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PAPER

Demultiplexing Method of Variable Capacity Optical OFDM Signal Using Time Lens-Based Optical Fourier Transform

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SUMMARY We propose and demonstrate a method that can demultiplex an optical OFDM signal with various capacity based on time lens-based optical Fourier transform. The proposed tunable optical OFDM signal demultiplexer is composed of a phase modulator and a tunable chromatic dispersion emulator. The spectrum of the variable capacity OFDM signal is transformed into Nyquist time-division multiplexing pulses with the optical Fourier transform, and the OFDM sub-carrier channels are dumultiplexed in the time-domain. We also propose a simple method for approximating and generating quadratic waveform to drive the phase modulator. After explaining the operating principle of the method and the design of some parameters in detail, we show successful demultiplexing of 4×8 and 4×10 Gbit/s optical OFDM signals with our proposed method as the preliminary investigation results.
key words: *optical signal processing, optical Fourier transform, optical OFDM, demultiplexer, optical communication*

1. Introduction

Optical orthogonal frequency division multiplexing (OFDM), which utilizes and transmits orthogonal sub-carrier channels whose symbol rates are equal to their frequency spacing, is being actively investigated because of its potential to realize highly spectral-efficient optical communication [1]–[6]. The optical OFDM is needed in photonic networks as well as point-to-point transmission. The channels with fixed grids and symbol rates are utilized in the existing photonic networks. While on the other hand, in the future adaptive photonic networks including an elastic network, the minimal bands are adaptively and flexibly allocated corresponding to the traffic and transmission distance in order to save the network resources [7]. This function is achieved by decreasing the guard bands, and changing the channel number, symbol rate, and/or modulation formats. As the optical OFDM can potentially contribute to the decrease of the guard bands, it is important to develop a high-speed and low-power consumption method or device, which can demultiplex an optical OFDM signal with variable capacity, namely, variable sub-carrier symbol-rate and/or the variable number of sub-carrier channels. We reported integrated-optic tunable optical OFDM demultiplexers that consisted of slab star coupler-based optical discrete Fourier transform (DFT) circuits [8]–[10]. These integrated-optic DFT circuits can deal with the limited range of capacity due to their finite scalability.

In this paper, we propose and demonstrate a method for demultiplexing a variable capacity optical OFDM signal using time lens-based optical Fourier transform [11], [12]. This method utilizes a phase modulator and a tunable chromatic dispersion emulator, namely, compensator. As the phase shift at the modulator and the chromatic dispersion can almost continuously be tuned, the proposed method can be applicable to flexible processing of an OFDM signal with wide capacity range. The time lens-based optical Fourier transform was already utilized to demultiplex fixed symbol-rate optical OFDM signals [13], [14]. The implementation of quadratic phase modulation, namely, linear frequency chirping to the OFDM signal is indispensable for carrying out the time lens-based Fourier transform. However, the generation of periodic quadratic waveform on the order of ten gigahertz is difficult. The required modulation was carried out with a phase modulator driven by an easily available cosine wave or through four wave mixing process using pump pulses, whose frequency was linearly chirped, in [13] or [14], respectively. Non-return-to-zero (NRZ) pulses are generally used in the OFDM communication. As the cosine wave can approximate the quadratic waveform within the limited range of a time slot, a guard interval, which accounted for half of the symbol period, was inserted into each time slot to utilize the effective time range of the cosine wave in [13]. This procedure corresponds to the use of return-to-zero pulses and reduces the spectral efficiency to half. We adopted the phase modulator in light of the future integration of the tunable OFDM demultiplexer. We could not demultiplex the NRZ signal-based OFDM subcarriers with the time lens-based optical Fourier transform, which utilized the phase modulator driven with the cosine wave. Therefore, in this investigation, we simply produce radio frequency (RF) quadratic waveform for driving the phase modulator with just two synchronized signal generators. The quadratic waveform is approximated with just two terms of Fourier series to extend the effective time range of the phase modulation. After explaining the configuration and operating principle of our proposed method in detail, we report the design of some operating parameters and preliminary experimental results to show the effectiveness of the method. 4×8 and 4×10 Gbit/s optical OFDM signals were successfully demultiplexed in the time-domain with our proposed method.

