Tb/s Coherent Optical OFDM Systems Enabled by Optical Frequency Combs

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***Abstract*—This paper discusses the realization of terabit per second high speed and high spectral-efficiency optical transmissions using much lower speed electronics and optoelectronics through parallel processing of coherent optical frequency combs at both the transmitter and receiver. The coherent and parallel processing enables electrical-to-optical and optical-to-electrical (E/O and O/E) conversion of wide-bandwidth optical signals which would otherwise exceeds the capability of conventional optoelectronics. In the first experiment, an optical frequency comb (OFC) generator provides 32 comb lines with less than 5-dB power variation. Subsequently, 1.008-Tb/s modulation capability is realized on 32 $\times$ 106 OFDM subcarriers with 16-QAM modulation in a 318-GHz seamless optical bandwidth. It demonstrates an effective way to generate an optical OFDM signal with tens of times wider optical bandwidth than that of analog-to-digital converters and digital-to-analog converters (ADC/DAC). The second experiment demonstrates simultaneous detection of multiple OFDM bands from a 32-band coherent optical OFDM signal using another optical frequency comb, a silica planar lightwave circuit (PLC) that implemented the major optical devices, and two pairs of balanced photodiodes. The experimental results indicate prospects for an optically integrated coherent optical OFDM system on a chip-scale platform.**

***Index Terms*—Coherent communication, modulation format, OFDM, optical frequency comb, signal processing.**

I. Introduction

TERABIT/s optical transmissions are readily available through conventional wavelength-division multiplexing (WDM). However, the spectral efficiency of such a WDM system is far below the Shannon limit, primarily due to the optical frequency gap that needs to be placed between the wavelengths. Alternatively, it is attractive to transmit Tb/s data by modulating a single laser source instead of multiple WDM lasers, and to possibly achieve high spectral efficiency from a simpler system configuration. To date, there have only been a few experimental demonstrations of Tb/s data transmissions using a single laser source, and they have all involved multiplexing the lower speed electronic signals ($<$ 100 Gb/s) to Tb/s optical signals, either in the time domain [1] or in the frequency domain [2], [3]. Recently, the availability of analog-to-digital converters and digital-to-analog converters (ADC/DAC) with greater than 10 GSample/s has enabled direct generation and detection of optical orthogonal frequency division multiplexing (OFDM) signals of less than 40 Gb/s [4], [5] and other techniques can be introduced for higher bit rates on a single laser line, e.g., RF multiplexing [6] and optical polarization multiplexing [6], [7]. In particular, multi-band coherent optical OFDM (CO-OFDM) systems have been demonstrated to generate high-speed signals from 100 Gb/s [8], [9] up to 10 Tb/s [10]. Since the comb lines of optical frequency combs are coherent to each other, it is possible to generate a seamless and wide bandwidth optical OFDM signal, which involves two steps: (i) electro-optical generation of lower speed optical OFDM signals on individual comb lines and (ii) coherent and orthogonal optical frequency multiplexing of the OFDM modulated comb lines. The second step provides an effective way to avoid the electronic bottleneck caused by the limited DAC speed.

This paper presents the architecture of Tb/s coherent optical OFDM systems using optical frequency combs at both the transmitter and receiver. The experiment exploits an optical frequency comb generating 32 comb lines with less than 5 dB power variation across the comb. The comb lines carry 1.008 Tb/s on 32 $\times$ 106 OFDM subcarriers with 16-QAM modulation in a 318-GHz seamless optical bandwidth, corresponding to a spectral efficiency of 3.17 b/s/Hz on a single polarization. This demonstrates an effective way to generate an optical signal with tens of times wider bandwidth than that of the ADC/DAC. So far, the experimental detection of such signals were performed on per OFDM band basis, either using a sweeping local coherent receiver [8] or an optical fast-Fourier transform (FFT) receiver [10]. Using an optical frequency comb at the receiver facilitates parallel coherent detection of multi-band OFDM signals by providing multiple comb lines as local lasers. However, the parallel structure needs many sets of optics and electronics for tens of OFDM bands, thus optical integration becomes critically important. The second experiment presents a receiver which uses a silica planar lightwave circuit (PLC) that implements the major passive optical devices for the optical slicing of multiple OFDM bands and the local optical frequency comb [11]. Using an optical frequency comb in the receiver also facilitates electrical spectrum synthesis of the wideband and seamless optical OFDM signal.

The remainder of this paper is organized into three sections. Section II presents the architecture and features of Tb/s coherent optical OFDM systems using optical frequency combs.

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Section III provides the proof-of-principle experiment for the generation, transmission and detection of the 1.008 Tb/s optical OFDM signal, and Section IV shows the simultaneous detection of multiple OFDM bands (within 79.5 GHz bandwidth) using another optical frequency comb, a silica PLC circuit, and two pairs of balanced photodiodes.

