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Bit-error Rate Performance of Nyquist Wavelength-Division Multiplexed Quadrature Phase-Shift Keying Optical Signals

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Abstract: We measure bit-error rates of polarization-multiplexed Nyquist-WDM QPSK signals, which have rectangular spectral shapes and channel spacing equal to the symbol rate. The spectral efficiency of 4 bit/s/Hz is achieved with negligible power penalty.
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1. Introduction

For realizing ultra-high capacity optical fiber networks, it is indispensable to improve the spectral efficiency in wavelength-division multiplexed (WDM) transmission systems. One approach of improving the spectral efficiency is the use of multilevel modulation formats such as *M*-ary phase-shift keying (PSK) and quadrature amplitude modulation (QAM) [1-2]. The 64-QAM transmission experiment at the single-channel bit rate over 100 Gbit/s has already been reported [1].

Another approach is tight spectral filtering of optical signals for reducing WDM channel spacing, and it is effective for any modulation format. The recent experiment has demonstrated long-haul transmission of WDM quadrature PSK (QPSK) signals over 9,000 km with a channel-spacing frequency equal to the symbol rate [3]. In order to minimize the penalty due to crosstalk between closely spaced WDM channels, it is required to reshape optical spectra through optimal filtering at the electrical stage or the optical stage.

The Nyquist filter can reduce the double-sided spectral width of the signal to its symbol rate without any inter-symbol interference (ISI). In particular, the Nyquist filter having a rectangular-shaped passband is ideal for WDM transmission systems, because the channel spacing can be set to the symbol rate. When rectangular-shaped spectra are multiplexed in the wavelength domain with no space between WDM channels, we can achieve the spectral-efficiency limit of 1 symbol/s/Hz per polarization without any penalty both from ISI and crosstalk between WDM channels. This method of multiplexing is now called Nyquist WDM [4]. Although orthogonal frequency-division multiplexing (OFDM) can reach the same spectral-efficiency limit [5], Nyquist WDM is much simpler in implementation aspects.

In this paper, we experimentally evaluate bit-error rate (BER) characteristics of the Nyquist WDM system, where polarization-multiplexed QPSK (PM-QPSK) signals with rectangular-shaped spectra are aligned at frequency interval equal to the symbol rate. We generate a 20-Gsymbol/s QPSK signal having a rectangular-shaped spectrum with a 10-GHz bandwidth, using digital-to-analog conversion (DAC) following digital signal processing (DSP) at the electrical stage and IQ optical modulation. Multiplexing such signals with channel spacing of 10 GHz, we achieve the spectral efficiency of 4 bit/s/Hz. BER measurements in such Nyquist WDM environment show that there are negligible power penalties stemming from either ISI or WDM crosstalk because of precise Nyquist filtering at the electrical stage.

2. Experimental setup for Nyquist WDM of PM-QPSK signals

We evaluate the BER performance of PM-QPSK signals in the Nyquist-WDM environment. The experimental setup is shown in Fig. 1(a). Three CW lights, which oscillate at 1550 nm and have a 3-dB linewidth of 150 kHz, were generated from distributed-feedback laser diodes (DFB-LDs). These lights were combined and modulated by a $LiNbO_3$ optical IQ modulator (IQM) all at once.

The symbol rate *S* was 10 Gsymbol/s. Two streams of the electrical analog signal led to the IQM were generated by DSP followed by DAC embedded in an arbitrary waveform generator (AWG). Fig. 1(b) shows details of DSP: A $2^9 - 1$ pseudo-random bit sequence at 20 Gbit/s was de-serialized into two streams at 10 Gbit/s through serial-to-parallel conversion (SPC). A finite impulse response (FIR) filter with 600 taps performed Nyquist filtering and pre-equalization of each stream, which had been up-sampled twice. Linear distortion due to electrical components was compensated for with pre-equalization. Tap coefficients of the FIR filter were determined so that the spectrum of the output signal had a rectangular shape with a single-sided bandwidth of $S/2$ = 5 GHz. Finally, each 10 Gbit/s pattern was output at 20 Gsample/s, and sent to DAC. The IQM was driven by the two electrical streams thus obtained, and generated three WDM channels having rectangular-shaped spectra with the bandwidth of S = 10 GHz. The WDM channel spacing δf was set to 11 GHz, 10 GHz, or 9.5 GHz. When $\delta f = S$, there is neither space nor overlap between adjacent WDM-channel spectra. Polarization multiplexing was achieved as follows: WDM signals were divided into two paths by a 3-dB coupler. Delay of several tens of ns was given to one of the paths. The two paths were combined with a polarization beam splitter (PBS).

