Asynchronous Multiuser Coherent OCDMA System With Code-Shift-Keying and Balanced Detection

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***Abstract*—An optical code division multiple access (OCDMA) system with coherent coding, code shift keying (CSK) data modulation, and balanced detection (CSK OCDMA) is proposed and theoretically investigated in this paper. The proposed scheme has better multiuser capability, simpler threshold setting in the receiver, and particularly, enhanced security compares with conventional OCDMA systems. A multiuser CSK-OCDMA system with 511-chip superstructure fiber Bragg gratings and a multiport encoder/decoder (E/D) pair was experimentally demonstrated. A bit-error-rate of less than 10^{-9} was achieved with up to ten and eight active users at data rates of 1.25 and 10.7 Gb/s, respectively, without any forward-error-correction or optical thresholding. The multiport E/D was used in a novel configuration to process multidimensional optical codes.**

***Index Terms*—Code shift keying, Fiber Bragg grating, modulation format, multiport encoder/decoder, optical code division multiple access, optical communication networks.**

I. Background

OPTICAL CODE division multiple access (OCDMA) is one promising alternative technique to time division multiple access (TDMA), wavelength division multiple access (WDMA), and subcarrier multiple access (SCMA) for next generation flexible access networks owing to its unique features, including its ability to allow fully asynchronous transmission with low latency access, soft capacity on demand, protocol transparency, simplified network management, and increased flexibility for quality of service (QoS) control [1]–[3]. In addition, since the data are encoded using pseudorandom optical codes (OCs) during transmission, it has also the potential to enhance the security in the network [4]–[6].

Fig. 1(a) illustrates the basic architecture and the working principle of an OCDMA passive optical network (PON). In the OCDMA-PON system, data are encoded into OCs by the OCDMA encoder at the transmitter, and multiple users share the same transmission media by using different OCs. At the receiver, the OCDMA decoder recognizes the OCs by performing matched filtering; auto-correlations for target OCs produce high-level outputs, whereas cross correlations for undesired OCs produce low-level outputs. Finally, the original data is recovered after electrical thresholding.

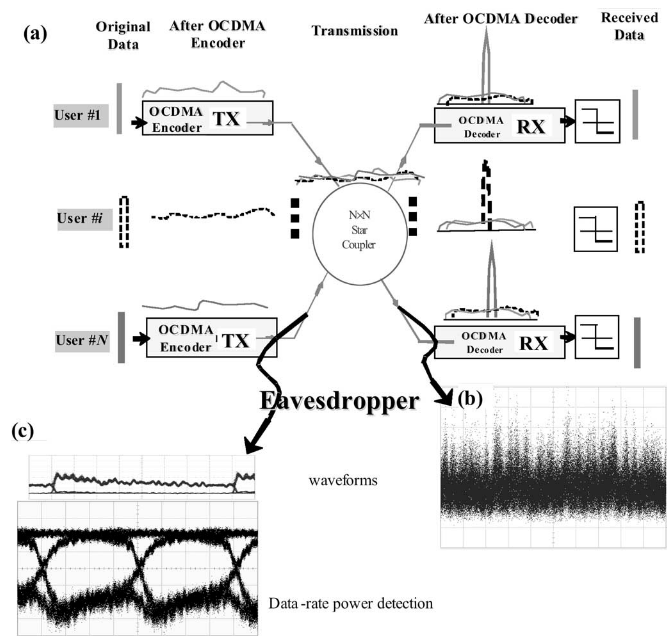

Fig. 1. (a) Working principle of an OCDMA network. (b) Waveform of signal tapped by eavesdropper after multiplexing. (c) Waveform and eye diagram of signal tapped by eavesdropper before multiplexing.

Recently, coherent OCDMA has drawn a lot of attention because of its overall superior performance over incoherent schemes due to advances in the development of compact, reliable encoder/decoders (E/Ds), such as planar lightwave circuits (PLCs), spatial lightwave phase modulators (SLPMs), superstructured fiber Bragg gratings (SSFBGs), and arrayed waveguide gratings (AWGs) [7]–[15]. In coherent OCDMA systems, an ultrashort optical pulse is either spectrally encoded time-spread (SPECTS) by a high-resolution phase E/D [8] or a spatial light phase modulator (SLPM) [9], [10], or directly time-spread encoded by SSFBG [11]–[13] or a multiport E/D with a waveguide grating configuration [14], [15]. The total throughput of asynchronous coherent time-spreading OCDMA has reached a record of 320 Gbps with more than 12 active OCDMA users and a frequency efficiency of 0.32 b/s/Hz [15], [16].

