Loop-Assisted Coherent Matched Detector for Parallel Time-Frequency Sampling

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(Invited Paper)

***Abstract*—Optical sampling is performed mostly in either time or frequency domain. In the former approach, sampling points are temporally taken by photo-mixing of received signals with locally generated ultrashort pulses. In the latter approach, the received signal is spectrally sliced and decomposed, which are taken as sampling points in the frequency domain. In this paper, as an alternative way, we propose and investigate an optical sampling technique called optical time-frequency-domain sampling, in which sampling points are taken in the time-frequency domain in an optoelectronic manner, by means of optoelectronic coherent matched detectors. Using this technique, it is possible to demultiplex and detect subchannels of ultrawideband multi-carrier signals at *e.g.* 100, 400 Gb/s, 1 Tb/s or higher, without relying on either ultrashort pulses or high-resolution optical filters necessary in the conventional time- or frequency-domain sampling approaches. Moreover, in this paper, we propose and demonstrate a loop-assisted coherent matched detector that simply and practically extends the time-frequency sampling to parallel sampling configuration just using a single coherent matched detector. Provided are some experimental proof focusing on demultiplexing and detection of orthogonal time-frequency-domain multipelxed (OTFDM) signals, a sort of ultrawideband multicarrier signals. All subchannels of 160-Gb/s QPSK-OTFDM signals are simultaneously detected and measured with the loop-assisted coherent matched detector employing a single set of low-speed 10-Gbaud photo-receivers.**

***Index Terms*—Coherent detection, coherent matched detection, loop-assisted coherent matched detection, optical sampling, parallel sampling, time-frequency-domain sampling.**

I. INTRODUCTION

In FUTURE high-capacity and high-spectral-efficiency optical fiber networks, multi-carrier transmission technologies are expected to be indispensable [1]–[4]. In addition to the enhancements in transmission capacity, the multi-carrier technologies increase flexibility in optical networks, enabling flexible channel and bandwidth assignments. Orthogonal frequency-division multiplexing (OFDM) and discrete multi-tone (DMT) are famous multi-carrier multiplexing approaches, which are based on electrical signal processing for sub-carrier multiplexing [1]–[3]. Although they exhibit features such as high spectral efficiency and high dispersion tolerance, frequency-spacing of the carriers can not be high, staying on the order of 100 MHz; in addition, the total bandwidth of the multiplexed signals are strictly restricted by electrical bandwidth to several 10 GHz. In order to explore ultra-high-bandwidth transmission at 100-400 Gb/s, 1 Tb/s or higher, optical multiplexing techniques need to be adopted in the multi-carrier systems, where sub-channels are multiplexed in the optical domain over multiple carriers with a frequency spacing of several 10 GHz. Optical orthogonal frequency-division multiplexing (o-OFDM) [5], super-channels [4], (Nyquist)-optical time-division multiplexing (OTDM) [6] *etc*, are examples of such multi-carrier multiplexing systems based on optical multiplexing.

Orthogonal time-frequency domain multiplexing (OTFDM) is another candidate in this category, as we previously demonstrated [7], [8]. In the multiplexing approach, ultra-wideband multi-carrier signals are multiplexed in the time-frequency domain in an electro-optic manner using multiple-parallel EO modulators; the OTFDM signals are demultiplexed in an opto-electronic manner using coherent matched detectors as we describe in this paper. OTFDM systems, based on the pair of multiplexing and demultiplexing techniques, enable ultra-high-speed (as fast as OTDM) and ultra-high-spectral-efficiency (as high as OFDM) multi-carrier transmission.

To receive and detect such ultra-wideband multi-carrier signals (OTDM, OFDM, OTFDM, and so on) with a bandwidth beyond the photo-detection bandwidth limit, the received signal should be optically demultiplexed and decomposed into low-speed sub-channels. Optical sampling technologies, in a broad sense, make a significant contribution to such high-bandwidth optical demultiplexing and detection. One challenge is how to simply construct optical sampling systems to equivalently enhance detection bandwidth. Time- or frequency-domain sampling approaches were widely investigated, so far [9]–[16]; however, both approaches demand more hardware complexity than OTFDM. For example, strict control on ultra-short pulses generation is required for the time-domain sampling techniques. Optical pulses should be as short as possible on the order of ps or fs and their waveforms should be appropriately shaped for high-extinction-ratio operation. If we take the

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frequency-domain sampling approaches, on the other hand, we need to rely on optical fast Fourier transform (FFT) circuits or equivalent optical high-resolution filters with a spectral resolution of GHz or higher [15], [16]. Another challenge is how we can construct a "parallel" optical sampling system. To detect all sub-channels of ultra-wideband multi-carrier signals, we need to use multiple sets of optical sampling systems arranged in parallel. A large-scale photonic integration technique would be helpful for the parallelization, especially when higher-bandwidth signals containing larger number of sub-channels are received [14].

