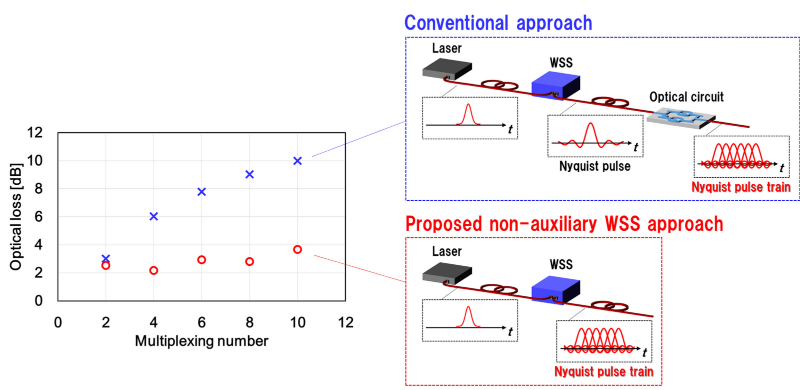
IEEE Photonics Journal
An IEEE Photonics Society Publication

Open Access

Low-Loss Optical Nyquist Pulse Train Generation Using Nonauxiliary Wavelength Selective Switch in Communication Band

Volume 11, Number 2, April 2019

Koji Takahashi
Yu Yamasaki
Takashi Inoue
Tsuyoshi Konishi, ***Member, IEEE***



DOI: 10.1109/JPHOT.2019.2905687
1943-0655

Low-Loss Optical Nyquist Pulse Train Generation Using Nonauxiliary Wavelength Selective Switch in Communication Band

Koji Takahashi, [1,2] **Yu Yamasaki**, [1] **Takashi Inoue**, [2] **and Tsuyoshi Konishi**, [1] ***Member, IEEE***

[1]Graduate School of Engineering, Osaka University, Osaka 565-0871, Japan
[2]Central Research Laboratory, Hamamatsu Photonics K. K., Shizuoka 434-8601, Japan

DOI:10.1109/JPHOT.2019.2905687

Manuscript received January 31, 2019; revised March 1, 2019; accepted March 12, 2019. Date of publication March 19, 2019; date of current version April 1, 2019. This work was supported by the Adaptable and Seamless Technology Transfer Program through Target-Driven R&D, Japan Science and Technology Agency. Corresponding author: Koji Takahashi (e-mail: koji.takahashi@crl.hpk.co.jp).

Abstract: We report low-loss optical Nyquist pulse train generation using a non-auxiliary wavelength selective switch (WSS). The typical approach for optical Nyquist pulse train generation involves two procedures. The first is conversion from a laser output Gaussian pulse to a Nyquist pulse via spectral filtering with a WSS. The second is multiplexing to generate a Nyquist pulse train with an optical circuit. To generate a high optical signal-to-noise ratio (OSNR) Nyquist pulse train, the first procedure was improved by developing a high-power laser and improving the filtering process by using nonlinear effects in a highly nonlinear fiber. The second procedure also has the potential to further improve the OSNR, because an optical circuit typically causes an optical loss of 9 dB in the case of eight-multiplexing. In this study, we demonstrate optical loss reduction for multiplexing using a nonauxiliary WSS approach without an auxiliary optical circuit. The experimental results show that the optical loss for the Nyquist eight-pulse train is successfully reduced to 2.8 dB.

Index Terms: Nyquist pulse, wavelength selective switch, pulse shaping, filtering algorithm.

1. Introduction

Optical Nyquist pulses have attracted much attention in recent years in the field of optical communication and optical signal processing [1]–[8]. Optical Nyquist pulses have remarkable properties such as a high bandwidth efficiency and the absence of inter-symbol interference (ISI), which can generate a more densely arranged optical pulse train in the time-domain compared with Gaussian and sech^2 type pulses. The densely arranged pulse train is suitable for high-speed optical time-division multiplexing (OTDM) transmission [1], [3], [5]–[7] and high-rate optical sampling [8].

The common method of generating a densely arranged optical Nyquist pulse train involves two procedures [1]. First, the spectral shape of a laser output is filtered into the raised-cosine type and converted to a Nyquist pulse. A wavelength selective switch (WSS) is used for the filtering [9]. Second, the converted single Nyquist pulse is multiplexed so that the pulse interval matches the Nyquist period to generate a densely arranged Nyquist pulse train. An optical circuit is used for multiplexing.

