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The use of a Nyquist filter for reducing an optical signal bandwidth in a coherent QAM optical transmission

Keisuke Kasai[a)], **Jumpei Hongo, Hiroki Goto, Masato Yoshida, and Masataka Nakazawa**

Research Institute of Electrical Communication, Tohoku University, 2–1–1 Katahira, Aoba-ku, Sendai 980–8577, Japan

a) *kasai@riec.tohoku.ac.jp*

Abstract: By introducing a Nyquist filter, we have successfully reduced a data signal bandwidth without intersymbol interference and transmitted a polarization-multiplexed 1 Gsymbol/s, 64 QAM (12 Gbit/s) coherent signal over 150 km in an optical bandwidth of 1.5 GHz.

Keywords: coherent transmission, QAM, Nyquist filter, frequency-stabilized laser

Classification: Photonics devices, circuits, and systems

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1 Introduction

Recently, quaternary phase-shift keying (QPSK) or a combination of phase-shift keying (PSK) and amplitude-shift keying (ASK) has been receiving a lot of attention because it doubles or multiplies N times the spectral efficiency of binary PSK (BPSK) [1, 2]. Quadrature amplitude modulation (QAM) is a very interesting way of increasing the spectral efficiency because 2^N QAM has N times the spectral efficiency of BPSK [3, 4]. We have demonstrated a polarization-multiplexed 1 Gsymbol/s, 64 QAM coherent signal transmission over 150 km, where we transmitted information at 12 Gbit/s in a 2 GHz optical bandwidth.

In a microwave system, data signal bandwidth reduction plays an important role in increasing the spectral efficiency. The Nyquist filter has been widely used in microwave transmission systems to reduce the signal bandwidth [6]. Here, we employed a Nyquist filter in a transmitter and achieved a 12 Gbit/s data transmission over 150 km in an optical bandwidth of 1.5 GHz.

2 64 QAM coherent optical transmission system with a Nyquist filter

Figure 1 shows the experimental setup we used for a polarization-multiplexed 1 Gsymbol/s, 64 QAM coherent optical transmission over 150 km. The optical source for the transmitter is a CW, C_2H_2 frequency-stabilized fiber laser with a 4 kHz linewidth [7]. The signal passes through an EDFA and is coupled to two QAM modulators consisting of single sideband (SSB) modulators [8]. We prepared two arbitrary waveform generators (AWG) to feed independent QAM signals into two orthogonal polarizations. It is well known in microwave communication that a Nyquist filter is very useful for reducing the bandwidth of the data signal without introducing intersymbol interference [6]. The Nyquist filter is a software digital filter that is applied to the QAM software data. After passing through the Nyquist filter, the QAM data is D/A-converted into analogue QAM data. The frequency-stabilized beam is also coupled to an optical frequency shifter, which provides a frequency up-shift of 2.5 GHz against the signal. Then the frequency-shifted signal is used as a pilot signal that tracks the optical phase of an LO (tunable tracking laser) under optical PLL operation. The polarization of the pilot signal is set so that it is the same as that of the polarization axes in the two QAM signals. After optical amplification with an EDFA, the two orthogonally polarized 64 QAM signals are combined with the pilot signal, and these signals are coupled into a 150 km-long transmission fiber (DSF 75 km × 2 spans)

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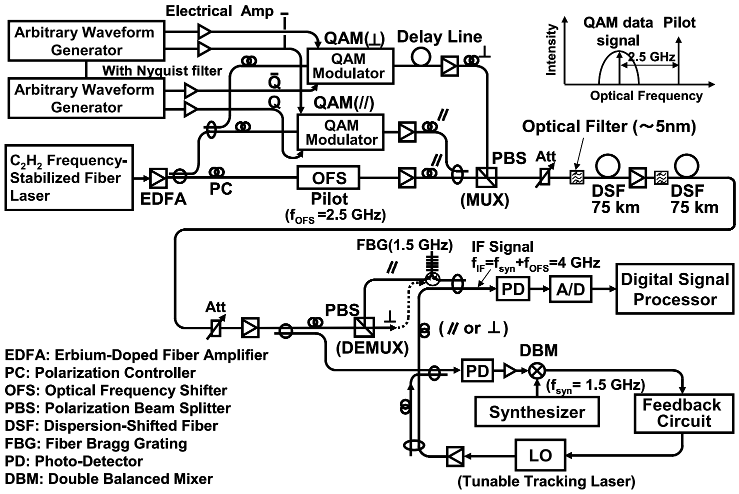