As an alternative to the time or frequency domain sampling, in this paper, we investigate optical sampling techniques based on the time-frequency domain sampling [7], [17], [18]. By using coherent matched detection, sampling points are taken in the time-frequency domain with an equivalently enhanced detection bandwidth; a sub-channel is demultiplexed from ultra-wideband multi-carrier signals [7]. The coherent matched detector is almost compatible with typically used digital intradyne detector [19]; one difference is that an optical comb is used as a local oscillator instead of using a continuous-wave (cw) light. We also propose and investigate, in this paper, a loop-assisted coherent matched detector, by which parallel sampling in the time-frequency domain is achieved just using a single set of coherent matched detectors [17], [18]. It is demonstrated that the system can detect and measure ultra-wideband signals beyond the bandwidth of photo-detectors, providing some experimental proof focusing on demultiplexing of 80-Gbaud OTFDM multi-carrier signals.

This paper is organized as follows. First, in Section II, conventional optical sampling techniques are briefly looked over. In Section III, time-frequency domain sampling techniques are described, where we discuss essential technologies for the sampling, including coherent matched detection and optical comb generation. Importance of parallelization is also discussed, there. Loop-assisted coherent matched detectors are described in Section IV, providing some experimental proof.

II. Optical Sampling Techniques

In general, optical sampling techniques are classified in three. First one is the technique based on photodetectors followed by electrical samplers, which is practically used in optical sampling oscilloscopes. Bandwidth of the systems is obviously restricted to several ten GHz by response of photodiodes and other electronics [20]. To overcome the bandwidth limitation, optical sampling techniques in the optical domain are investigated, which are recognized as the second and third approaches, here. The second approach, optical-sampler-based one, utilizes all-optical sampling techniques, where received signals are sampled in an optical manner, by using four-wave-mixing or second-harmonic generation in nonlinear materials [9]. All-optical filtering circuits are also useful in the approach [15], [16]. High-bandwidth operation is achieved at an expense of increased system complexity. The third one is the approach based on opto-electronic sampling that uses photo mixing in photodiodes [10]–[13], including coherent matched detection we focus on in this paper, which would greatly simplify optical-domain sampling.

We can also classify the optical sampling techniques in a different way as follows: (1) time-domain [9]–[11], [13], [14], (2) frequency-domain (*i.e.* wavelength-domain) [12], [15], [16] or (3) time-frequency domain [7], [17], [18] sampling approaches. The time-domain approaches enable temporally acquiring sampling points of optical waveforms. In all-optical methods, the received signals are optically mixed with ultra-short optical pulses by using four-wave-mixing in nonlinear materials [9]; in opto-electronic methods, homodyne or intradyne mixing in photodiodes are used for temporal sampling [10], [11], [13], [14]; in any way, ultra-short pulses are inevitable. Other approaches are based in the frequency domain, where the received signal is spectrally sliced in optical frequency/wavelength domain capturing its all frequency components [15], [16]. Optical Fast Fourier Transform (FFT) or equivalent filtering circuits are required for all-optical sampling, which can be achieved by photonic integrated circuits [16]; homodyne or intradyne detection is also useful for spectral slicing in an opto-electronic manner [15]. In the time-frequency domain sampling approach, described in this paper, sampling points of the waveform are taken in the time-frequency domain instead of using either time- or frequency-domain approaches. The technology does not rely on ultra-short pulses, ultrafast all-optical mixing, high-resolution filters or optical FFT circuits. The system is a generalized extension from the time- or the frequency domain sampling; in other words, the time- and frequency-domain sampling are special cases of the time-frequency-domain sampling. As will be discussed later we can construct a robust and versatile sampling system, especially when parallel sampling configuration is adopted.

III. Time-Frequency Domain Sampling

For realization of the time-frequency domain sampling in an opto-electronic way, the following technologies are essential: (1) coherent matched detection, (2) optical comb generation, (3) parallelization of the detectors (parallel sampling). The first one, coherent matched detection, enables ultra-wideband time-frequency sampling using opto-electronic photo detection. The second one, optical comb generation, is essential to the coherent matched detection. Parallelization of the coherent matched detectors is important for flexibly receiving all sub-channels of ultra-wideband multi-carrier signals. In this section, these technologies are described in detail one by one, and Figs. 1 and 3 will describe (1) coherent matched detection and (3) parallelization of the detectors, respectively.

A. Opto-Electronic Coherent Matched Detection

A coherent-matched detector[1] is a detector that enables detection of ultra-wideband signals in the time-frequency domain, relying on neither time-domain nor frequency-domain sampling.

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[1] "Coherent-matched detection" is primarily different from the technology called "matched filtering," which optimizes waveform shaping and noise filtering, applied especially in single-carrier coherent receivers. In coherent-matched detection, the received signals are matched with a locally generated comb and one particular waveform is taken as a sampling point in the time-frequency domain, as we explain in this section. In a broad sense, the process can be also interpreted as a sort of filtering; however, the matching process in an opto-electronic manner enables handling ultra high-bandwidth signals beyond the electrical bandwidth.