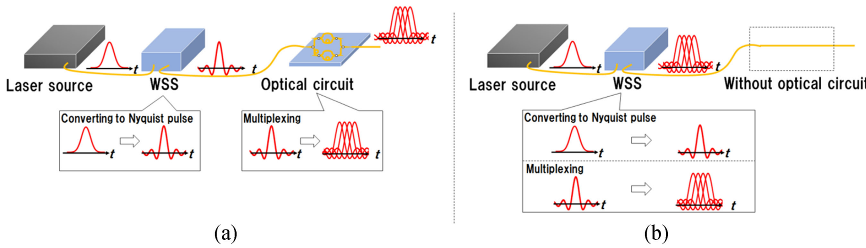


Fig. 1. Schematic of conventional and proposed approach: (a) Conventional approach with optical circuit, (b) Our approach without optical circuit.

It is important to consider the output power of a laser source and total optical losses of a generation system in order to generate an optical Nyquist pulse train with a high optical signal-to-noise ratio (OSNR); hence, the first procedure has been modified. A hydrogen cyanide frequency-stabilized mode locked fiber laser with a high output power has been developed [10]. Further, a highly nonlinear fiber has been introduced before a WSS for broadening the spectral width of a laser output Gaussian pulse to generate a shorter Nyquist pulse [11], [12]. This leads to lower optical loss caused by spectral filtering with a WSS.

In addition to the first procedure, the second procedure also has the potential to improve the OSNR because an optical circuit typically causes optical losses of 3 dB at each coupling point. From this perspective, a non-auxiliary WSS approach which we have proposed can avoid the use of an auxiliary optical circuit because the WSS enables multiplexing as well as spectral filtering [13]. It was demonstrated in the near-infrared band using a WSS based on a liquid crystal on silicon-spatial light modulator (LCOS-SLM) to integrate Nyquist probe pulse train generation system not to use any bulky optical elements for multiplexing.

In this paper, we introduce a non-auxiliary WSS approach in the optical-communication band to improve optical losses caused by multiplexing. We experimentally demonstrate Nyquist pulse train generation with a non-auxiliary WSS and evaluate the optical losses depending on the multiplexing number by generating trains with a pulse number up to 10.

2. Method

The method of generating a Nyquist pulse train with a non-auxiliary WSS is described in this section. A schematic of the conventional and the proposed approach is shown in Fig. 1. The difference between the proposed and conventional approach is with or without an optical circuit. In the proposed approach, a filter function of a WSS both converts a pulse to a Nyquist pulse and performs multiplexing to avoid the use of an auxiliary optical circuit. We have proposed a unique method to design a filter function for low-loss Nyquist pulse train generation that utilizes the ISI-free property of Nyquist pulses [13]. The method of design is described below.

The amplitude spectrum of a single Nyquist pulse is defined by following equation [1].

$$R(\omega) = \begin{cases} 1, & 0 \leq \left|\dfrac{\omega}{2\pi}\right| \leq \dfrac{1-\alpha}{2T} \\ \frac{1}{2}\left\{1 - \sin\left[\dfrac{\pi}{2\alpha}\left(\dfrac{T}{\pi}|\omega| - 1\right)\right]\right\}, & \dfrac{1-\alpha}{2T} \leq \left|\dfrac{\omega}{2\pi}\right| \leq \dfrac{1+\alpha}{2T} \\ 0, & \left|\dfrac{\omega}{2\pi}\right| \geq \dfrac{1+\alpha}{2T} \end{cases}, \tag{1}$$

where α is the roll-off factor, T is the periodic interval of zero-crossing points, and ω is the angular frequency. The complex-amplitude spectrum of a densely arranged Nyquist pulse train $A_{NPT}(\omega)\exp[i\ \ \phi_{NPT}(\omega)]$ is expressed by the product of (1) and the function for generating a pulse train $A_{train}(\omega)\exp[i\ \ \phi_{\mathrm{train}}(\omega)]$. The most simple way to obtain $A_{train}(\omega)$ and $\phi_{\mathrm{train}}(\omega)$ is Fourier transformation of temporally separated delta functions [14], [15], as shown in the following equation.

$$A_{train}(\omega) = \left| \sum_{k=1}^{N} \exp\left[i\tau_k\left(\omega - \omega_0\right)\right] \right|, \tag{2}$$

$$\varphi_{train}(\omega) = \mathrm{Arg}\left(\sum_{k=1}^{N} \exp\left[i\tau_k\left(\omega - \omega_0\right)\right] \right), \tag{3}$$

$$\tau_k = (k - N/2 - 1/2)\,\Delta t,$$

where N is the multiplexing number of a train, τ_k is the delay time of each pulse, Δt is the pulse interval, ω_0 is the center angular frequency, and k is a positive integer that takes values from 1 to N. The filter function for generating a Nyquist pulse train *Filter* (ω) is obtained by using (2) and (3) as follows.