II. Tb/s Coherent Optical OFDM Systems Using Optical Frequency Combs

An optical frequency comb is a large number of precisely spaced spectral lines. It is desirable to have a flat optical frequency comb with independent adjustment of center wavelength and comb spacing [12], [13]. In general, there are two approaches for optical frequency comb generation: mode-locked lasers [10], [14] and strong E/O modulation on a continuous-wave (CW) laser [12], [13]. The former approach has been demonstrated for 10-Tb/s signal generation [10]. This paper chooses the latter because it can independently configure the comb center frequency and comb frequency spacing. This method is capable of generation of more than 30 comb lines [2], [13] and therefore it enables the Tb/s signal generation in Section III, which is ten times faster than the previous report [8].

Fig. 1 shows the architecture of Tb/s coherent optical OFDM systems using optical frequency combs. At the transmitter side, the comb generator converts a single laser line to multiple comb lines, which are inherently coherent with each other. This coherent characteristic facilitates optical OFDM generation across the entire bandwidth of the multiple comb lines. The comb lines pass through a spectral demultiplexer (demux), optical in-phase/quadrature (IQ) modulators, and a spectral multiplexer (mux) for the data encoding on individual comb lines. The optical IQ modulators may include the power equalization of comb lines with proper power level controls of RF driving signals, or may be followed by tunable optical attenuators to equalize the power of individual comb lines. The subsequent broad optical signal can be seamless if the frequency spacing of the comb lines is an integral multiple of the OFDM subcarrier spacing and therefore all of the OFDM subcarrier from different comb lines are orthogonal to each other [8]. This is readily achievable once the comb generator and OFDM modulators are frequency synchronized. Therefore, the inherently coherent comb lines enable the generation of much wider bandwidth optical OFDM signals than that of the state-of-the-art ADC/DAC and optoelectronics. This method resembles the RF OFDM generation using oscillator banks and filter banks which were used before the introduction of FFT/IFFT using digital signal processing (DSP) [15], [16]. The optical frequency comb replaces the usual bank of lasers, not only reducing the cost but also maintaining the coherence among the comb lines. In principle, since the optical frequency comb consists of orthogonal comb lines, this transmitter structure will still generate an optical OFDM signal regardless of the modulation format on individual comb lines [10]. However, using OFDM modulation on every comb line enables the system to mitigate fiber dispersion impairments using a reasonable amount of overhead [17]. For convenience, comb lines after OFDM modulation are called OFDM bands.

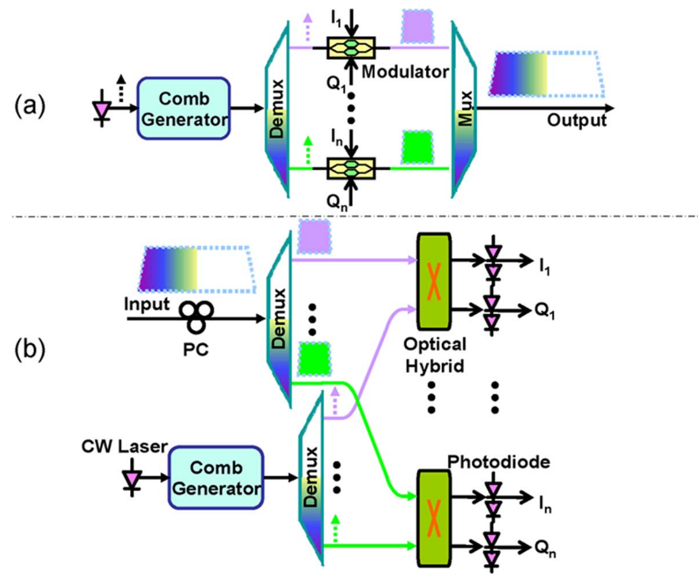

Fig. 1. (a) Transmitter and (b) receiver of Tb/s coherent optical OFDM systems using optical frequency combs. Dashed arrows and boxes illustrate the optical spectra at various stages. PC: polarization controller.

Fig. 1(b) shows that a separate optical frequency comb and the coherent optical OFDM signal go through respective demuxes, so that each spectral slice of the OFDM signal and its corresponding comb line are directed to the optical hybrid for coherent detection in parallel. A polarization controller aligns the polarization states of the incoming signal and the local optical frequency comb. After the optical hybrid, balanced photodiodes down-convert the optical signals to the electrical domain, where conventional RF OFDM receiver units, including ADCs and DSP, recover the transmitted data. While the majority of the DSP is similar to the well-known RF and optical OFDM receiver, some additional signal processing is included to handle the optical spectrum slicing.

