60 Gbit/s, 64 QAM LD-based injection-locked coherent heterodyne transmission over 160 km with a spectral efficiency of 9 bit/s/Hz

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Abstract: We report an injection-locked 60 Gbit/s 64 QAM coherent transmission employing a laser diode (LD) based heterodyne demodulation circuit. The LDs for the transmitter and receiver were InP-based external cavity laser diodes (ECLDs) emitting at 1538.8 nm. By using an injection locking technique with locking range of 100 MHz, we achieved low phase noise carrier synchronization between the data and the local oscillator with a phase noise of 0.3 deg. As a result, a polarization-multiplexed 64 QAM data signal was successfully transmitted over 160 km with a spectral efficiency of 9 bit/s/Hz.

Keywords: injection locking, semiconductor laser, coherent transmission, heterodyne demodulation

Classification: Fiber optics, Microwave photonics, Optical interconnection, Photonic signal processing, Photonic integration and systems

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1 Introduction

To satisfy the rapidly growing demand for capacity in optical fiber backbone networks, coherent optical transmission with a multi-level modulation format has been intensively investigated [1]. In coherent transmission, phase synchronization between transmitted data and a local oscillator (LO) is indispensable especially for high multiplicity modulation in quadrature amplitude modulation (QAM) transmission. For data, some phase synchronization schemes have already been developed with software [2, 3] or hardware circuits [4, 5]. Among them, an injection-locking scheme is a very interesting way to realize low phase noise carrier synchronization with a simple receiver configuration [6].

In recent years, several coherent transmission techniques employing injection locking schemes have been demonstrated [7, 8]. QPSK [7] and 8-QAM [8] orthogonal frequency-division multiplexed (OFDM) injection-locked coherent transmissions have been reported. However, these experiments all used a residual carrier in the middle of the OFDM signal as an injection seed, and this residual carrier must have a high optical signal noise ratio (OSNR). This means that a high ratio is required between the optical intensities of the residual carrier and the data signal. The result is S/N degradation of the data, which makes it difficult to apply this approach to higher-order QAM transmission. The highest multiplicity reported thus far has been just 8 QAM in an OFDM injection-locked coherent transmission. Furthermore, the bit rate was below 15 Gbit/s, and the maximum spectral efficiency (SE) was only 2.3 bit/s/Hz.

In the work described in this paper, by employing a simple LD-based injection-locked coherent heterodyne detection circuit, we successfully transmitted a single carrier 60 Gbit/s, 64 QAM with an SE of as high as 9 bit/s/Hz. An InP-based external cavity laser diode (ECLD) [9] was used for the transmitter and LO. We added a tone that was 3.33 GHz higher than the center frequency of the data, to the input data. This tone signal was used as a high OSNR injection seed to realize stable injection locking without OSNR degradation of the data signal. Together with heterodyne demodulation by the injection-locked LO, we realized a 64 QAM coherent transmission with a bit rate of 60 Gbit/s over a distance of 160 km. The SE of 9 bit/s/Hz obtained in this experiment is the highest yet reported for an injection-locked coherent transmission.

2 Experimental setup for 60 Gbit/s, 64 QAM injection-locked coherent optical transmission

Fig. 1 shows our experimental setup for a 60 Gbit/s, polarization-multiplexed (Pol-Mux), 5 Gsymbol/s 64 QAM coherent transmission with an injection locking
scheme. We used a 4 kHz linewidth, InP-based ECLD with an external Bragg grating on a silica planar lightwave circuit emitting at 1538.8 nm as a transmitter [9]. A CW light signal from the ECLD was IQ-modulated with a 5 Gsymbol/s, 64 QAM signal and a pilot tone signal generated by an arbitrary waveform generator (AWG) at 10 Gsample/s. Fig. 2 shows their electrical spectra. The pilot tone signal was located beside the QAM data 3.33 GHz from the carrier frequency. The power ratio between the pilot tone and the data was 1:10. The pilot tone was used as an injection locking seed at the receiver. Here, we adopted a Nyquist filter with a roll-off factor of 0.2 at the AWG that enabled us to reduce the bandwidth of the QAM signal to 6 GHz. A pre-equalization process was also employed to compensate for the distortions caused by individual components such as the IQ modulator and AWG by using a 99-tap finite impulse response (FIR) digital filter. At the same time, pre-compensation was employed for the nonlinear phase rotation caused by

Fig. 1. Experimental set-up for 60 Gbit/s, 64 QAM 160 km coherent transmission.

Fig. 2. RF spectrum of 5 Gsymbol/s, 64 QAM data signal.
self-phase modulation (SPM) during transmission. The Pol-Mux of the data was achieved with a polarization beam combiner (PBC). These signals were transmitted over two 80-km single-mode fiber (SMF) spans with an erbium doped fiber amplifier (EDFA) between them.