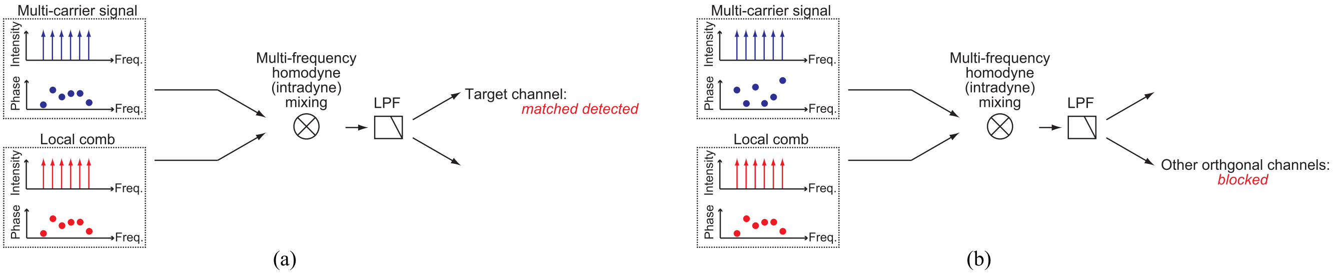


Fig. 1. Principle of coherent matched detection; A received signal is (a) matched detected if the signal and local comb are matched in amplitude and phase each other, and (b) blocked if they are orthogonal; LPF: low-pass filter.

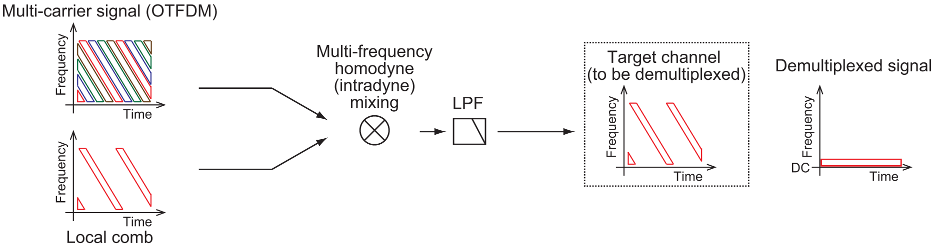


Fig. 2. Time-frequency chart explaining demultiplexing of OTFDM signals (the chart shows that each tributary is linearly chirped, exampled for simplicity).

Fig. 1 shows the principle of the coherent matched detection. Basically, a coherent homodyne or intradyne detector is utilized in the detection scheme, which is based on phase-diversity detection employing an optical hybrid coupler followed by balanced detectors. Different from such typical coherent detectors, a locally generated optical comb, called local comb hereafter, is used as a local-oscillator instead of using a continuous-wave (CW) light. (We do not need to care temporal waveform of the local comb; however, relative phase differences among the local comb lines should be fixed.) In the coherent matched detection, a received ultra-wideband multi-carrier signal is homodyne- or intradyne-mixed over multiple frequencies with the local comb. We can selectively detect a particular waveform that is exactly matched in the amplitude and phase with the local comb. This is because only the matched components are down-converted to the baseband frequencies, whereas non-matched components are converted to the higher frequency region; accordingly, the target waveform is selectively matched detected by applying low-pass filters to the photodetected signals. Through the process, the signal matched with the waveform is coherently matched detected, as shown in Fig. 1(a); whereas, the signal is fully blocked out if the signal has a waveform orthogonal against that of the local comb [Fig. 1(b)]. By using this coherent matched detection, it is possible to demultiplex one particular target sub-channel from the ultra-wideband multi-carrier signals and the sub-channel can be demodulated by signal processing performed in DSP followed by the coherent matched detector.

The process of the coherent matched detector can be explained well using a time-frequency chart as shown in Fig. 2. As shown in the figure, a local comb with comb lines that have certain phase relationships is described as red tilted box in the chart (For simplicity, we draw the chart with a linearly chirped comb as an example; however, any other patterns are acceptable in the time-frequency chart). Through coherent matched detection, one particular waveform with the time-frequency pattern exactly matched with that of the local comb is selectively extracted and matched detected. When using OTFDM multiplexing, one target signal can be simply demultiplexed by coherent matched detection (in the figure, the tilted boxes in different colors stand for individual sub-channels of the OTFDM signals). This demultiplexing and demodulation scheme does not rely on any optical/electrical FFT circuits or optical channel selection filters. In addition, it also does not request ultra-short pulses conventionally required in the time-domain sampling.