The key feature of the receiver architecture is the O/E conversion of very wideband or high-speed signals via optical spectrum slicing and electronic spectrum synthesis. Based on Fig. 1(b), Fig. 2 further illustrates this feature for O/E conversion of three comb lines with OFDM modulation. Optical spectrum slicing is achieved primarily by the demux and secondarily by electrical antialiasing filters that can have much sharper frequency responses (edges) than the optical demuxes. Here, unlike conventional WDM systems which require frequency guard bands, the multiplexer at the transmitter and the demux at the receiver for the optical OFDM signal need to be gapless or strongly overlapping [2], [18], to pass all of the spectral components. As Fig. 2(a) indicates, the frequency components of the three OFDM bands are seamless. Each demultiplexed OFDM band has unwanted frequency components at the slice edges from the neighboring OFDM bands, e.g., the dashed frequency components in Fig. 2(b). In a carefully designed system, these frequency components are still orthogonal to the demultiplexed OFDM band and consequently cause no interference. The utilization of an optical frequency comb in place of multiple local lasers guarantees that the phase relationship among optical spectral slices is preserved after

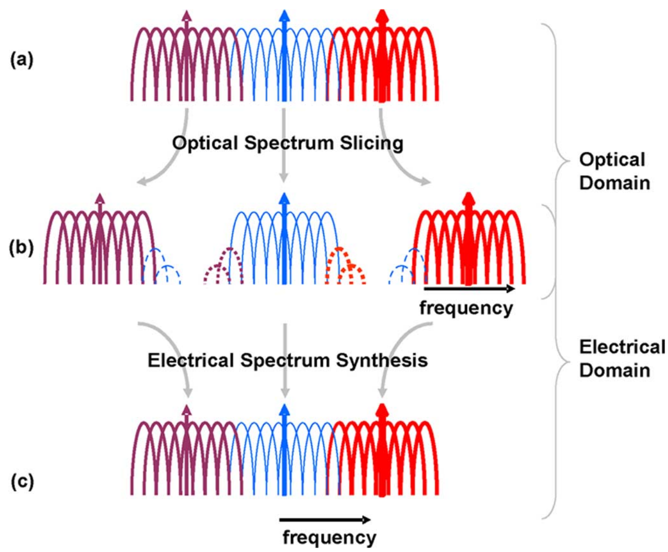

Fig. 2. Optical-to-electrical conversion of three OFDM bands via optical spectrum slicing and electrical spectrum synthesis. (a) The three OFDM bands in the optical domain; (b) OFDM bands after gapless optical spectrum slicing; (c) The three OFDM bands in the electrical domain after electrical spectrum synthesis. The arrows stand for the position of the comb lines. The dashed spectral components are eliminated through electrical spectrum synthesis.

O/E conversion. For these two reasons, the DSP can eliminate the unwanted frequency components in the frequency domain and can stitch the spectra of multiple OFDM bands together to recover the original data (referred to as electrical spectrum synthesis). From this perspective, the receiver structure is similar to the frequency interleaved ADC [19] and a photonic sampled and demuxed ADC [20], since the optical frequency comb is the optical sampling pulse source in the time domain. The report in [11], [18] demonstrated the real-time measurement of 160-GHz wide arbitrary optical signals. In comparison, Section IV will show that optical OFDM signals have a less stringent requirement on the frequency response of the receiver structure since OFDM is resilient to the irregularity/distortion in the frequency domain.

In Fig. 1, the Tb/s capability requires an array of optical devices, DACs/ADCs and DSPs for parallel processing. The feasibility relies on optical and electrical integration. In fact, a chip-scale device with a configuration very similar to Fig. 1(a) has shown the capability of manipulation of individual comb lines for optical arbitrary waveform generation [2], [21], [22]. Already a chip-scale device has implemented all the required demuxes and optical hybrids in Fig. 1(b), which is detailed in the other reports for optical arbitrary waveform measurement (OAWM) [18], [11]. The experiment in Section IV employs the identical chip in a coherent optical OFDM receiver.

To reach 1 Tb/s, there are several variations which incorporate a different number of the comb lines and different modulation formats to generate the OFDM signal. The experiment in Section III employs 32 comb lines and 16-QAM modulation on a single polarization for an effective data rate of 1.008 Tb/s. Another variation is 16 comb lines with polarization multiplexed 16-QAM modulation to double the spectral efficiency. It is also possible to achieve greater than Tb/s capacity with more

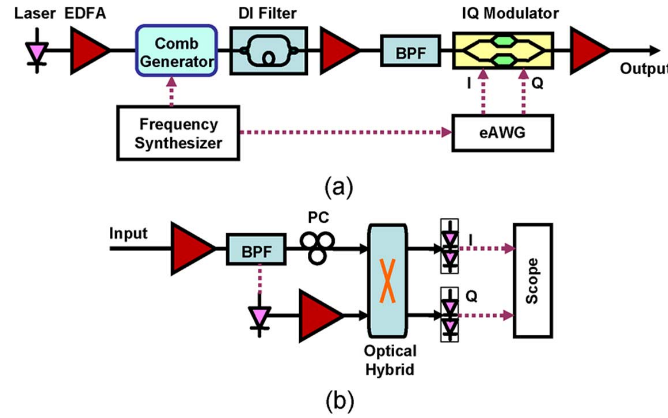

Fig. 3. (a) Transmitter and (b) receiver setup of Tb/s coherent optical OFDM. DI: delay interferometer; PC: polarization controller; BPF: bandpass filter; eAWG: electrical arbitrary waveform generator. EDFA: erbium-doped fiber amplifier. Dashed lines are electrical connections.

comb lines or higher order modulation formats. These variations are subject to system tradeoffs between performance and complexity.