Fig. 1. Experimental setup for polarization-multiplexed 1 Gsymbol/s, 64 QAM coherent optical transmission over 150 km.

with a coupled power of −11 dBm. After the transmission, the two QAM signals are heterodyne-detected with an LO signal whose phase is locked to the pilot signal. Since the LO polarization can be arbitrarily rotated with a polarization controller, two orthogonally polarized QAM signals can be independently detected. The power level of the LO coupled to the PD is increased to 1 dBm. Then an IF data signal is A/D-converted and accumulated in a high-speed digital scope. This transmission system operates in an off-line condition, where all the digital data are demodulated by software. The linewidth of the electrical spectrum of the beat signal between the pilot and LO signals at 1.5 GHz was less than the frequency resolution of the spectrum analyzer of 10 Hz. The phase noise estimated by integrating the SSB noise power spectrum was 6.1×10^{-3} rad.

Figures 2 (a) and (b) show the electrical spectrum of the IF data signal

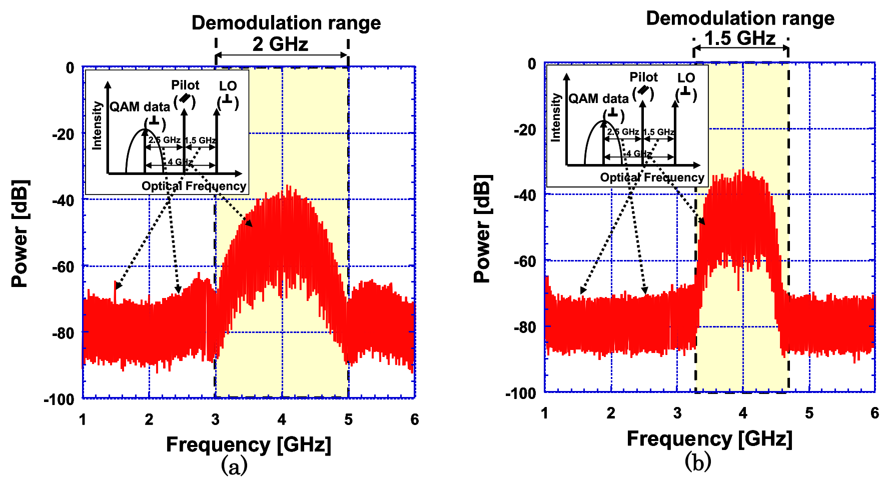

Fig. 2. Electrical spectrum of the IF data signal. (a) Without a Nyquist filter, (b) with a Nyquist filter. Inset: relationship between optical frequencies of QAM data signals, pilot signal and LO signal.

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without and with a Nyquist filter when the polarization of the QAM signal is orthogonal to that of the pilot signal. The inset figure shows the relationship between the optical frequencies of the QAM data signal, the pilot signal and the LO signal. By using a raised-cosine Nyquist filter with a roll-off factor of 0.35, the bandwidth of the QAM data signal was successfully reduced from 2 GHz to less than 1.5 GHz as shown in Fig. 2 (b). Here the demodulation bandwidth was set at 1.5 GHz in the optical domain by using a narrowband FBG filter [9]. Almost the same spectrum was obtained for the parallel data condition.

