ELectronics EXpress

IEICE Electronics Express, Vol.5, No.18, 776–781

Polarization and frequency division multiplexed 1 Gsymbol/s, 64 QAM coherent optical transmission with 8.6 bit/s/Hz spectral efficiency over 160 km

Hiroki Goto[a], Masato Yoshida, Tatsunori Omiya, Keisuke Kasai, and Masataka Nakazawa

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

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

Abstract: Quadrature amplitude modulation (QAM) is an excellent modulation format for realizing optical communication systems with a high spectral efficiency aiming at 10 bit/s/Hz. We describe a three-channel frequency division multiplexed (FDM) and polarization-multiplexed 1 Gsymbol/s, 64 QAM coherent transmission over a 160 km SMF with a 1.4 GHz spacing. The total capacity for each channel reaches 36 Gbit/s in an optical bandwidth of 4.2 GHz, resulting in a spectral efficiency of 8.6 bit/s/Hz.

Keywords: coherent transmission, QAM, frequency division multiplexing, polarization multiplexing, frequency-stabilized laser

Classification: Photonics devices, circuits, and systems

References

[1] S. Tsukamoto, D.-S. Ly-Gagnon, K. Katoh, and K. Kikuchi, "Coherent demodulation of 40 Gbit/s polarization-multiplexed QPSK signals with 16-GHz spacing after 200-km transmission," in *OFC2005*, Anaheim, CA, 2005, Postdeadline paper PDP 29.

[2] X. Zhou, J. Yu, D. Qian, T. Wang, G. Zhang, and P. D. Magill, "8x114 Gb/s, 25-GHz-spaced, PolMux-RZ-8PSK transmission over 640 km of SSMF employing digital coherent detection and EDFA-only amplification," in *OFC2008*, San Diego, CA, 2008, Postdeadline paper PDP 1.

[3] S. L. Jansen, I. Morita, and H. Tanaka, "10x121.9-Gb/s PDM-OFDM transmission with 2-b/s/Hz spectral efficiency over 1,000 km of SSMF," in *OFC2008*, San Diego, CA, 2008, Postdeadline paper PDP 2.

[4] M. Nakazawa, M. Yoshida, K. Kasai, and J. Hongou, "20 Msymbol/s, 64 and 128 QAM coherent optical transmission over 525 km using hetero-

DOI: 10.1587/elex.5.776
Received August 11, 2008
Accepted August 20, 2008
Published September 25, 2008

ELectronics EXpress

dyne detection with frequency-stabilized laser," *Electron. Lett.*, vol. 42, pp. 710–712, 2006.
[5] J. Hongou, K. Kasai, M. Yoshida, and M. Nakazawa, "1 Gsymbol/s, 64 QAM Coherent optical transmission over 150 km with a spectral efficiency of 3 bit/s/Hz," *IEEE Photon. Technol. Lett.*, vol. 19, pp. 638–640, 2007.
[6] M. Yoshida, H. Goto, K. Kasai, and M. Nakazawa, "64 and 128 coherent QAM optical transmission over 150 km using frequency-stabilized laser and heterodyne PLL detection," *Opt. Express*, vol. 16, pp. 829–840, 2008.
[7] K. Kasai, A. Suzuki, M. Yoshida, and M. Nakazawa, "Performance improvement of an acetylene (C_2H_2) frequency-stabilized fiber laser," *IEICE Electron. Express*, vol. 3, pp. 487–492, 2006.
[8] S. Shimotsu, S. Oikawa, T. Saitou, N. Mitsugi, K. Kubodera, T. Kawanishi, and M. Izutsu, "Single side-band modulation performance of a $LiNbO_3$ integrated modulator consisting of four-phase modulator waveguides," *IEEE Photon. Technol. Lett.*, vol. 13, pp. 364–366, 2001.
[9] H. Nyquist, "Certain topics in telegraph transmission theory," *AIEE. Trans.*, vol. 47, pp. 617–644, 1928.
[10] A. Suzuki, Y. Takahashi, and M. Nakazawa, "A polarization-maintained, ultranarrow FBG filter with a linewidth of 1.3 GHz," *IEICE Electron. Express*, vol. 3, pp. 469–473, 2006.

