSFBG) [7].

Multiuser OCDMA networks can be grouped in two classes according to the synchronization requirement. Synchronous OCDMA operates under the best-case situation, with proper timing coordination [4]–[6]. On the other hand, asynchronous OCDMA systems should be able to operate in the worst-case scenario without any timing coordination [7]. The capability of asynchronous multiuser access is of key importance for practical applications.

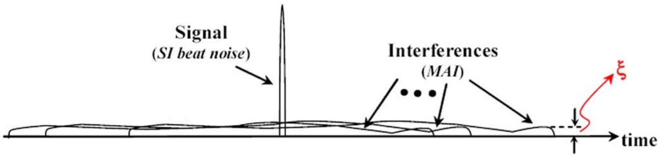

Fig. 1. Received signal and interferences in asynchronous OCDMA.

In an asynchronous, multiuser coherent OCDMA network, signal and interferences are received with random overlap as shown in Fig. 1, and the major limitations to the number of simultaneous active users are the signal-interference (SI) beat noise as well as multiple access interference (MAI) noise [3]. The MAI could be effectively eliminated by employing time gating techniques in synchronous OCDMA [4], [5]. Optical thresholding is another approach to suppress MAI that could operate in asynchronous environment [5]–[8]. However, the SI beat noise, which is predominant in coherent OCDMA systems, cannot be suppressed by these techniques [8].

Reducing the interference level ξ is an effective method to suppress both SI beat noise and MAI noise [3]. One approach is using either slot-level or chip-level timing coordination [4]–[6]. Up to 12-user 10-Gb/s/user coherent OCDMA has been achieved by using time gating, optical thresholding, as well as slot and chip-level timing coordination [5]. However, this is a synchronous approach, and in a truly asynchronous environment, it can not work even with two active users [6].

An effective approach to suppress ξ in a truly asynchronous environment is to employ ultralong optical codes (OCs) [3]. By using the record-long 511-chip 640-Gchip/s SSFBG E/D and an optical thresholder, up to 10-user asynchronous OCDMA transmission has been demonstrated at 1.25 Gb/s [7]. However, it is difficult to use ultralong code at a higher data rate since the chip rate becomes impracticably high [9]. Therefore, to enable truly asynchronous multiuser OCDMA operating at a data rate as high as 10 Gb/s is still a challenge.

In this letter, we propose a novel approach for ξ suppression by using an E/D in an arrayed-waveguide-grating (AWG) configuration, and demonstrate an asynchronous 12-user × 10.71-Gb/s OCDMA experiment with forward-error-correction (FEC) technique.

II. ENABLING TECHNIQUES

The SLPM-type E/D operates only on the phase of the optical signal, therefore, the auto- and cross-correlation signals

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Color versions of Figs. 1–6 are available online at http://ieeexplore.ieee.org.

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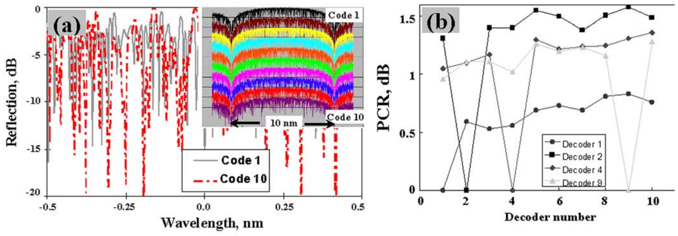

Fig. 2. (a) Spectra and (b) PCR of 511-chip SSFBG with different code.

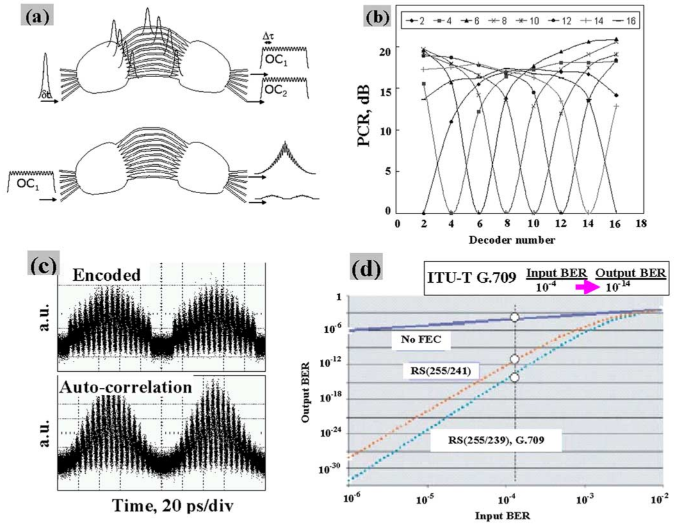

Fig. 3. (a) Architecture, (b) PCR, and (c) encoded/decoded waveforms of AWG-based multiport E/D; (d) BER performance improvement of FEC.

have equal energy [6] and their power-contrast ratio (PCR) is almost 0 dB. On the other hand, the power reflection spectra of SSFBG-type E/D with different codes have different profiles, as it is shown in Fig. 2(a), and the auto-correlation energy is larger than cross-correlation. Fig. 2(b) shows the measured PCR for the 511-chip SSFBG with average value about 1 dB.