At the receiver, the transmitted signals were split into two arms after the EDFA. In one arm, the pilot tone signal as an injection seed was extracted by an etalon filter with a 50 MHz bandwidth and then injected into the LO. The inset in Fig. 1 shows the self heterodyne beat spectrum between the injection seed and the ECLD. The residual data signal still remained around the seed signal at −35 dB down from the peak. As an LO, we used a frequency-tunable ECLD with 4 kHz linewidth. The configuration was the same as that of the transmitter except that the isolator was removed. We adjusted the path length difference between the two arms with an accuracy of 1 m. Polarization demultiplexing was carried out with a polarization controller (PC) in front of a polarization-diverse 90-degree optical hybrid. The QAM signals were heterodyne-detected with the injection-locked LO by using the polarization-diverse 90-degree optical hybrid and four balanced photo-detectors (B-PDs). After heterodyne detection, the data signal was A/D-converted using a digital oscilloscope (40 Gsample/s, 16 GHz bandwidth) and demodulated in an offline condition with a digital signal processor (DSP). We calculated the bit error rate (BER) from 123 kbit demodulated signals.

3 Experiment results

First, we describe the injection locking condition in the experiment. Here, we optimized the injection power of the seed signal with back-to-back demodulation experiments. Fig. 3(a) shows the error vector magnitude (EVM) of demodulated 64 QAM data as a function of the injection power. The EVM maintained a value of 2.5% with injection powers in the −27 to −20 dBm range. At an injection power lower than −27 dBm or above −20 dBm, the injection locking operation became unstable resulting in EVM degradation. Fig. 3(b) shows the locking range characteristics of the LO as a function of the injection power. The locking range was 100 MHz with an injection power of −20 dBm. On the basis of these results, we set the injection locking power at −20 dBm to obtain a wide locking range and best EVM.
We evaluated the injection locking performance with an intermediate frequency (IF) signal between the pilot tone signal and the injection-locked LO. Fig. 4(a) shows the electrical spectrum of the IF beat signal with a 2 MHz span. The linewidth of the spectrum was less than 10 Hz, which was below the measurement resolution. Fig. 4(b) shows the single-sideband (SSB) phase noise spectrum measured with an electrical spectrum analyzer. The RMS of the phase noise variance of the signal estimated by integrating the SSB noise power spectrum from 10 Hz to 1 MHz was only 0.3 degrees. Compared with the performance of our previous optical phase-locked loop (OPLL) using an optical voltage controlled oscillator (OVCO) [10], the phase noise was reduced from 0.6 to 0.3 degrees. This was because the LD had a wideband locking range compared with the 4 MHz loop bandwidth of our previous OPLL [10]. Although there were residual data around the seed signal as shown in the inset of Fig. 1, the injection locking performance was not affected, because the locking range was sufficiently narrow compared with the frequency separation of 300 MHz between the pilot tone and the data signal.

![Fig. 4. Characteristics of injection locking circuit. (a) Beat spectrum between pilot tone and injection-locked LO, (b) SSB phase noise spectrum.](image)

![Fig. 5. Optimization of launch power in 120 Gbit/s, 64 QAM – 160 km coherent transmission.](image)
Fig. 5 shows the BER of a demodulated 5 Gsymbol/s, 64 QAM signal after a 150 km transmission for various powers launched into each fiber span obtained with SPM compensation. Based on these results, the launch power was optimally set at −1 dBm (QAM data: −4 dBm/pol. and pilot tone: −14 dBm). Fig. 6 shows the OSNR degradation during transmission. After a 160 km transmission, the OSNR was degraded from 40 to 35 dB. Fig. 7(a) and (b), respectively, show the constellations for the 64 QAM data for back-to-back and 160 km transmissions. Their respective EVMs were 2.5% and 3.1%.

Fig. 8 shows the BER characteristics versus the OSNR for a detected 64 QAM signal with a 0.1 nm resolution under back-to-back and after a 160 km transmission. After 160 km, error free demodulation was realized with an OSNR of over 31 dBm. The OSNR penalty at a BER of $2 \times 10^{-3}$ after transmission was 4 dB. This penalty was caused by cross phase modulation (XPM) between the two polarizations and the OSNR degradation of the pilot tone signal, which will lead to the S/N degradation of the injected LO after transmission.

![Fig. 6. Optical spectra of 60 Gbit/s, 64 QAM data signal before and after 160 km transmission.](image1)

![Fig. 7. Constellations of 64 QAM signal (a) back-to-back, and (b) after 160 km transmission, respectively.](image2)
4 Conclusions

An LD-based 60 Gbit/s, 64 QAM coherent transmission was demonstrated by using a heterodyne demodulation circuit with an injection locking scheme. By using a pilot tone signal as an injection seed signal with high OSNR, low phase noise carrier synchronization was realized. Consequently, we successfully transmitted a 64 QAM data signal over 160 km with an SE of 9 bit/s/Hz.

Fig. 8. BER characteristics for 60 Gbit/s, 64 QAM-160 km transmission.