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2. Configuration, Operating Principle, and Operating Parameters

2.1 Configuration and Operating Principle

Figure 1 shows a schematic and operating principle of a tunable optical OFDM demultiplexer, which comprises a phase modulator and a tunable chromatic dispersion compensator. The phase modulator and chromatic dispersion compensator provide the OFDM signal with periodic frequency chirping (angular frequency chirp rate: K) of period (time slot of the OFDM symbol) T and group velocity dispersion D, respectively. D is expressed with the following equation.

$$D = -\frac{\lambda^2}{2\pi c}\sigma, \tag{1}$$

where λ, c, and σ are a wavelength, light speed in the vacuum, and chromatic dispersion, respectively. The periodic frequency chirping is provided for the OFDM signal by applying the periodic quadratic waveform to the phase modulator. In Fig. 1, when we denote an input signal into the tunable demultiplexer by $p(t)$ (t: time), an output signal $q(t)$ of the demultiplexer is expressed with the following equation [11], [12].

$$q(t) = A\int_{-\infty}^{\infty} p(t')\exp\left(j\frac{Kt'^2}{2}\right)\exp\left[-\frac{j}{2D}(t-t')^2\right]dt', \tag{2}$$

where A and j are a constant and an imaginary unit, respectively. Then, when D and K satisfy the following condition

$$D = \frac{1}{K}, \tag{3}$$

the output signal $q(t)$ of Eq. (2) is transformed into the following equation.

$$q(t) = A\exp\left(-j\frac{Kt^2}{2}\right)\int_{-\infty}^{\infty} p(t')\exp\left(j\frac{t}{D}t'\right)dt'. \tag{4}$$

Equation (4) indicates that $q(t)$ is time-domain Fourier transform of the input signal $p(t)$ [11], [12]. The Fourier transform is indispensable for demultiplexing the OFDM signal [1]–[6]. Although the term $\exp(-jKt^2/2)$ in Eq. (4) shows that the output signal has frequency chirping, we do not have to compensate for this chirping. Since we assume that the demultiplexer in Fig. 1 is used at the receiver, the chirping does not deteriorate the signal. As shown in Fig. 1, the OFDM signal spectrum, whose sub-carrier frequency spacing is defined as Δf ($= 1/T$), is transformed into a Nyquist time-division multiplexing (TDM) pulse with the Fourier transform of Eq. (4), whose time spacing Δt is denoted by the following equation [13], [14].

$$\Delta t = \frac{2\pi\Delta f}{K}. \tag{5}$$

Thus the OFDM sub-carrier channels can be demultiplexed in the time-domain. As the angular frequency chirp rate K

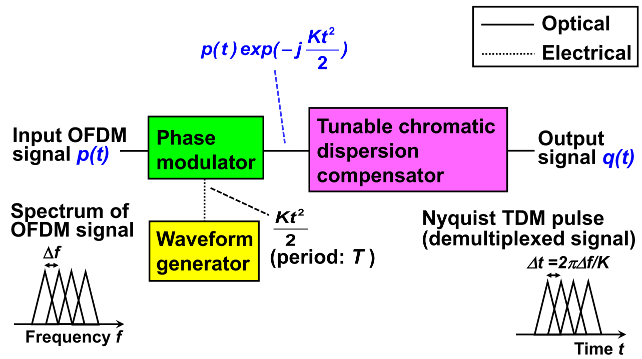


Fig. 1 Schematic and operating principle of tunable optical OFDM demultiplexer.

or the group velocity dispersion D can flexibly be tuned, the demultiplexer can process the OFDM signal with wide range of capacity.

When we define the periodic quadratic phase shift $Kt^2/2$ of period T as $x(t)$, $x(t)$ is expanded with the following Fourier series.

$$x(t) = \frac{KT^2}{24} + \frac{KT^2}{2\pi^2}\sum_{k=1}^{\infty}\frac{(-1)^k}{k^2}\cos(k2\pi\Delta f t). \tag{6}$$

We utilize the first two cosine terms for simply generating approximate quadratic waveform to drive the phase modulator. This corresponds to the use of two synchronized signal generators SG1 and SG2, whose frequencies are Δf and $2\Delta f$, respectively. The amplitude ratio and phase difference between the two generators must be set to 4:1 and π, respectively. When we denote the voltage amplitude of SG1 and the half-wave voltage of the phase modulator by V_1 and V_π, respectively, the following relation must be fulfilled with regard to Eq. (6).

$$\frac{V_1}{V_\pi}\pi = -\frac{KT^2}{2\pi^2}. \tag{7}$$

From Eqs. (1), (3), and (7), the relation between the chromatic dispersion σ and V_1 is obtained as follows.

$$\sigma = \frac{cV_\pi}{\pi^2\lambda^2\Delta f^2 V_1}. \tag{8}$$

The demultiplexing of various symbol rate and number OFDM sub-carriers is possible within the realizable range of the parameters σ and V_1.