$$Filter(\omega) = \frac{A_{NPT}(\omega)\exp\left[i\varphi_{NPT}(\omega)\right]}{A_{in}(\omega)\exp\left[i\varphi_{in}(\omega)\right]} = \frac{R(\omega)\left|\sum_{k=1}^{N}\exp\left[i\tau_k\left(\omega-\omega_0\right)\right]\right|\exp\left[i\mathrm{Arg}\left(\sum_{k=1}^{N}\exp\left[i\tau_k\left(\omega-\omega_0\right)\right]\right)\right]}{A_{in}(\omega)\exp\left[i\varphi_{in}(\omega)\right]}, \tag{4}$$

where $A_{in}(\omega)\exp[i\,\phi_{in}(\omega)]$ is the complex amplitude spectrum of the pulse input to a WSS.

However, when using (4), the optical loss increases as N increases similar to that in an optical circuit; thus, it is not possible to reduce the loss even if only a WSS is used. To resolve this problem, we have proposed a new filter function obtained by considering the phase combination of the delta functions. For a Nyquist pulse train in which T and Δt are equal, the pulses in the train do not interfere with the other pulses due to the ISI-free property. Therefore, even though any phase combinations are used, the intensity of each pulse after multiplexing is retained. In the case of phase combination, (4) is modified as follows.

$$Filter(\omega) = \frac{R(\omega)\left|\sum_{k=1}^{N}\exp\left[i\tau_k\left(\omega-\omega_0\right)+\varphi_k\right]\right|\exp\left[i\mathrm{Arg}\left(\sum_{k=1}^{N}\exp\left[i\tau_k\left(\omega-\omega_0\right)+\varphi_k\right]\right)\right]}{A_{in}(\omega)\exp\left[i\varphi_{in}(\omega)\right]}, \tag{5}$$

where ϕ_k is the phase of the k-th pulse. Since the filter function varies depending on the phase combination, the loss is also dependent on that. Therefore, a low-loss filter function can be designed by determining the optimal phase combination.

The method for designing the filter function described above can use any variable N, T, Δt, α, and ω_0, which means the method is highly flexible with regard to the pulse-train parameters.

3. Simulation

The reduction in optical losses with the non-auxiliary WSS approach compared with that of an optical circuit in the communication band was simulated. The filter functions for generating Nyquist pulse trains based on the proposed design method were established and the optical loss due to multiplexing was evaluated. The Nyquist pulse train parameters were set as follows to verify the pulse-number dependence of the loss: $N = 2, 4, 6, 8, 10$; $T = 10$ ps; $\Delta t = 10$ ps; $\alpha = 0.5$; and $\lambda_0 = 1561.96$ nm. Here, λ_0 is center wavelength. Then, the five filter functions for each N value were calculated.

To find the optimal phase combination of ϕ_k, all the phase combinations were searched in the step of $2\pi/32$ according to the following five steps. (i) The values of ϕ_k were set from the values of $2\pi/32 \times m$ (m: integer from 0 to 31). Here, ϕ_k was set to be equal to ϕ_{N-k+1} to reduce the calculation cost of searching. Under the condition, the number of phase combination to be searched was $32^{N/2}$ for the N-Nyquist pulse train. (ii) The set values of ϕ_k were substituted into the numerator of (5) to obtain the intensity spectrum of the Nyquist pulse train. (iii) Using the obtained intensity spectrum, the amount of the loss caused by multiplexing, which is equivalent to the spectral area ratio of the single Nyquist pulse and the Nyquist pulse train, was calculated. (iv) The values of ϕ_k were set to

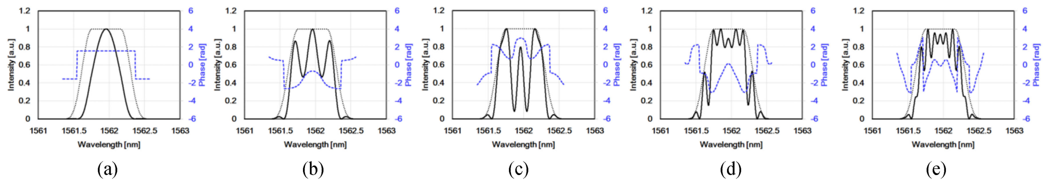


Fig. 2. Simulated spectral waveforms of optical Nyquist pulse trains: (a) $N = 2$, (b) $N = 4$, (c) $N = 6$, (d) $N = 8$, and (e) $N = 10$. The dotted black line shows the intensity of the single Nyquist pulse, the solid black line shows the intensity of the Nyquist pulse train, and the dashed blue line shows the phase of the Nyquist pulse train.