The description above explains the coherent matched detection operated under the condition for multi-frequency homodyne mixing, which means that each carrier of the received multi-carrier signal has the phase and frequency exactly same as those of corresponding local comb line. In more practical situation, however, there are phase and frequency offset between them because the local comb is generated from a laser source on the receiver side, independently of signal carrier generation on the transmitter side. With the help of digital signal processing (DSP) in the coherent matched detectors, the phase and frequency offsets (and their drifts) are canceled out in the same way as with intradyne detection used in single-carrier coherent receivers. The functions of signal processing applied in the coherent matched detector are basically same as those in the single-carrier receiver; in addition, DSP can be clocked at the speed of tributary sub-channel which is the same order of processing speed for single-carrier reception (we do not need to accelerate it to cover the full rate of the optically multiplexed signals). This is because, in the coherent matched detection, the waveform and bandwidth of the down-converted signal is similar to typical single-carrier coherent detected signals; thus, frequency and phase offsets are canceled with commonly used algorithms based on carrier recovery and carrier phase estimation techniques, such as fourth-power algorithm [19]. The scenario for clock recovery in the system is also the same as the single-carrier receiver case. An external clock recovery circuit should be used and the clock phase of the recovered clock should be optimized to catch the optimal sampling points if DSP (and analog-to-digital converters (ADCs)) is clocked at the symbol rate of the sub-channels (tributaries). A more practical method is to adopt an oversampling technique, where the clock phase becomes detectable owing to the increased sampling points in the time domain. It is known that two sampling points per symbol is a solution practical in high-speed optical coherent detection. Adaptive equalizers based on FIR or MIMO filters implemented in the over-sampled DSP can adaptively absorb the clock-phase misalignment. Even in the coherent matched detector, over sampling at the rate twice the tributary's symbol rate is helpful for such clock recovery processing.

B. Optical Comb Generation

For proper coherent matched detection of multi-carrier signals, the local comb should satisfy the following conditions: (1) all frequencies should have equal amplitude within a certain bandwidth (rectangular spectral profile), (2) all frequency components should be phase-locked each other.

The former condition originates from the fact that all the frequency components of the multi-carrier signals, usually equal in amplitude, can be down-converted to the baseband frequencies with equal efficiency if all the frequency components of the local comb have the equal amplitude, *i.e.*, the local comb has a flat spectrum. To avoid detecting undesired out-of-band components of the multi-carrier signals, suppressing crosstalk from neighboring bundles of other channels, rectangular spectral profile is preferred in terms of spectral shape of the local comb. The rectangular profile is also advantageous for the time-frequency sampling with the minimized local comb bandwidth.

As for the latter condition required for the local comb, the relative phase difference among the comb lines should be fixed to ensure that a target waveform with a particular fixed phase pattern in its spectrum is selectively matched detected. The phase relationships among the frequency components of the local comb can be arbitrary, which means that we do not need to shape the local comb into temporally impulsive ultra-short pulse waveform. In addition, the absolute phase of the local comb is not necessarily fixed because the DSP followed by the detector can track the phase variance (drift) as we typically perform carrier phase estimation in a single-carrier coherent receiver [19].

In this context, optical comb generators based on electro-optic (EO) modulators are suitable for generation of such local combs; among them, especially, a Mach-Zehnder modulator based flat comb generator (MZ-FCG) is a good candidate because it can stably and flexibly synthesize a spectrally flattened optical comb from a continuous-wave (CW) light by simply using a single-stage Mach-Zehnder modulator (MZM) [21]. In this comb generator, the CW light input into the MZM is deeply modulated by applying large-amplitude sinusoidal signals. It is known that high-order sideband components generated in the modulator are spectrally flattened, if we drive it under the following flat-spectrum condition [21].

$$\Delta A \pm \Delta\theta = n\pi + \frac{\pi}{2}, \tag{1}$$

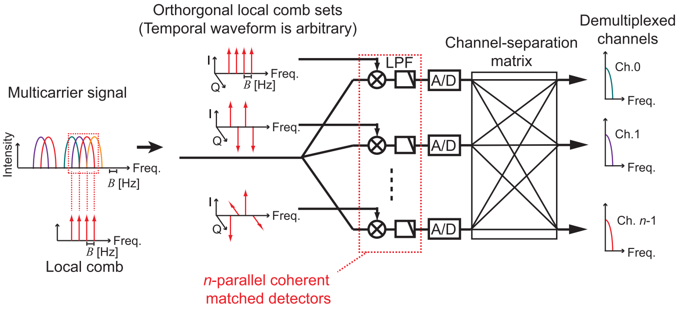


Fig. 3. Multiple-parallel coherent matched detector; n sets of coherent matched detectors are arranged in parallel. The local combs led to the detectors are orthogonal each other. All sub-channels are restored by the channel-separation matrix.; LPF: low-pass filter, A/D: analog-to-digital converter.

where ΔA and $\Delta\theta$ are normalized as induced phase shift in the modulator waveguides; physically, $2\Delta A$ corresponds to the difference between the zero-to-peak phase shifts induced by the sinusoidal signals applied to the electrodes on the MZM arms; $2\Delta\theta$ is the DC phase difference, *i.e.* optical bias of the MZM.

In practice, the intensities of frequency components of the generated local comb are not perfectly equal. Spectral ripples remain in the generated comb. This causes some mismatch in the process of coherent matched detection, which increases the receiver penalty slightly.

C. Parallelization

The coherent matched detector described above selectively separates and detects a single sub-channel of the received multi-carrier signal. In order to demultiplex and detect all sub-channels of the multi-carrier signals, multiple sets of coherent matched detectors are required, which should be arranged in parallel, as shown in Fig. 3.