2.2 Operating Parameters

By using Eq. (8), we calculated the specific relation between the chromatic dispersion σ of the tunable compensator and the SG1 voltage amplitude normalized by the modulator half-wave voltage V_1/V_π. The results, when changing the sub-carrier channel spacing Δf of the optical OFDM signal, are shown in Fig. 2. The wavelength λ used for the calculation was 1552.524 nm. Figure 2 is useful in determining the specific operating parameters V_1 and σ of the tunable optical OFDM demultiplexer in Fig. 1.

Figure 3 shows the calculated maximum number of usable channels versus channel spacing Δf with regard to the OFDM sub-carriers. We derived the maximum channel number to satisfy the condition that the demultiplexed Nyquist TDM pulses had to fit the confines of the OFDM symbol time slot T. We assumed that the time lens-based optical Fourier transform was ideally carried out, namely, the phase modulator was completely driven with the quadratic waveform over the entire time slot T, and the chromatic dispersion compensator did not contain group delay ripples. The Δf was changed at 1 GHz intervals. The wavelength used for the calculation was 1552.524 nm. We assume that we use an optical gate to demultiplex the Nyquist TDM pulse of the tunable demultiplexer output in the time-domain. In Fig. 3, we used time spacing of the Nyquist TDM pulse Δt, which was indicated in Eq. (5), as parameters, and set Δt to 5 to 30 ps. A non-linear optical loop mirror or electro-absorption modulator-based optical gate, whose gate opening time was 1.1 [14] or 2.3 ps [15], respectively, was reported. Therefore, the above-mentioned Δt values are realistic. The value V_1/V_π, or the chromatic dispersion σ, which relates to the realization of the above-mentioned Δt range, is 3.07×10^{-1} (Δt: 30 ps, Δf: 11 GHz) to 4.05 (Δt: 5 ps, Δf: 5 GHz), or 24.9 (Δt: 5 ps, Δf: 25 GHz) to 746.3 ps/nm (Δt: 30 ps, Δf: 5 GHz), respectively. Figure 3 can be utilized to determine the parameters of an optical OFDM communication system, in which the tunable demultiplexer in Fig. 1 is used.

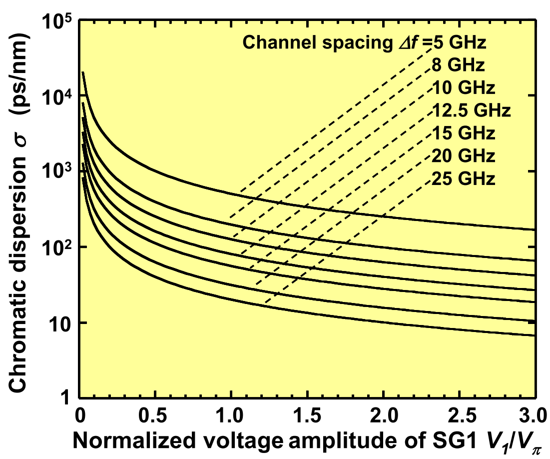


Fig. 2 Relation between chromatic dispersion σ and SG1 voltage amplitude normalized by modulator half-wave voltage V_1/V_π.

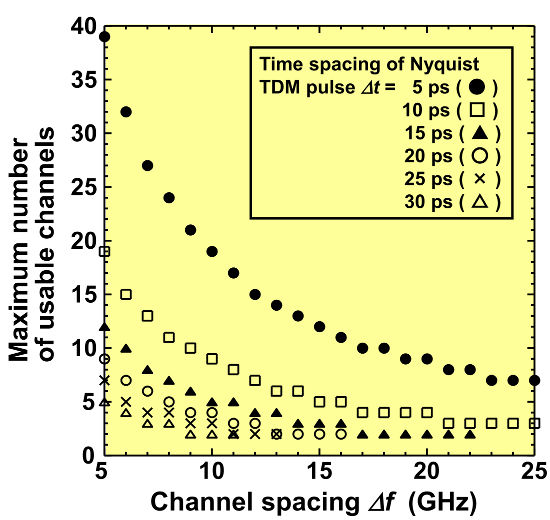


Fig. 3 Maximum number of usable channels versus channel spacing with regard to OFDM sub-carriers.

