Optimization of Roll-off Factor in Ultrahigh-speed WDM Nyquist Pulse Transmission

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SUMMARY We optimized the roll-off factor for a 1.28 Tbit/s/ch (320 Gbaud PDM-DQPSK) WDM Nyquist pulse transmission. We found that the optimum α value in the WDM system was 0.5, as with a single-channel transmission, despite the degradation caused by inter-channel XPM.
keywords: *OTDM, Nyquist pulse, high symbol rate, Tbit/s transmission*

1. Introduction

To keep up with the enormous increase in global information traffic, high-speed transmission with a single-channel bit rate beyond 1 Tbit/s has become an important research target. Recently, wavelength-division multiplexed (WDM) transmission at > 1 Tbit/s/ch using high-speed A/D and D/A converters and electric multiplexers has been reported [1,2]. However, the transmission distance is still limited to less than 1000 km, and a further increase in the symbol rate is also difficult due to the bandwidth limitation of electric devices.

On the other hand, optical time-division multiplexing (OTDM) can realize a faster symbol rate beyond the speed and bandwidth limitation. We have proposed the OTDM transmission of optical Nyquist pulses [3] and realized ultrahigh-speed single-channel transmissions including a 10.2 Tbit/s-300 km DQPSK transmission at 2.56 Tbaud [4] and a 15.3 Tbit/s-160 km 64 QAM transmission at 1.28 Tbaud [5]. Recently, we have also demonstrated the 12.8 Tbit/s (1.28 Tbit/s/ch x 10 ch) WDM transmission of 320 Gbaud PDM-DQPSK signals over 1500 km using α = 0 optical Nyquist pulses [6].

The waveform and spectrum of a Nyquist pulse are characterized by a parameter called the roll-off factor α ($0 \leq \alpha \leq 1$). The waveform is expressed by a sinc function (α = 0) or quasi-sinc function (α > 0). With α > 0, its ringing decays faster than with α = 0, but regardless of the α value, the ringing crosses zero periodically. This feature enables us to realize bit-interleaving without inter-symbol interference (ISI) by placing adjacent pulses at every zero-crossing point.

For a single-channel Nyquist pulse transmission [7,8], we reported that the system performance can be improved by setting the roll-off factor α at 0.5. When our aim is to realize a high capacity WDM Nyquist pulse transmission, the roll-off factor α for WDM transmission has to be once again optimized since a WDM system is vulnerable to inter-channel cross-phase modulation (XPM).

In this paper, we report the optimization of the roll-off factor α in a 1.28 Tbit/s/ch WDM Nyquist pulse transmission. The optimum α value thus obtained in the WDM system was also found to be α = 0.5 as in the single-channel case.

2. Experimental setup for roll-off factor optimization in 1.28 Tbit/s/ch WDM Nyquist pulse transmission

Figure 1 shows our experimental setup for 1.28 Tbit/s/ch (320 Gbaud PDM-DQPSK) WDM Nyquist pulse transmission. As a pulse source for a channel under test (CUT), we used a wavelength-tunable continuous-wave laser diode (CW-LD) and a 40 GHz optical comb generator [9]. The pulse was DQPSK modulated at 40 Gbaud with a 2^{11}-1 PRBS. The generated 40 Gbaud DQPSK signal was then bit-interleaved to 320 Gbaud with delay-line Mach-Zehnder interferometers (MZIs) on a planar lightwave circuit (PLC) as an OTDM emulator. After polarization multiplexing, we used an optical programmable filter with a liquid crystal [10] as pulse shaper #2 to shape the signal into an optical Nyquist pulse with roll-off factors α = 0, 0.25, 0.5, 0.75, and 1. In parallel to CUT, we generated loading dummy channels from a 40 GHz mode-locked fiber laser (MLFL). With a highly nonlinear dispersion-flattened fiber (HNL-DFF), the spectrum of the MLFL output pulse was broadened over the entire bandwidth of 3.5 THz in the C-band. After employing OTDM and PDM in the same way as CUT, we shaped the spectrum so that it exhibited a flattop profile that had a rectangular dip by using pulse shaper #1, where the dip was kept open for CUT. We sliced the other part of the flattened spectrum into WDM channels, which were shaped into optical Nyquist pulses and then provided with different time delays to remove any correlation between channels. The loading dummy channels were finally combined with a CUT at pulse shaper #2. In the transmitter, we also generated a 40 GHz clock tone from a CW-LD, which was intensity-modulated at 40 GHz.

