Dual-Rate Linear Optical Sampling for Remote Monitoring of Complex Modulation Formats

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Abstract: We demonstrate linear optical sampling using simultaneous pulsed and CW local oscillators to enable phase tracking of a data modulated carrier. The technique enables the direct measurement of remotely received signals with low phase noise.

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1. Introduction

Coherent measurement techniques such as linear optical sampling (LOS) are poised to become invaluable tools for characterizing the complex modulation formats envisioned for future networks operating at 100 Gb/s and beyond. LOS promises a 1 THz measurement bandwidth with amplitude and phase sensitivity by quadrature mixing the signal to be characterized with a train of ultra-short sampling pulses in equivalent time [1].

A primary challenge of measuring the phase of coherent signals using LOS is removing the phase noise and drift of the modulated carrier. Previous approaches have used an ultra-stable carrier with slow drift that can be curve fit [1], phase-referencing which requires access to the unmodulated light [2], and a one-symbol delay technique which only gives the time-differential phase [3]. Our solution here is to simultaneously measure the signal with pulsed and continuous-wave (CW) local oscillators (LO's), such that the pulsed measurement captures the high-bandwidth data modulation in equivalent-time and the CW measurement tracks the lower bandwidth phase drift in real-time.

2. Experiment and discussion

Figure 1 illustrates our dual rate system, which contained a 100 MHz frequency comb pulsed LO and a kHz linewidth CW tracking LO. The pulsed source was filtered to 0.5 nm to reduce noise. A key to operation was the phase-locking of the CW source to a single comb tooth (mode) of the pulsed source at an offset frequency of 60 MHz (see Fig. 1b). The two LO's were distributed to separate quadrature demodulators where they were each mixed with the modulated data signal to be characterized. We generated the data signal by externally phase modulating a dense wavelength-division-multiplexing-grade distributed feedback (DFB) laser. Its ~10 MHz linewidth was wavelength locked to reduce drift to less than the 100 MHz comb spacing over a measurement duration of 1 ms. As shown in Fig. 1b, the CW laser was positioned near the data laser such that the separation was much less than the 350 MHz bandwidth of the quadrature demodulators. Measurements were synchronized to a 10 MHz frequency derived from the pulsed LO repetition rate. The four demodulator output channels and the electrical error signal from the phase lock circuit were simultaneously sampled at 2 GS/s by the A/D converter.

The electric field of the data signal was reconstructed offline as follows. Being oversampled, the pulsed LO data was decimated by a factor of 20 to yield data only at the peaks of the 100 MHz sampling pulses. These quadrature waveforms were used to calculate amplitude and phase signals which were high-bandwidth. By contrast, the phase from the CW LO waveforms was calculated using all of the measurement points, and then decimated by a factor of 20. What remains from differencing the phases measured each way is only the high-bandwidth data phase, seen in

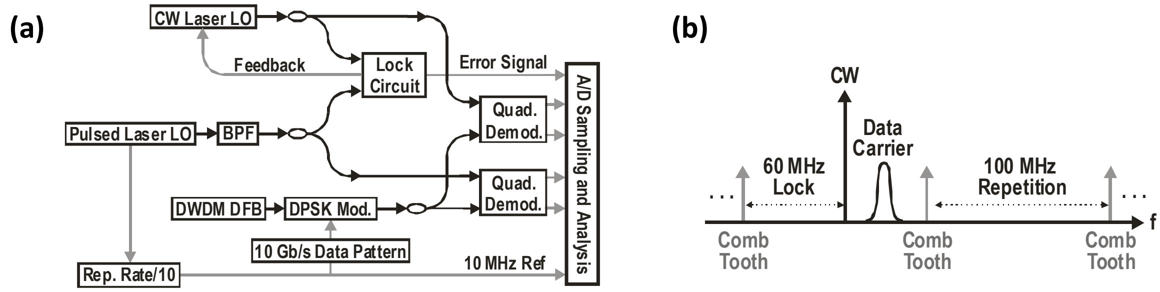

Fig. 1. The dual-rate LOS system (a) and its spectral content (b). A/D: analog to digital converter; BPF: bandpass filter; DWDM DFB: dense wavelength-division multiplexing distributed feedback laser; PSK: phase shift keying; CW: continuous wave; LO: local oscillator. Black lines – optical fiber paths, grey lines – electrical paths.