Generally, in a coherent OCDMA, where the time-spreading factor is N ($N \approx$ length of code), the interference level is

$$\xi \approx 1/(N * \mathrm{PCR}) \tag{1}$$

As an example, to support ten active users in a coherent OCDMA network with chip-rate detection, ξ should be lower than -27 dB [3]. We need $\geqslant$500-chip OCs with PCR ≈ 0 [7]; but if PCR $= 10$ dB, a 50-chip code can work properly, and if PCR increases up to 20 dB, 5-chip codes are sufficient. Therefore, a new method to reduce ξ, without employing ultralong OC and high chip rate, is to use OCs with ultrahigh PCR.

The AWG-based multiport E/D has been proposed that is able to simultaneously generate and recognize a set of time-spread OCs in optical packet switching system [10], [11]. Fig. 3(a) illustrates the coding principle of the E/D: if a short light pulse is driven into one of the device inputs, 16 copies of the pulse are generated by the input slab coupler, with phases given by the Rowland circle configuration. The optical pulses travel different paths in the grating and the output slab coupler recombines the pulses to built 16 codes at the device outputs. Each phase shift keyed code is composed of 16 chips with the same amplitude and multiple level phases; the differential path delay in the AWG grating is 5 ps, larger than the input pulsewidth, so that the chips in the OC do not overlap and the code chip rate (and free spectral range) is 200 Gchip/s.

The recognition is performed by forwarding an OC into one of the device inputs and obtaining all correlation signals, simultaneously. The orthogonality of two codes stems from the Parseval theorem: if spectral channels do not overlap, the codes are orthogonal. In this way, we achieve very high PCR compared to other coding devices, as shown in Fig. 3(b). Codes generated at non-adjacent ports are "more orthogonal," since the crosstalk between the corresponding frequency channels is lower, and in this case, PCR can be as high as 15–20 dB, and $\boldsymbol{\xi}$ is significantly reduced. Therefore, the AWG-based OCDMA E/D can accommodate more active users at high data rate (>10 Gb/s).

Fig. 3(c) shows the waveforms of the encoded/decoded signal from the AWG E/D. Unlike the SPLM or SSFBG, the auto-correlation of AWG E/D is not with needle shape but spread in a broad (bit) duration. Therefore, optical thresholding cannot improve the performance with data-rate detection [8]. On the other hand, FEC is a very powerful technique to enhance the system performance. The International Telecommunication Union Telecommunication Standardization Sector (ITU-T) has recommended the interface for optical transport network (OTN) that consists of Reed–Solomon (RS) FEC [12]. As shown in Fig. 3(d), the RS(253, 239) FEC can improve the bit-error rate (BER) from 10^{-4} to 10^{-14} with approximately 6-dB net coding gain. Therefore, FEC can be included in OCDMA system to enhance the noise tolerance [2].

III. EXPERIMENTS AND DISCUSSION

Fig. 4 shows the experimental setup. A 10.71-GHz optical pulse stream was modulated with an OTN frame. The frame contains $2^{31} - 1$ pseudorandom bit sequence payload data and FEC parity. The optical signal was forwarded into Port 1 of the 16×16 ports, 200-Gchip/s AWG-based encoder and 16 different OCs have been generated at the 16 output ports; each code is composed of 16 chips as it is shown in Fig. 3(c). The coding loss is about 9 dB [10], [11]. These 16 signals were mixed in asynchronous manner with balanced power, random delay, random bit phase, and random polarization states emulating a 16×10.71-Gb/s asynchronous OCDMA network. The signal was then boosted and fed into Port 1 of the AWG decoder. The decoded signal from output Port 1 was sent for detection.

