Frequency-Offset PLL for Synchronous Optical Sampling of OTDM Signals

Erik Benkler, Andreas G. Steffan, and Harald R. Telle

Abstract—**We demonstrate a novel synchronization scheme for optical sampling which is based on a nonstandard phase-locked loop (PLL). Phase comparison is performed at a 10-GHz optical time-division-multiplexing (OTDM) base rate, thus avoiding ultrafast detectors and electronics. The employed frequency-offset PLL allows synchronous sampling of OTDM signals (or any other signals with bit rates given by integer multiples of the base rate), which would be impossible using a standard PLL. This provides a higher degree of flexibility for problem-specific sweeping than asynchronous sampling.**

Index Terms—**Optical sampling, optical time-division multiplexing (OTDM), synchronization, timing jitter.**

I. Introduction

ULTRAFAST signal monitors are required in optical time-division-multiplexing (OTDM) systems in order to analyze detrimental effects on the bit-error rate, which can occur in the building blocks of the optical transmission line at OTDM bit rates. Since the bandwidth of state-of-the-art photodetectors and electrical sampling oscilloscopes is insufficient at OTDM bit rates of up to 640 Gb/s [1], several all-optical sampling techniques have been demonstrated in the recent years.

Optical sampling in general is an equivalent-time sampling technique based on cross-correlation between the optical signal under test and short optical sampling pulses at a lower, conveniently detectable rate [2]–[5]. The cross-correlation signal represents the power of the data stream during the short sampling pulse. Proper synchronization and controlled sweeping within the time slots of the data signal must be achieved in order to generate eye diagrams of the data signal. The usual approach is a sampling mode with the sampling frequency f_s slightly detuned from the Nth subharmonic of the clock rate f_c or bit rate $f_{\rm bit}$, resulting in sweeping with an equivalent-time infeed of $\Delta T = T_s - NT_{\rm bit} = 1/f_s - N/f_{\rm bit}$. This scheme is denoted as asynchronous sampling in this letter in contrast to synchronous sampling, where the sampling frequency is an exact subharmonic of the bit rate. It should not be confused with techniques not requiring a clock signal which are sometimes called asynchronous as well. Though in asynchronous sampling mode-sweeping is fast and occurs automatically, it suffers from a major drawback: It is impossible to achieve problem-specific sweeping, e.g., to stop sweeping at a specific point of equivalent time as it is necessary for amplitude or timing noise measurements.

Manuscript received July 13, 2006; revised December 13, 2006.

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Digital Object Identifier 10.1109/LPT.2007.891212

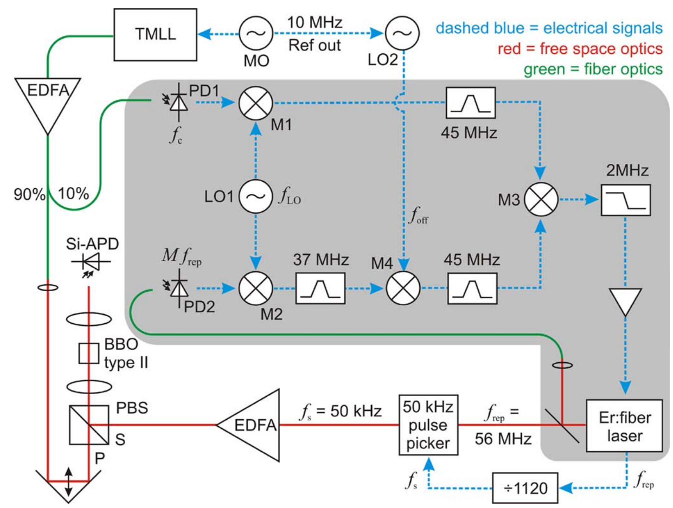

Fig. 1. Experimental setup. MO: 10-GHz master oscillator; TMLL: 10-GHz picosecond laser; PBS: polarizing beam splitter; LO: local oscillator.