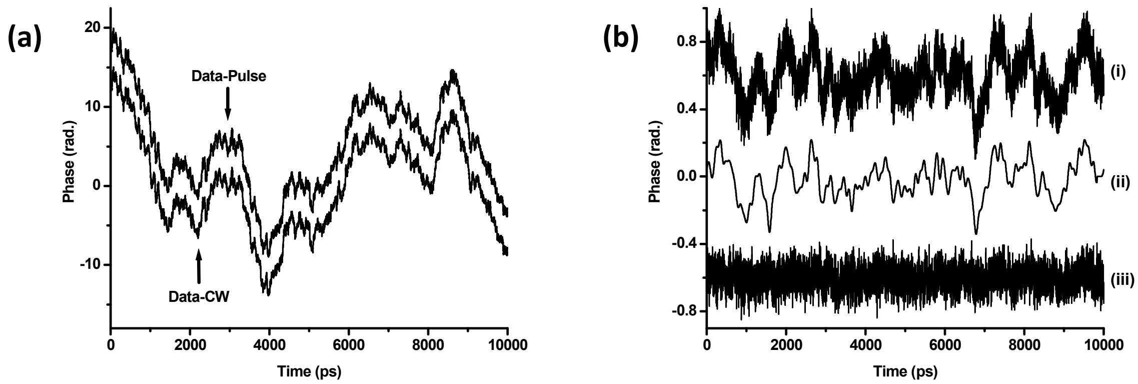

Fig. 2. Demonstration of reference-free phase tracking of an unmodulated DFB carrier, showing in (a) the phase measured by the two different local oscillators, and in (b) the difference in phase (i), the electrical error signal (ii), and the final normalized phase (iii).

equivalent-time by the pulsed LO but filtered in real-time from the CW LO measurement.

Figure 2 demonstrates the effectiveness of this approach, for a DFB without modulation. In Fig. 2a, a strong correlation can be seen in the phases measured both ways, despite a fluctuation of more than 30 radians. Their difference is plotted as curve (i) in Fig. 2b, and shows peak to peak noise fluctuations of less than a radian. Curve (ii) is the measured electrical error signal from the phase-lock circuit, which represents the residual phase difference between the CW and pulsed LO that is not removed by the lock. It shows a strong correlation to the slower variations of curve (i), and can be subtracted to obtain the featureless phase shown by curve (iii). The standard deviation of curve (iii) is 67 mrad, which can be reduced to 5.6 mrad with N=100 averages.

We applied our dual rate LOS technique to the measurement of a repeated DPSK-modulated 16-bit data sequence at 10 Gb/s. The word-synchronous amplitude and phase of the signal electric field are shown in Fig. 3, where the grey dots are the unaveraged overlay of the repeated waveform and the solid line is a 2 ps bin average. The pattern dependent ripple in the amplitude is clearly resolved and is attributed to the limited bandwidth of the modulator driver. The averaged phase is drift-free and shows clearly the π phase shifts expected of DPSK modulation, with an 8 mrad noise level equivalent to results obtained using phase-referencing [2]. Near the bit transitions are phase distortions which are apparent even after averaging and come about due to the phase ambiguity arising at maximum extinction of the modulator where the signal-to-noise ratio approaches zero.

We have demonstrated a dual-rate LOS technique which allows the drift of a modulated signal carrier to be tracked and removed effectively, thus making possible the direct measurement of phase at remotely located optical performance monitoring nodes in coherent communications networks.

3. References

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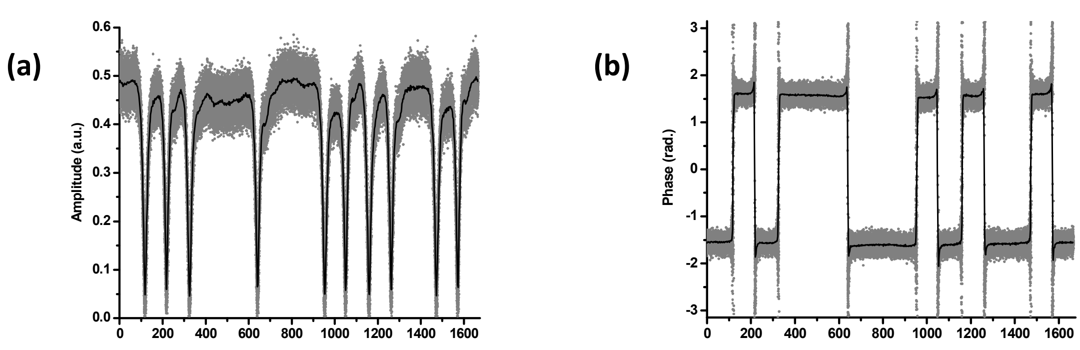

Fig. 3. DPSK modulated signal measured with dual-rate LOS, showing (a) amplitude and (b) phase without carrier drift. Grey dots – unaveraged waveform, black line – averaged waveform.