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Coherent Detection of Multi-level Coded Optical Signals

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We discuss a digital coherent receiver, which can demodulate multi-level coded optical signals. The carrier phase is estimated with digital signal processing, and the optical complex amplitude is entirely restored without the optical phase-locked loop.

I. INTRODUCTION

Recently, with the advent of high capacity WDM transmission technologies, the spectral efficiency has become one of the main concerns of researchers. Coherent optical receivers are very attractive for increasing the spectral efficiency because any kind of multi-level modulation format can be introduced by using such receivers.

We have recently demonstrated a digital coherent receiver [1]. The in-phase and quadrature components of an optical signal are retrieved using a homodyne phase-diversity receiver without locking the phase of the local oscillator (LO). The carrier phase is recovered after homodyne detection by means of digital signal processing (DSP). While an optical phase-locked loop (PLL) that locks the LO phase to the signal phase is still difficult to achieve, DSP circuits become increasingly faster and provide us with simple and efficient means for estimating the carrier phase. In addition, electrical signal processing such as group-velocity dispersion (GVD) compensation is achievable in the homodyne receiver, making the coherent scheme more attractive. This paper describes the principle of operation of our DSP-based homodyne phase-diversity receiver and its applications.

II. PPRNCIPLE OF OPERATION OF THE COHERENT RECEIVER

The optical phase-diversity homodyne receiver used in our experiments is shown in Fig.1 [1]. Orthogonal states of polarization for LO and the incoming signal create the 90° hybrid necessary for phase diversity. With the $\lambda/4$ waveplate (QWP), the polarization of the LO becomes circular, while the signal remains linearly polarized and its polarization angle is 45° with respect to the principle axis of polarization beam splitters (PBSs). After passing through the half mirror (HM), the polarization beam splitters separate the two polarization components of the LO and signal while two balanced photodiodes PD1 and PD2 detect the beat between the LO and signal in each polarization.

Let the complex amplitude of the signal be represented by

$$E(t) = E_s(t)\exp\left[j\left(\theta_s(t)+\theta_n(t)\right)\right], \quad (1)$$

where $E_s(t)$ is the signal amplitude, $\theta_s(t)$ the phase modulation and $\theta_n(t)$ the carrier phase in reference to the LO phase. Then, the currents from PD1 and PD2 are expressed as

$$I_{PD1}(t) = RE_{LO}E_s(t)\cos\left[\theta_s(t)+\theta_n(t)\right], \quad (2)$$

$$I_{PD2}(t) = RE_{LO}E_s(t)\sin\left[\theta_s(t)+\theta_n(t)\right], \quad (3)$$

where R is the responsitivity of the photodiodes and E_{LO} the amplitude of LO. The electrical signals I_{PD1} and I_{PD2} contain information on the in-phase and quadrature components of the complex amplitude of the optical signal.

The signals $I_{PD1}(t)$ and $I_{PD2}(t)$ are simultaneously sampled once every symbol period T with analog-to-digital converters (ADCs). We can thus reconstruct the signal complex amplitude, ignoring unimportant constants, as

$$E_{sx}(iT) = I_{PD1}(iT) + jI_{PD2}(iT), \quad (4)$$

where T denotes the sampling time interval, and i the number of samples.

Since the linewidth of semiconductor DFB lasers Δf used as the transmitter and LO typically ranges from 100 kHz to 10 MHz, the optical carrier phase $\theta_n(t)$ varies much more slowly than the phase modulation, whose symbol rate is 10 Gsymbol/s in our experiments. Therefore, by averaging the carrier phase over many symbol intervals, it is possible to obtain an accurate phase estimate. In the case of M-ary PSK signals, we take the M-th power of $E_s(iT)$ because the phase modulation is removed from $E_s(iT)^M$. Averaging $E_s(iT)^M$ over $2k+1$ samples constitutes a phase estimate as

$$\theta_e(iT) = \arg\left(\sum_{j=-k}^{k} E_s((i+j)T)^M\right)/M. \quad (5)$$

The phase modulation $\theta_s(iT)$ is determined by subtracting $\theta_e(iT)$ from the measured phase of $\theta(iT)$.

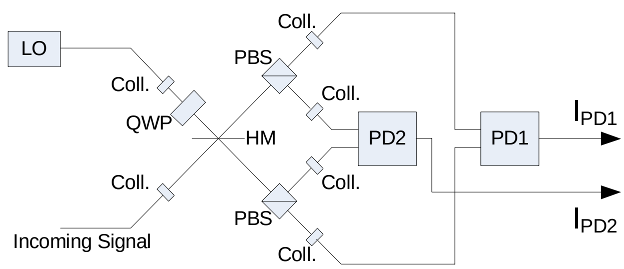

Fig.1 Construction of the homodyne phase-diversity receiver.