1 Introduction

Finding a way to improve the spectral efficiency of optical transmission systems is becoming more important as the demand for capacity rapidly increases. Coherent optical transmission systems with a high spectral efficiency of more than 2 bit/s/Hz have recently been demonstrated by several research groups using quadrature phase-shift keying (QPSK) [1], 8-PSK [2], and orthogonal frequency division multiplexing (OFDM) [3]. The highest spectral efficiency demonstrated in a dense wavelength division multiplexing (DWDM) transmission experiment was 4.2 bit/s/Hz, and was reported by X. Zhou et al in 2008 [2] who used a polarization-multiplexed return-to-zero (RZ) 8-PSK format.

Of the many available modulation formats, coherent 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 binary PSK [4]. We have already reported polarization-multiplexed 1 Gsymbol/s, 64 and 128 QAM coherent signal transmissions over 150 km with a single channel [5, 6].

In this paper, we describe a three-channel frequency division multiplexed (FDM) and polarization-multiplexed 1 Gsymbol/s, 64 QAM coherent transmission over a 160 km single-mode fiber (SMF) with a 1.4 GHz spacing. The total capacity for each channel reaches 12 Gbit/s in an optical bandwidth of 1.4 GHz, resulting in a spectral efficiency of 8.6 bit/s/Hz. In other words, 36 Gbit/s transmission is successfully achieved with an FDM bandwidth of 4.2 GHz.

DOI: 10.1587/elex.5.776
Received August 11, 2008
Accepted August 20, 2008
Published September 25, 2008

IEICE Electronics Express, Vol.5, No.18, 776–781

2 Frequency division multiplexed QAM coherent optical transmission

Figure 1 shows the experimental setup we used for an FDM 1 Gsymbol/s, 64 QAM coherent optical transmission over 160 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 split into two arms. One part is coupled to a multi-carrier generator (MCG) consisting of an LN phase modulator at a modulation frequency of 1.4 GHz. In the MCG, three carriers are generated with the same power level. Then these carriers are coupled to two IQ modulators consisting of three Mach-Zehnder modulators [8]. We prepared two arbitrary waveform generators (AWGs: 4 Gsample/s, 1 GHz bandwidth) to feed I and Q signals into the IQ modulators for independent polarization multiplexing. It should be noted that three FDM channels of each polarization state are modulated with the same data in this experiment, and therefore this does not fully represent a realistic system. We adopted a Nyquist software filter at the AWG [9]. By using a raised-cosine Nyquist filter with a roll-off factor of 0.35, the bandwidth of the QAM signal was reduced from 2 GHz to less than 1.4 GHz. The other frequency-stabilized beam is coupled to an optical frequency shifter (OFS), which provides a frequency downshift of 2.1 GHz against the signal. Then the frequency-shifted signal is used as a pilot tone signal that tracks the optical phase of an LO (tunable tracking laser) under optical PLL operation. The polarization of the pilot tone signal is set so that it is the same as one of the polarization axes in the QAM signals. After passing through the EDFAs, the QAM signals are then combined with the pilot tone signal and these signals are coupled into a 160 km-long transmission fiber (SMF 80 km × 2 spans). The total coupled

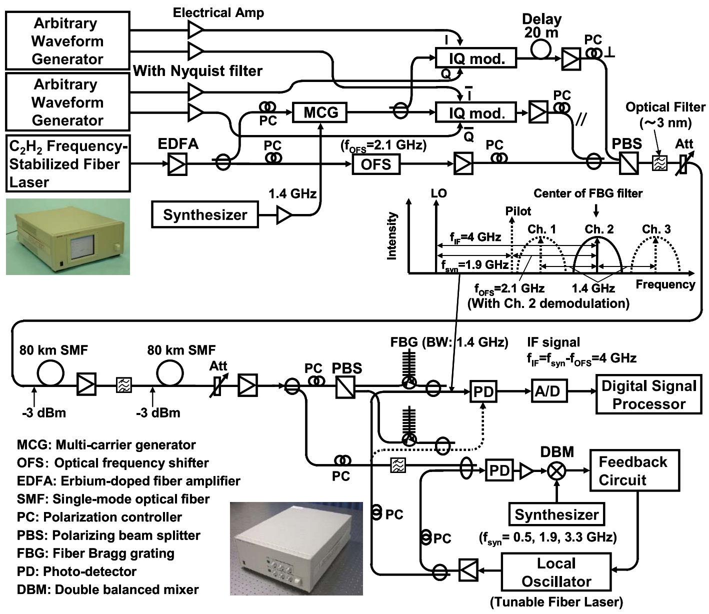

Fig. 1. Experimental setup for frequency division multiplexed QAM coherent optical transmission over 160 km.

