Flexible and lossless baud-rate switching for 4-time slots Nyquist OTDM signals using wavelength selective switch

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Abstract We demonstrate a flexible and lossless baud-rate switching process of the Nyquist OTDM signals using a wavelength selective switch (WSS) equipped with 4 output ports for different time slots. We generate the Nyquist OTDM signals with different baud rates without using any static OTDM devices such as an optical circuit. The WSS-only configuration allows a flexible baud rate switching by changing the filter functions applied to the WSS. The proposed system can successfully switch among 40, 80 and 120-Gb/s signals with a switching duration of 80 ms.

key words: Nyquist pulse, wavelength selective switch, elastic network, filter function.

Classification: Optical hardware

1. Introduction

An elastic optical network with flexible frequency grid has garnered much attention as a means to satisfy the demands of rapidly increasing communication traffic [1, 2, 3]. In the elastic optical network, the frequency grid can adjust flexibly to the minimum required bandwidth for each wavelength-division multiplexing (WDM) signal. Therefore, the elastic optical network efficiently utilizes limited optical frequency resources and realizes ultra large capacity communication exceeding 1 Tbaud/s that usually requires a wide bandwidth. In addition, the use of flexible symbol rate is advantageous to accommodate various modulation schemes and different baud rate signals [4, 5]. A Wavelength Selective Switch (WSS) [6, 7, 8] is one of promising devices for handling flexi-grid add-drop WDM channels [9, 10, 11] and a baud rate variable transponder [12, 13, 14].

Nyquist optical time division multiplexing (OTDM)-WDM is one of the suitable communications methods for the elastic optical network because the rectangular spectral shape of a Nyquist pulse maximizes the spectral efficiency [15, 16]. Further, optical Nyquist OTDM transmission realizes ultra-high baud rate transmission due to the dense arrangement of the optical Nyquist pulses in the time domain that possess inter-symbol interference free (ISI free) property [17, 18, 19, 20, 21]. Previously, several reports have demonstrated the generation [17, 22, 23, 24] and detection [25, 26] of the optical Nyquist pulse.

To generate the elastic Nyquist OTDM signals with an arbitrary baud rate, two flexible procedures are required. The first procedure is to generate a raised-cosine spectral shape of an optical Nyquist pulse by filtering a laser output spectrum. In this procedure, the width of the spectrum is flexibly changed so that the zero-crossing period of the Nyquist pulse is equal to the reciprocal of the baud rate to satisfy the ISI-free condition. A WSS is used for the flexible spectral filtering [12, 13, 14, 17]. The second procedure is multiplexing for generating the Nyquist OTDM signals. In this procedure, the number of multiplexes and the pulse interval is changed flexibly in accordance with the baud rate.

An optical circuit, a typical device used for OTDM, is not suitable for the second flexible procedure because the optical circuit—being a static device—does not have a flexible number of multiplexes and the pulse interval. An OTDM module with the optical delay lines is another candidate for this procedure, which can control the pulse interval. However, a high precision control of micro stages is necessary for adjusting the pulse interval, which means that it is difficult to switch at the same speed as the first procedure by using a WSS. Further, their devices cause optical losses because they consist of multiple 3-dB couplers, and the optical losses increase as an increment of the multiplexing number.

Earlier, we proposed a WSS-only approach [27], that can realize a flexible and lossless baud-rate switching for the Nyquist OTDM signals. This approach can generate an optical Nyquist pulse train using a WSS only and does not require any devices for OTDM. Using the WSS-only approach, we have demonstrated the generation of optical Nyquist pulse trains in the near-infrared band without any established OTDM device [27] as well as the generation of power-efficient optical Nyquist trains[28, 29]. Recently, we have demonstrated
the flexible baud rate switching for the Nyquist OTDM signals [30]; however, the system configuration used in this work [30] is not suitable for the data modulation of each time slot because we used a single output port in WSS.

In this paper, we propose the modified configuration of the WSS-only approach to accommodate the data modulation of each time slot by using a WSS with four output ports and experimentally demonstrate flexible baud-rate switching for the 4-time slots Nyquist OTDM signals. We generated the Nyquist OTDM signals with the baud rates of 40, 80 and 120 Gbaud/s using a 10-GHz sech^2 pulse laser and switched the signals flexibly. We discuss the optical loss of the WSS-only approach with the modified configuration.

