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60 Gbit/s 64 QAM-OFDM coherent optical transmission with a 5.3 GHz bandwidth

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Abstract: We present a 60 Gbit/s polarization-multiplexed coherent optical OFDM transmission at 5 Gsymbol/s by employing 64 QAM subcarrier modulation. We adopted a frequency-stabilized fiber laser and an optical PLL to achieve this high multiplicity in the subcarrier modulation. As a result, we successfully transmitted 60 Gbit/s data over 160 km with a demodulation bandwidth of only 5.3 GHz.

Keywords: coherent transmission, orthogonal frequency division multiplexing, quadrature amplitude modulation, spectral efficiency, frequency-stabilized laser, optical phase-locked loop

Classification: Fiber-optic communication

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1 Introduction

Increasing the spectral efficiency in WDM transmission systems is one of the most important subjects in optical communications research in terms of expanding the transmission capacity within a finite optical bandwidth. Coherent quadrature amplitude modulation (QAM) [1, 2, 3] is one of the most spectrally efficient modulation formats. We have already described the highest reported spectral efficiency of 10 bit/s/Hz with a polarization-multiplexed FDM transmission of 128 QAM signals [4]. Moreover, QAM multiplicity has recently been increased to 256, and 64 Gbit/s data have been transmitted at 4 Gsymbol/s in a 5.4 GHz optical bandwidth [5].

Orthogonal frequency division multiplexing (OFDM) is another attractive candidate for highly spectral-efficient transmission. The multi-carrier transmission of low-speed orthogonal subcarriers enables us to improve both spectral efficiency and dispersion tolerance by adopting high-level subcarrier modulation formats and employing coherent detection [6, 7, 8, 9]. A 1 Tbit/s per channel OFDM transmission has been demonstrated that takes advantage of these features, [7]. Recently, intensive efforts have been made to achieve higher spectral efficiency in OFDM by increasing the QAM multiplicity. A spectral efficiency of 7.0 bit/s/Hz has already been realized with 32 QAM subcarrier modulation, where 8×65.1 Gbit/s polarization-multiplexed OFDM signals were transmitted with a channel spacing of 8 GHz [8].

In this paper, we describe a polarization-multiplexed 64 QAM-OFDM transmission at 5 Gsymbol/s over a 160 km standard single-mode fiber (SSMF). This is the highest subcarrier QAM multiplicity in coherent OFDM, and it was made possible by using a frequency-stabilized fiber laser and an optical PLL technique. 60 Gbit/s data (58.8 Gbit/s without OFDM overhead)

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were successfully transmitted with a demodulation bandwidth of 5.3 GHz. This indicates the possibility of a spectral efficiency as high as 11.1 bit/s/Hz in a multi-channel transmission, which is almost the same as the level we achieved in a single-carrier 256 QAM transmission [5].

2 Experimental setup for 64 QAM-OFDM coherent optical transmission

The experimental setup for a 5 Gsymbol/s 64 QAM-OFDM coherent optical transmission over 160 km is shown in Fig. 1. The optical source for the transmitter is a continuous-wave (CW) C_2H_2 frequency-stabilized fiber laser with a 4 kHz linewidth and an optical frequency of f_c = 194.8218264 THz [11]. An arbitrary waveform generator (AWG) running at 10 Gsample/s generates a 5 Gsymbol/s baseband OFDM signal. At the AWG, binary data for transmission are first encoded into a 64 QAM format, and training symbols (TS) are added to the QAM data. Furthermore, the QAM data are pre-compensated for the phase rotation caused by SPM in the transmission line. The QAM data are divided into 512 subcarriers. The amplitude balance of I and Q data and their skews are adjusted for each subcarrier to realize pre-equalization (Pre-EQ) to compensate for the frequency response of the