Fig. 5(a) shows the measured spectra of encoded (upper row) and decoded (middle row) signals with different numbers of active users (K). Fig. 5(c) shows the eye diagrams of the decoded signals at decoder Port 6 for different values of K. The measured BER performances are shown in Fig. 6. To guarantee that the system can operate in an asynchronous environment, we intentionally adjusted the PCs and tunable optical delay lines to test the system performance under the worst-case scenario in the experiment. From Fig. 6(a), up to $K = 14$ has been achieved with BER $<10^{-10}$ for decoder Port 6. However, the BER performances are not uniform for different users, and at Port 16, which is one of the worst ports, BER $<10^{-10}$ can be achieved for up to $K = 12$. This is mainly due to the nonuniformity of PCR as the result of the design and fabrication imperfectness of the AWG E/D. Fig. 6(b) shows the BER performances for four different users (decoder Ports 2, 6, 10, 16) with $K = 12$. In all these cases, BER $<10^{-10}$ has been achieved verifying that

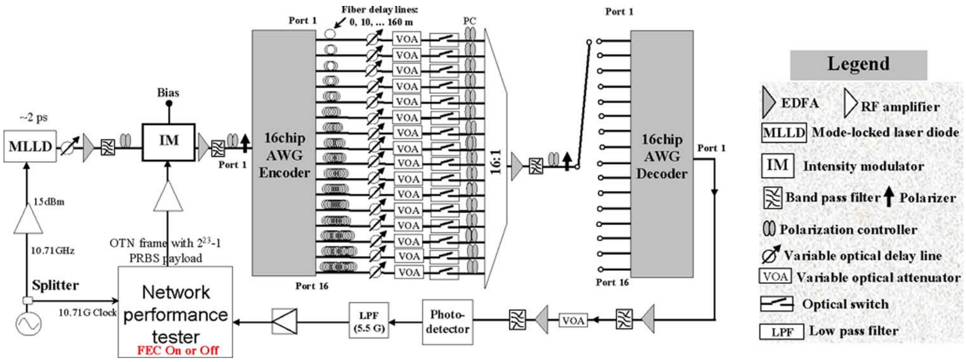

Fig. 4. Experimental setup.

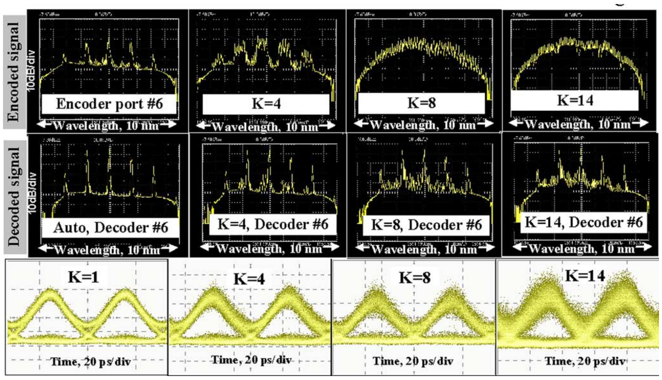

Fig. 5. Spectra of encoded (upper row) and decoded (middle) signals, and eye diagrams (lower row) of signal decoded at Port 6.

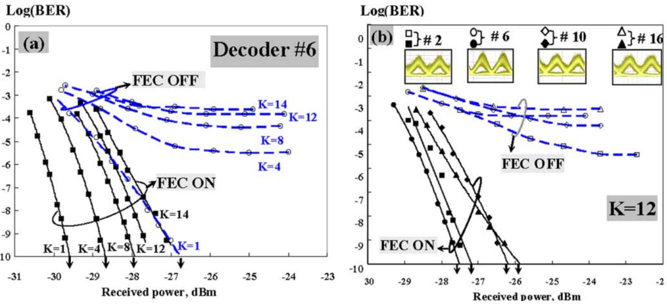

Fig. 6. Measured BERs for (a) decoder 6, (b) $K = 12$.

12 × 10.71 Gb/s has been successfully demonstrated in the experiment. The coding gain obtained in the experiment can be estimated to be larger than 5.3 dB.

IV. CONCLUSION

A new approach, which can significantly suppress the interference noises in an asynchronous OCDMA system without using ultralong OC, has been proposed by employing an AWG-based multiport E/D with high PCR. FEC has been also applied for the first time in OCDMA system. A 12-user 10.71-Gb/s asynchronous OCDMA experiment has been successfully demonstrated to transmit ITU-T G.709 OTN frames. The nonuniformity of PCR could be further improved by optimizing the design and fabrication of E/D. The frequency efficiency could reach ~0.32 in a WDM/OCDMA network [13]. Combining a larger scale AWG-based E/D with FEC, a high performance asynchronous OCDMA passive optical network could be envisioned with up to several tens active users transmitting at more than 10-Gb/s data rate.

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