However, there are several issues with coherent OCDMA systems using an on-off-key (OOK) data format (OOK-OCDMA)

1) OOK-OCDMA with data-rate detection has very poor multiuser performance in an asynchronous environment, mainly due to the severe multiple-access-interference

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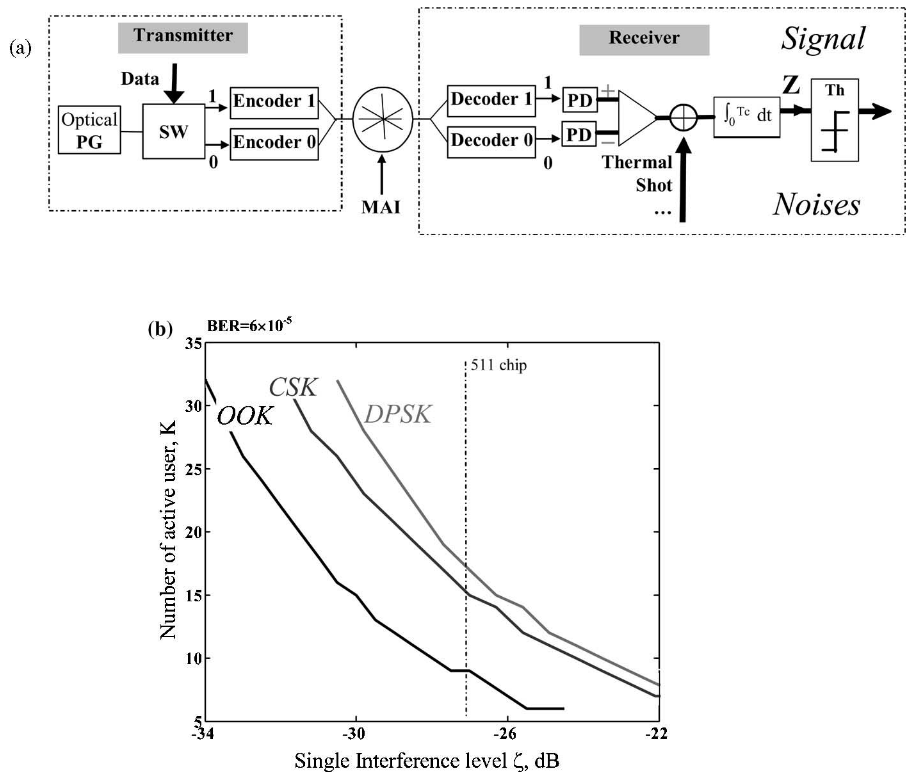

Fig. 2. (a) Proposed CSK-OCDMA scheme. (b) K versus ζ for OOK-, CSK-and DPSK-OCDMA.

(MAI) and signal-interference (SI) beat noise present in coherent OCDMA systems [3].

2) OOK-OCDMA has some security vulnerabilities. The security issues in conventional OCDMA have been brought up recently, and are now receiving increasing attention [4], [5]. Basically, the security of an OCDMA system is guaranteed only if the eavesdropper can tap into the signal from the network after the OCDMA multiplexing. As shown in Fig. 1(b), the signal is noise-like and the eavesdropper cannot decipher the signal without knowledge of the OC. However, if the eavesdropper can tap the signal before the multiplexing, as is shown in Fig. 1(c), even though the data have been encoded using pseudorandom OCs, the eavesdropper could easily break the security by simple data-rate power detection without any information about the OC.
3) The noise probability distributions for marks "1" and "0" are asymmetric in OOK-OCDMA [3], [6], [16]. Therefore, optimal bit-error-rate (BER) performance requires real-time estimation of the number (K) of active users and dynamic threshold level setting in the receiver [3], which is complicated and not cost effective.

The differential-phase-shift-keying (DPSK) data modulation format and balanced detection (BD) have been proposed in OCDMA to overcome these limitations [6], [16]. However, DPSK-OCDMA is still not sufficient to guarantee network security because an eavesdropper could still decipher the transmitted data without any knowledge of the OC, using a common DPSK decoder and a data-rate power detector.