The optical spectra of WDM signals thus obtained with α = 0, 0.5, and 1 are shown in Figs. 2-4, respectively. We allocated WDM channels for each roll-off factor within a fixed bandwidth at ~3.5 THz, and therefore there were 10, 8, and 6 WDM channels for α = 0, 0.5, and 1, respectively. We evaluated the BER at the shortest wavelength channel with a fixed wavelength as the CUT for each roll-off factor.

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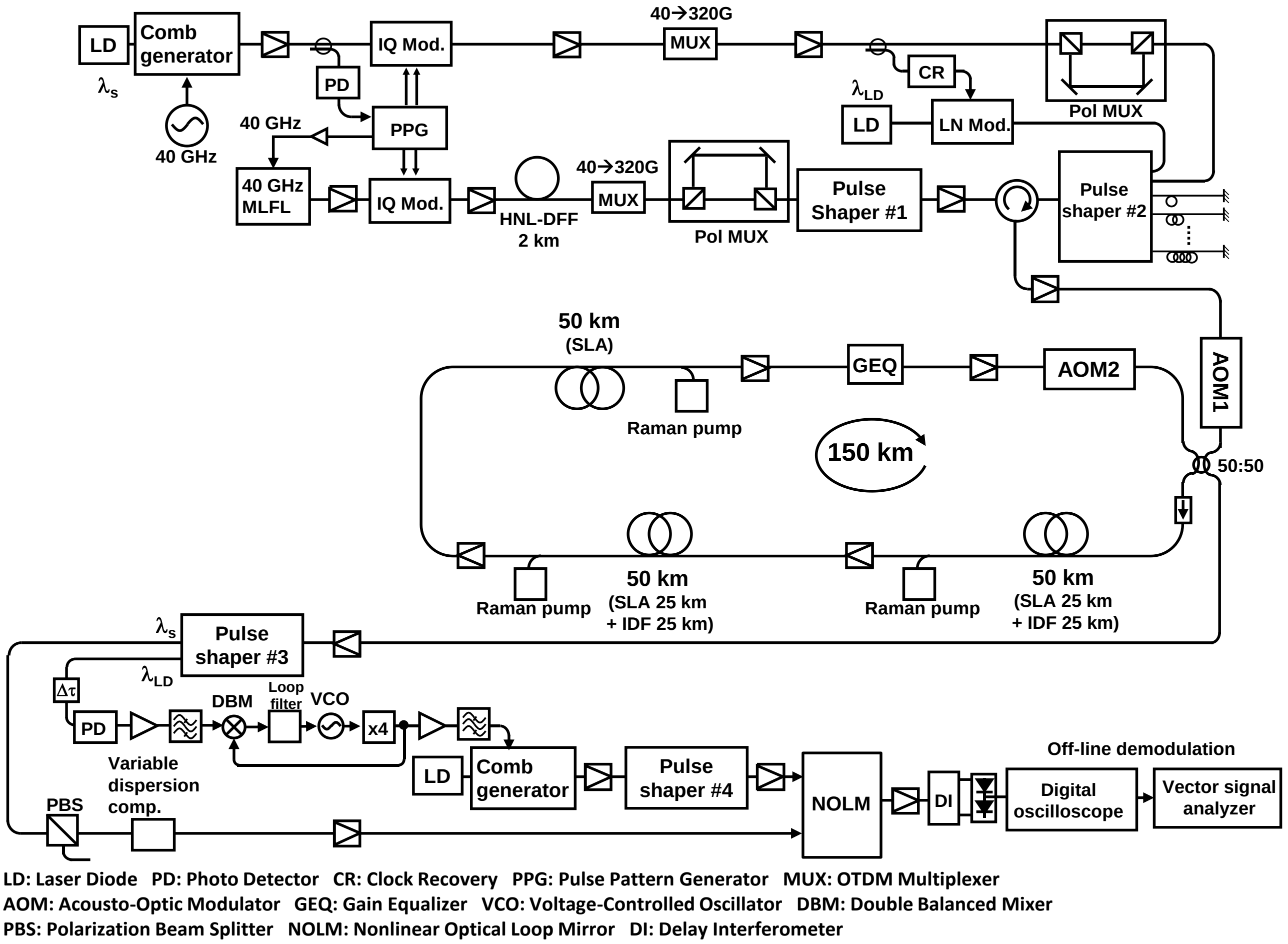