In the system, the received signals are firstly split in n by using an optical splitter and the split signals are individually led to n sets of coherent matched detectors. The coherent matched detectors are driven with local comb sets orthogonal each other. Under the driving condition, each detector matches to a particular optical waveform spectrally overlapped with the local comb; as a result, n sets of orthogonal waveforms are individually down-converted to the baseband frequencies, and all the sub-channels are demultiplexed. Since the process is linear and the dimension of the parallelization is large enough to cover this multi-channel signals, all the components within the bandwidth are completely projected on n bases defined in the time-frequency domain, all information of the amplitude and phase of the received signal is preserved through the coherent matched detection process.

This configuration is useful to demultiplex sub-channels of orthogonal time-frequency domain multiplexing (OTFDM) signals [8], a sort of ultra-wideband multi-carrier signals, where sub-channels are carried by multi carriers that have the same amplitude and phase characteristics as those of the local combs in the receiver. In this situation, the multi-carriers for the sub-channels and local combs are matched well regardless to their temporal waveform. However, in general, the local combs are not always matched with other types of multi-carrier signals. To

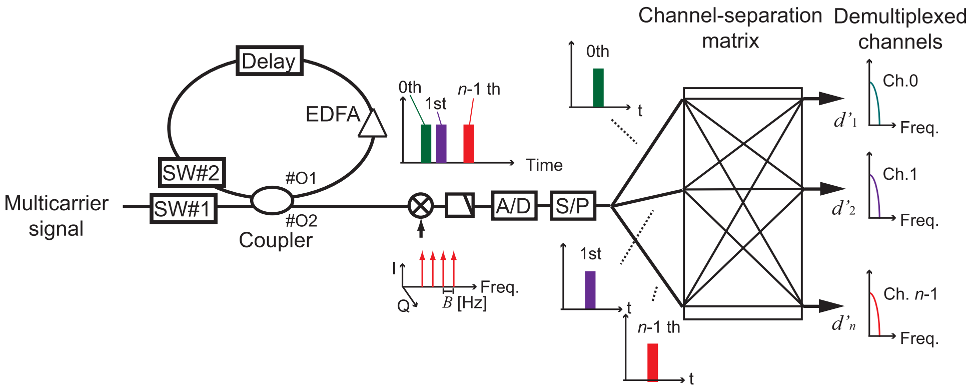


Fig. 4. Loop-assisted coherent matched detector; The recirculating loop section helps to buffer the received signal and lets the buffered signals arrive at different times to the single-set coherent matched detector; SW: optical switch, EDFA: erbium-doped fiber amplifier, A/D: analog-to-digital converter, LPF: low-pass filter, S/P: serial-to-parallel converter.

be matched with other types of multi-carrier signals other than OTFDM, we need to control the amplitude and phase of the local comb according to the type of the received multi-carrier signals. A channel-separation matrix implemented in a digital signal processor (DSP) [22] helps flexibly satisfy the matching condition between the target sub-channel and local comb.

As shown in Fig. 3, the n sets of coherent matched detected signal are digitized and led to the channel separation matrix implemented in a DSP. In the matrix, the signals are linearly converted and projected on other bases fit to another type of multi-carrier multiplexing system. All sub-channels of any types of multi-carrier signals are recovered here assisted by the channel separation matrix. Since the amplitude and phase relationships of the local combs are pre-known except the optical carrier phase of the cw light (input to the comb generator), we can choose a matrix suitable for the channel separation. In case of OTFDM systems, the channel separation matrix yields unit matrix if the sub-carriers of OTFDM signals and local comb are generated with comb generators operated under the same condition. We can apply tailored matrices for other types of multi-carrier signals. Another good point of the matrix processing is that multi-input-multi-output (MIMO) equalization can be also implemented in the matrix section in order to mitigate impairments in the transmission systems, like wavelength dispersion, and so on [23].

IV. LOOP-ASSISTED CONFIGURATION FOR PARALLEL COHERENT MATCHED DETECTION

Multiple sub-channels in ultra-wideband multi-carrier signals can be simultaneously demultiplexed by using multiple-parallel coherent matched detectors. One issue is that larger-scale parallelization of the coherent matched detectors is necessary if we try to detect higher bandwidth signals with greater channel numbers. If we focus on data transmission, of course, this issue can not be avoided because we need to reserve enough hardware resources to detect all channels. For measurement and characterization of ultra-wideband multi-carrier signals, however, we can save hardware resources. A loop-assisted coherent matched detector we propose is a suitable solution to increase the order of parallelization without increasing hardware complexity and useful for measurement of ultra-wideband multi-carrier signals [17], [18]

Fig. 4 shows the basic construction of the loop-assisted coherent matched detector. The detector consists of a recirculating loop and a single-set coherent matched detector. In principle, the received signal is first input to the recirculating loop section; afterward, it is led to the coherent matched detector section. The loop section has the role to take multiple copies of the received signals and lead them to the coherent matched detector at different arrival times. The amount of delay given to the signals is controlled by the combination of an optical fiber delay and two optical switches in the loop.