DOI: 10.1587/elex.5.776
Received August 11, 2008
Accepted August 20, 2008
Published September 25, 2008

power is set at -3 dBm to remove nonlinear effects such as XPM and FWM. In addition, the total transmission length is only 160 km. Therefore, the low coupled power and the short link allow us to assume that the present system is linear. After the transmission, the QAM signals are heterodyne-detected with an LO signal whose phase is locked to the pilot tone signal. Since the LO polarization can be arbitrarily rotated with a polarization controller, orthogonally polarized QAM signals can be independently detected. The power level of the LO coupled to the PD is 1 dBm. Then an IF data signal is A/D-converted and accumulated in a high-speed digital scope (40 Gsample/s, 12 GHz bandwidth). This transmission system operates in an off-line condition, where all the digital data are demodulated by software.

In Fig. 1, the inset figure shows the relationship between the optical frequency and the QAM signals, pilot tone signal, and LO signal with Ch. 2 demodulation. Here the frequency of the synthesizer in the optical PLL circuit, f_{syn}, is set at 1.9 GHz. By changing f_{syn} to 0.5 or 3.3 GHz, Ch. 1 or Ch. 3 data, respectively, can be demodulated at the same IF. The linewidth of the electrical spectrum of the beat signal between the pilot tone signal and LO signal 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 6.0×10^{-3} rad.

Figure 2 (a) shows the electrical spectrum of the beat signal between the QAM signals and a single-frequency fiber laser. There were three main FDM channels with the same power levels and residual harmonic signals on both sides with a power level of about 10% against the total power of the QAM signals. Figure 2 (b) shows the electrical spectrum of the IF signal of the Ch. 2 data when the polarization of the signal was orthogonal to that of the pilot tone signal. Here the Ch. 2 data were extracted by using a narrowband FBG filter with a bandwidth of 1.4 GHz [10]. Although there were residual components of Ch. 1 and Ch. 3 data, they were removed with a digital filter in a digital signal processor (DSP). Almost the same spectrum was obtained for the parallel data condition. With Ch. 1 demodulation, a residual pilot tone signal with a relatively larger power was detected. However, this was

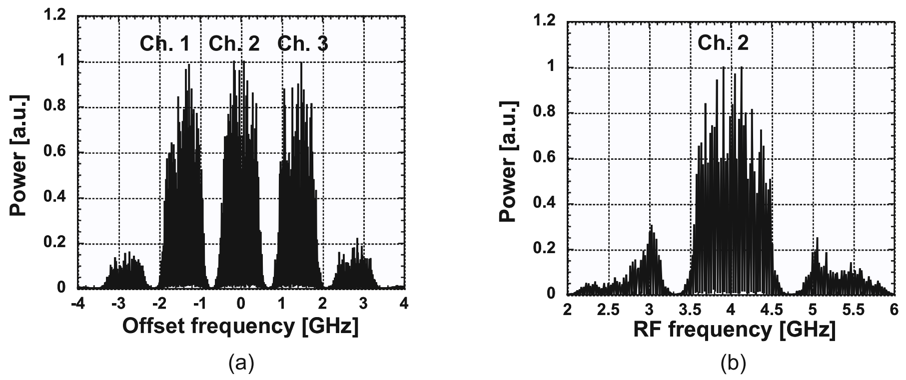

Fig. 2. Electrical spectra of the beat signal between the QAM signals and a CW fiber laser (a) and IF signal of Ch. 2 data (b).

DOI: 10.1587/elex.5.776
Received August 11, 2008
Accepted August 20, 2008
Published September 25, 2008

IEICE Electronics Express, Vol.5, No.18, 776–781

also removed by the digital filter.

3 Transmission results

Figure 3 (a) shows the bit error rate (BER) characteristics under a back-to-back condition and after a 160 km transmission for an FDM 1 Gsymbol/s, 64 QAM signal. The word length was limited to 4096 symbols by the DSP, which corresponds to a BER of 4×10^{-5}. We measured the BER 10 times, and the average values are plotted in Fig. 3 (a). On the horizontal axis, the received power is converted into that of each channel. The BER characteristics were almost the same for all the channels. The power penalty was approximately 1.5 dB at a BER of 4×10^{-5} for all channels, but no error was observed when the received power level was above −40 dBm. Figure 3 (b)–(d)