III. Experimental Results and Discussions of 1.008-Tb/s Coherent Optical OFDM

Implementation of the architecture in Fig. 1 requires either many discrete components or photonic integrated circuits. This Section provides a proof-of-concept experiment where one optical IQ modulator modulates all of the comb lines and a combination of a tunable filter and a tunable laser steps through and detects each OFDM band.

A. Experimental Details

Fig. 3 shows the experimental arrangement. In the transmitter, an optical frequency comb generator modulates a single-frequency laser (less than 100-kHz linewidth) with strong amplitude and phase modulation to generate an optical frequency comb with a frequency spacing of 9.9375 GHz, controlled by a frequency synthesizer [2]. Fig. 4(a) shows the measured optical spectrum that exhibits more than 32 comb lines. Between the comb lines, there are unintended spectral spurs due to the imperfection of the comb generator. Fig. 4(b) shows the spectrum after a 10-GHz delay-interferometer periodic filter (DI filter) partially suppressed the energy between the comb lines. It is not necessary to use the DI filter for the architecture in Fig. 1(a), where the demux can have high isolation [18] and filter out the unintended spectral lines. The spectrum in Fig. 4(b) also illustrates the set of 32 comb lines with a power variation of less than 5 dB obtained after filtering with an approximately 310-GHz bandpass optical filter with sharp edges (only a −20 dBc spur remains at each end of the spectrum). An electrical arbitrary waveform generator (eAWG) operating at 12 GSample/s operates as the DAC, and drives an optical IQ modulator to encode all the comb lines simultaneously with 16-QAM OFDM. There are three erbium-doped fiber amplifiers (EDFAs) in the transmitter to compensate for the loss of the comb generator, the optical filters, and the optical IQ modulator. The OFDM symbol is from a 128-point long FFT and 106 subcarriers are used to

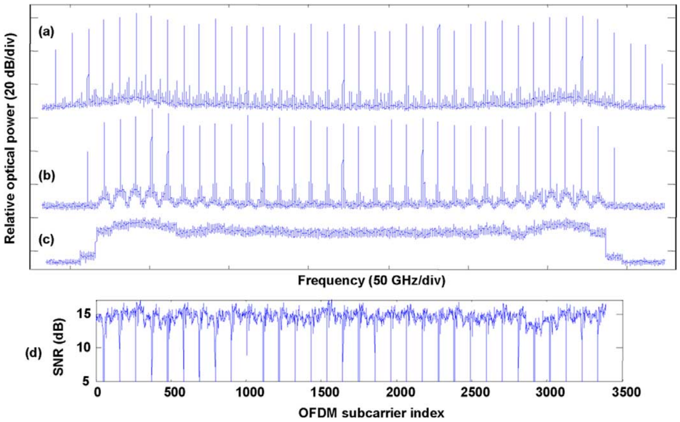

Fig. 4. High-resolution optical spectra of (a) after the comb generator, (b) after the DI filter and the bandpass filter with sharp edges, and (c) the generated 1.008-Tb/s optical OFDM signal. The spectra's vertical-axes are shifted for display and they are measured by the swept coherent heterodyne method with a resolution of 100 MHz. (d) The estimated electrical SNR performance for all the OFDM subcarriers. The comb lines in (a) and (b) are aligned with the SNR dips in (d).

carry the pilot and data information. The cyclic prefix is 1/16 of the FFT length. After the conventional OFDM transmitter signal processing, there are additional procedures to compensate for the imperfections of the transmitter hardware, e.g., the non-flat E/O response of the optical IQ modulator and the length mismatch between I and Q paths. Fig. 4(c) depicts the optical spectrum after the OFDM modulation. Since the eAWG and the frequency synthesizer are synchronized and the comb line spacing is configured according to the OFDM parameters (i.e., the comb line spacing is 106 times of OFDM subcarrier spacing), all of the OFDM subcarriers from different OFDM bands are orthogonal to each other. Fig. 4(c) shows the seamless 32×106 subcarriers within the 318-GHz optical bandwidth. This demonstrates an effective way to generate a tens of times wider bandwidth optical signal than that is possible using direct modulation on a single laser. Compared with the transmitter architecture in Fig. 1(a), the experimental transmitter in Fig. 3(a) cannot control the power of individual comb lines and encode independent data onto different comb lines. However, it does not compromise the subsequent bit-error-ratio (BER) investigation, because it represents a worse-case scenario in terms of power variation and the peak-to-average ratio (PAR) of the generated wideband OFDM signals [8].