3. Experimental Results

Figure 4 shows the specific configuration of the tunable optical OFDM demultiplexer based on the time lens method. The demultiplexer consists of a $LiNbO_3$ (LN) phase modulator and a fiber Bragg grating (FBG)-type tunable optical chromatic dispersion compensator [16]. The bandwidth, half-wave voltage V_π, and loss of the used phase modulator were 32.0 GHz, 4.1 V, and 2.3 dB, respectively. The chromatic dispersion tuning range, dispersion setting resolution, bandwidth, and loss of the tunable dispersion compensator were ±400 ps/nm, 5ps/nm, 80 GHz, and 3.4 dB, respectively. Based on the investigation in Chapter 2, we utilized two synchronized signal generators SG1 (frequency: Δf) and SG2 (frequency: $2\Delta f$) for driving the phase modulator, which have prescribed amplitude ratio 4:1 and phase difference π.

Figure 5 shows the experimental set-up we used to carry out preliminary evaluation of the tunable OFDM demultiplexer in Fig. 4. After we generated optical frequency combs with 8 or 10 GHz spacing by modulating a lightwave phase of a distributed-feedback (DFB) laser diode (LD) (wavelength: 1552.54 nm) with a sinusoidal wave, we selected four flat line spectra with a variable bandwidth and rectangular-shaped bulk-optic filter. Then we modulated even and odd channels, which were divided by a bulk-optic interleave filter with tunable free spectral range (FSR) char-

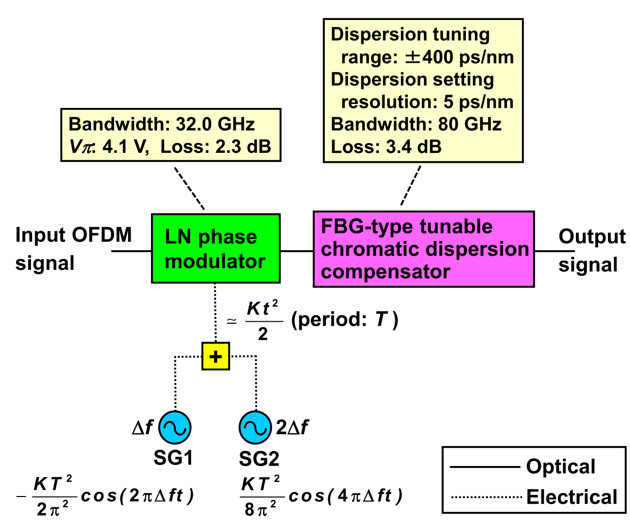


Fig. 4 Specific configuration of tunable optical OFDM demultiplexer.

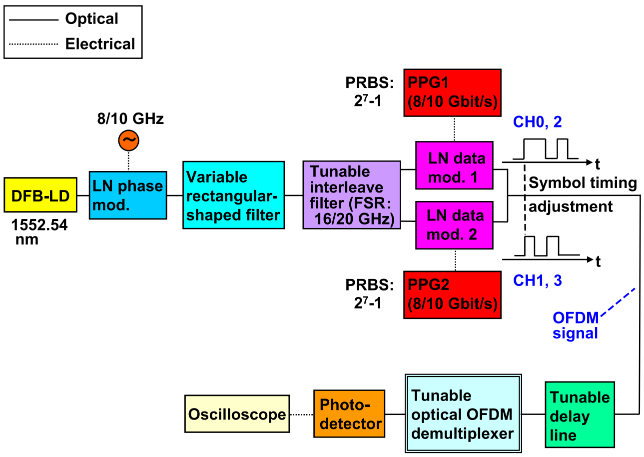
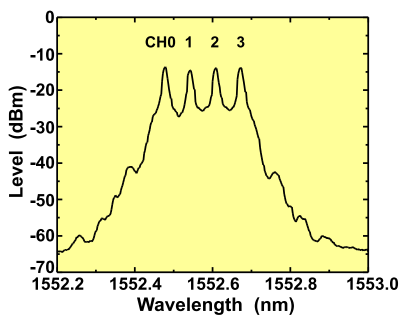
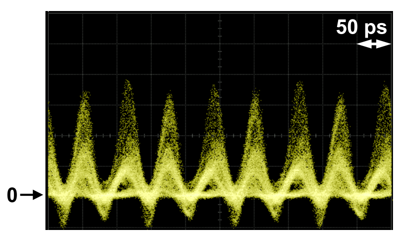


Fig. 5 Experimental set-up to evaluate tunable OFDM demultiplexer.