The CSK technique has been proposed in OCDMA systems with a single detector (SD) [5] and balanced detection (BD) [17]. CSK-OCDMA with SD has been demonstrated using SLPM E/D to enhance security with respect to OOK-OCDMA [5]. CSK-OCDMA with BD has been demonstrated using a PLC en/decoder with about 3 dB sensitivity improvement compared to OOK-OCDMA, mostly due to BD [17].

In this paper, we will theoretically investigate the performance of CSK-OCDMA with BD, and we describe an experimental demonstration of an asynchronous multiuser coherent CSK-OCDMA system using 511-chip, 640-Gchip/s SSFBGs, and a multiport E/D pair in a novel configuration for multidimensional OC processing.

II. Proposed CSK-OCDMA Scheme

Fig. 2(a) schematically shows the proposed CSK-OCDMA scheme. At the transmitter side, optical pulses generated by an optical pulse generator (PG) are sent to an input port of an optical switch (SW), which is driven by binary data, so that the bits "1" and "0" go to different ports of the SW and are encoded by different OCDMA encoders, and combined again after the encoders generating the CSK-OCDMA signal. The CSK-OCDMA signals from different users are multiplexed and transmitted in the network. At the receiver side, two different OCDMA decoders decode the received bits "1" and "0," and the signals are detected at the positive and negative ports of a balanced detector, respectively

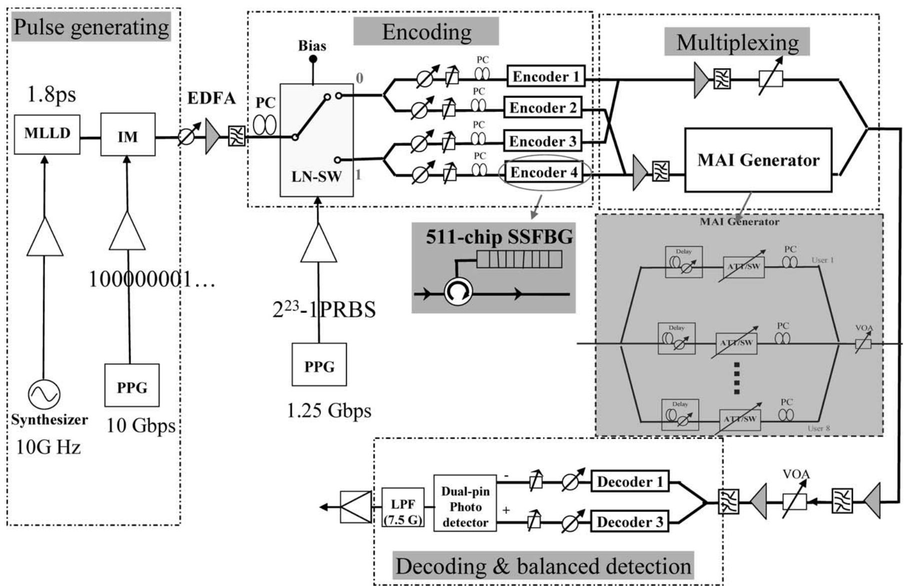

Fig. 3. Experimental setup for demonstrating coherent CSK-OCDMA using 511-chip SSFBG encoder/decoder.

Equations (1) and (2) below are the electric fields of the received signals for marks “1” and “0,” respectively.

$$
\begin{aligned}
E_1(t) =& D(t)\sqrt{P_{d1}}\exp j(\omega_{d1}t + \phi_{d1}(t)) \\
&+ \sum_{i=1}^{m} \sqrt{P_{i1}}\exp j\left(\omega_{i1}(t-\tau_{i1}) + \phi_{i1}(t-\tau_{i1})\right) \quad (1)\\
E_0(t) =& (1-D(t))\sqrt{P_{d0}}\exp j(\omega_{d0}t + \phi_{d0}(t)) \\
&+ \sum_{i=1}^{m} \sqrt{P_{i0}}\exp j\left(\omega_{i0}(t-\tau_{i0}) + \phi_{i0}(t-\tau_{i0})\right). \quad (2)
\end{aligned}
$$

In these equations, the subscripts “0” and “1” indicate the bit, and $D(t) \in \{0, 1\}$ is the value of the binary data. Similar to that discussed in [3], P_d andP_i are the optical powers of the decoded signals from the targeted (data) and untargeted users (interferers), respectively; ω_d and ω_i are their optical frequencies; ϕ_d and ϕ_i are the corresponding phase noise terms; and τ_i is the network transit delay of the interferer with respect to the data. The phase noises ϕ_d and ϕ_i are assumed to be mutually independent, Gaussian-distributed Wiener-Levy stochastic processes.