Fig. 3(b) shows the receiver setup. The received signal passes through an EDFA to compensate for loss and then a 0.32-nm wide bandpass filter. A tunable laser followed by another EDFA acts as the local oscillator for the coherent detection of every OFDM band. The 0.32-nm bandwidth includes at least four OFDM bands and there is additional self-mixing noise in the photodiodes from those OFDM bands. Consequently, at the optical hybrid output, the power of the local laser is at least 15 dB larger than the data signal, which improves suppression of the self-mixing noise. Two pairs of balanced photodiodes perform O/E conversion and provide two RF signals to a real-time sampling oscilloscope. The total power into each photodiode is approximately 3 dBm. There are 5-GHz antialiasing low-pass filters at the output of the eAWG and at the input of the oscilloscope, respectively, to suppress the crosstalk between the OFDM bands. The sampling rate of the oscilloscope is 50-GSample/s in this experiment. A computer loads the sampled sequences from the oscilloscope and performs the DSP as detailed in [8], [23]. For the 106 OFDM subcarriers in each OFDM band, 96 are used for the BER calculation, and 6 for the pilot-aided phase estimation [23]. The laser sources in the setup have some frequency jitter, and therefore the four lowest frequency subcarriers near dc are not used to avoid the dc-leakage problem. The total effective bit rate after considering the 7% Reed–Solomon forward-error correction (FEC) overhead is 1.008 Tb/s with a spectral efficiency of 3.17 b/s/Hz without polarization multiplexing. Fig. 4(d) shows the signal-to-noise ratio (SNR) estimation across all of the OFDM subcarriers following the procedure in [5], [24]. The SNR dips are a manifestation of the dc-leakage at every comb line position and may be mitigated by using optical hybrids with more accurate splitting ratios and phase shifts and more closely matched balanced photodiodes. These SNR dips indicate that the OFDM subcarriers close to dc have poorer performance and may not be used to carry data information. Fig. 4(d) also shows that there is no significant performance degradation for the subcarriers at the edge of each OFDM band, even though they are adjacent to the subcarriers from the neighboring OFDM bands. This clearly demonstrates the orthogonality between the OFDM bands.

B. BER Measurement Results

Fig. 5 shows the BER performance of the optical back-to-back transmission. The three BER curves in Fig. 5(a) are based on single laser line/OFDM band without optical frequency comb generation. These measurements help to determine the minimum ADC sampling rate and clock synchronization between the DAC and ADC. Each OFDM band occupies 9.9375-GHz optical bandwidth, therefore a 12.5 GSample/s quadrature ADC sampling rate is sufficient. However, Fig. 5(a) shows that there is approximately 1-dB sensitivity difference between the 12.5-GSample/s and the 50-GSample/s sampling rates, possibly resulting from the antialiasing filters. This work uses a 50-GSample/s sampling rate for a better performance and applications sensitive to cost may use the lower sampling rate. In field applications, a clock connection between the DAC at the transmitter and the ADC at the receiver does not exist. Therefore, the receiver DSP must track the clock from the detected signal and feed it back to the ADC. The experiment utilized improved pilot-aided phase estimations according to the method in [25]. The six pilot subcarriers are simultaneously used for laser phase noise estimation and ADC sample rate tracking. To prove the effectiveness of the enhanced method, the sampling rate of eAWG is intentionally set to 11.999 GSample/s. The BER curves in Fig. 5(a) shows no performance degradation without clock synchronization between DAC and ADC. The length of OFDM symbol will affect the effectiveness of this method [25]. Therefore, for the BER measurement in

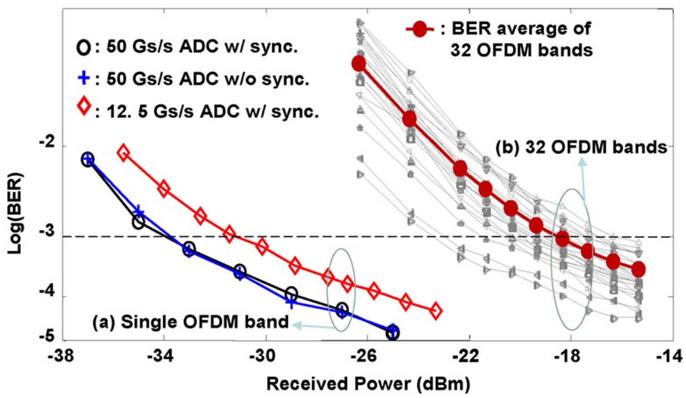

Fig. 5. Optical back-to-back BER measurements for (a) single OFDM band, (b) 32 OFDM bands. The gray and thin curves are the BER of individual OFDM bands.

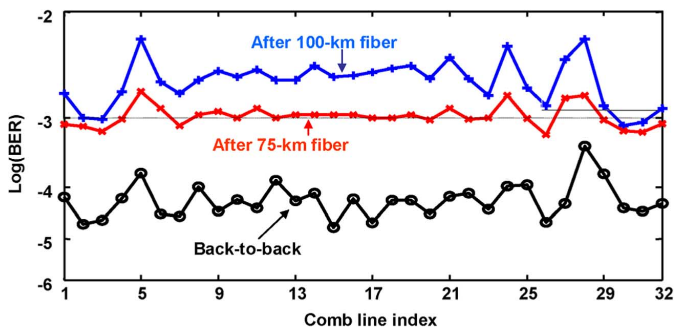

Fig. 6. BER of individual OFDM bands before and after 75-km and 100-km fiber transmission, respectively.

this Section, there is no clock connection required between the eAWG and the real-time oscilloscope.

