Impact of Local Oscillator Phase Noise on Long-Haul Transmission of 120-Gbaud Digital Sub-Carrier Signals

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Abstract: The EEPN penalty was measured separately from other factors in 5120-km transmission of 120-Gbaud 16QAM signal for different LO lasers. Digital subcarrier multiplexing suppressed the EEPN-induced NGMI deterioration by ~0.4 at 102,400 ps/nm.

1. Introduction

Digital signal processing (DSP)-enabled coherent communications have the ability to compensate for transmission degradation, increase spectral efficiency, and acquire carrier tracking at the receiver. However, it has been observed that coherent received signals remain degraded by frequency modulation (FM) noise from the local oscillator (LO) laser, even after DSP for dispersion and laser phase noise compensation. This enhanced noise is commonly known as equalized enhanced phase noise (EEPN) [1]. Various studies have been conducted to assess EEPN failure in various systems such as single carrier quadrature amplitude modulation (QAM) and subcarrier (SC) systems [2,3]. All of these studies consider only lasers with the ideal Lorentz linear FM noise spectrum. In particular, the consideration that lasers generally have a non-white FM noise spectrum has been analyzed by adding digital noise to received electrical data [4]. The fundamental reason for the increased sensitivity has been shown to be the displacement of the symbol after dispersion compensation of the electrical domain caused by EEPN interference from local FM noise. This causes timing jitter and inter-symbol interference.

In this paper, we evaluated the degradation in EEPN signal quality due to white and non-white noise during 120-GBaud 16QAM subcarrier transmission, using commercially available ITLA light sources, A, B, and C, which has different FM-noise spectrum as LO light sources for coherent transmission. It was confirmed that the EEPN transmission penalty was as small as 0.02 dB in the case of a light source with lower MHz order FM noise by comparing the transmission penalties of light sources A, B, and C with the FM noise spectrum. In addition, it was confirmed that the sub-carrier multiplexed signal is suppressed the EEPN-induced NGMI deterioration from 0.4 to smaller than 0.01 by increasing the number of SCs to 8, even if the FM noise is higher than 10^5 Hz^2/Hz. The SC signal turned out to be suitable for long-distance transmission.

2. Laser FM noise

A schematic of an experimental setup for phase noise acquisition is shown in Fig. 1 (a). The continuous light from ITLA was input into the local oscillator port of the integrated coherent receiver (ICR). The external cavity laser (ECL), which has specified linewidth of smaller than 100 kHz, was input into the signal port after passing through a polarization controller. A digital sampling oscilloscope (DSO) operating at a sampling rate of 12.5 GS/s captured 12.5 M samples from the output electrical beat signal detected by the ICR. Then the signals were fed into a signal processing as shown in Fig. 1(b). The DC offset of the ICR and the frequency offset between the ECL and local ITLA were removed from the captured data. Then, a calculated FM noise spectrum was obtained by taking the moving average of nine subsets of the data [5].

Fig. 1(c) shows the results for a laser FM noise spectrum under the condition that LO light was used for the three different ITLA light sources A, B, and C. The FM noise was large in the order of C, B and A at frequencies above the MHz order.

3. Digital sub-carrier signal transmission with laser phase noise

Figure 2 (a) shows the experimental setup. On the Tx side, a 128-GSa/s arbitrary waveform generator (AWG) was used to generate radio frequency (RF) signals. The single-ended linear driver amplifiers with a gain of 11 dB was used to drive a 120-Gbaud subcarrier RF signal for a lithium niobate-based polarization-division-multiplexed (PDM) in-phase quadrature modulator (IQM). The subcarrier signal can be selected from 120 Gbaud × 1 SC, 60 Gbaud × 2 SC, 30 Gbaud × 4 SC, and 15 Gbaud × 8 SC. Each subcarrier signal was used perform spectrum shaping with root-raise cosine filter of roll-off factor of 0.0625 as shown in figure 2 (b). The PDM-16QAM subcarrier signal was modulated with a continuous wave of 1547.436 nm output from an adjustable external cavity laser (ECL) amplified