II. Description of the Novel Synchronization Scheme

In this letter, we present a novel synchronization scheme operating in a synchronous mode with low system jitter due to timing discrimination at a 10-GHz data clock. We first discuss a simplified version of the phase-locked loop (PLL) for synchronous sampling, applicable if bit rate $f_{\rm bit}$ and clock rate f_c coincide. Later, this PLL is supplemented to enable synchronous sampling of signals with OTDM bit rates, i.e., integer multiples of the clock rate. In the synchronous mode, the sampling frequency is phase-locked to the Nth subharmonic of the bit rate

$$f_s = f_{\rm bit}/N = f_c/N. \tag{1}$$

The experimental implementation is sketched in Fig. 1. We will first describe the PLL highlighted as a gray shaded box. Both the $f_c = 9.968$–GHz optical data clock and the $M = 178$th (nearest to data clock) harmonic of $f_{\rm rep} = 56$ MHz are detected by fast InGaAs photodiodes, PD1 and PD2. Subsequently, using a common 10.013-GHz local oscillator, these signals are down-converted to an intermediate frequency (IF) near 45 MHz and narrow bandpass filtered (4 MHz) for noise reduction. The 37-MHz bandpass filter and mixer M4 are disregarded in this discussion of the simplified PLL. Instead, the output of M2 is treated as directly connected to the 45-MHz bandpass filter. Mixing the down-converted signals in M3 leads to a phase comparison which virtually takes place at 10 GHz (i.e., despite transfer to the IF, the high slope steepness of the 10-GHz signals is exploited) and is independent of the phase noise of the 10-GHz local oscillator [6]. The resulting error signal is used to control the repetition rate f_{rep} of the sampling laser. For this purpose, a mode-locked Er : fiber laser with a piezo-mounted mirror in a free-space section is employed [7]. The return-to-zero (RZ) data signal consists of a 10-GHz pulse train (1.8-ps full-width at half-maximum pulsewidth) generated by a tunable hybridly mode-locked semiconductor laser (u^{2}t TMLL1550). In order to increase the peak power of the sampling pulses and to reduce the sampling rate for facile data acquisition, a pulse picker sends every 1120th pulse from the laser into an erbium-doped fiber amplifier (EDFA) and discards the other pulses. The resulting sampling pulses at the sampling rate $f_s = f_{\mathrm{rep}}/1120 = 50$ kHz are shorter than 100 fs behind the dispersion-optimized EDFA, enabling 100-fs temporal resolution of the optical sampling oscilloscope. Since the 56-MHz pulse train from the oscillator is synchronized with the 10-GHz data clock, the sampling pulses are synchronized as well according to (1), with the harmonic order $N = M \cdot 1120$.

Besides the low timing jitter, our synchronous sampling scheme offers flexible problem-specific sweeping capabilities due to the absence of the nonius- (vernier)-like continuous sweep in asynchronous sampling mode. For example, sweeping over the shape of the bits in order to record an eye diagram is achieved either electronically by introduction of a phase ramp between the IF signals in the PLL, or mechanically by an optical delay line. Sweeping can thus be stopped at any equivalent-time position of the data pattern, e.g., at half the maximum value enabling accurate timing jitter measurements by slope detection [3], [5] or long-term visualization of the eye opening at any other equivalent time position of interest.

The synchronization scheme can be extended to OTDM data streams with bit rates of $f_{\mathrm{bit}} = 2^H f_c, H \in \mathbb{N}$, or more general of any integer multiple of the $f_c =$ 10-GHz OTDM base rate (clock rate before multiplexing), $f_{\mathrm{bit}} = L f_c, L \in \mathbb{N}$. For the reasons stated above, it is desirable to enable synchronous sampling for high bit-rate OTDM signals as well. However, the simple PLL scheme discussed so far cannot be directly applied in this case, because optical detectors with a bandwidth as large as the bit rate would be required. Nevertheless, the 10-GHz OTDM base rate is either directly available or can be derived from the data signal by clock recovery [8]. Consequently, we employ a frequency-offset PLL, which performs the phase discrimination at merely 10-GHz base rate, but allows proper synchronous sampling of OTDM signals.