The BER curves in Fig. 5(b) are of the 32 OFDM bands. Although the BER calculation is per OFDM band, the measured received power is for the 1.008-Tb/s signal which includes 32 OFDM bands in the 318-GHz bandwidth. The -19.35-dBm power before the EDFA corresponds to a 32-dB optical SNR (OSNR). The varying BER performance among different OFDM bands results mostly from the 5-dB line-to-line power variation of the frequency comb prior to OFDM modulation. This also degrades the BER performance of the 1.008-Tb/s signal, since its BER is the average of the 32 OFDM bands. The required OSNR at 10^{-3} BER is 33 dB, which may be improved by at least 3 dB by further flattening the optical frequency comb.

Fig. 6 shows the BER performance of the individual OFDM bands before and after the 75-km and 100-km standard single-mode fiber (SSMF) transmission, respectively. After balancing the nonlinear tolerance at the transmitter side and the OSNR tolerance at the receiver side, the launch power into fiber is set at 4 dBm, and 75 km appears to be the longest distance with a best BER of 1.09×10^{-3} for 1.008 Tb/s. The relatively lower launch power is due to the fact that the comb lines carry identical OFDM modulation, which leads to a higher peak-to-average ratio (PAR) for the generated OFDM signal. The BER fluctuations across the OFDM bands reflect the power variation in Fig. 4(b).

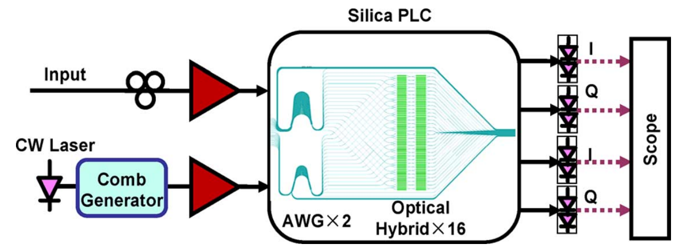

Fig. 7. Receiver setup using a silica PLC (with the layout design) for the detection of two optical slices. The PLC outputs multiple spectral slices but only two are used. AWG: arrayed-waveguide gratings.

IV. Experimental Results and Discussions of Simultaneous Detection of Multiple OFDM Bands Using a Silica PLC

This Section describes experimental results from a different receiver structure employing a local optical frequency comb and a silica PLC that contains two 16-channel optical arrayed-waveguide gratings (AWGs) for spectral demultiplexing and 16 optical hybrids. The inset of Fig. 7 shows the design layout of the silica PLC. The larger AWG has narrow passbands to isolate individual comb lines and to direct them to different hybrids. The smaller AWG has overlapping passbands and is gapless. Its purpose is to direct different portions of the signal spectrum to different optical hybrids. More information on the transmission characteristics can be found in [11].

A. Experimental Setup Using the PLC

The experiment in this Section uses the identical transmitter shown in Fig. 3(a) but employs a new receiver structure with the PLC illustrated in Fig. 7 that implements the architecture in Fig. 1(b). The incoming broadband OFDM signal and the local optical frequency comb are optically processed by the silica PLC. There is no optical bandpass filter because of the filtering functions inside the PLC. The demuxes have a frequency spacing of 40 GHz, and correspondingly, the local optical frequency comb has 39.75 GHz spacing instead of 9.9375 GHz that has been configured to the transmitter optical frequency comb. This configuration is optimized for current DACs and ADCs, because generally the DAC at the transmitter has a lower sampling rate and narrower bandwidth than the ADC at the receiver. Two pairs of balanced photodiodes converts two slices of optical spectra to RF signals, ready for digitization on the real-time sampling oscilloscope operating at 50 GSample/s. There are no external electrical filters and the overall electrical bandwidth of O/E conversion is determined by the oscilloscope itself. A computer loads the sequences to emulate the RF OFDM receiver. Detection of more spectral slices requires more balanced photodiodes and digitizers. Yet, simultaneous detection of two optical spectral slices is sufficient to show the feasibility of the receiver in Fig. 1(b).