Fig. 1. Experimental setup for 1.28 Tbit/s/ch (320 Gbaud PDM-DQPSK) WDM Nyquist pulse transmission.

The WDM signal was then launched into a 150 km recirculating loop, which was composed of three 50 km spans. We used a 25 km super large area fiber (SLA) and a 25 km inverse dispersion fiber (IDF) for the first and second spans, and a 50 km SLA for the third span. This recirculating loop was a dispersion-managed transmission link in which the second- and third-order dispersions were simultaneously compensated for every 150 km. To compensate for the span losses (~12 dB), we used erbium-doped fiber amplifiers (EDFAs) and Raman amplifiers. To improve the OSNR, we set the Raman amplifier gain at 8 dB, which was 4 dB higher than that in our previous work on a 12.8 Tbit/s-1500 km WDM transmission [6]. The first-order polarization-mode dispersion (PMD) was mitigated by using polarization controllers (PCs) installed in each span. We employed a gain equalizer (GEQ) in the loop for residual dispersion compensation and gain equalization. After the transmission, the WDM signal was demultiplexed and detected at the receiver, whose setup is as described in [6].

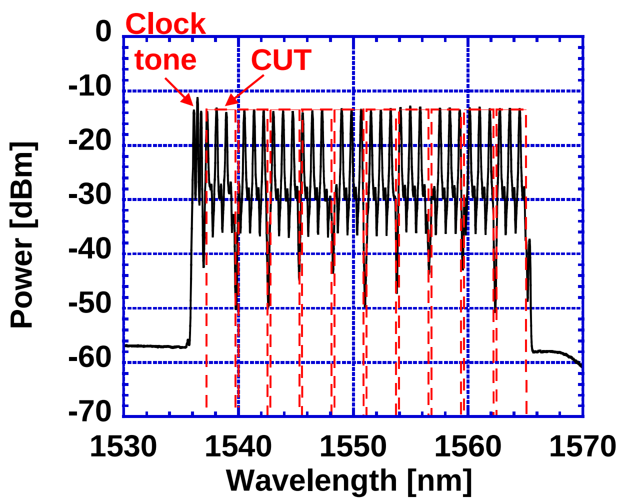

Fig. 2. Optical spectrum of 1.28 Tbit/s/ch, 10 ch WDM non-coherent optical Nyquist pulses with roll-off factor α=0.

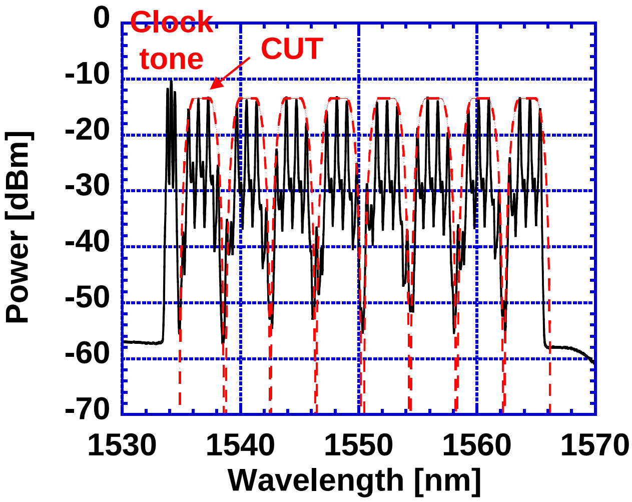

Fig. 3. Optical spectrum of 1.28 Tbit/s/ch, 10 ch WDM non-coherent optical Nyquist pulses with roll-off factor α=0.5.