For an OCDMA system employing chip-rate detection, the output signal Z from the integrator is

$$Z = \int_0^{Tc} \Re(E_1E_1^* - E_0E_0^*)dt + \int_0^{Tc} n_0(t)dt. \quad (3)$$

For an ideal CSK-OCDMA system, $P_{d0} = P_{d1} = P_d, \omega_{d0} = \omega_{d1} = \omega_d$, and Z could be simplified as

$$
\begin{aligned}
Z =& (2D(t)-1)T_c\Re P_d + (MAI_1 - MAI_0) + (SIBN_1 \\
&- SIBN_0) + (IIBN_1 - IIBN_0) + \int_0^{Tc} n_0(t)dt. \quad (4)
\end{aligned}
$$

Here, T_C is the chip duration; $\Re$ is the responsivity of the photo-detector; and MAI, $SIBN$, and $IIBN$ are terms for MAI, signal-interference, and interference-interference beat noises, respectively. Their expressions are the same as those in equation (2) of reference [3]. Assuming that MAI_1, $SIBN_1$, and $IIBN_1$ are independent random variables with respect to MAI_0, $SIBN_0$, and $IIBN_0$, the total noise variance in CSK-OCDMA is twice as high as that in OOK-OCDMA.

Fig. 2(b) shows the maximum number of active users (K) with a BER of 6×10^{-5} versus single interference level ζ. Compared to OOK-OCDMA, CSK-OCDMA can tolerate a ζ more than 3 dB higher for a given value of K, whereas DPSK-OCDMA can tolerate a ζ up to 1 dB higher than CSK-OCDMA. Therefore, the multiuser capability in CSK-OCDMA is improved with respect to OOK-OCDMA, and is slightly decreased with respect to DPSK-OCDMA. The requirement for real-time K estimation and dynamic threshold level setting can also be relaxed in the proposed CSK-OCDMA scheme, in the same way as in the DPSK-OCDMA with balanced detection [6]. And more importantly, the security can be significantly improved in the CSK-OCDMA system because an eavesdropper cannot decipher the signal without knowing the OCs [4]–[6].

III. Demonstration of CSK-OCDMA With SSFBG Encoder/Decoder

We experimentally demonstrated the proposed CSK-OCDMA scheme using an SSFBG E/D, and compare it to OOK-OCDMA. Fig. 3 shows the experimental setup. In the pulse generation section, a 1.25-GHz optical pulse train with $\sim$ 1.8-ps pulsewidth was generated by a mode-locked laser diode (MLLD) and an intensity modulator (IM). In the encoding section, a lithium niobate optical switch (LN-SW) was driven

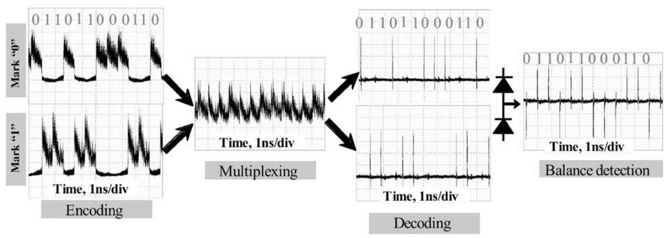

Fig. 4. Waveforms of fixed pattern signals in the system after encoding, multiplexing, decoding, and balanced detection.

