# Optical Vector Signal Analyzer Based on Differential Direct Detection

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**Abstract** *A versatile optical vector signal analyzer based on a differential direct detection scheme is presented. The analyzer measures phase, intensity, eye diagrams and constellations. The performance is demonstrated for a 112 Gbit/s PolMUX DQPSK signal and other formats.*

## Introduction

Various modulation formats[1,2,3] are under discussion for 100 Gbit/s transmission and beyond, including RZ, DPSK, QPSK, QAM combined with polarization-multiplexing (PolMUX). The difficulty though is that no cheap and versatile vector signal analyzer is available that allows a full characterization of the constellation diagrams, the eye diagrams and the time dependency of optical phase and intensity. Practical tools based on coherent detection schemes or on optical sampling techniques have recently come to the market[4,5]. Yet, while all of these tools work well, they are expensive since they rely either on a narrow-bandwidth coherent laser that is limited in its tuning range, or on mode-locked laser sources.

It has recently been shown that by means of differential direct detection schemes one can recover both phase and intensity of an optical signal[6,7].

In this paper, we demonstrate an optical vector signal analyzer (OVSA) that analyzes PolMUX signals by employing pairs of delay interferometers with delay $\tau$. We recover the phase difference and the intensity of optical signals as a function of multiples of $\tau$. The delay $\tau$ is tuned according to the bitrate and the requested number of samples per symbol (SpS). Experimentally we demonstrate the successful reception of a 112 Gbit/s (i.e., 28 GBd) PolMUX DQPSK signal, and of other formats. The temporal resolution is limited by the fine adjustment of $\tau$ and by the bandwidth of the photodiodes.

## Operation Principle

The schematic setup of an OVSA for analyzing PolMUX DQPSK signals is shown in Fig. 1(a). The input signal is split into two orthogonally polarized beams with a polarization beam-splitter (PBS), and processed by pairs of tunable optical delay interferometers (TODI) having (orthogonal) cosine and sine characteristics, respectively. The TODIs are connected to balanced receivers. The complex optical input signal with an envelope $r(t) = |r(t)|\exp[j\phi(t)]$ is split to two paths, and sent to two TODIs. In the TODI, the signal is further split to two arms having a delay difference $\tau$. Delayed and non-delayed signals
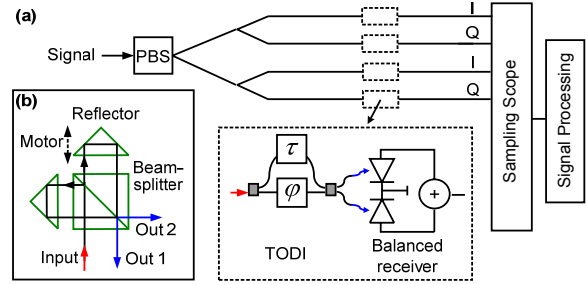


**Fig. 1**: (a) Optical vector analyzer scheme. (b) Free-space optics layout of tunable optical delay interferometer (TODI)

interfere at the output ports. Orthogonal interferometer characteristics are achieved by a relative phase offset in the arms of one TODI with respect to the other TODI amounting to $\varphi = \pi/4$ and $\varphi = -\pi/4$, respectively. The balanced receivers' output currents of the in-phase (I) and quadrature (Q) TODI are

$$i_I = k\,|r(t)|\,|r(t-\tau)|\cos\!\left(\Delta\phi(t)+\frac{\pi}{4}\right),$$

$$i_Q = k\,|r(t)|\,|r(t-\tau)|\sin\!\left(\Delta\phi(t)+\frac{\pi}{4}\right), \qquad (1)$$

where $k$ is a constant, and $\Delta\phi(t) = \phi(t) - \phi(t\text{-}\tau)$. These output currents then are electrically sampled with an Agilent sampling oscilloscope. An off-line software tool then extracts the complex current[7]

$$i = i_I + j i_Q. \qquad (2)$$

An approximation for the amplitude $|r(t)|$ and an exact relation for the phase $\phi(t)$ at time $t = t_0 + n\tau$ (with respect to an arbitrary reference phase at $t_0$) leads to[7]

$$r(t_0 + n\tau) = \left| i(t_0 + n\tau)\cdot i(t_0 + n\tau + \tau) \right|^{\frac{1}{4}}$$

$$\times\exp\!\left( j\sum_{m=1}^{n}\!\left( \arg\!\big(i(t_0+m\tau)\big)-\frac{\pi}{4}\right) \right)\exp\big(j\phi(t_0)\big). \qquad (3)$$