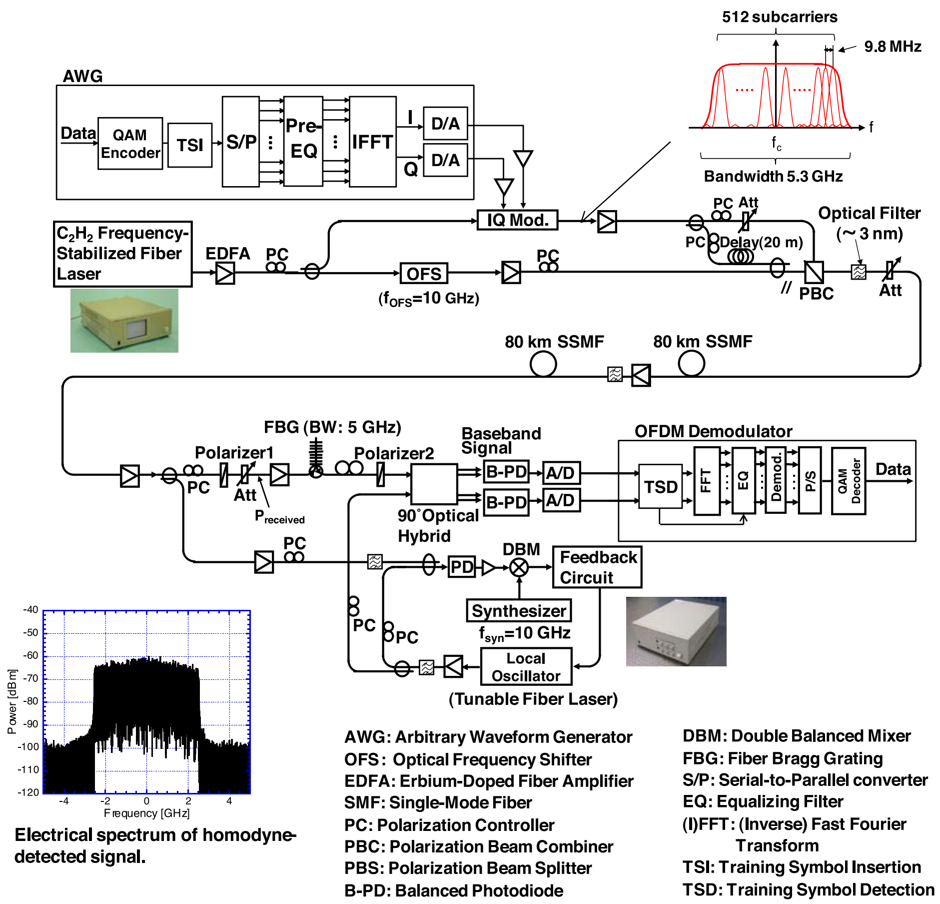

Fig. 1. Experimental setup for 64 QAM-OFDM coherent optical transmission. The inset shows the electrical spectrum of a homodyne-detected signal.

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transmission system. The data are finally D/A converted after an IFFT has been performed, and fed into an IQ modulator. Here, the symbol rate per subcarrier is 9.8 Msymbol/s, the FFT size is 1024, and four of every 204 OFDM symbols are assigned as TS. Since the transmission distance is relatively short this signal does not contain a guard interval. The bandwidth of the baseband signal is 5.3 GHz.

The laser output is split into two paths, and one is modulated with the OFDM data at the optical IQ modulator, followed by polarization multiplexing. The other part of the laser output is frequency down-shifted by 10 GHz against the signal, which is used as a pilot tone signal. On the receiver side, it tracks the optical phase of a local oscillator (LO) under optical phase-locked loop (OPLL) operation. The polarization of the pilot signal is matched to one of the polarization axes of the two OFDM signals. The polarization-multiplexed OFDM signals and the pilot signal are then coupled into a 160 km SSMF. Each fiber span is 80 km long, and its loss is compensated for only by the EDFA. The launched power into each span is set at –4 dBm. This power level is optimized to minimize the impairment caused by fiber nonlinearity and SNR.