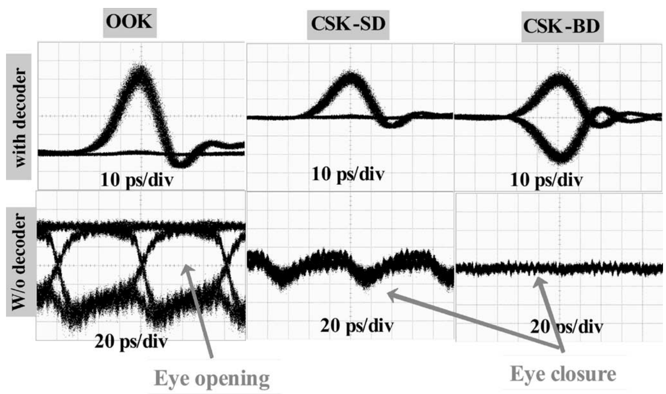

Fig. 5 Eyedigrams for OOK- and CSK-OCDMA with SD and BD.

by a $2^{23} - 1$ pseudo random bit sequence (PRBS) at a data rate of 1.25 Gb/s. For CSK data modulation, the upper and lower output ports represented the bits "0" and "1," respectively, whereas only the lower output port was used for OOK data modulation. In the experiment, both the encoders and decoders were 511-chip, 640-Gchip/s SSFBGs [12], [13]. Encoders 1 and 3 were used for the targeted user in CSK-OCDMA, representing bits "0" and "1," respectively; encoders 2 and 4 were used for the untargeted user (interferer). On the other hand, for OOK-OCDMA, encoders 3 and 4 were used for the targeted user and the interferer, respectively. In the following multiplexing section, the encoded signals were combined into two paths: the upper path was for the targeted user and the lower one was constructed as an MAI generator, as shown in the inset, to emulate up to 15 interferers. Tunable attenuators, fixed and tunable optical delay lines, and polarization controllers were used to test the performance in a truly asynchronous environment, as has been done in previous experiments [15], [16], [18].

Fig. 4 shows the waveforms of CSK-OCDMA signals with a fixed data pattern after encoding, multiplexing, decoding, and balanced detection, respectively. The eye diagrams of OOK-OCDMA and CSK-OCDMA with SD and BD are compared in Fig. 5. The upper row in Fig. 5 shows the correctly decoded signals for single user transmission. The lower row shows the encoded signals detected by the photodetector without any decoding process (data-rate power detection). The opening and closing of the eye clearly show that an eavesdropper could easily break the network security in OOK-OCDMA without any knowledge of the OC, in contrast, CSK-OCDMA showed enhanced security.

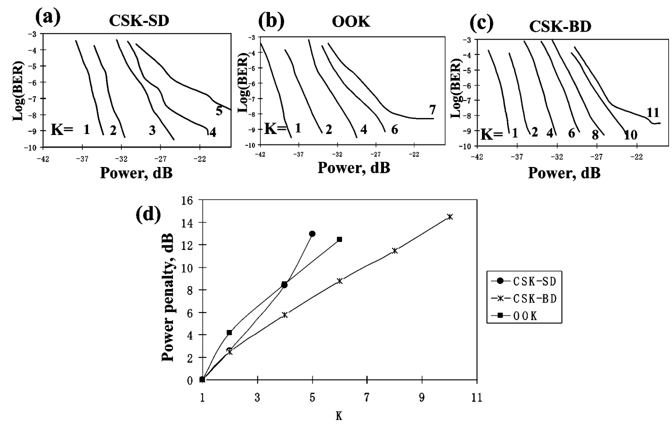

Fig. 6. BER performances of (a) CSK-OCDMA with SD. (b) OOK-OCDMA. (c) CSK-OCDMA with BD. (d) Power penalty versus number of active users K.

Fig. 6(a)–(c) shows the BER performances of these three schemes for different numbers of active users (K) and Fig. 6(d) shows the power penalty versus K. For OOK-OCDMA, a BER of less than 10^{-9} was achieved for up to six active users, which is the same result as we obtained in a previous study [18]. For CSK-OCDMA with SD, a BER of less than 10^{-9} was achieved with at most four active users. This poor performance is mainly due to the much higher interference level in CSK-OCDMA than in OOK-OCDMA, because in this case optical signals were transmitted for both bits "0" and "1". However, for CSK-OCDMA with BD, this number was significantly improved to ten, which is mainly attributed to the higher noise tolerance of the BD scheme. Compared with the previous results obtained with the same SSFBG E/Ds, the performance of CSK-OCDMA was similar to that of an OOK-OCDMA system with optical thresholding [18]. We can conclude that CSK-OCDMA with BD had significantly improved multiuser capability, compared to the other two schemes studied in this experiment.