Fig. 5 shows the timing chart of the switching control for the recirculating loop. First, the input signal is temporally gated by using the first optical switch (#1) that has a rectangular switching window with a passing window width of T_s and a switching interval of T_r. The time-gated signal is led to the optical loop consisting of a 2x2 optical coupler, fiber delay line, EDFA and another optical switch (#2). After merging into the loop through the optical coupler, the signal travels along the loop several times; the time-gated signals in different round-trips are taken out from the port #O2 of the optical coupler. The propagation loss of the loop is compensated by the EDFA and the signal recirculating is terminated by using the second optical switch (#2) placed in the loop. The optical switch (#2) is operated in a complementary way against the first one (#1). The optical delay in each round trip, τ, is set at $\tau = T_s + T_g$, where T_g is a guard time reserved for switching transit. The loop delay τ also needs to satisfy $n'\tau = T_r$ for an integer n', so that the gated signal by the optical switch (#1) rounds in n' times before the termination. Under this condition, n' copies of the time-gated input signal are received with a single set of coherent matched detectors. Of course, $n' \geq n$ should be satisfied to detect n sets of sub-channels.

To equivalently achieve parallel time-frequency domain sampling and orthogonally detect all sub-channels using this setup, the loop delay needs to be controlled more carefully in addition to the timing control for recirculation mentioned above. The delay should be aligned at $\tau = (m + i/n)/B$ [sec], where B is a symbol rate of the tributary channel; i is an arbitrary integer; n is a number of the multiplexed sub-channels; in addition, m

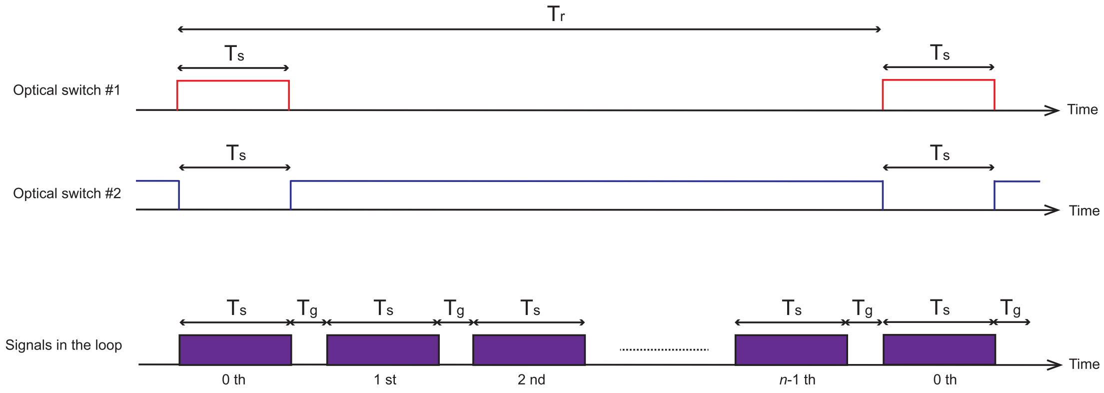


Fig. 5. Time chart in the recirculating loop for controlling the time-gated received signal.

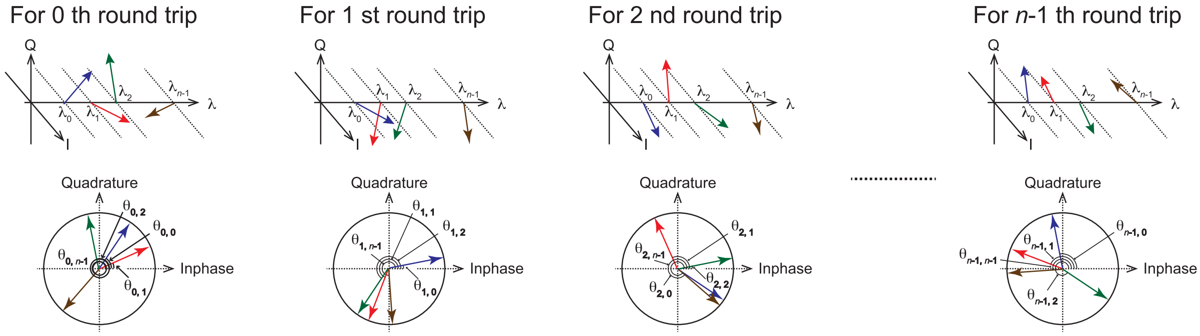


Fig. 6. Phase relationships among frequency components of local combs; $\theta_{i,k}$ stands for the optical phase of comb line at λ_k $(k = 0, 1, \cdots, n-1)$ after the i-th roundtrip, which is related as $\theta_{i,k} = \theta_{0,k} + \frac{i(2k+1-n)\pi}{n}$, where $\theta_{0,k}$ is the initial phase of the comb line at λ_k before roundtrips and n is assumed to be even, for simplicity.