2. Method

In this section, the method for switching Nyquist OTDM signals using the WSS-only approach is described. The approach can flexibly switch the baud rate of the signals in the same way as a switching optical path with a WSS. The schematic diagram of the proposed approach is shown in Fig. 1. In this approach, the Nyquist OTDM signals are generated only using a WSS with multiple output ports. The baud-rate switching can be realized by changing the filter function set—including multiple filter functions for each time slot—applied to the WSS. The applied filter function set for a desired baud rate is selected from a filter bank of pre-stored filter function sets. Therefore, the switching duration of the approach is equivalent to that of the WSS. In Fig. 1, the filter function set (II) for a baud rate of 80 Gbaud/s is selected from the filter function sets available in the filter bank as an example.

The filter function set for generating Nyquist OTDM signals with the baud rate \( B \) must satisfy the following three conditions: (1) the zero crossing period of a Nyquist pulse \( T \) is equivalent to \( 1/B \); (2) the repetition rate of each time slot \( R \) is \( B/N \), where \( N \) is the number of time slots equivalent to the number of output ports of the WSS; and (3) the adding delay time in each time slot \( \tau \) is set so that the time lags between the neighboring time slots are \( 1/B \) (here, \( k \) is a positive integer that takes values from 1 to \( N \)). Therefore, the parameters \( T \), \( R \), and \( \tau \) should be changed in accordance with \( B \). The filter function set, \( F(\omega) \), satisfying the above-mentioned conditions can be designed using the following equation, which is modified from the filter function for a single output port [30].

\[
F_k(\omega) = \frac{S(\omega)A_{rep}(\omega)\exp[i\phi(\omega)]}{A_{m}(\omega)\exp[i\phi_m(\omega)]}\exp[i\tau_k(\omega - \alpha_B)] \quad (1)
\]

where \( S(\omega) \) is the raised-cosine spectrum of a Nyquist pulse with the zero-crossing period of \( 1/B \) as defined in Eq. (2) [17]; \( A_{rep}(\omega)\exp[i\phi(\omega)] \) includes the function for increasing \( R_S \) from the repetition rate of the laser \( R_L \) to \( B/N \), as defined in Eq. (3); \( \omega \) is the angular frequency; \( \omega_0 \) is the central angular frequency; and \( A_{m}(\omega)\exp[i\phi_m(\omega)] \) is the complex amplitude spectrum of an input pulse to the WSS.

\[
S(\omega) = \begin{cases} 
\frac{1}{2} \left[ 1 - \sin \left( \frac{\pi}{2\alpha} \left| \frac{\omega}{\omega_0} - 1 \right| \right) \right] & 0 \leq \frac{\omega}{\omega_0} \leq \frac{1 - \alpha}{2} B \\
0 & \frac{1 - \alpha}{2} B \leq \frac{\omega}{\omega_0} \leq \frac{1 + \alpha}{2} B \\
\frac{1}{2} \left( 1 + 1 - \sin \left( \frac{\pi}{2\alpha} \left| \frac{\omega}{\omega_0} - 1 \right| \right) \right) & \frac{1 + \alpha}{2} B \leq \frac{\omega}{\omega_0} \leq \frac{1 + \alpha}{2} B 
\end{cases} \quad (2)
\]

\[
A_{rep}(\omega) = \sum_{m=1}^{N_{S/L}} \exp[i\tau_m(\omega - \omega_0) + \phi_m].
\]

\[
\phi_m(\omega) = \text{Arg} \left[ \sum_{m=1}^{N_{S/L}} \exp[i\tau_m(\omega - \omega_0) + \phi_m] \right].
\]

\[
\tau_m = (m - N_{S/L} + 1/2)\omega_0 / R_L, \quad N_{S/L} = \frac{B}{N R_L}
\]

where \( \alpha \) in Eq. (2) is the roll-off factor and \( \phi_m \) in Eq. (3) is the phase of each pulse in the time domain.