IV. Demonstration of Multiuser CSK-OCDMA With Multiport Encoder/Decoder for Multidimensional Optical Code Processing

In a recent work, an AWG-based multiport E/D [14] has been successfully used in asynchronous multiuser OCDMA experiments with OOK or DPSK data formats; the main advantage of this E/D over an SSFBG E/D is the unique feature of having a very high power contrast ratio (PCR) [15], [16]. Another important feature of this device, which makes it very promising for CSK-OCDMA, is the ability to simultaneously process a set of time-spread optical codes (OCs) [19]. Fig. 7 shows the proposed novel configuration in which different input ports of a multiport E/D are used to process multidimensional OCs in a CSK-OCDMA system. In contrast to the configuration in [19], where *different* OCs were generated using different wavelengths to avoid mutual beat noise, in CSK-OCDMA, different OCs (represented by marks "0" and "1," respectively) never overlap with each other, so all of the OCs can use the same wavelength without worrying about mutual beating.

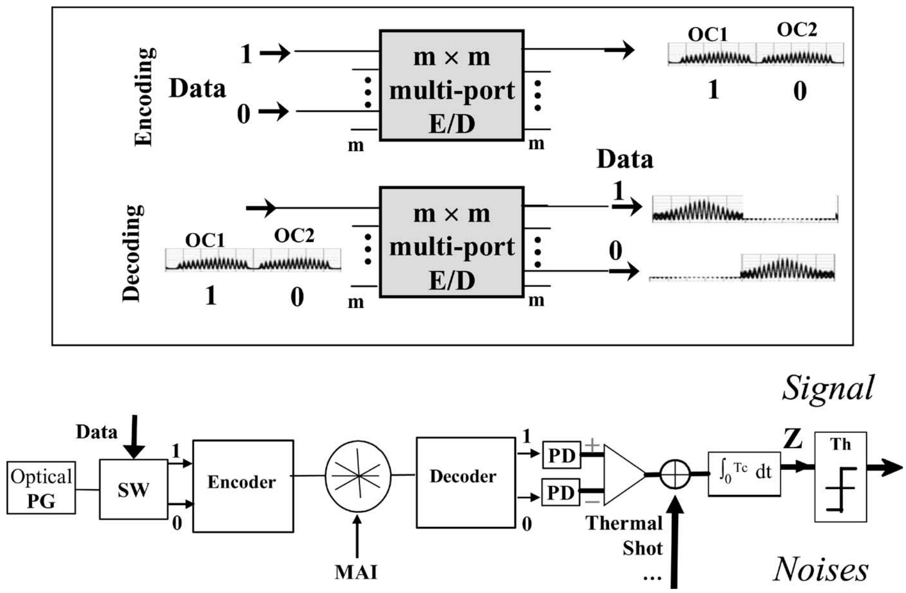

Fig. 7. Multiports E/D for multidimensional OC processing.