III. BIT-ERROR RATE MEASUREMENTS OF *M*-ARY PSK SIGNALS

The back-to-back BER of the BPSK, QPSK, and 8-PSK signals was measured to access the receiver performance [2]. The DFB laser output was modulated through $LiNbO_3$ phase modulators to generate PSK signals at a symbol rate of 10 Gsymbol/s. The received signal was amplified with an erbium-doped fiber amplifier (EDFA) to –10 dBm before it was detected with the coherent receiver. The linewidth of the transmitter and the LO was about 150 kHz and frequency drifts of the lasers were kept below 10 MHz. The signals I_{PD1} and I_{PD2} were simultaneously sampled at a rate of 20 Gsample/s with analog-to-digital converters (ADCs). The collected samples were resampled to keep only one point per symbol and combined to form a 100-ksymbol stream. The signal was demodulated through the digital phase estimation process described in Sec.II, and the number of bit errors was counted through off-line measurements. Fig.2 shows BERs measured as a function of the received power. Fig.3 represents the constellation map of the 8-PSK signal obtained in the error-free state.

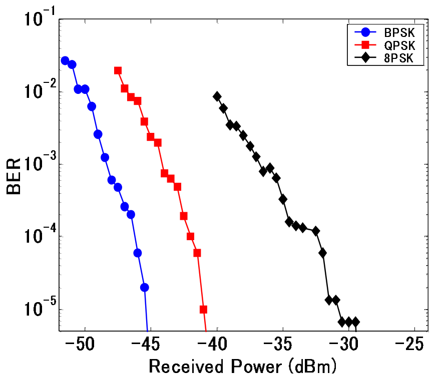

Fig.2 Back-to-back BER curves for BPSK, QPSK, and 8-PSK signals.

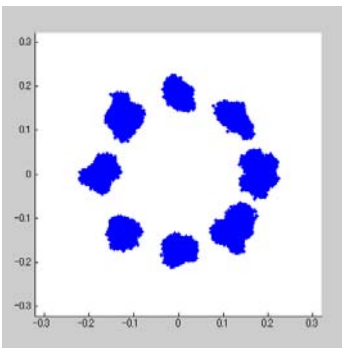

Fig.3 Constellation map for the 8-PSKsignal.

IV. POST-PROCESSING FUNCTION

Coherent detection can linearly recover the amplitude and phase information of optical signals. Therefore, post-processing of the received signal allows fully electronic compensation for chromatic dispersion, which is a linear transfer function operating on the optical complex amplitude. In this section, we demonstrate unrepeated transmission of 20-Gbit/s optical QPSK signals over a 200-km standard single-mode fiber (SMF), where after homodyne phase-diversity detection, digital signal processing is employed for carrier phase estimation as well as dispersion compensation [3]. A total dispersion of up to 4,000 ps/nm is compensated effectively through a simple transversal digital filter implemented in our coherent receiver.

Fig. 4 shows measured BER of the 20-Gbit/s QPSK signals, when the fiber dispersion is compensated with various filters. For comparison, the back-to-back BER is also shown in Fig. 4. We find that even a small number of taps provides significant improvement of the BER performance. 39 taps are sufficient to compensate for dispersion value of 4,000 ps/nm. Although chromatic dispersion is thus compensated to significant degree, power penalties of about 5 dB still remain after transmission of 200-km distance. These penalties may stem from the nonlinear distortion due to the relatively large input power and non-ideal filter coefficients.

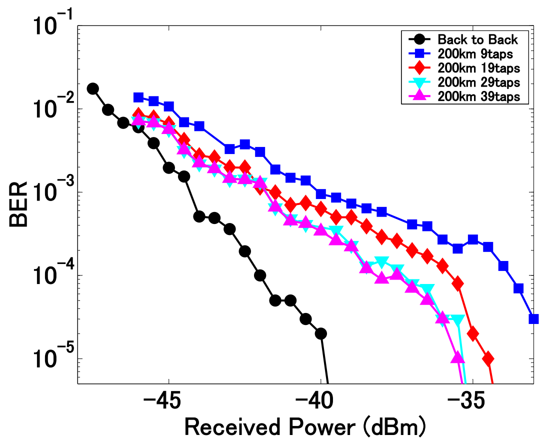

Fig.4 BERs measured as a function of the received power after transmission through a 200-km SMF.

V. CONCLUSION

We have investigated the homodyne phase-diversity receiver, where the carrier phase is estimated with digital signal processing, alleviating locking the phase of the local oscillator to the carrier phase. We have demonstrated demodulation of *M*-ary PSK signals (*M*=2, 4, 8) at the symbol rate of 10 Gsymbol/s, and post-compensation for chromatic dispersion of 4,000 ps/nm with such receiver.

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