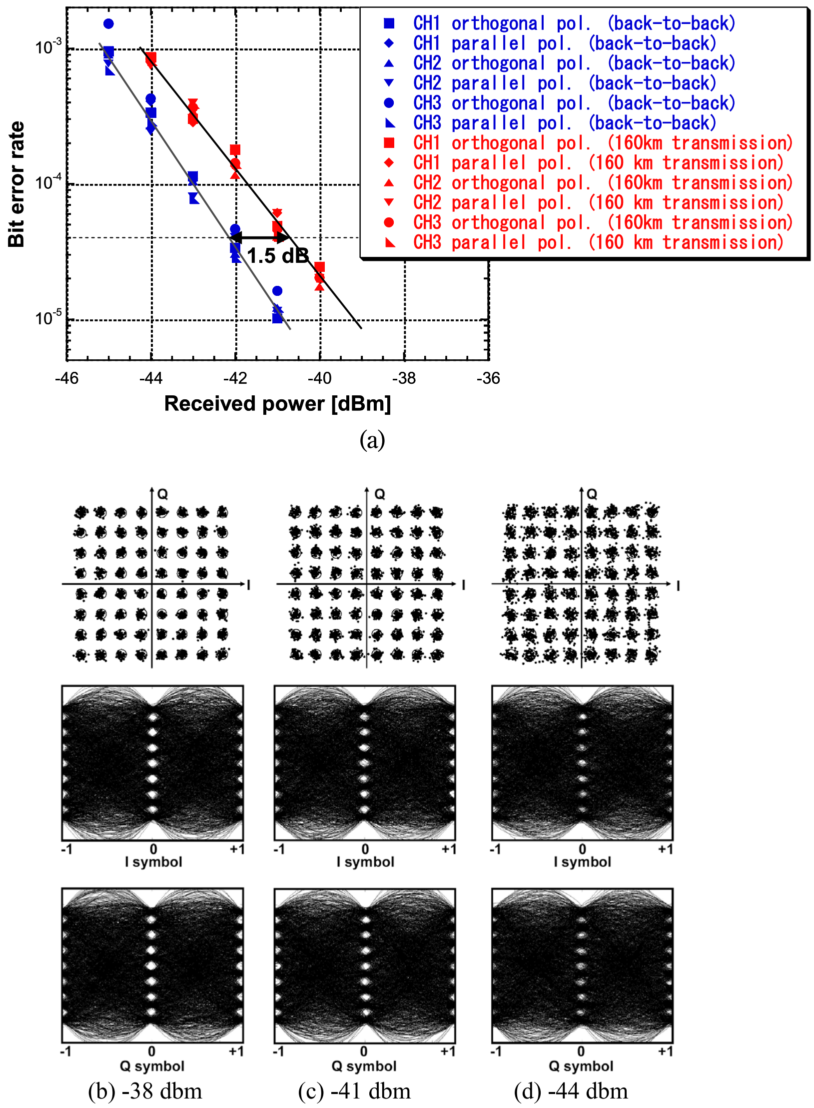

Fig. 3. Transmission results. (a): BER as a function of received power. (b), (c), (d): Constellations and eye patterns for Ch. 2 data with orthogonal polarization after a 160 km transmission as a function of the received power.

DOI: 10.1587/elex.5.776
Received August 11, 2008
Accepted August 20, 2008
Published September 25, 2008

IEICE Electronics Express, Vol.5, No.18, 776–781

shows the constellations and eye patterns for the Ch. 2 data after a 160 km transmission, where the polarization of the signal is orthogonal to the pilot tone signal. Figure 3 (b)–(d) correspond to received power levels of −38, −41, and −44 dBm, respectively. When the received power was −41 dBm, as shown in (c), the constellation points overlapped and the eye opening was reduced. These results indicate that above −40 dBm, polarization-multiplexed 1 Gsymbol/s, 64 QAM (12 Gbit/s) data were successfully transmitted over 160 km in a three-channel FDM with a 1.4 GHz spacing.

In this experiment, each channel was not decorrelated, resulting in some correlations between data. With data correlation, because of enhanced coherent nonlinearity the transmission condition may become worse than when the channels are decorrelated. Nevertheless, we have obtained successful transmission results. Although there is no bit crossing between the channels due to the small walk-off, the inter-channel effect is very weak as the symbol rate and the coupled power are low and the link length is short. In addition, a linear cross talk between the channels is negligible because the channel spacing is sufficient and DSP BPF can easily eliminate other channels.

4 Conclusions

We have successfully transmitted an FDM 1 Gsymbol/s, 64 QAM coherent optical signal over 160 km with a 1.4 GHz spacing. A spectral efficiency of 8.6 bit/s/Hz was achieved.

DOI: 10.1587/elex.5.776
Received August 11, 2008
Accepted August 20, 2008
Published September 25, 2008