After transmission, one of the polarizations of the OFDM signal is extracted with Polarizer 1 and preamplified with an EDFA. The received power is changed by using a variable optical attenuator in front of the preamplifier. The signal is passed through a fiber Bragg grating (FBG) filter with a bandwidth of 5 GHz and Polarizer 2 for ASE noise reduction. Then, it is homodyne-detected by an LO signal with a 90-degree optical hybrid. The LO signal source is a frequency-tunable tracking fiber laser with a 4 kHz linewidth. The phase of the LO signal is locked to the pilot signal with an OPLL circuit. The electrical spectrum of a beat signal between the pilot tone (f_c – 10 GHz) and LO signals (f_c) under OPLL operation is shown in Fig. 2. The linewidth 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 0.48 deg. This value is smaller than the nearest angle

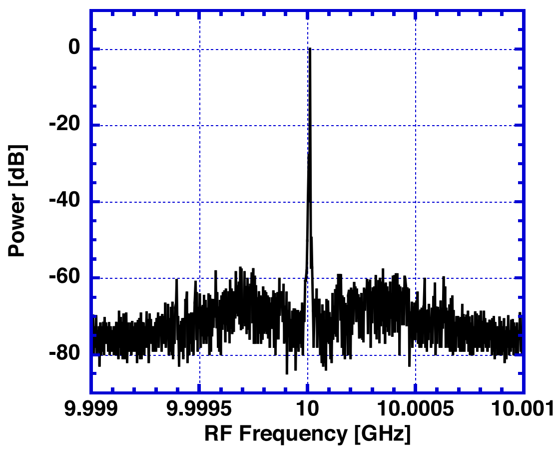

Fig. 2. Electrical spectrum of a beat signal between a pilot signal and an LO under PLL operation.

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between adjacent symbols of 64 QAM of 4.7 deg. Since the LO polarization can be arbitrarily rotated with a polarization controller, orthogonally polarized OFDM signals can be independently detected. After detection with two balanced photo-detectors, the data are A/D-converted and accumulated in a high-speed digital oscilloscope. Then, the digital data are demodulated by a digital signal processor (DSP) in an off-line condition. The electrical spectrum of the homodyne-detected signal under a back-to-back condition is shown in the bottom left of Fig. 1. The demodulation bandwidth was set at 5.3 GHz by using a digital filter. At the DSP, the OFDM signal is demodulated with an FFT, and then an equalization (EQ) filter is adopted for each subcarrier to compensate for amplitude and phase distortion with the aid of a TS, which is extracted before the FFT. Finally the bit error rate (BER) is calculated after conversion to a binary data sequence.

3 Transmission results

Figure 3(a-1) shows the optical spectrum of the optical OFDM signal before transmission. With a resolution bandwidth of 0.1 nm, the OSNR is more than 35 dB. Figure 3(a-2) shows the optical spectrum after a 160 km transmission. The OSNR is reduced by 5 dB owing to ASE noise, but it is still a sufficiently high value for error-free transmission with 64 QAM. Figure 3(b) shows the BER performance back-to-back and after a 160 km transmission. Here, the DSP memory size for demodulation was limited to 102,400 symbols, which corresponds to a BER calculation limit of up to 1.6×10^{-6}. The solid line indicates a theoretical back-to-back curve. The cause of this penalty from the theoretical BER may be imperfect implementation of the hardware, for example the AWG and the IQ modulator. The power penalty at a BER of 10^{-5} was approximately 2 dB for both polarizations, but error-free performance with a BER below the calculation limit was achieved with a received optical power above −25 dBm. If we allow a BER up to the FEC threshold of 2×10^{-3}, it should be possible to extend the transmission distance further. Figure 3(c) shows constellation maps obtained back-to-back (c-1) and after a 160 km transmission (c-2) for orthogonal polarization at a received power of −25 dBm. A similar clear constellation was also obtained for parallel polarization. As a result, 60 Gbit/s data (corresponding to a raw data rate of 58.8 Gbit/s after excluding 2% TS overheads) were successfully transmitted over 160 km with a demodulation bandwidth of 5.3 GHz. This indicates that there is the possibility of realizing a spectral efficiency of 11.1 bit/s/Hz for a multi-channel transmission if the frequency of the pilot signal is brought as close as possible to the data signal.