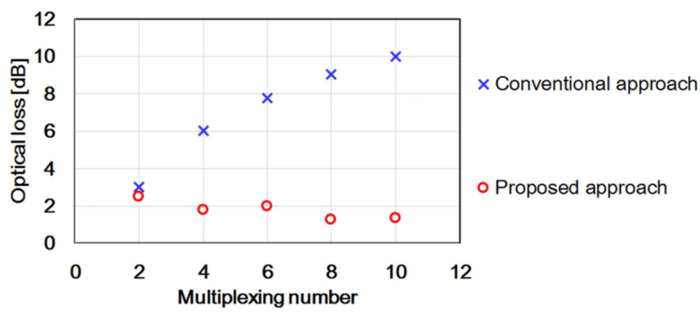


Fig. 3. Simulated optical loss due to multiplexing for pulse trains of different N values. The red circles show the loss for the proposed approach and the blue crosses show the loss for the conventional approach with an optical circuit.

different values and the step (ii) and (iii) were repeated until all phase combinations were searched. (v) The values of ϕ_k with the lowest loss were determined as the optimal values of ϕ_k. The obtained phase combinations for each N value were as follows: $\phi_k = \{1.57, 1.57$ rad$\}$ for $N = 2$, $\phi_k = \{1.57, 6.09, 6.09, 1.57$ rad$\}$ for $N = 4$, $\phi_k = \{4.91, 0.00, 3.53, 3.53, 0.00, 4.91$ rad$\}$ for $N = 6$, $\phi_k = \{1.77, 5.89, 0.00, 4.52, 4.52, 0.00, 5.89, 1.77$ rad$\}$ for $N = 8$, and $\phi_k = \{4.91, 0.39, 2.56, 3.93, 3.93, 3.93, 3.93, 2.56, 0.39, 4.91$ rad$\}$ for $N = 10$. The maximum value of N is 10 so far, which is limited by the calculation cost.

The spectral waveforms of the Nyquist pulse trains were calculated using the optimized phase combinations, and the results are shown in Fig. 2. To understand the filtering process, the intensity spectrum of a single Nyquist pulse is also shown in Fig. 2. The optical losses due to multiplexing were calculated for each N value, and the results are shown in Fig. 3. The optical losses that occur when using an optical circuit, which are $3.01 \times \log_2(N)$ dB corresponding to 3.01 dB at each coupling point, are also shown in Fig. 3 for comparison. The figure shows that the proposed method reduces the optical losses compared to the conventional method for all values of N. The optical loss for an eight-pulse train is reduced to 1.25 dB from 9.03 dB.

The temporal waveforms of the Nyquist pulse trains were evaluated to determine if the intensity of each pulse is maintained after multiplexing, as per the theory. The temporal waveforms were obtained using the inverse Fourier transform of the spectral waveforms shown in Fig. 2. The results are shown in Fig. 4. The circles in the graphs highlight the intensities at the peaks of the pulses in the trains. Figure 4 shows that the intensities at the peaks are constant, which means that the intensity of each pulse is retained because of the ISI-free property, as per the theory.

4. Experiment

Nyquist pulse trains were generated with a non-auxiliary WSS using optimally designed filter functions, and the dependency of optical losses on the multiplexing number in the communication band was experimentally evaluated. The experimental setup and the results are described below.

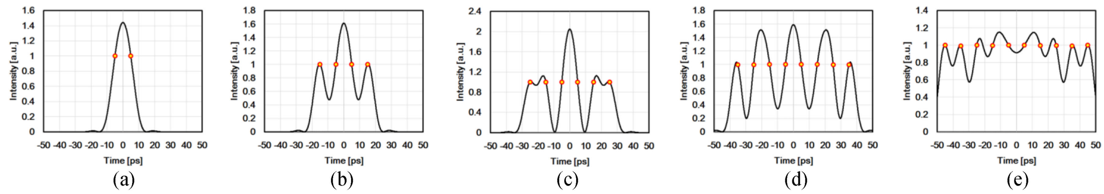


Fig. 4. Simulated temporal waveforms of optical Nyquist pulse trains: (a) $N = 2$, (b) $N = 4$, (c) $N = 6$, (d) $N = 8$, and (e) $N = 10$. The circles highlight the intensities at the peaks of each pulse in the train.