Our WSS-only approach is originally developed to aim at the reduction of the optical loss in repetition rate tuning process [28]. In the flexible baud rate switching, the optical loss caused by increasing \( R_S \) from \( R_L \) to \( B/N \), can be effectively reduced. In our method, \( R_S \) is increased at a little optical loss by modulating both amplitude \( A_{rep}(\omega) \) and phase \( \phi_{rep}(\omega) \) over all vertical mode of the laser source, not by the conventional approach of removing the unnecessary vertical modes of the laser source. Both amplitude \( A_{rep}(\omega) \) and phase \( \phi_{rep}(\omega) \) of each vertical mode are adjusted so that the optical loss can be minimized as much as possible. Although the optical loss cannot be completely avoided, it is effectively improved compared with the conventional approach.
The variable optical attenuators (VOA) are used separately for each time slot as the hypothetical data modulator for verification before forming the Nyquist OTDM signal. The generated Nyquist OTDM signals were measured with a 63-GHz digital sampling oscilloscope (DSO) and a 4-GHz real time oscilloscope (RTO) for short and longtime-scale measurements, respectively. The short time-scale measurements were performed for evaluating the temporal waveforms of the Nyquist OTDM signals, and the long time-scale measurement was performed for evaluating the switching duration.

We designed the three filter function sets for the Nyquist OTDM signals with a different baud rates of 40, 80, and 120 Gbaud/s based on Eq. (1) and stored them in a filter bank as the filter sets (I), (II), and (III), respectively. The filter functions were designed to minimize the optical loss due to amplitude modulation according to $A_{\text{opt}}(\phi)$. Since $A_{\text{opt}}(\phi)$ varies depending on the values of $\phi_m$, the combination of $\phi_m$ was selected so as to minimize the loss. To find the optimal phase combination of $\phi_m$, we searched all phase combinations in $2\pi/32$ steps. As a result of the search, in the cases of 40 and 80 Gbaud/s, the losses were constant regardless of $\phi_m$, and they were 0 and 3.0 dB, respectively. Therefore, in those cases, any values of $\phi_m$ can be used. In the case of 120 Gbaud/s, the amount of loss varied from 2.2 to 4.8 dB depending on $\phi_m$. Then, the phase combination of $\phi_m$ that resulted in the loss of 2.2 dB were selected. The selected values of $\phi_m$ were $\{0.00 \text{ rad}\}$, $\{1.57, 1.57 \text{ rad}\}$ and $\{1.57, 0.00, 1.57 \text{ rad}\}$ for 40, 80 and 120 Gbaud/s, respectively. The three filter functions of different baud rates for a time slot 1 are shown in Fig. 3, and the parameters of the filter function sets are summarized in Table 1.

### Table 1 Parameters of filter function sets.

| Baud rate of OTDM signals B [Gbaud/s] | Filter set (I) | Filter set (II) | Filter set (III) |
|-------------------------------------|----------------|----------------|-----------------|
| Repetition rate of each time slot $R_r$ [GHz] | 40 | 80 | 120 |
| Zero crossing period $T_c$ [ps] | 25 | 12.5 | 8.3 |
| Roll off factor $\alpha$ | 0.5 | 0.5 | 0.5 |
| Adding time delay of time slot 1 $\tau_1$ [ps] | 0 | 0 | 0 |
| Adding time delay of time slot 2 $\tau_2$ [ps] | 0 | 0 | 0.12 |
| Adding time delay of time slot 3 $\tau_3$ [ps] | 0 | -1.25 | 0.23 |
| Adding time delay of time slot 4 $\tau_4$ [ps] | 0 | -1.25 | -0.12 |

### 3. Experimental setup

The experimental setup is shown in Fig. 2. A fiber laser (Pritel, UOC-05-14G) with a center wavelength of 1550 nm, a pulse width of 1.8 ps, and a repetition rate of 10 GHz was used as the light source. The sech² pulse from the laser was incident on a WSS with four output ports (Finisar, WaveShaper 4000S) to generate 4-time slots Nyquist OTDM signals. The fiber length of each time slot was set so that the time lags were 25 ps. These four Nyquist pulses with different time lags correspond to different time slots before multiplexing, which are combined together to form the Nyquist OTDM signals with 4 times baud-rate than that of a single slot. In addition, the baud-rate can be easily upgraded by providing plural Nyquist pulses before combining them.