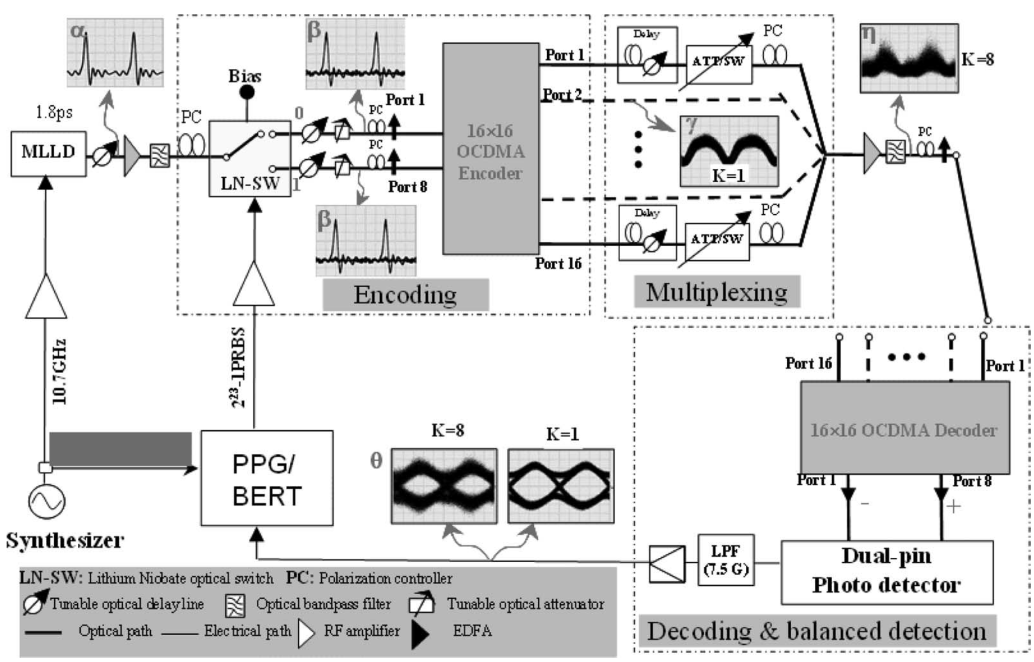

Fig. 8. Experimental setup.

Fig. 8 shows the experimental setup, and the insets are the eye diagrams measured at different points. The MLLD generated a 1.8-ps optical pulse train with a 10.7-GHz repetition rate. The LN-SW was driven by 10.7-Gbps $2^{23} - 1$ PRBS data. The signals from the upper and lower output ports of the LN-SW, which represent bits "0" and "1," respectively, were then forwarded to ports 1 and 8 of the 16×16-ports encoder to generate 16-chip, 200-gigachip/s OCs [14]. Inset γ is the eye diagram of the generated CSK-OCDMA signal. It contains two different codes with equal energy; therefore, the security is enhanced with respect to OOK-OCDMA [4], [5]. Sixteen different CSK-OCDMA signals were generated at the 16 encoder output ports, and were then mixed in a truly-asynchronous manner with balanced powers, random delays, random bit phases, and random polarization states [15], [16]. Inset η shows the eye diagram of the multiplexed signals of eight CSK-OCDMA users $(K = 8)$. Fig. 9(a) and (b) are the waveforms of encoded signals from output port 1 for bits "1" and "0," respectively, measured by an optical sampling oscilloscope with a bandwidth of about 500-GHz. Fig. 9(c) shows the waveforms of CSK-OCDMA

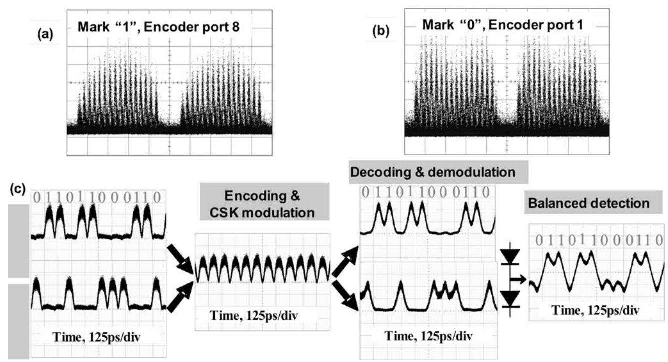

Fig. 9. Waveforms of different signals in the system. (a) and (b) Measured by ~ 500 GHz optical sampling oscilloscope. (c) Measured by ~ 30-GHz oscilloscope.

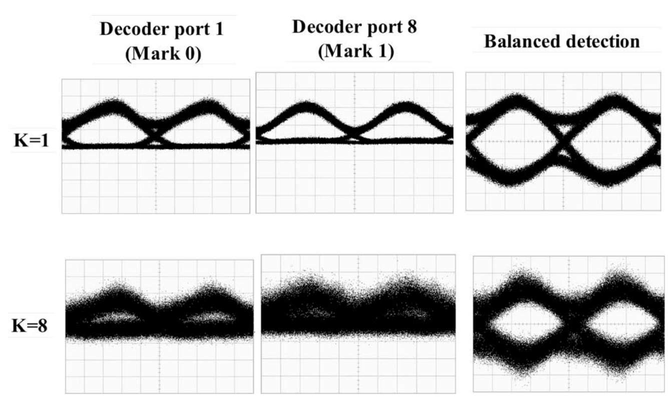

Fig. 10. Eye diagrams of the received signals with different K.