The modulation format on every OFDM subcarrier is 4-QAM and therefore the total data rate reduces to 500.4 Gb/s. This change is due to that 4-QAM is more forgiving to laser phase noise and ASE noise [5]. The experimental system cannot provide enough OSNR for a good BER measurement of 16-QAM because the optical signals experience approximately 14–17 dB insertion loss after the PLC. The local optical frequency comb only contains two dominant comb lines to most efficiently use the EDFA's limited output power. The receiver signal processing includes frequency locking between the transmitter and receiver comb lines. The DSP also compensates for some hardware imperfections, e.g., the different time delays between two optical spectral slices and deviation from 90° of the optical hybrids. The OFDM bands are divided in the frequency domain. The subsequent signal processing mainly consists of the parallel RF OFDM signal processing units. In this paper, those units are independent. This independence means that the electrical spectrum synthesis described by Fig. 2 is not always necessary for OFDM signals because the information is encoded in the frequency domain, in contrast to the signal encoded in the time domain [18]. On the other hand, electrical spectrum synthesis can obtain the full field information of the whole optical OFDM signal, especially the phase relationship among the OFDM bands that is not easy to obtain by the per OFDM band detection methods that do not use an optical frequency comb [8], [10]. This additional information may provide the opportunity to compensate for nonlinear optical distortions, e.g., optical fiber nonlinearities that are best described in the time domain and involve all the OFDM bands. The best approach to take advantage of this feature is beyond the scope of this paper, but there will always be a trade-off between performance and computational complexity, which is widely discussed in the literature [26]–[28].

B. Experimental Measurements and Discussions

Fig. 8(a) shows the received RF spectra of two optical slices before electrical spectrum synthesis. As Fig. 2 has explained, the redundant and overlapped spectral components in the middle of Fig. 8(a) can be removed by electrical spectrum synthesis. In other words, the two spectra can be seamlessly stitched together. Fig. 8(b) is the SNR estimation of all the OFDM subcarriers within the two optical spectral slices. The SNR degradation at the edge of each slice is from the 16-GHz bandwidth of the oscilloscope (>20 GHz would be ideal). The SNR difference among different OFDM bands results from the power variation of the comb lines. The SNR curve is a direct reflection of the receiver frequency response. It is clear that the disadvantages of this receiver architecture are the non-uniform electrical frequency response and dc-leakage associated with the detection of each spectral slice. However, these effects only cause minor degradation on the whole OFDM signal, because those OFDM subcarriers located at the frequencies with the worst frequency response can be simply discarded without unreasonable overhead or penalty. For example, in Fig. 8(b), the four OFDM subcarriers around the 212th and 636th OFDM subcarriers are discarded in the BER calculation, i.e., 4/106 overhead. Due to the limited frequency response of the sampling oscilloscope, only six OFDM bands out of the eight are selected for BER calculation.

Fig. 8 also clearly shows that the partitioning of optical spectral slices can be different than the OFDM bands. A received spectral slice is four times wider than the OFDM band in this Section. One advantage of this arrangement is that there are fewer OFDM subcarriers affected by the dc leakage problem. For example, there is no dc-leakage problem at the 530th and 742nd OFDM subcarriers in Fig. 8, where the transmitter comb lines exist. Therefore, more OFDM subcarriers can be used to carry data information, leading to a reduced overhead. Another advantage is that the receiver can use fewer ADCs. For example, if the ADCs have a bandwidth of 20 GHz (not the 16 GHz in this experiment), then eight ADCs with proper designs will be enough to sample 320-GHz of optical bandwidth and provide 1-Tb/s capacity.

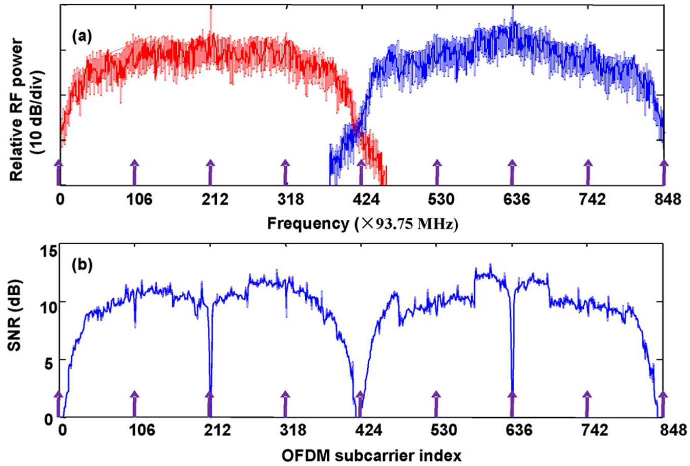

Fig. 8. (a) Received RF spectra of two optical spectral slices. (b) SNR estimation for all the OFDM subcarriers in the received two bands. The arrows on the horizontal-axes indicate the transmitter comb line position.

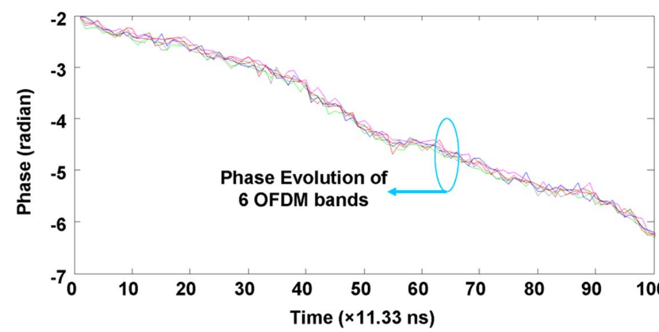

Fig. 9. Estimated individual phase evolution of 6 OFDM bands.