In this section, we discuss the experiments for switching the Nyquist OTDM signals. Three signals were switched by changing the filter function set of: (I) 40-Gbaud/s, (II) 80-Gbaud/s, and (III) 120-Gbaud/s Nyquist OTDM signals. Firstly, we evaluated the generated signals of each time slot. Secondly, we evaluated the OTDM signals without and with attenuation to demonstrate the modulation of each time slot signal. Finally, we measured the switching duration of the signals.

The waveforms of each time slot were measured by the DSO. The measured waveforms are shown in Fig. 4. The dashed lines in Fig. 4(a), (b), and (c) are drawn at the intervals of 25, 12.5, and 8.3 ps, respectively. In Fig. 4, the peaks of the pulses are located at the dashed lines, and the time slot of each pulse does not overlap indicating that the repetition rate of each time slot and the time lags between the slots are appropriately controlled for the selected baud rates.
The waveforms after OTDM without and with attenuation were measured with the DSO. The attenuation of each time slot was applied as follows; Slot 1, 2, 3, 4 = (0, off, 0, 3), (0, 0, off, 3), (0, off, 0, 3) dB for 40, 80, 120 Gbaud/s, respectively. The waveforms of the Nyquist OTDM signals without and with attenuation are shown in Fig. 5. The dashed lines are drawn at the same intervals as Fig. 4, and the numbers under the graphs show the time slot numbers. As shown in Fig. 5, the intensity of peaks on the dashed lines are constant without attenuation for each baud rate, which indicates that the generated OTDM signals satisfy the ISI-free condition with the appropriate zero-crossing period and the time lags. In Fig. 5, the graphs with attenuation show that the pulses are appropriately attenuated, which means that the WSS-only approach using the WSS with multiple output ports is suitable for the data modulation of each time slot.

The switching duration was measured by the RTO. The switching was conducted manually and periodically, and the switched signals of time slot 1 were measured with the RTO. The results are shown in Fig. 6, where Fig. 6(a) and (b) show the data measured with the RTO in 4-s/div and 40-ms/div time scale, respectively. In Fig. 6(a)–(b), the three OTDM signals with the filter function sets (I), (II), and (III) can be distinguished by the signal intensity level corresponding to the average optical power of 2.72, −0.03, and 1.14 dBm, respectively. In Fig. 6(a), the switching of three signals is successfully demonstrated, and the switching duration was found to be 80 ms from Fig. 6(b).

4. Discussion

We discuss the optical loss of the WSS-only approach with four output ports. The optical loss of the WSS-only approach is the sum of the optical losses owing to spectral filtering with the WSS and the combiner from four ports to single port. The former loss is calculated from the filter function based on Eq. (1) and the later loss is assumed to be 6 dB.

We calculated the optical loss of the approach and compared it with the typical optical loss of an optical circuit. The repetition rate of a laser $R_L$ was set to 10 GHz. The simulated optical losses are shown in Fig. 7. The typical optical loss of an optical circuit, which are $3.01 \times \log_2(BR_L)$ dB are also shown in Fig. 7 for comparison. In Fig. 7, the optical loss of the WSS-only approach is almost constant even the baud rate increases in contrast to the optical circuit.
5. Conclusions

We successfully demonstrated the flexible and lossless baud-rate switching of the 4-time slots Nyquist OTDM signals with a WSS-only approach. The WSS-only approach is not only used for the generation of a Nyquist pulse but also for multiplexing; therefore, it has an advantage in terms of the flexible operation as this approach does not use a static device for OTDM. Hence, the proposed approach allows a flexible switching of the baud rates of the Nyquist OTDM signals in the same way as switching the optical path with a WSS. We proposed the modified configuration of the WSS-only approach by adding four output ports in the WSS for suitable data modulation. We experimentally tested the switching operation of the proposed approach. Three Nyquist OTDM signals of 40, 80, and 120-Gbaud/s with 4-time slots were switched by changing the filter functions at a switching duration of 80 ms. We simulated the optical loss of the WSS-only approach with four output ports and the results indicated the lossless property of our method. Based on the results obtained in this work, we believe that the WSS-only approach may prove to be an effective technique for realizing the elastic optical network.

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