

# Fundamentals of measuring changes of the state of polarization (SOP) with Novoptel PM1000

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# Outline

## Slides:

- Definition of polarization, Poincaré sphere
- Stokes vectors, normalization types
- Polarization changes, birefringence
- Limitations of measuring polarization changes
- Mueller matrix measurement
- Recording types of PM1000
- Timestamps / Synchronization

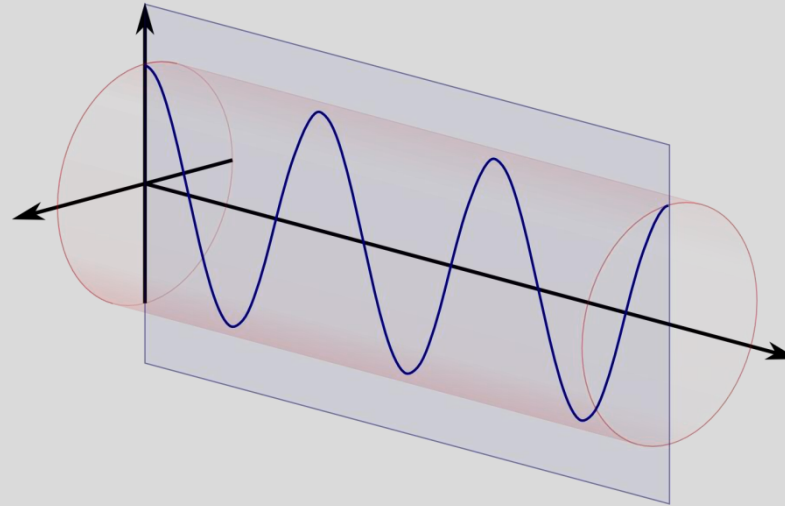
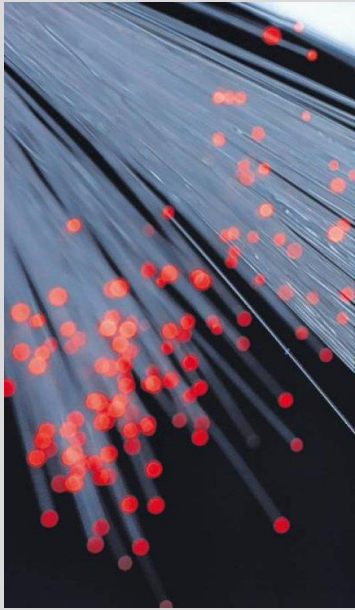


Demo of PM1000 GUI



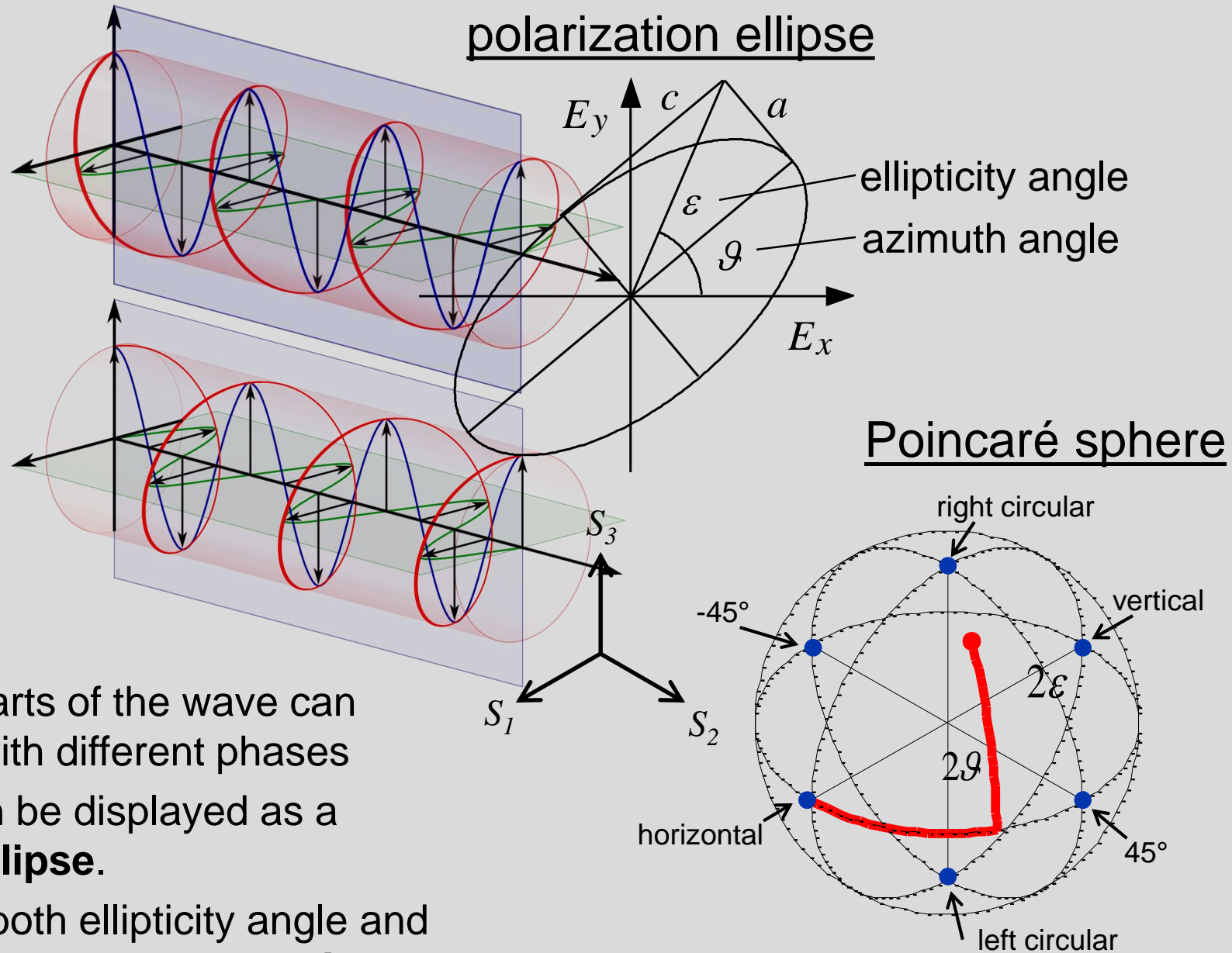
Demo of recording and  
analyzing data with Matlab