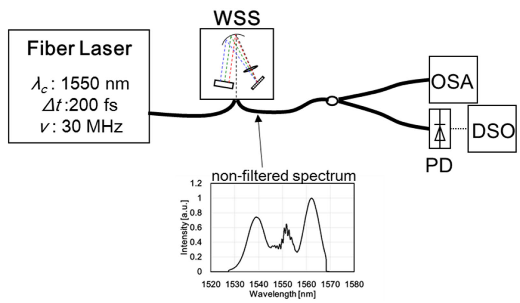


Fig. 5. Schematic of experimental setup: WSS: wavelength selective switch; OSA: optical spectrum analyzer; PD: photo detector; DSC: digital sampling oscilloscope. The spectrum is the output spectrum obtained from the WSS without filtering.

4.1 Experimental Setup

The experimental setup is shown in Fig. 5. A broadband fiber laser (Calmar, FPL-M2CFF-OSU-01) with a center wavelength of 1550 nm, pulse width of 200 fs, and repetition rate of 30 MHz was used as the light source. The output of the laser was incident onto a WSS (Finisar, WaveShaper 1000 S) and the Nyquist pulse train was generated by spectral modulation based on the filter function designed using the method described in Section 2. The specification of the WSS as follows: the bandwidth was 1527.4–1567.5 nm, the spectral resolution was 0.08 nm, and the insertion loss was 3.89 dB. The intensity spectrum of the generated Nyquist pulse train was measured with an optical spectrum analyzer (OSA) with a spectral resolution of 0.01 nm. The temporal waveform was measured with a measurement system composed of a 53-GHz photodetector (PD) and 63-GHz digital sampling oscilloscope (DSO).

4.2 Experimental Results

Nyquist pulse trains were generated with different values of N for evaluating the optical loss and the accuracy of the generated waveforms. The Nyquist pulse train parameters were the same as those used in the simulation. The filter functions were calculated based on (5). The optimized phase combinations from section 3 and the measured spectrum after the WSS was applied without filtering, which is shown in Fig. 5, were substituted for ϕ_k and $A_{in}(\omega)$, respectively. Here, $\phi_{in}(\omega)$ was assumed to be 0 because the total fiber length from the laser to the PD was 9 m, which had a minimal effect on the 10-ps Nyquist pulse waveform.

The intensity and phase spectra of the laser were modulated using the WSS based on the calculated filter function, and the filtered spectra were measured using the OSA. The measured and simulated spectra are shown in Fig. 6 for comparison. The measured spectra were normalized such that the areas of the simulated and measured spectra are equal. The RMS errors were 0.0035, 0.017, 0.027, 0.055, and 0.16 for $N = 2$, 4, 6, 8, and 10, respectively. The error increases with an increasing N value because finer spectral filtering is required for larger N values.

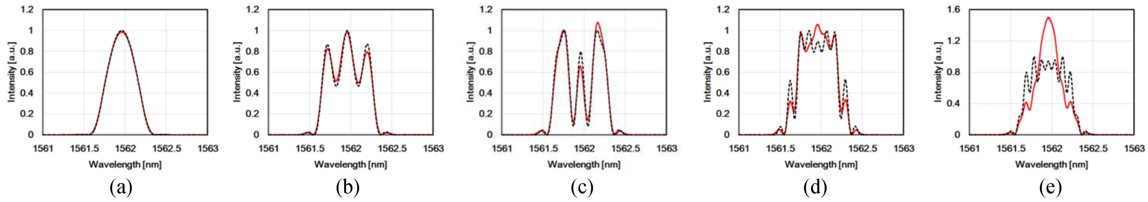


Fig. 6. Measured spectral waveforms of optical Nyquist pulse trains; (a) $N = 2$, (b) $N = 4$, (c) $N = 6$, (d) $N = 8$, and (e) $N = 10$. The solid red line shows the measured data and the dashed black line shows the simulated data.