The PM Nyquist-WDM QPSK signals were preamplified with an erbium-doped fiber amplifier (EDFA) and then incident on an optical homodyne receiver composed of a local oscillator (LO), 90° optical hybrids in a polarization-diversity configuration, and four balanced detectors. The linewidth of a DFB-LD used for LO was 150 kHz. Electrical outputs from the receiver were stored in sets of 2×10^6 samples by using a digital oscilloscope running at 20 Gsample/s with an 8-GHz analog bandwidth. The aliasing effect could be suppressed by the sampling rate twice as high as the symbol rate and the analog bandwidth restriction below 10 GHz. BER measurements were performed offline as follows: The received PM-QPSK signal was polarization-demultiplexed and equalized with 64-tap, half-symbol-spaced adaptive FIR filters in the butterfly configuration in the DSP circuit. Their tap coefficients were updated based on the constant-modulus algorithm (CMA). The symbol was decoded after carrier-phase estimation based on the 4-th power algorithm, and finally bit errors were counted.

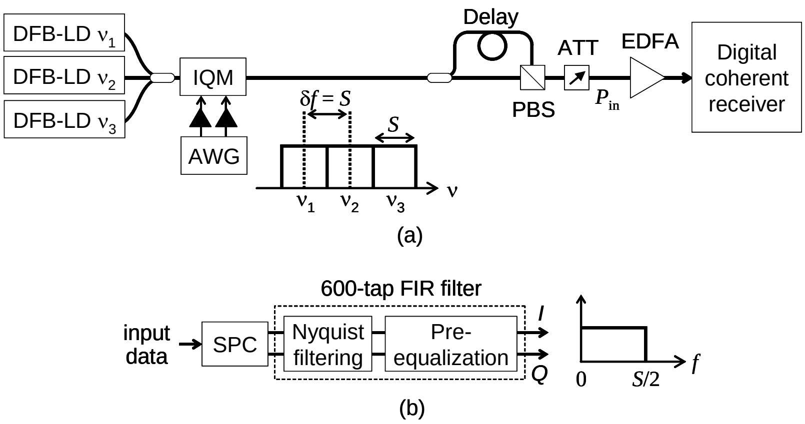

Fig. 1 (a) Experimental setup for Nyquist WDM of PM-QPSK signals. Three WDM channels having the bandwidth of S are aligned at the frequency interval $\delta f = S$, where S denotes the symbol rate. P_{in} is the power before preamplification. ATT: variable optical attenuator. (b) DSP in AWG for generating the signal with the rectangular-shaped spectrum, whose single-sided bandwidth is $S/2$.

3. Experimental results

Fig. 2(a) represents the RF spectrum of the 10-Gbit/s electrical analog signal generated from AWG. We observe the nearly-ideal rectangular-shaped spectrum with a single-sided bandwidth of 5 GHz. The spectral component beyond 5 GHz is suppressed by over 20 dB. When the IQM is driven by such electrical signals, we can obtain the QPSK signal with the rectangular-shaped spectrum as shown in Fig. 2(b). The optical spectrum is tightly restricted in the range of 10 GHz although the observed slope of the spectrum is not so steep due to the resolution limit of 0.01 nm of our optical spectrum analyzer.

Fig. 3(a) illustrates the constellation map of the single-channel 20-Gbit/s QPSK signal when the power P_{in} before the preamplifier is −40 dBm. The map is clearly separated in four phase states, enabling symbol discrimination.

Open circles in Fig. 4(a) show BERs of the single-channel 20-Gbit/s QPSK signal, whereas crosses indicate BERs of a 20-Gbit/s NRZ-QPSK signal without any spectral filtering. The dashed curve represents the theoretical result in the shot-noise limited condition. Although the 4-dB penalty from the dash curve is observed in the Nyquist filtering case, this is comparable to that in the un-filtered case. Therefore, the penalty due to Nyquist filtering is negligible.

Figs. 3(b), (c), and (d) show the constellation maps of the center channel in the single-polarization three-channel WDM system, when channel-spacing frequencies δf are 11 GHz, 10 GHz, and 9.5 GHz, respectively. In each case, the power P_{in} of the center channel is −40 dBm before the preamplifier. The four phase states are clearly separated when $\delta f \geq 10$ GHz, whereas degradation due to crosstalk from adjacent channels is remarkable when $\delta f = 9.5$ GHz.