(a)



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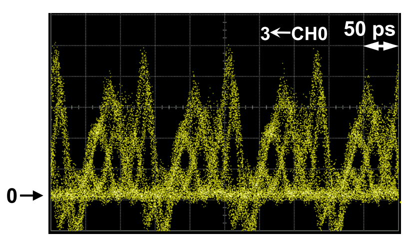
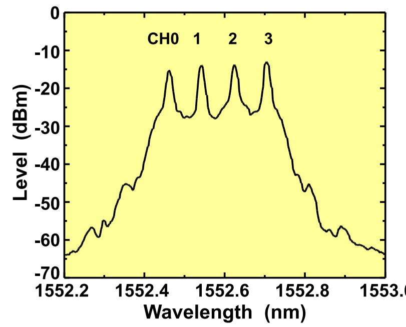


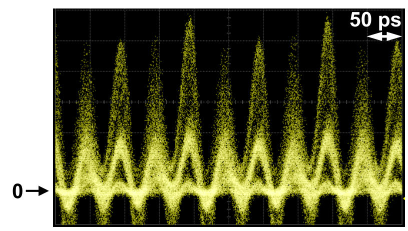
(c)

Fig. 6 Measured (a) spectrum and (b) eye diagram of 4×8 Gbit/s OFDM signal, and (c) eye diagram of demultiplexed sub-carrier channels.

acteristics, with two LN intensity data modulators. The intensity modulators were driven with two different sequences of 8 or 10 Gbit/s NRZ on-off keying (OOK) data from two pulse pattern generators (PPGs) so that adjacent channels were decorrelated. The pseudo-random bit sequence



(a)



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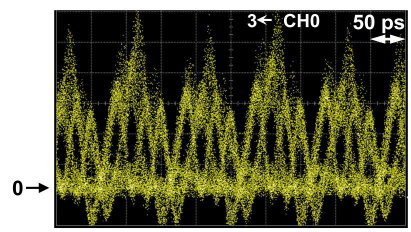

(c)

Fig. 7 Measured (a) spectrum and (b) eye diagram of 4 × 10 Gbit/s OFDM signal, and (c) eye diagram of demultiplexed sub-carrier channels.

(PRBS) of both data was $2^7 - 1$. The two PPGs were synchronized with a signal generator for driving the phase modulator. With a view to producing an OFDM signal, the two sets of modulated lights were combined after adjusting their symbol timing by tuning the RF phase difference between the PPG outputs. The OFDM signal after passing through a tunable bulk-optic delay line was introduced into the tunable OFDM demultiplexer shown in Fig. 4, and demultiplexed sub-carrier channels were evaluated with a sampling oscilloscope after the optic-electric conversion at a photo-detector. The delay line was used to adjust the timing between the OFDM signal and the phase modulation carried out in the demultiplexer. The SG1 and SG2 in Fig. 4 were synchronized to the PPGs in Fig. 5.

Figures 6 and 7 show measured spectra and eye diagrams of OFDM signals, and eye diagrams of demultiplexed sub-carrier channels with regard to 4 × 8 and 4 × 10 Gbit/s OFDM signals, respectively. In Figs. 6(a) and 7(a), the spectra deviate from the ideal rectangular shape of the OFDM signal because, in our all-optical OFDM communication experiments, we utilized the sub-carriers modulated with OOK signals and the OOK signals caused the comb-like spectral shapes. The intensity deviations among four OFDM sub-carrier spectra were 0.9 and 2.3 dB in Figs. 6(a) and 7(a), respectively. We conclude, from Figs. 6(c) and 7(c), that the frequency-domain sub-carrier channels were clearly demultiplexed into the time-domain channels. The parameters V_1/V_π, K, and σ used for demultiplexing, and the time spacing Δt, which was estimated from K and Eq. (5), are summarized in Table 1. The products of K and D were 0.998 and 0.984 for 8 and 10 Gbit/s sub-carrier demultiplexing, respectively. These results indicate that the relation between K and D shown in Eq. (3) was well satisfied in both cases. The measured Δt also agreed well with the prospective values described in Table 1. The Q-factors and bit error rates (BERs) of demultiplexed 8 and 10 Gbit/s channels were evaluated from the measured characteristics in Figs. 6(c) and 7(c), respectively, by using the following equations [17].