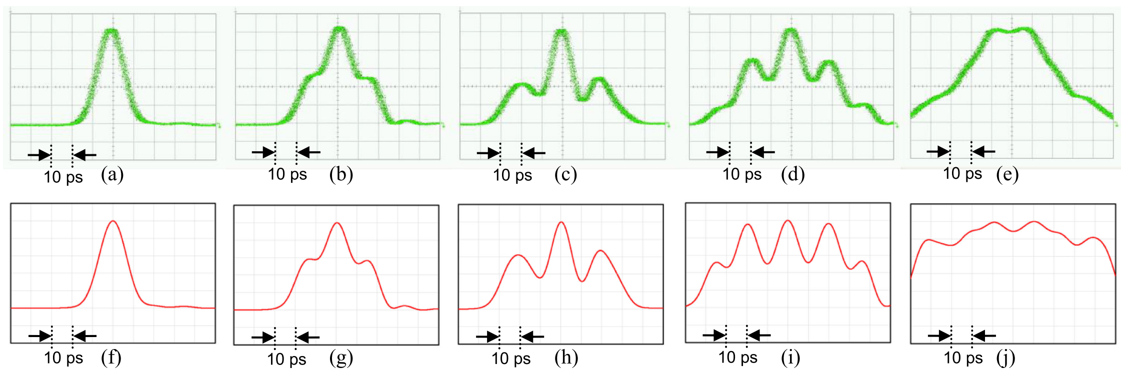


Fig. 7. Measured and calculated temporal waveforms of optical Nyquist pulse trains with the oscilloscope; measured waveforms for (a) $N = 2$, (b) $N = 4$, (c) $N = 6$, (d) $N = 8$, and (e) $N = 10$; calculated waveforms for (f) $N = 2$, (g) $N = 4$, (h) $N = 6$, (i) $N = 8$, and (j) $N = 10$.

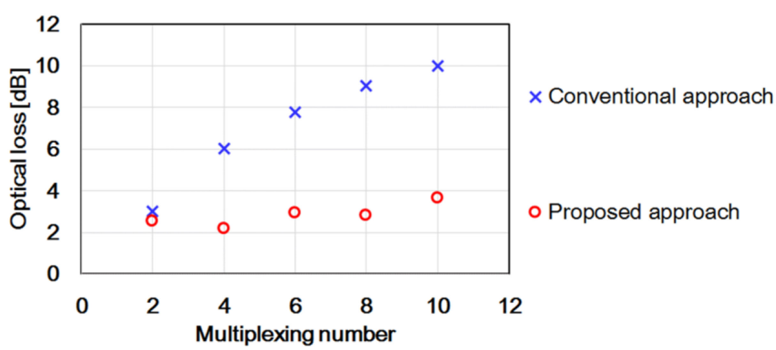


Fig. 8. Measured optical loss due to multiplexing for pulse trains with different N values. The red circles show the measured data and the blue crosses show the simulated loss for the conventional approach with an optical circuit.

The temporal waveforms of the generated Nyquist pulse trains were measured using the measurement system. The measured waveforms were a convolution of the actual waveforms and the impulse response function of the measurement system. To compare the measured waveforms with theoretical waveforms, the theoretically convoluted waveforms were determined using the measured impulse response function. The impulse response was measured using the shortest non-filtered pulse with a pulse width of 200 fs. The measured and calculated waveforms are shown in Fig. 7. The measured waveforms are mostly in agreement with calculated ones, which indicates that the Nyquist pulse trains were successfully generated.

The optical powers after the application of the WSS were measured and the optical losses due to multiplexing were determined. The results are shown in Fig. 8. The simulated optical losses that occurred when an optical circuit is used are also shown in Fig. 8 for comparison. The measured

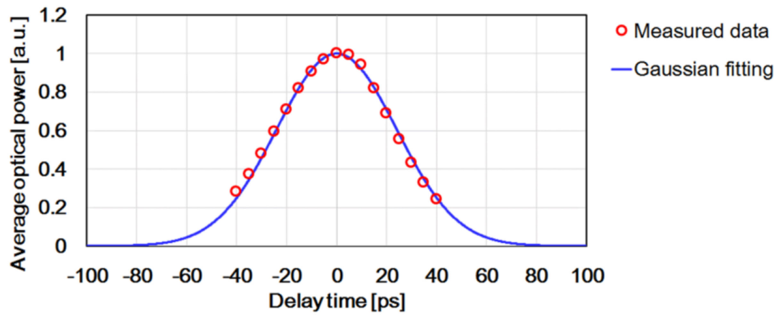


Fig. 9. Measured temporal window of the WSS. The red circles show the measured data and the blue solid line shows the Gaussian fitting curve.

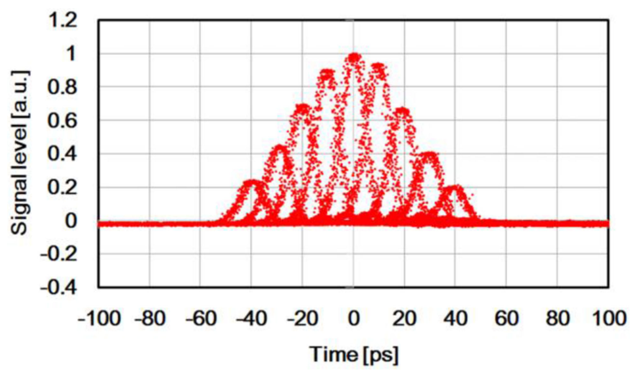


Fig. 10. Measured temporal waveforms of delayed pulses with delay time of −40 to 40 ps in 10-ps steps.

losses are decreased for all values of N. In the case of eight-multiplexing, the loss is reduced to 2.81 dB from 9.03 dB. These results show that the non-auxiliary WSS approach can be used to realize low-loss Nyquist pulse train generation despite an increase in the multiplexing number.