Dots in Figs. 4 (b), (c), and (d) represent BERs of the center channel. As a reference, we indicate the single-channel BERs shown in (a) by open circles. We find that crosstalk between WDM channels due to spectral overlap is entirely suppressed as far as δf is larger than 10 GHz.

Fig. 3(e) shows the constellation map of the recovered *x*-polarization component of the center channel in the PM three-channel WDM system, when the power of each polarization component is −40 dBm before the preamplifier and $\delta f = 10$ GHz. BERs for *x*- and *y*-polarization components are plotted by dots and crosses in Fig. 4(e), respectively. Since these BER-measurement results are almost the same as that of the single-polarization case, the receiver-sensitivity degradation due to polarization multiplexing is negligible.

4. Conclusion

We have evaluated BER characteristics of PM-QPSK signals in three-channel Nyquist-WDM environment. Nyquist filtering and pre-equalization based on DSP in the transmitter enabled us to generate the 20-Gbit/s optical QPSK signal having the 10-GHz rectangular-shaped spectrum without ISI penalty. After multiplexing three Nyquist-WDM channels, we conducted BER measurements of the center channel. Even when the channel spacing is set to the symbol rate, crosstalk between WDM channels is entirely suppressed. Together with polarization multiplexing, we can achieve the spectral efficiency of 4 bit/s/Hz without any power penalty from the single-channel case.

Acknowledgements

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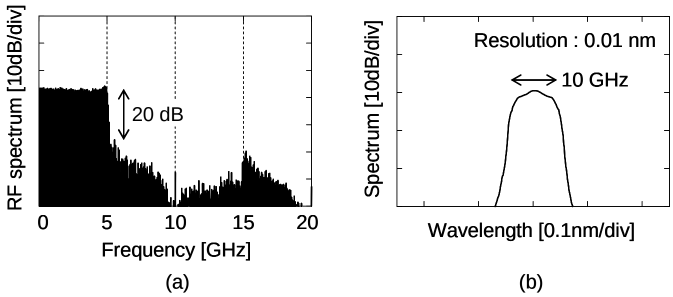

Fig. 2 (a) RF spectrum of the electrical signal generated from AWG. (b) Optical spectrum of the single-channel QPSK signal. The resolution of the optical spectrum analyzer is 0.01 nm.

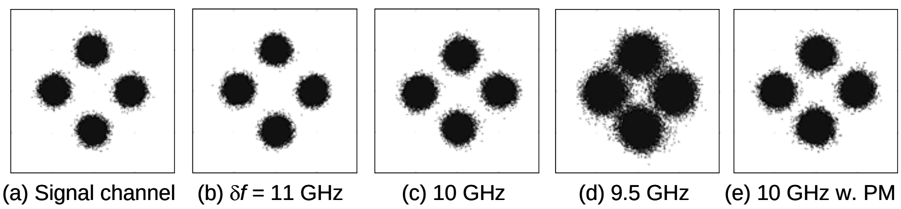

Fig. 3 Constellation map measured for (a) the signal-channel case. Constellation maps of the center channel in the three-channel WDM system with the channel spacing (b) $\delta f = 11$ GHz, (c) 10 GHz, and (d) 9.5 GHz. (e) Constellation map of the *x*-polarization component of the center channel in the PM three-channel WDM system with $\delta f = 10$ GHz.

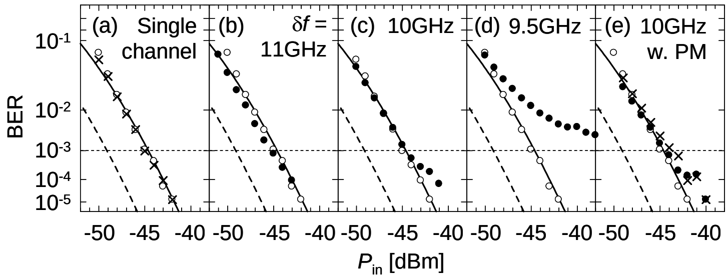

Fig. 4 BER as a function of the power P_{in} before preamplification. (a) Single-channel QPSK, (b) WDM QPSK with the channel spacing δf of 11 GHz, (c) 10 GHz, and (d) 9.5 GHz. (e) WDM PM-QPSK with $\delta f = 10$ GHz.