Digital Optical Phase Locked Loop for Real-Time Coherent Demodulation of Multilevel PSK/QAM

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Abstract: We propose a digital optical phase locked loop (DOPLL) for real-time demodulation of high-speed multilevel PSK/QAM. It was simply implemented using low-speed digital signal processor after electrical sampling to demodulate high-speed BPSK, QPSK and 16QAM.

OCIS codes: (060.4510) Optical communications; (060.1660) Coherent communications;

1. Introduction

Optical multi-level modulation formats based on phase-shift-keying (PSK), quadrature amplitude modulation (QAM), and so on, are promising for optical fibre transmission with great spectral efficiency [1-4]. For demodulation of such multi-level signals, a digital coherent receiver is a powerful method, where optical carrier phase of a received signal is recovered by high-speed electrical digital signal processor (DSP) [5-7]. However most of the reports are based on off-line signal processing due to difficulty in development of high-speed DSP. On the other hand, an optical phase locked loop (OPLL) has been investigated as an alternative approach to achieve the demodulation of such coherent signals [8-10] with assistance of i) pilot or residual optical carrier [8], or ii) Costas loop circuits [9] or high-speed decision-driven loop [10]. But, the conventional OPLL-based schemes have the following disadvantages: i) receiver sensitivity or modulation efficiency is sacrificed due to the added carrier; and ii) it is difficult to deal with high-order or high-speed PSK signals because of the complexity of the electronics.

However, as the optical phase of lasers typically drift at 10 KHz~10MHz; it is not necessary to use high-speed circuits operated at (or higher than) the symbol rate of the received signals to recover the optical carrier. In this report, we demonstrate a high-speed real-time coherent demodulation scheme using a digital optical phase locked loop (DOPLL). Therein, a received high-speed coherent signal is firstly down-converted to a slower one by using electrical samplers and then its optical carrier could be recovered with an aid of slow-speed electrical DSP and feedback to optical frequency of an optical local oscillator (LO). By this DOPLL, high-speed multi-level signals can be demodulated without using high-speed DSP.

12.5-Gbaud PSK, QPSK and 16QAM were successfully demodulated by the developed DOPLL, where 32-M Samples/s DSP was implemented for decision-driven feedback loop. The developed DOPLL can be worked at the symbol rate up to 40 Gbaud.

2. Principles of real-time coherent demodulation by DOPLL

Fig. 1 shows the principle of real-time coherent demodulation based on DOPLL. The DOPLL consists of the sections for (a) optical phase detector, (b) low-speed electrical DSP, and (c) optical voltage controlled oscillator (OVCO). In the section for optical phase detector, I and Q components of the received signal projected to an optical local oscillator is detected with an optical 90-degree hybrid coupler followed by balanced detectors.

The detected I and Q components at bit rates of B are led to the DSP section for carrier phase recovery. In the section, the I and Q signals are firstly sampled down to B/n Hz (n = 1, 2,…) with a pair of electrical samplers. The down converted signals are introduced into an electrical DSP clocked at B/n Hz. In the DSP, an optical carrier phase of the received signals is recovered from the sampled I, Q signals using the algorisms [5-7] based on digital signal processing similar to digital coherent detection. In this report, the method based on decision-driven feedback is implemented in the DSP. Note that such signal processing for carrier phase recovery can be easily achieved in real-time operation even using low-cost and slow-speed electrical DSP with sampling rate of several MHz. In the DSP, a loop filter is also implemented to obtain an error signal for feedback.

The error signal calculated from the recovered carrier phase is fed back to the optical OVCO as shown in section (c) in Fig. 1. The OVCO consists of a laser source, optical single-sideband modulator (OSSB) driven with an electrical VCO. Through this configuration, the optical frequency of the CW source can be widely and precisely controlled proportionally to the calculated error signal. Therefore, by this DOPLL, LO is phase locked to the high-speed incoming signal and thus, the received signal can be detected in a homodyne way. At the output port of the 90-degree hybrid, demodulated I and Q components can be directly obtained, and simply analyzed in real time. No any other high-speed DSP is required for data recovery.

3. Experiments

Fig. 2 shows experimental setup. In the transmitter side, 12.5-Gbaud BPSK, QPSK or 16QAM was synthesized. Therein, a CW light generated from a fiber distributed feedback laser (F-DFB) with a spectral linewidth of ~ 5 kHz was modulated with pairs of PRBS data sequences (215-1) using a quad-parallel Mach-Zehnder.