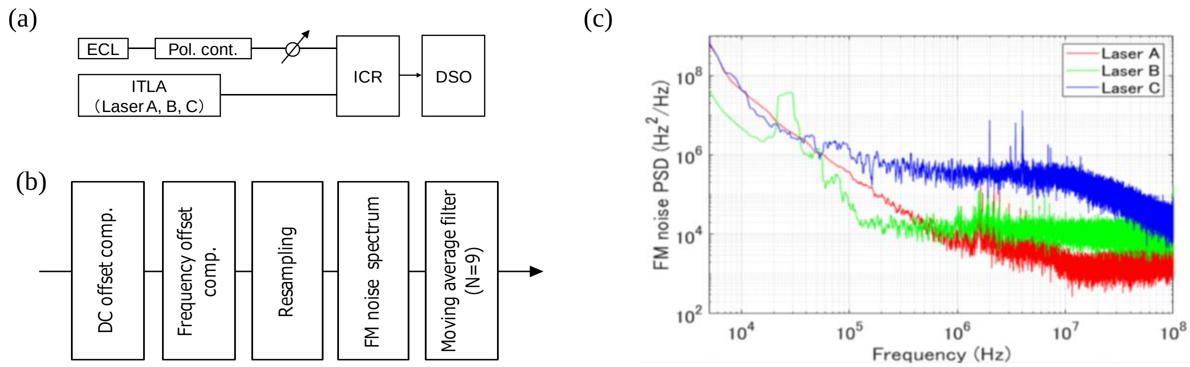

Fig.1 (a) Experimental setup for evaluating laser FM noise, (b) signal processing of received beat signals, (c) results for laser FM noise spectrum.

up to 23 dBm by using an erbium-doped fiber amplifier (EDFA). The interference channel with 137.5-GHz grid spaced WDM bandwidth of 4.2 THz was emulated by using amplified spontaneous emission noise and an optical gain equalizer (GEQ). The signal and interference channels were fed into a flexible grid wavelength selection switch (WSS) to multiplex the channels.

The generated WDM signal was sent into a recirculation loop consisting of two spans of 80-km PSCF which has residual chromatic dispersion of 1600 ps/nm. A GEQ that flattened the gain slope, and an EDFA and backward Raman amplification compensates for fiber loss every 80-km span of PSCF. The input power to the launched fiber was set to +1.6 dBm/channel to avoid extra nonlinear noise.

On the receiver (Rx) side, the received signal was amplified using EDFA and filtered by an optical bandpass filter (OBPF). The signal was detected by a coherent receiver consisting of an optical hybrid and four balanced photodetectors (BPDs). The local oscillator input to the optical hybrid used lasers A, B or C described in Section 2. A 256-GS/s digital storage oscilloscope (DSO) digitized the received signal. In offline Rx-DSP, it was demodulated with the same algorithm as in Reference [6] in the case of a single carrier signal. For subcarriers, after de-maxing the subcarrier signal from the received signal, the signal sampling rate was converted to two samples per symbol. After chromatic dispersion compensation, Polarization separation and imperfections of the transceiver were compensated by inputting a pair of subcarrier signals that are symmetrical across DC of the carrier to the 8×2 MIMO equalizer [6]. Frequency offset and phase noise were compensated by a pilot-assisted digital phase-locked loop with a pilot overhead of 3.2 % [7]. Normalized generalized mutual information (NGMI) was derived from the log likelihood ratios.

Figure 2 (c) shows the distance dependence of the NGMI of the 120-Gbaud single-carrier signal. The transmission characteristics are evaluated with the setting that the light source on the Tx side is ECL and the lasers A, B, and C are used as LO. In addition, it will be evaluated even if the laser relationship is changed. The transmission impairments due to EEPN decreases in the order to the light source A, B, C, which is the same as the relationship of the amount of frequency noise above the MHz order of the FM noise spectrum in Fig. 1 (c). In particular, the signal quality deterioration due to EEPN is larger when the laser C is used as LO light. When the FM noise in the MHz region is on the order of 10^4 Hz^2/Hz, the EEPN-induced NGMI deterioration is as small as 0.02 or less at 5120 km with residual chromatic dispersion of 102,400 ps/nm, even if using the Laser B which has a peak in the FM noise spectrum around 20 kHz.

Figure 2 (d) shows the EEPN-induced NGMI degradation for the different numbers of subcarriers. The EEPN-induced NGMI degradation is obtained as the difference in NGMI when the laser C is used as the LO light source and when the laser C is used as the Tx light source. Note that the resulting EEPN penalty excludes the EEPN penalty when using ECL as an LO light source. While, given the ECL line width as narrow as 100 kHz, the excluded penalty can be considered to be sufficiently small. The measured NGMI variation on the number of subcarrier, i.e. 1, 2, 4, and 8, is within 0.01. Hence, the same characteristics are obtained regardless of the number of SC. The larger number of subcarrier division signals was more advantageous in terms of the amount of impairment associated with transmission. While, the EEPN-induced NGMI deterioration increase to 0.4 after 5120-km transmission, when the FM noise is above 10^5 Hz^2/Hz. Furthermore, in the digital SC transmission experiment, even if the FM noise is higher than 10^5 Hz^2/Hz, the EEPN-induced NGMI deterioration is suppressed from 0.4 to smaller than 0.01 by increasing the number of SCs to 8. These results show that the SC multiplexed signal can significantly suppress the signal quality deterioration due to EEPN.