is an integer that satisfies $m = (int)(T_s + T_g)/B$. Under this condition, the relative delay between the i-th time-gated signal stream and local comb becomes $i/(nB)$. Therefore, the appropriate delay control in the loop equivalently enables coherent matched detection in parallel, which are orthogonally operated each other. In general, m is set at a large value, like 10000 or larger, in order to keep the temporal window T_s (and T_g) long enough (e.g. $>$ micro seconds). Relative phase relationships of the local comb lines in different round-trips are summarized in Fig. 6. Note that this loop-assisted system is equivalent with n-parallel coherent matched detectors; however, it just uses a single-set of coherent matched detector, and we can easily and flexibly increase n without increasing hardware complexity. In the system, we can continuously take sampling points in the temporal window of T_s; however, the system need to sleep for $(n-1)(T_s + T_g)$ before restarting acquisition for the next temporal frame. To combine it with measurement system based on offline DSP (e.g. by using real-time oscilloscope), we need to reserve an n-time larger buffering memory to achieve the same record length comparing with single-channel digital coherent receivers.

V. EXPERIMENTAL DEMONSTRATION

A. Experimental Setup

Fig. 7 shows the experimental setup for loop-assisted coherent matched detector. As ultra-wideband multi-carrier signals, OTFDM signals were used [8] because signals multiplexed in this way are the simplest case for proving the concept. To generate OTFDM signals, on the transmitter side, an optical comb with 18 frequency components with a frequency spacing of 10 GHz was firstly generated from a Mach-Zehnder modulator based flat comb generator (MZ-FCG) [21]. The generated comb was data modulated with an inphase-quadrature (IQ) modulator in a quadrature-phase-shift keying (QPSK) format at a symbol rate of 10 Gbaud with a pattern length of 2^{15}–1, where all the comb lines were modulated in the same data stream. The QPSK modulated signal was shaped with a rectangular spectral profile with an optical band-pass filter (OBPF) and led to an optical-delay-line-based OTFDM multiplexer with optical delays long enough for decorrelation among sub-channels. The number of multiplexing order was upto 8; with this configuration, 20-, 40- or 80-Gbaud OTFDM signal was generated.

On the receiver side, we constructed a loop-assisted coherent matched detector. To achieve 8-parallel coherent matched detection, we input the received signal into recirculating loop section, where the input signal was time-gated with a timing window of 1 μs, and then the gated signal was recirculated by several times (in this setup, upto 8 times) in the loop. The loop consists of a 500-m standard single-mode fiber (SMF) and an EDFA, and acoustic-optic modulator (AOM) switches. After the recirculating loop, 8 sets of the recirculated signals were input into the signal port of the hybrid coupler with the timing delay of 100m+12.5i [ps]. The timing was aligned at the value with an optical tunable delay line. The actual value of m was 25400. On the other hand, another comb was generated as a

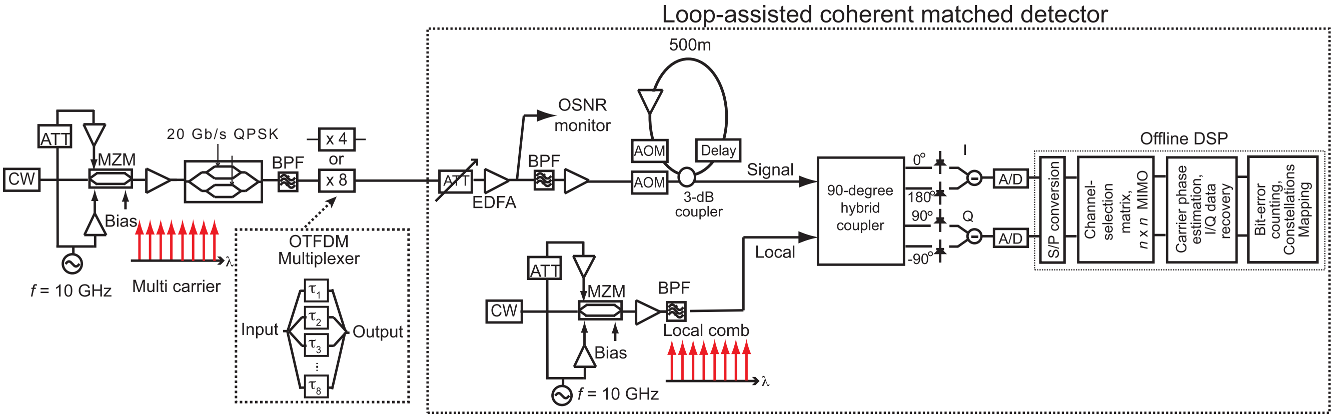
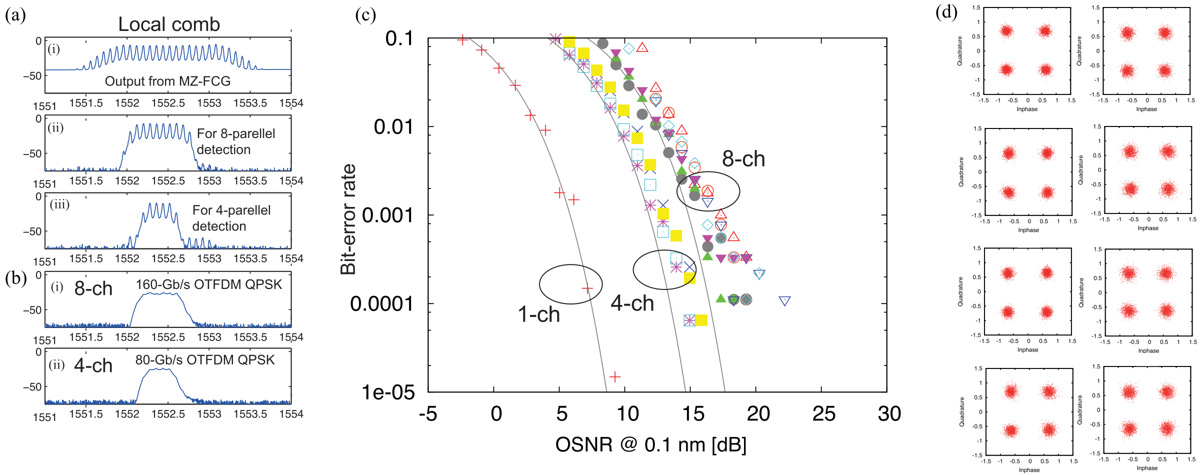