5. Discussion

The difference between the measured and simulated optical losses shown in Figs. 8 and 3, respectively, is discussed here. The difference increases with an increasing value of N due to a temporal window of the WSS. The temporal window attenuates the optical power of the pulses positioned in the edges of the temporal window. For larger values of N, the temporal positions of the first and the final pulses move to the edges, which means that the loss increases with increasing values of N. The effect of the temporal window on the optical losses depends on the width of the window, which is in inverse proportion to the spectral resolution [16]; hence, the impact of width of temporal window or the spectral resolution is discussed below.

To measure the width of the temporal window of the WSS used in the experiment, the average optical powers of the delayed single pulses with different delay time were measured. To delay the pulse, linear phase spectrum was applied to the WSS. The delay times were set from −40 to 40 ps in 5-ps steps. The measured powers are shown in Fig. 9. The red circles show the measured powers and the blue solid line shows the Gaussian fitting curve. From the width of the Gaussian, the width of the temporal window was found to be 57 ps. The temporal waveforms of the delayed single pulses were also measured using the measurement system to investigate the effects of the temporal window. The delay times were set from −40 to 40 ps in 10-ps steps. The nine-measured waveforms are plotted in the same graph shown in Fig. 10. The graph show that the delayed pulses are attenuated in accordance with the temporal window, which indicates that the 57-ps temporal window affects the optical losses in the case of 10-ps-interval Nyquist pulse trains.

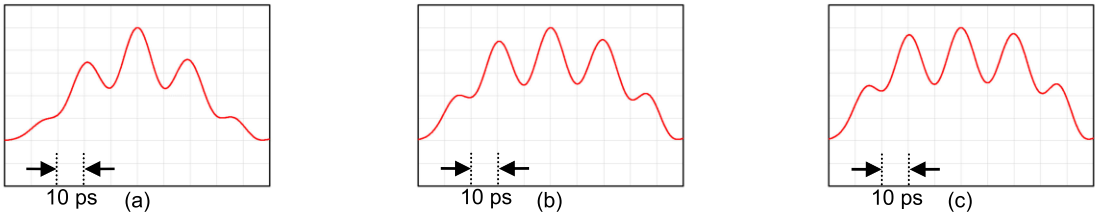


Fig. 11. Calculated temporal waveforms of eight-Nyquist pulse train considering a temporal window of a WSS with different width of (a) 57 ps, (b) 114 ps, and (c) 228 ps.

To investigate the dependency of the optical losses on the width of the temporal window, we simulated the three cases with the different width of 57, 114, and 228 ps, which cases correspond to the spectral resolution of 0.08, 0.04, and 0.02 nm, respectively. The three temporal waveforms of eight-Nyquist pulse train considering the temporal window were calculated. The calculated waveforms were obtained by multiplying the theoretical waveform shown in Fig. 4(d) and the temporal windows, and then convoluting the multiplied waveforms and the impulse response of the measurement system. The results are shown in Fig. 11. From Fig. 11, the calculated waveform considering the temporal window is approaching the ideal waveform shown in Fig. 7(i) as an increment of the width. The optical losses considering the window were also calculated, and results were 2.78, 1.69, 1.36 dB with the width of 57, 114, and 228 ps, respectively. The value of 2.78 dB with the 57-ps window is in good agreement with the experimental value of 2.81 dB, which indicates that the cause of the difference between the measured and simulated optical loss is the temporal window of the WSS. It is also found that a WSS with 228-ps temporal window realizes low-loss optical Nyquis pulse train generation as almost same level of the theoretical value of 1.25 dB.

To widen the width of the temporal window, a grating in a WSS should be more dispersive [9]. Although a more dispersive grating also reduce an overall bandwidth, the bandwidth of the WSS used here is sufficient to generate a Nyquist pulse with $T = 10$ ps. The customized WSS with a more dispersive grating can be used to fill the difference between the measured and simulated losses.