Fig. 9 shows the estimated phase evolution of six OFDM bands within the simultaneously detected two optical spectral slices. Each curve is independently estimated by the method described in [23]. Except for the random noise fluctuation, the overlap of six curves from two optical slices simultaneously demonstrates that the generated OFDM bands at the transmitter are coherent to each other and more importantly, the receiver in Fig. 7 is capable of O/E conversion of the optical spectral slices while preserving the optical phase relationship between them, thanks to the optical frequency combs at the transmitter and receiver. Fig. 9 also demonstrates that the relative coherence is maintained after splitting and recombining of the signal and optical frequency comb inside the PLC. For reference, the report in [18] provides another proof through signals expressed in the time domain. The shared phase evolution among OFDM bands also provides an additional possibility to reduce the number of

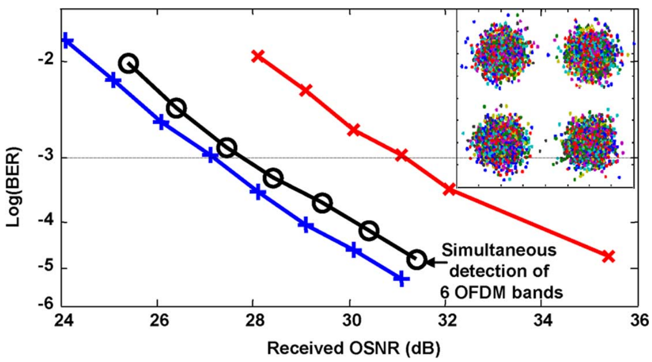

Fig. 10. Optical back-to-back BER measurements with the silica PLC. The two curves with crosses are the results of individual measurement of two OFDM bands. The curve with circles and the inset constellation are the results of simultaneous detection of six transmitted OFDM bands in two received optical spectral slices.

pilot subcarriers used for phase estimation, leading to a reduced overhead.

Fig. 10 shows the BER measurement using the PLC in an optical back-to-back transmission. The two BER curves (crosses) are for the individual measurement of two OFDM bands (centered on the 212th and 636th OFDM subcarrier in Fig. 8(b)) in two optical slices, respectively, and they show the successful detection of individual spectral slice by using the PLC. The difference between the two measured BER curves is caused partly from the 1.6-dB power difference through the PLC. The third BER curve (circles) is for the simultaneous detection of the six OFDM bands, containing OFDM subcarrier 54 to 371 and 498 to 795 in Fig. 8(b). As expected, the BER curve for the simultaneous measurement lies between the two BER curves of individual OFDM band measurement. This result indicates that there is no apparent penalty associated with the parallel/simultaneous detection in the experimental setup and ensuing DSP. While Fig. 10 shows results from two optical slices, a larger scale experiment covering > 1 Tb/s is possible by detecting all optical slices with a sufficient number of photodiodes, ADCs, and DSPs. The larger scale experiment and fabrication of a lower loss silica PLC will be a subject of future work.

The transmitter and receiver presented in Fig. 1 are highly parallel structures. Based on the experimental investigation in this Section, the optical integration needs to provide more uniform and low-loss transmissions for every optical slice. The arrays of ADCs/DSPs need to communicate with each other for electrical spectrum synthesis, not necessary using high-speed communications. The circuit integration of many sets of photodiodes and ADCs/DSPs has other problems, such as electrical isolation, power dissipation, etc., all topics for future studies.

V. Conclusion

This paper has introduced Tb/s coherent optical OFDM systems using optical frequency combs at both the transmitter and receiver to replace the usual bank of lasers, capable of generating and detecting much wider bandwidth, multi-band optical OFDM signals than that of direct utilization of current ADCs and DACs. Therefore, these systems can scale beyond the electrical bandwidth limit of current ADCs and DACs. The comb lines are inherently coherent to each other and have a well-controlled frequency spacing. These characteristics enable optical OFDM signal generation across comb lines at the transmitter, and also enable optical spectrum slicing and electrical spectrum synthesis at the receiver. The experiment involved the transmitter generating tens of times wider bandwidth optical OFDM signals than that of the ADC/DAC. While the non-uniform frequency response and dc-leakage in the receiver limited the performance, optical OFDM signals are well adapted to this receiver structure and are resilient to the distortion in the frequency domain.

The first experiment has demonstrated the generation, transmission, and detection of the 1.008-Tb/s optical OFDM signal with a spectral efficiency of 3.17 b/s/Hz on a single polarization. The lower ADC sampling rate and clock synchronization between the DAC and ADC have also been investigated. The second experiment has shown the feasibility of the proposed system architecture on an optically integrated silica PLC platform. Coherent optical OFDM systems using optical frequency combs require only one laser source at both the transmitter and receiver, and they provide a viable approach for spectra-efficient and impairment-resilient optical transmissions scalable beyond Tb/s capacity.

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