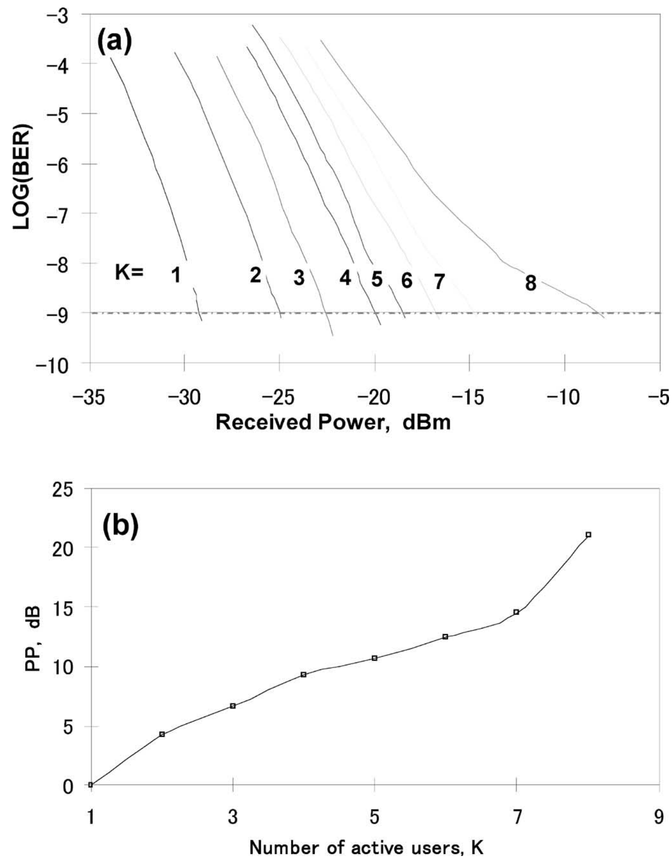

Fig. 11. BER performances.

signals with a fixed data pattern after encoding, multiplexing, decoding, and balanced detection measured by an oscilloscope and a ~ 30 GHz PD.

At the receiver, a multiport decoder performed multidimensional OC recognition signals from output ports 1 and 8 were decoded for bits "0" and "1," respectively. The decoded signals were detected by a balanced detector followed by a low-pass filter with 7.9-GHz cutoff frequency to perform data-rate detection. Fig. 10 shows the measured eye diagrams with SD and BD for $K = 1$ and 8. The multiport E/D performed the multidimensional OC processing with a very high contrast ratio and good uniformity, guaranteeing that the CSK-OCDMA system worked properly.

Fig. 11(a) shows the measured BER performance versus the received optical power for different K values. A BER of less than 10^{-9} was achieved with up to eight active users without using forward-errorcorrection (FEC) and optical thresholding. Fig. 11(b) shows the power penalty versus K at a BER of 10^{-9}. This result is much better than in OOK-OCDMA, where asynchronous multiuser OCDMA transmission was assisted by FEC [15] or optical thresholding [18]. DPSK-OCDMA has shown better performance in experiments to transmit data for up to 12 active users ($K = 12$) at a BERof less than 10^{-9} [15], [16]; this result is in full agreement with the theoretical predictions of Section II. In the new configuration using a multiport E/D for multidimensional OC processing, the cross correlation level was relatively higher than in the standard configuration [14] because two different input ports were simultaneously used. Although this effect degraded the BER performance in the experiment, it can be further improved by using a larger scale multiport E/D. In addition, the poor extinction ratio of the SW also degraded the system performance.

V. Conclusion

We investigated the CSK-OCDMA scheme with coherent coding, CSK data modulation, and balanced detection. The proposed scheme had better multiuser capability and simpler threshold setting in the receiver than OOK-OCDMA. In particular, CSK-OCDMA had superior security to both OOK- and DPSK-OCDMA, which makes it an attractive candidate for secure transmission systems.

We experimentally demonstrated asynchronous multiuser CSK-OCDMA transmission with a 511-chip SSFBG and achieved a BER of less than $10^{-9}$with up to ten active users at 1.25 Gb/s. This level of performance can only be achieved in OOK-OCDMA systems by using optical thresholding.

We also experimentally demonstrated a multiuser CSK-OCDMA system with a single multiport E/D in a novel 3-D configuration. This device is attractive for CSK-OCDMA because of its high PCR, and ability to process multidimensional OCs with a single device. A BER of less than 10^{-9} was achieved with up to eight active users at a data rate of 10.7 Gb/s.

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