$$Q = \frac{\mu_1 - \mu_0}{\sigma_1 + \sigma_0}, \quad (9)$$

$$BER = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right) = \frac{1}{\sqrt{\pi}} \int_{\frac{Q}{\sqrt{2}}}^{\infty} e^{-t^2} dt, \quad (10)$$

where μ_i and σ_i ($i = 0, 1$) are average amplitude and an amplitude standard deviation of mark i, respectively. As we did not carry out the optical gating for complete sub-carrier demultiplexing and direct BER measurement, we estimated the Q-factors and BERs assuming that the following ideal conditions were satisfied. One condition was that the gating procedure was completely carried out by using the optical gate with realistic 10 ps opening time [14], [15]. The others were that the distribution of mark and space samples followed Gaussian statistics, and that the BER measurement decision level was optimized. The obtained Q factors and BERs are summarized in Tables 2(a) and (b) for demultiplexed 8 and 10 Gbit/s sub-carrier channels, respectively. The estimated BERs were less than or equal to 2.8×10^{-6} and below the forward error correction (FEC) limit (3.8×10^{-3}) in all the channels. The obtained results from Figs. 6 and 7, and Tables 2 confirm that the tunable demultiplexing operation with regard to the optical OFDM signal was preliminarily and successfully achieved with our proposed method that utilized the time lens-based optical Fourier transform having simple approximation of the quadratic waveform.

Table 1 Summary of used parameters and estimated time spacing.

OFDM signal (Gbit/s)	Normalized voltage amplitude V_1/V_π	Angular frequency chirp rate K (ps^{-2})	Chromatic dispersion σ (ps/nm)	Time spacing between demultiplexed channels Δt (ps)
4 x 8	5.46 x 10^{-1}	-2.17 x 10^{-3}	360	23.2
4 x 10	4.43 x 10^{-1}	-2.75 x 10^{-3}	280	22.9

Table 2 Summary of estimated Q factors and BERs for demultiplexed (a) 8 Gbit/s and (b) 10 Gbit/s sub-carrier channels.

(a)

Channel number	Average optical intensity (dBm)	Q-factor (dB)	BER
0	-8.8	15.9	2.1 x 10^{-10}
1	-10.6	13.9	3.2 x 10^{-7}
2	-8.2	15.9	1.8 x 10^{-10}
3	-9.5	14.5	4.8 x 10^{-8}

(b)

Channel number	Average optical intensity (dBm)	Q-factor (dB)	BER
0	-8.4	13.3	1.8 x 10^{-6}
1	-8.9	13.1	2.8 x 10^{-6}
2	-5.9	13.8	5.3 x 10^{-7}
3	-6.9	13.9	3.3 x 10^{-7}

4. Conclusion

We proposed and demonstrated a demultiplexing method of a variable capacity optical OFDM signal, which utilizes time lens-based optical Fourier transform. The tunable demultiplexer is composed of an LN phase modulator and an FBG-type tunable optical chromatic dispersion compensator. We also showed a simple approximation and generation method of the quadratic waveform required for driving the phase modulator. This method used two synchronized signal generators whose frequencies were equal to and twice the frequency spacing of the OFDM sub-carrier channels. With a view to showing the effectiveness and preliminary operation of our proposed method, we successfully carried out experiments to demultiplex 4×8 and 4×10 Gbit/s optical OFDM signals. The estimated bit error rates were below the FEC limit in all the channels.

As our proposed method concentrates on the direct tunable demultiplexing of optical OFDM sub-carrier channels in the optical domain, it does not have other functions including demodulation of a sub-carrier signal with a higher-order modulation format and dispersion compensation, which digital signal processing (DSP) of the coherent optical communication system equips. However, we think that the method potentially has an advantage that its processing speed is higher than the DSP. The progress of the future hybrid integrated-photonic technology may mitigate the configuration complexity of the method.

Acknowledgments

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