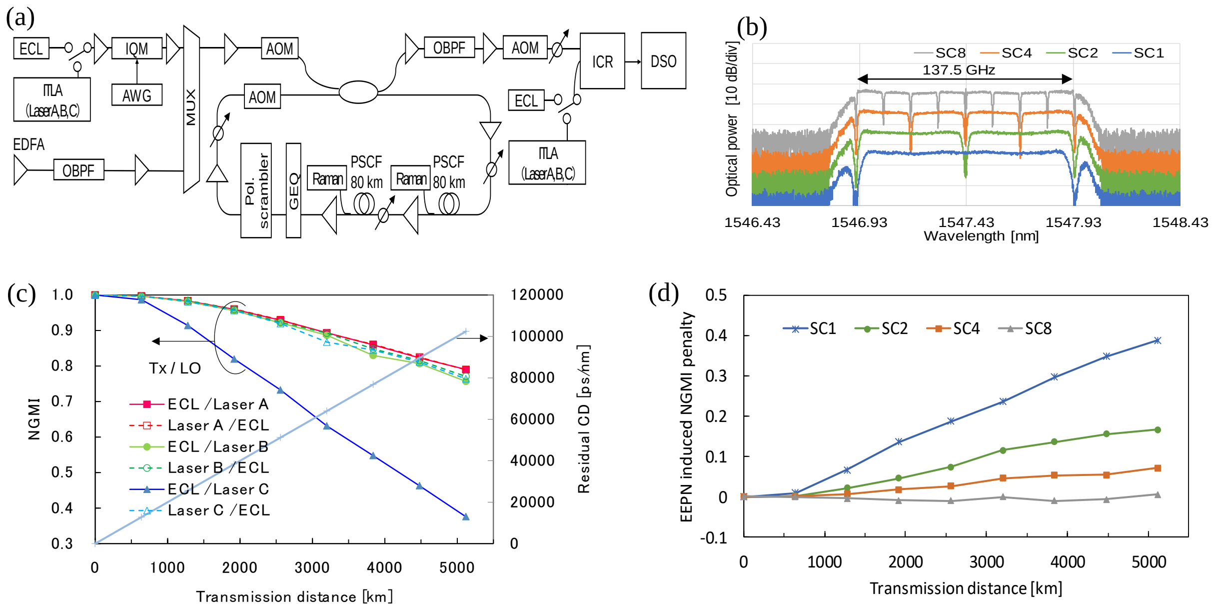

Fig.2 (a) Experimental setup for digital sub-carrier signal transmission with laser phase noise, (b) optical spectrum of the digital sub-carrier signal, (c) NGMI of 120-Gbaud signle carrier 16QAM signal versus distance and (d) EEPN induced NGMI penalty of digital sub-carrier signals using the laser C

4. Conclusion

We evaluated the NGMI deterioration caused by the EEPN effect for 120-GBaud 16QAM subcarrier transmission, where commercially available different three ITLA light sources were used as LO of coherent transmission. We analyzed the FM phase noise spectrum of the three lasers having different white and non-white noise. In fiber transmission experiments, the EEPN-induced NGMI deterioration was measured separately from other transmission penalty factors such as fiber non-linearity by exchanging LO light sources between ITLA and ECL. From these results, when the FM noise in the MHz region is on the order of 10^4 Hz^2/Hz, the EEPN-induced NGMI deterioration is as small as 0.02 or less at 5120 km transmission with chromatic dispersion of 102,400 ps/nm. While, the EEPN-induced NGMI deterioration increase to 0.4, when the FM noise is above 10^5 Hz^2/Hz. Furthermore, in the digital SC transmission experiment, even if the FM noise is higher than 10^5 Hz^2/Hz, the EEPN-induced NGMI deterioration is suppressed from 0.4 to smaller than 0.01 by increasing the number of SCs to 8. The SC signal turned out to be suitable for long-distance transmission.

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