## Experimental Setup

Our TODI is a free space interferometer. As shown in Fig. 1(b), one of the paired reflectors is mounted on a piezo-actuator which provides 2×2 nm increments for phase and time delay adjustments. The tunable delay range is $\tau = 0\ldots100$ ps. The beamsplitter is carefully chosen so that it performs similarly for both orthogonal polarization states. The setup can be miniaturized with our LIGA micro-optical bench technology[8].
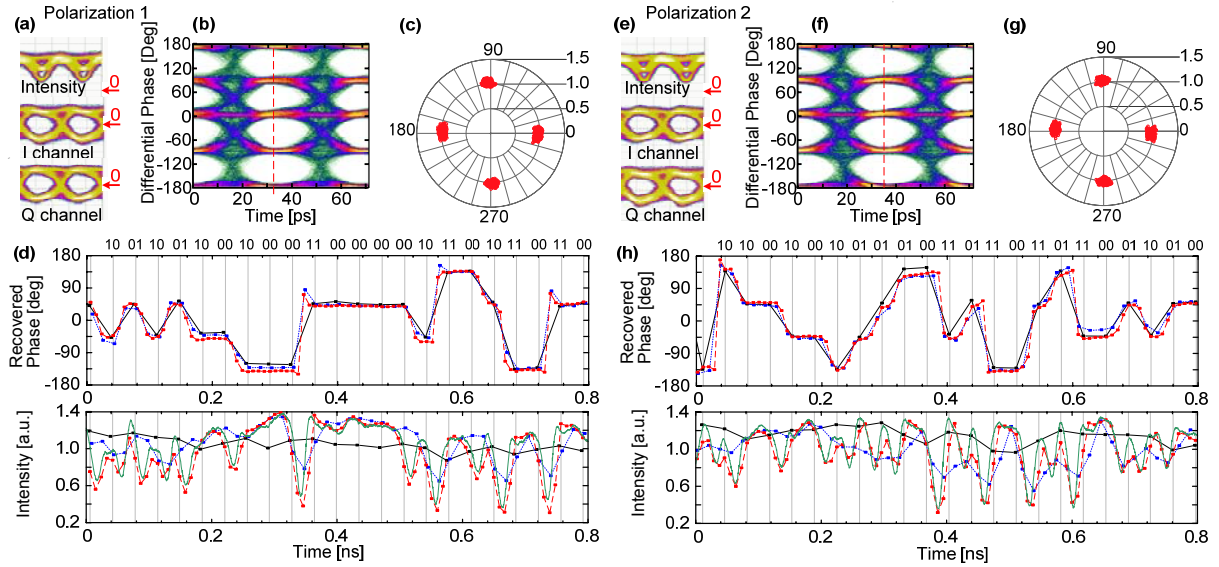
**Fig. 2**: Detection of 2,085 symbols. (a) & (e): Measured intensity and I&Q channel eye diagrams; (b) & (f): differential phase eye diagrams with sampled once per symbol (SpS = 1); (c) & (g): constellation diagrams of DQPSK signal for each of two orthogonal polarizations; (d) & (h): recovered intensity and phase as a function of time with SpS = 1 (– • –), SpS = 2 (··· ■ ···) and 4 (--- ■ ---); Directly measured intensity (———) shown for comparison. Symbol frame centers marked in grey ( | )

## Experimental Results

An optical 112 Gbit/s PolMUX DQPSK signal with a symbol rate of 28 GBd at $\lambda$ = 1,555.75 nm and a pseudo-random sequence length of $2^{11}-1$ is launched into the OVSA. The polarization in front of the PBS was matched to the vertical and horizontal polarization of the receiver pairs, respectively. We first set the delay to 35.7 ps corresponding to the symbol duration of a 28 GBd signal. The I and Q waveforms are then detected with photodiodes (cut-off frequency about 75 GHz) and sampled by an Agilent sampling oscilloscope, Fig. 2(a)(e). The waveforms are subsequently off-line processed. The differential phase, the recovered phase and the intensity can be calculated with equations (2) and (3). By overlaying the recorded 2,085 symbols, the differential-phase eye diagrams can be plotted, Fig. 2(b)(f) for the two polarizations,

respectively. The constellation diagrams of the Pol-MUX DQPSK are plotted in Fig. 2(c)(g). The fully recovered phase and amplitude of the signal are plotted in Fig. 2(d)(h). The result of the sampling process with SpS = 1, i.e., a delay of $\tau$ = 35.7 ps is shown as (– • –). Setting the delay to 17.85 ps and 8.9 ps, i.e., to SpS = 2 (··· ■ ···) and SpS = 4 (--- ■ ---), provides more accurate results. The recovered phase at SpS = 4 reveals the most details, and the recovered intensity at SpS = 4 matches best with the measured intensity (———) that has been recorded as a check.

We tested the OVSA with other modulation formats at various bitrates, namely with a DQPSK signal at 42.7 GBd, a DPSK signal at 28 GBd, an NRZ signal at 28 Gbit/s, and a CSRZ signal at 10 Gbit/s, see Fig. 3. The constellation diagrams are plotted with the samples positioned at the symbol center.
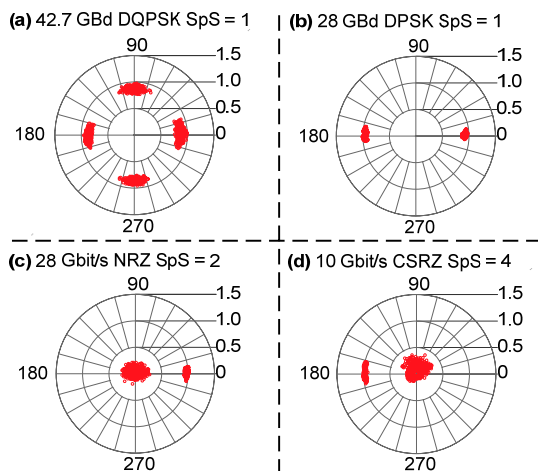
## Conclusions

The design of a format-transparent optical vector signal analyzer having a tunable sampling rate and bitrate is explained. Its function is demonstrated for 112 Gbits/s PolMUX QDPSK signals and other formats.

## Acknowledgement

**Fig. 3**: Constellations of (a) 42.7 GBd DQPSK SpS = 1, (b) 28 GBd DPSK SpS = 1, (c) 28 Gbit/s NRZ SpS = 2, and (d) 10 Gbit/s CSRZ SpS = 4.

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