Fig. 7. Experimental setup; CW: continuous-wave laser, ATT: attenuator, MZM: Mach-Zehnder modulator, BPF: optical band-pass filter, OTFDM: orthogonal time-frequency domain multiplexing, EDFA: erbium-doped fiber amplifier, OSNR: optical signal-to-noise ratio, AOM: acousto-optic modulator, Delay: tunable optical delay, A/D: analog-to-digital converter, S/P: serial-to-parallel converter.



Different symbols stand for BERs of different subchannels

Fig. 8. Experimental results; (a) Optical spectra of local comb for (i) original comb generated from MZ-FCG, (ii) 8×, (iii) 4× parallel coherent matched detection, (b) optical spectra of $n \times$ 20-Gb/s OTFDM-QPSK, (i) $n = 8$ and (ii) 4, (c) BER measured against required OSNR at 0.1 nm, (d) constellations of demultiplexed and demodulated QPSK signals (8 ch), measured at OSNR (at 0.1 nm) = 32.9 [dB].

local comb by using another MZ-FCG. The number of comb lines was eight, which covered the full bandwidth of 160-Gb/s OTFDM-QPSK signal. With this setup, the relative optical delay between the received signal and the local comb becomes 12.5i [ps], which ensures orthogonality between the local combs for demultiplexing sub-channels of the OTFDM signals. The recirculated signal was intradyne-mixed with the local comb with a typical digital intradyne receiver with offline signal processing. For the multi-frequency intradyne mixing, we used an optical hybrid coupler followed by balanced detectors. The inphase and quadrature balanced detected channels were digitized with a real time oscilloscope with a sampling rate of 50 GSa/s and analog bandwidth of 12.5 GHz.

The captured channels were offline processed in the following way. Firstly, the signals were re-sampled at 20 Gsa/s to emulate 2 samples per symbol DSP system. Then low-pass filters were applied with a passband shape of root-raised-cosine (RRC) with a roll-off factor of 0.9. (For simplicity, frequency offsets were canceled earlier by tracking the recovered carrier.) The filtered signal was led to the channel separation matrix (unit matrix, in this case) and all subchannels were separately demultiplexed. Clock was recovered from the demultiplexed signals and the sampling points were determined. MIMO equalization was applied to the demultiplexed signals to eliminate residual crostalks among subchannels, which originated from residual spectral ripples of the local comb, imperfectness in the OTFDM transmitter and so on, Carrier-phases of the demultiplexed signals were estimated with a fourth-power algorithm; then, the QPSK constellations were restored and bit-error rates of them were calculated after symbol decision.

B. Experimental Results

Experimental results are shown in Fig. 8. In the figure, (a) shows optical spectra of local comb for time-frequency sampling. Fig. 8(b) shows the optical spectra of n x 20-Gb/s

OTFDM-QPSK signals. Fig. 8(c) are the bit-error-rate (BER) characteristics of the demultiplexed channels measured as a function of received OSNR at 0.1 nm. For reference, we also measured BER for signals with different carrier numbers, 1x, 4x, which are coherent matched detected with 4-parallel configuration. In the plot, theoretical BERs for single-carrier QPSK signals at corresponding symbol rate are also plotted as dotted curves. All the channels show around 1–3 dB OSNR penalty from the theoretical limit. Measured constellations for 8 sub-channels demultiplexed are shown in Fig. 8(d). Clear constellations were observed, which means that all channels were successfully separated and demodulated without significant crosstalk.

VI. CONCLUSION

We have investigated opto-electronic time-frequency domain sampling based on coherent matched detection, which enables detection and characterization of ultra-wideband multi-carrier signals. A loop-assisted configuration has been proposed for parallel arrangement of a coherent matched detector. Through experimental demonstration focusing on demultiplexing of 160-Gb/s OTFDM QPSK signals, the concept of the loop-assisted coherent matched detector was successfully proved.

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Authors’ biographies not available at the time of publication.