In the receiver side, the multilevel signal was received and demodulated by the DOPLL. In the frontend of the DSP, a pair of electrical samplers with analogue bandwidth of 35 GHz was utilized to sample the received I-Q components. The sampling rate was set at 32 MHz, and the DSP was also synchronized to the same clock rate. In the DSP, the sampled IQ components were reconstructed on the phasor space again; each symbol was discriminated by giving two-dimensional thresholds; carrier phase of the received signal relative to the local was estimated. The proportional and integral (PI) of the estimated phase error is calculated and introduced into the feedback section through a loop filter. In the OVCO, optical SSB modulation was performed in the following way. A Z-cut MZM biased at the null point was push-pull driven with a sinusoidal signal generated from an electrical VCO; the upper-side band components of the generated DSB-SC signal was suppressed with a delayed MZI. The centre frequency of the electric VCO was set at 10 GHz and free-spectral range of the delayed MZI was 40 GHz. For simplicity, the CW source was shared in the transmitter and receiver sides, but independently frequency-shifted using independent OSSB modulators.

Firstly, we investigated demodulation of BPSK at 12.5 Gb/s. Threshold for symbol discrimination in the decision-driven feedback circuit was set on the quadrature axis. Once the DOPLL circuit was turned on, two symbols were stably locked at the position of inphase axes. A stable phase constellation could be directly observed in a real-time oscilloscope, as shown in Fig. 3 (a). Eye diagrams of demodulated signal were directly monitored just using a conventional sampling oscilloscope (Fig. 3(d)). Error free operation (BER<10-9) was achieved with the received power of -31 dBm, and shown in Fig. 3(f). For QPSK, thresholds were placed on the I and Q axis in the phasor space, by which 4 symbols were discriminated for decision-driven feedback. As shown in Fig. 3. (b), clear constellation was observed, and clear eye opening both for I and Q components were also observed (Fig. 3(e)). This two dimensional decision-driven feedback used for QPSK was approximately effective for higher-order QAM signals. Phase tracking for 16QAM was also confirmed and constellation under the phase-locked operation is shown in Fig. 3 (c). The digital OPLL developed can be operated at up to 40 Gbaud because bandwidths of the balanced detectors and electrical samplers were wide enough.

4. Summary

A real-time coherent demodulation of high-speed multilevel PSK/QAM was achieved using a DOPLL which was based on slow-speed DSP circuits. 12.5-Gbaud BPSK, QPSK and 16QAM were successfully demodulated. The digital OPLL can be worked at up to 40 Gbaud.

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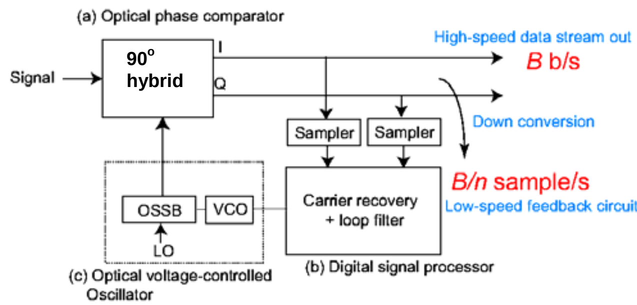

Fig. 1. Principle of real-time demodulation of high-bit-rate coherent signals using DOPLL.

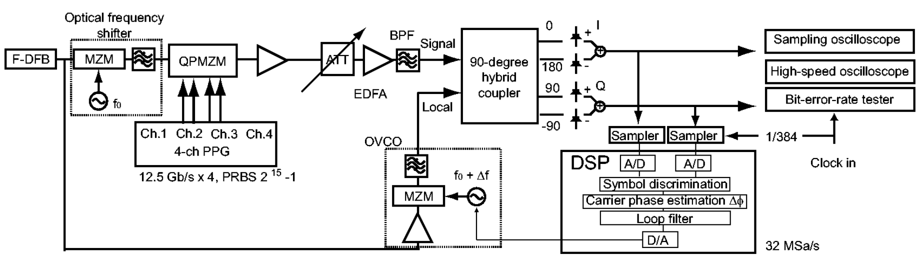

Fig. 2. Experimental setup.

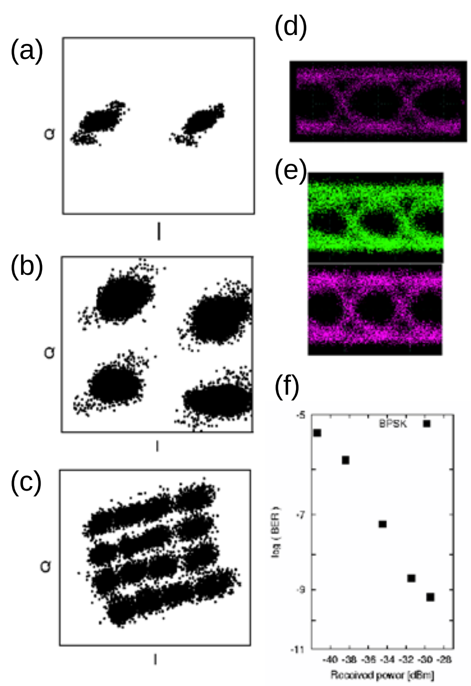

Fig. 2. Constellation maps of real-time received signals; (a) BPSK, (b) QPSK, (c) 16QAM; Eye patterns: (d) BPSK (e) I and Q components of QPSK; (f)Bit-error-rate characteristics of BPSK