If the simplified PLL described so far would be used performing phase discrimination at the base rate f_c, the sampling period would be an integer multiple of the base period $T_s = NT_c$. Since the OTDM signal has a bit period being a submultiple of the base period $T_{\mathrm{bit}} = T_c/L$, not all OTDM bits but only bits on the base period grid would be sampled, leading to an incomplete representation of the OTDM signal in the resulting eye diagram. Fig. 2 depicts the situation for the case $L = 4$. A change of the sampling frequency by a suitable *fraction* of the base rate, e.g., given by the bit period (or a change by a multiple N of this fraction, cf. Fig. 2), allows for sampling of the other

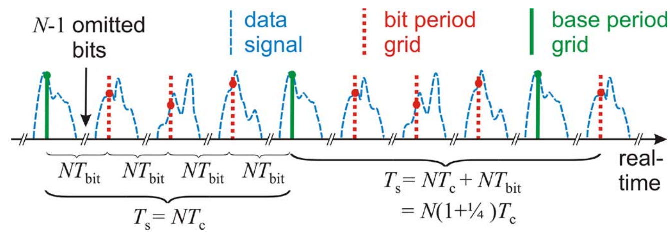

Fig. 2. Synchronous optical sampling with phase discrimination at the base rate for a one to four multiplexed OTDM signal ($L = 4 \Rightarrow T_c = 4T_{\mathrm{bit}}$).

bits on the bit period grid as well. Furthermore, prolonging the sampling interval by integer multiples of the clock period does not alter the sampling result. The required sampling period thus can be expressed as

$$T_s = NT_c + KNT_c + NT_c/L, \qquad K \in \mathbb{N}. \tag{2}$$

With $f_s = 1/T_s$ and $f_c = 1/T_c$ this results in the required sampling frequency $f_s = f_c/(N + KN + N/L)$, which can be written as the implicit equation

$$f_s = (f_c - (K + 1/L) f_s)/N. \tag{3}$$

Comparison with the harmonic PLL condition $f_s = f_c/N$ [cf. (1)] shows that the sampling condition (3) is satisfied if an offset frequency

$$f_{\mathrm{off}} = (K + 1/L) f_s \tag{4}$$

is subtracted from f_c. In the actual implementation, this is done by adding f_{off} with the additional mixer M4 in the opposite arm of the PLL which had been disregarded in the preceding discussion of the simplified PLL.

III. Experiment

The TMML1550 laser is synchronized to the 10-GHz master oscillator (Agilent E8257D) by hybrid mode-locking. The 1.8-ps 10-GHz pulse train from the laser is amplified by an EDFA (IPG Fibertech EAD-125-C). 10% of the light is used for detection of the 10-GHz optical clock with photodiode PD1 and the remaining 90% are sent to the cross correlator via an optical delay for sweeping in the synchronous sampling mode. Nonlinear cross-correlation is accomplished by sum frequency generation in a 5-mm β–barium–borate (BBO) crystal with type-II phase-matching for second-harmonic background suppression. A silicon avalanche photodiode detects the sum frequency signal, which is recorded with an AD card clocked by the sampling frequency.

To generate a programmable offset frequency for adaption to different OTDM bit rates, an RF synthesizer with subhertz resolution (LO2) is synchronized to the master oscillator. A value of $K = 150$ in (4), i.e., an offset frequency near 7.5 MHz is chosen, leading to an IF of 37 MHz behind mixer M2. The sum frequency signal at $f_{\mathrm{off}} + 37$ MHz passes the 45-MHz bandpass filter and is mixed in M3 with the signal from M1, generating the error signal to control the repetition rate of the sampling laser.

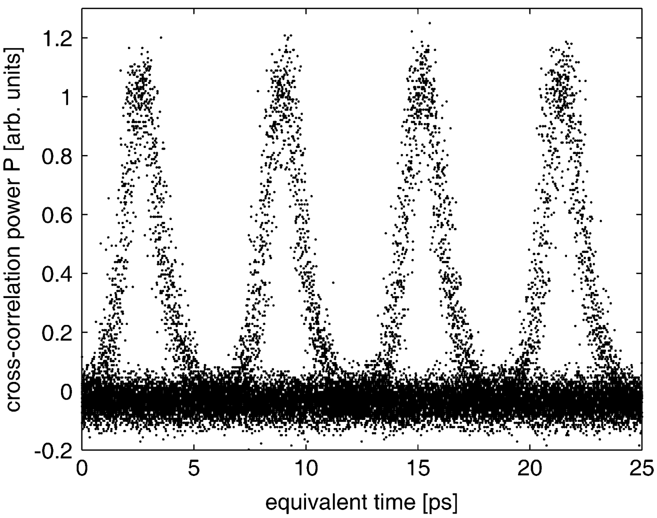

Fig. 3. 160-Gb/s eye diagram of a data stream consisting of the periodic bit pattern $\ldots,0000000000000001\;0000000000000001\;0000000000000001,\ldots$