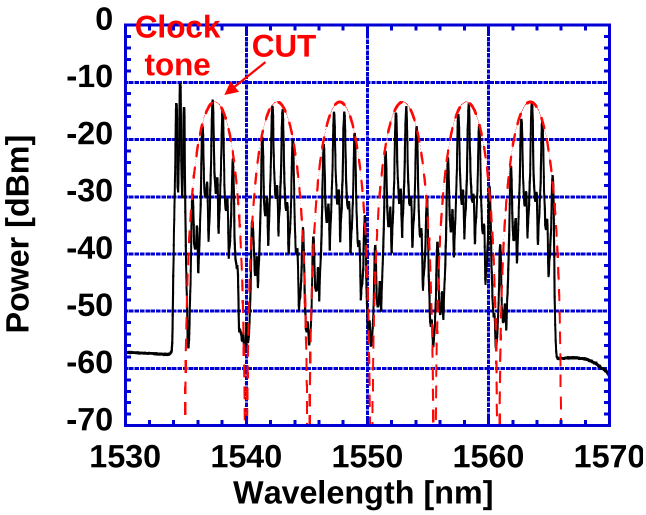

Fig. 4. Optical spectrum of 1.28 Tbit/s/ch, 10 ch WDM non-coherent optical Nyquist pulses with roll-off factor α=1.

3. Results and discussion

We measured the dependence of the BER on transmission distance for each roll-off factor at the CUT. We focused on the X-polarization signal for the BER measurement. In general, the difference between the X- and Y-polarization BER values can occur due to polarization dependent loss (PDL) and gain (PDG), but in our experiment they were mitigated by adjusting the PCs in the recirculating loop. Figure 5 shows the BER for 8 OTDM tributaries after a 1500 km transmission. As shown in Fig. 5, almost the same BER is obtained for X- and Y-polarizations, and therefore in the experiments described hereafter we measured only the X-polarization BER.

Next, we measured the BER for 8 OTDM tributaries and evaluated their average and variation for each transmission distance. Figure 6 shows the BER performance for each roll-off factor as a function of distance. With α = 0, 0.25, and 0.75, we obtained a BER below the 20% overhead FEC threshold ($2x10^{-2}$) after a 1800 km transmission. However,

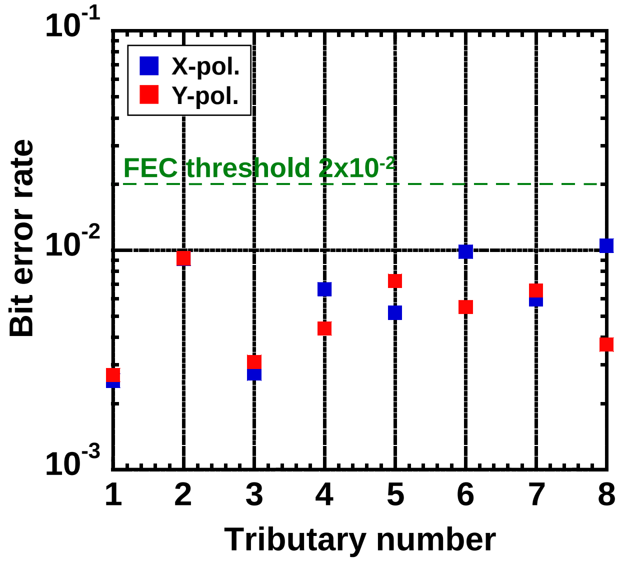

Fig. 5. BERs for 8 OTDM tributaries and 2 polarizations after 1500 km transmission with roll-off factor α=0.5.

with α = 1, the transmission distance was reduced to 1500 km. Figure 6 clearly shows that the transmission distance can be successfully extended to 2100 km by optimizing the roll-off factor at α = 0.5.