6. Conclusion

The optical losses for optical Nyquist pulse multiplexing with a non-auxiliary WSS in the communication band were successfully reduced. The non-auxiliary WSS approach does not use an auxiliary optical circuit, which causes optical losses, for multiplexing. Instead multiplexing is performed using a filter function for a WSS, which has an addition spectral filtering role in generating Nyquist pulses. Since the loss in the non-auxiliary WSS approach depends on the filter function, the filter function was optimized to reduce the loss using the proposed design method, which utilizes the ISI-free property of Nyquist pulses. The optical loss was reduced to 2.81 dB from 9.01 dB using the optimized filter function in the case of an eight-Nyquist pulse train. The difference between the experimental and simulated optical losses was due to the temporal window of the WSS. The loss can be reduced to a simulated value of 1.25 dB by using a customized WSS with a more dispersive grating. In addition to the other advantages of low loss and integration of the non-auxiliary WSS approach, the dispersion caused in an optical circuit does not have to be considered in this method, which is useful when using shorter Nyquist pulses.

References

[1] M. Nakazawa, T. Hirooka, P. Ruan, and P. Guan, “TDM transmission with an optical Nyquist pulse train,” *Opt. Express*, vol. 20, no. 2, pp. 1129–1140, 2012.

[2] M. A. Sato *et al.*, “Optical sinc-shaped Nyquist pulses of exceptional quality,” *Nature Commun.*, vol. 4, pp. 1–11, 2013.

[3] T. Hirooka, D. Seya, K. Harako, D. Suzuki, and M. Nakazawa, "Ultrafast Nyquist OTDM demultiplexing using optical Nyquist pulse sampling in an all-optical nonlinear switch," *Opt. Express*, vol. 23, no. 16, pp. 20858–20866, 2015.
[4] C. Cincotti *et al.*, "Flexible power-efficient Nyquist-OTDM transmitter, using a WSS and time-lens effect," in *Proc. Opt. Fiber Commun.*, 2015, paper W3C. 5.
[5] R. Schmogrow *et al.*, "512QAM Nyquist sinc-pulse transmission at 54 Gbit/s in an optical bandwidth of 3 GHz," *Opt. Express*, vol. 20, no. 6, pp. 6439–6447, 2012.
[6] J. Zhang, J. Yu, Y. Fang, and N. Chi, "High speed all optical Nyquist signal generation and full-band coherent detection," *Sci. Rep.*, vol. 4, 2014, Art. no. 6156.
[7] K. Harako, D. O. Otuya, K. Kasai, T. Hirooka, and M. Nakazawa, "High-performance TDM demultiplexing of coherent Nyquist pulses using time-domain orthogonality," *Opt. Express*, vol. 22, no. 24, pp. 29456–29464, 2014.
[8] M. Hiraoka *et al.*, "Power efficient optical serial-to-parallel conversion using fractional OFDM-based linear technique," *IEICE Electron. Express*, vol. 14, no. 6, pp. 1–8, 2017.
[9] M. A. F. Roelens *et al.*, "Dispersion trimming in a reconfigurable wavelength selective switch," *J. Lightw. Technol.*, vol. 26, no. 1, pp. 73–78, Jan. 2008.
[10] M. Yoshida, K. Yoshida, K. Kasai, and M. Nakazawa, "1.55 μm hydrogen cyanide optical frequency-stabilized and 10 GHz repetition-rate-stabilized mode-locked fiber laser." *Opt. Express*, vol. 24, no. 21, pp. 24287–24296, 2016.
[11] K. Kimura, J. Nitta, M. Yoshida, K. Kasai, T. Hirooka, and M. Nakazawa, "Single-channel 7.68 Tbit/s, 64 QAM coherent Nyquist pulse transmission over 150 km with a spectral efficiency of 9.7 bit/s/Hz." *Opt. Express*, vol. 26, no. 13, pp. 17418–17428, 2018.
[12] K. Harako, D. Seya, T. Hirooka, and M. Nakazawa, "640 Gbaud (1.28 Tbit/s/ch) optical Nyquist pulse transmission over 525 km with substantial PMD tolerance," *Opt. Express*, vol. 21, no. 18, pp. 21062–21075, 2013.
[13] K. Takahashi, K. Watanabe, T. Inoue, and T. Konishi, "Multifunctional wavelength-selective switch for Nyquist pulse generation and multiplexing," *IEEE Photon. Technol. Lett.*, vol. 30, no. 18, pp. 1641–1644, Sep. 2018.
[14] B. von Vacano, T. Buckup, and M. Motzkus, "*In situ* broadband pulse compression for multiphoton microscopy using a shaper-assisted collinear SPIDER," *Opt. Lett.*, vol. 31, no. 8, pp. 1154–1156, 2006.
[15] A. Galler and T. Feurer, "Pulse shaper assisted short laser pulse characterization," *Appl. Phys. B*, vol. 90, pp. 427–430, 2008.
[16] A. W. Weiner, "Ultrafast optical pulse shaping: A tutorial review," *Opt. Commun.*, vol. 284, no. 15, pp. 3669–3692, 2011.