3 Transmission results

Figures 3 (a), (b) and (c) show the constellations and eye patterns after a 150 km transmission with different received powers of −26, −29 and −32 dBm,

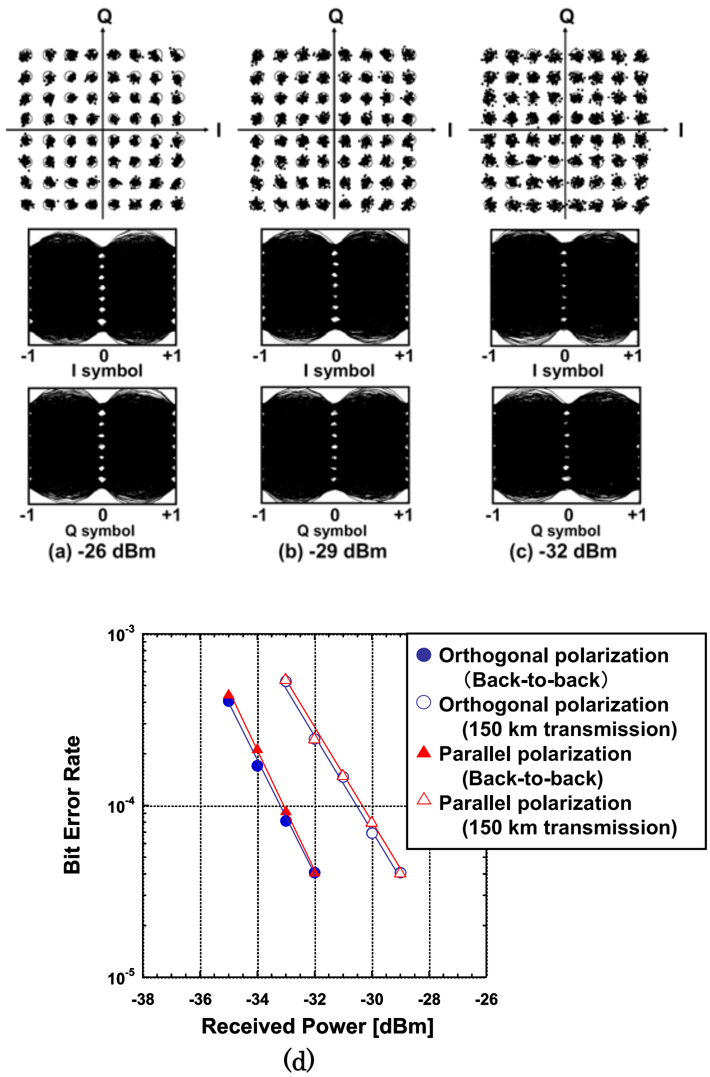

Fig. 3. Transmission results. (a), (b), (c): Constellations and eye patterns for a 64 QAM signal with orthogonal polarization after 150 km transmission with different received powers. (d): BER as a function of the received power.

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respectively, where the polarization of the QAM signal is orthogonal to the pilot signal. Error-free operation is confirmed in Fig. 3 (a) at −26 dBm. However, when the received power was set at −29 dBm, the constellation points overlapped and the eye opening was reduced as shown in Fig. 3 (b). The constellation and the eye opening were worse for a received power of −32 dBm. Almost the same data were obtained under the parallel data condition.

Figure 3 (d) shows the bit error rate (BER) characteristics for a polarization-multiplexed QAM transmission. The word length was limited to 4096 symbols, which corresponds to a BER of up to 4×10^{-5}. It is interesting to see that the parallel polarization between the QAM and the pilot signals has very little effect on the 150 km transmission. This is because the pilot signal power was set at the minimum level (−12.8 dBm) for stable optical PLL. The power penalty was approximately 3 dB for both polarizations, but no error was observed up to 4×10^{-5} when the received power level was above −29 dBm. These results indicate that polarization-multiplexed 1 Gsymbol/s, 64 QAM data were successfully transmitted over 150 km above −29 dBm.

4 Conclusions

We employed a Nyquist filter to reduce the data signal bandwidth. A polarization-multiplexed 1 Gsymbol/s, 64 QAM (12 Gbit/s) coherent optical signal have been successfully transmitted over 150 km in an optical bandwidth of 1.5 GHz.

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