Figure 7 shows the BER as a function of roll-off factor measured at 2100 km. It can be seen that the minimum BER is obtained at α = 0.5, and it was degraded for both lower and higher α values, where the degradation with higher α value is faster. This dependence is in good agreement with that in a single-channel transmission [7,8], where we found the optimum roll-off factor to be around 0.5. As α decreases, the transmission performance is degraded due to a large overlap between adjacent pulses. As α increases, the performance also degrades although the pulse overlap decreases. This is caused by a lower tolerance to nonlinearity as the pulse

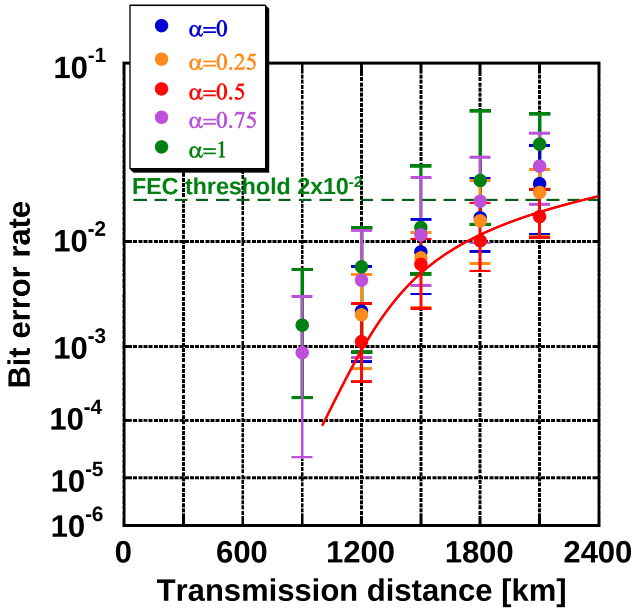

Fig. 6. BER performance as a function of transmission distance for each roll-off factor. Circles represent the average BER among 8 OTDM tributaries and the bars represent their variation. α = 0.5 is depicted with a red line.

waveform becomes closer to that of a conventional RZ pulse and the peak power increases under a fixed average power. The result in Fig. 7 indicates that this α dependence is also valid in the WDM case.

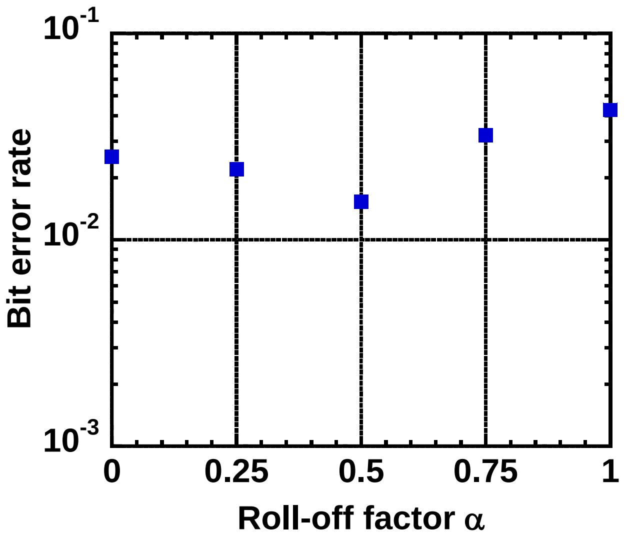

Fig. 7. Roll-off factor dependence of BER at 2100 km.

4. Conclusion

We optimized the roll-off factor α in a 1.28 Tbit/s/ch (320 Gbaud PDM-DQPSK) WDM Nyquist pulse transmission. Despite the degradation caused by inter-channel XPM, the roll-off factor dependence of the WDM system was in good agreement with that in a single-channel transmission, where the optimum α value was 0.5.

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