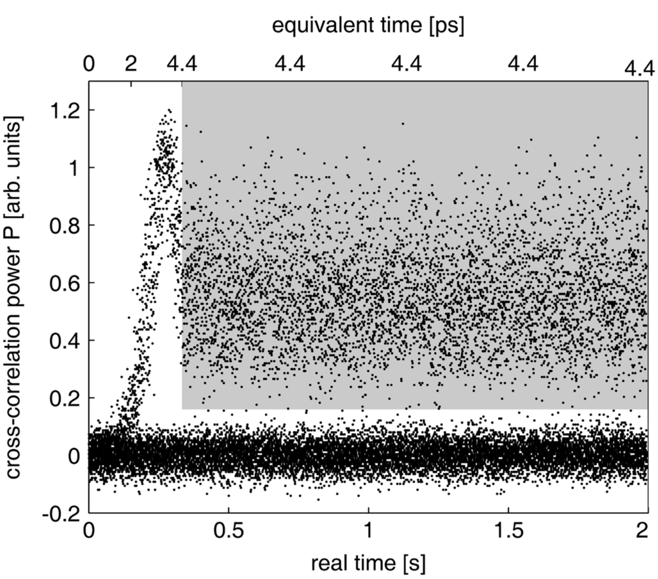

Fig. 4. Flexible sweeping as a unique feature of synchronous optical sampling. At $t_{\mathrm{real}} = 0.33$ s, sweeping is stopped and the eye opening is monitored.

To demonstrate the sampling capability at 160 Gb/s, we measured a 160-Gb/s eye diagram using synchronous sampling with sweeping by means of an optical delay line. The exact base clock frequency was $f_c = 9.975503125$ GHz and the required offset frequency was 7.503125 MHz ($N = 178 \times 1120, f_s = 50$ kHz and (4) with $L = 16, K = 150$). For simplicity, we sampled the 10-GHz pulse train emerging from the TMLL1550, which is equivalent to a 160-Gb/s RZ data stream with the periodic bit sequence of 15 "zero" bits followed by one "one" bit (Fig. 3). The standard deviation of the cross-correlation power P at the peak is a measure for the amplitude fluctuations and amounts to $\sigma_A \approx 11\%$. The main source of this amplitude noise is not the TMLL1550 ($\sigma_A < 2\%$ measured by independent method). It is rather caused by the pulse picker which adds amplitude noise to the sampling pulse train and was not optimized in this first demonstration of the synchronous optical sampling scheme. It should be noted that the choice of 160-Gb/s bit rate is not limited by the synchronization scheme, but at 320 Gb/s and above, the 1.8-ps-long data pulses start to overlap. Hence, eye diagrams at 320 and 640 Gb/s are not shown here.

Variable sweeping as a unique feature of synchronous optical sampling is demonstrated in Fig. 4. For $0 \leqslant t_{\mathrm{real}} < 0.33$ s (real time), the optical delay between data signal and sampling pulse train has been changed at a constant rate as in the case of Fig. 3. Then, at $t_{\mathrm{real}} \approx 0.33$ s or $t_{\mathrm{eq}} \approx 4.4$ ps, the delay was kept constant in order to monitor the eye opening at half the peak value. The cross-correlation power fluctuations in the gray shaded region ($t_{\mathrm{real}} > 0.33$ s, $P > 0.16$ arbitrary units) have a standard deviation of $\sigma_P \approx 0.17$ arbitrary units. From this value determined at sampling rate 50 kHz during 1.67 s, the timing jitter can be deduced. Since σ_P also contains amplitude noise of the sampling pulses, the system timing jitter is estimated as

$$\sigma_t = k\sqrt{\sigma_P^2 - (\sigma_A/2)^2} \approx 147 \text{ fs} \tag{5}$$

using the slope $k \approx 0.92$ ps/arbitrary unit at half the peak value. The timing jitter mainly results from the poor phase noise characteristics of the RF synthesizer (LO2).

IV. Conclusion

We have proposed and demonstrated a novel synchronization scheme with low jitter due to phase discrimination at a 10-GHz OTDM base rate. Insertion of an offset frequency in the PLL used for synchronization allows synchronous sampling of OTDM RZ signals with flexible bit rates given by an integer multiple of the 10-GHz base rate.

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