4 Conclusion

We have reported a polarization-multiplexed 5 Gsymbol/s (60 Gbit/s) OFDM transmission with 64 QAM-512 subcarriers over a 160 km SSMF that we achieved by using coherent detection with a frequency-stabilized fiber laser and an optical PLL technique. This result corresponds to a raw data rate of

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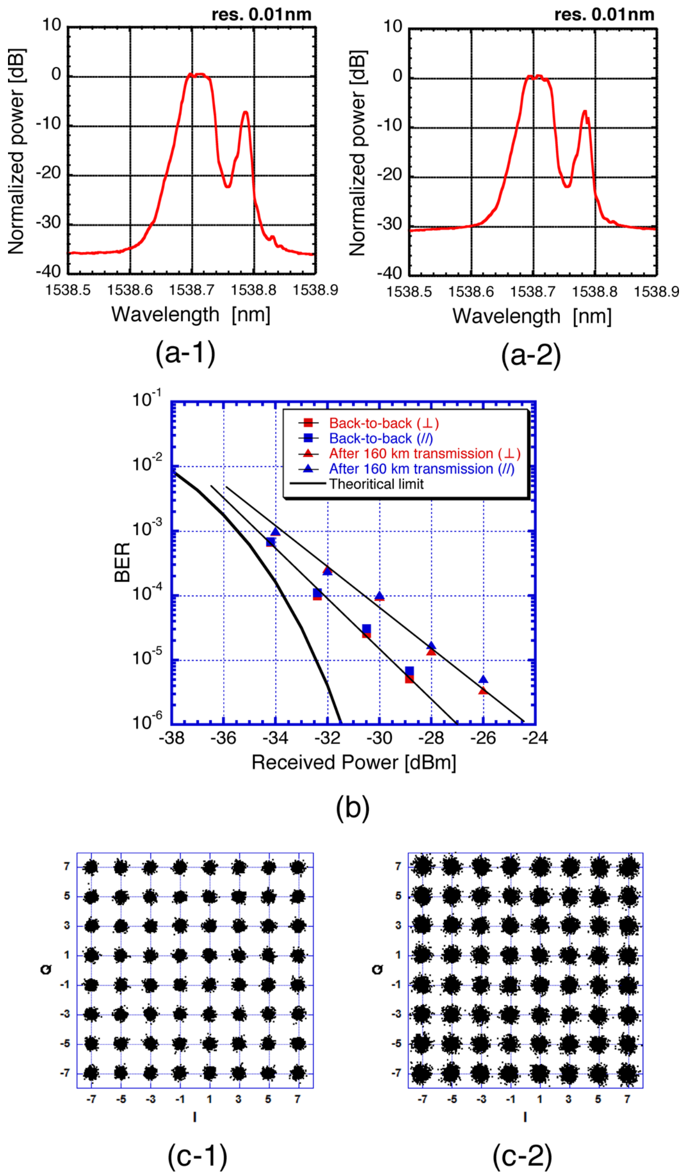

Fig. 3. Transmission results. Optical spectrum of an OFDM signal before transmission (a-1) and after 160 km transmission (a-2). BER characteristics for polarization-multiplexed 5 Gsymbol/s 64 QAM-OFDM transmission over 160 km (b). Constellation maps obtained back-to-back (c-1) and after 160 km transmission (c-2).

58.8 Gbit/s with a demodulation bandwidth of 5.3 GHz, and thus indicates the possibility of achieving a spectral efficiency as high as 11.1 bit/s/Hz for FDM transmission.

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