# Definition of Polarization



- Light is an electromagnetic (transverse) wave:
- During transmission, an electrical and a magnetical field oscillates perpendicular to the transmission direction
- The **State of Polarization (SOP)** defines the oscillation direction of the electrical field, e.g. „vertical polarization“

# Definition of Polarization



- 2 orthogonal parts of the wave can superimpose with different phases
- Every SOP can be displayed as a **polarization ellipse**.
- The double of both ellipticity angle and azimuth angle span the **Poincaré sphere**.

# Stokes vectors

- Normalized Stokes vector with 3 parameters and length 1:

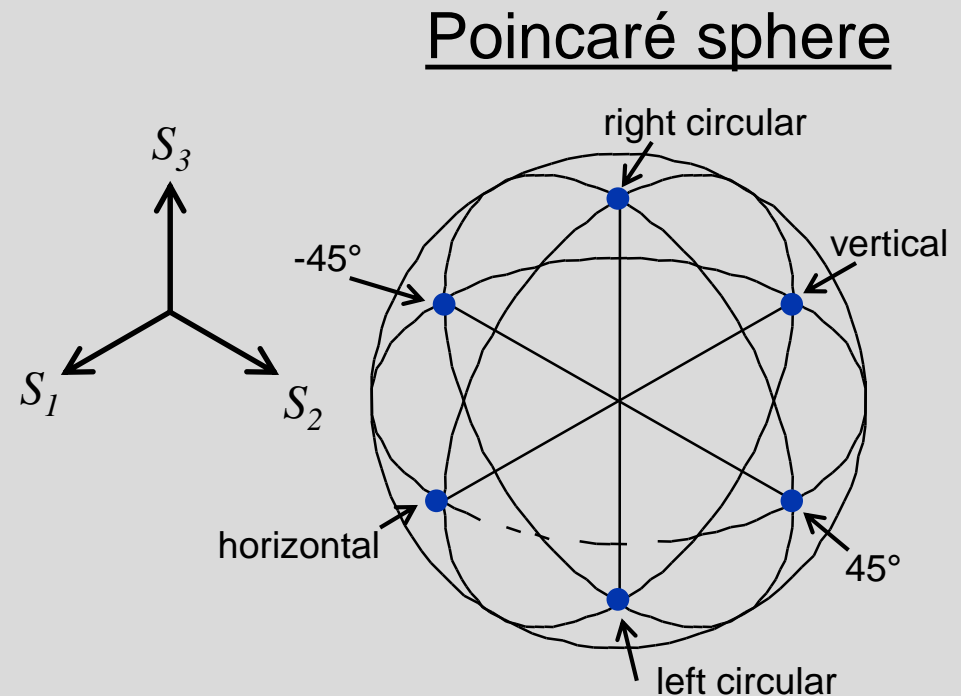
$$\vec{S} = \begin{pmatrix} S_1 \\ S_2 \\ S_3 \end{pmatrix} = \begin{pmatrix} \cos 2\epsilon \cdot \cos 2\vartheta \\ \cos 2\epsilon \cdot \sin 2\vartheta \\ \sin 2\epsilon \end{pmatrix}$$

- Fundamental polarizations:

horizontal:	$\begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}$	vertical:	$\begin{pmatrix} -1 \\ 0 \\ 0 \end{pmatrix}$
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+45°:	$\begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}$	-45°:	$\begin{pmatrix} 0 \\ -1 \\ 0 \end{pmatrix}$
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right circular:	$\begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$	left circular:	$\begin{pmatrix} 0 \\ 0 \\ -1 \end{pmatrix}$
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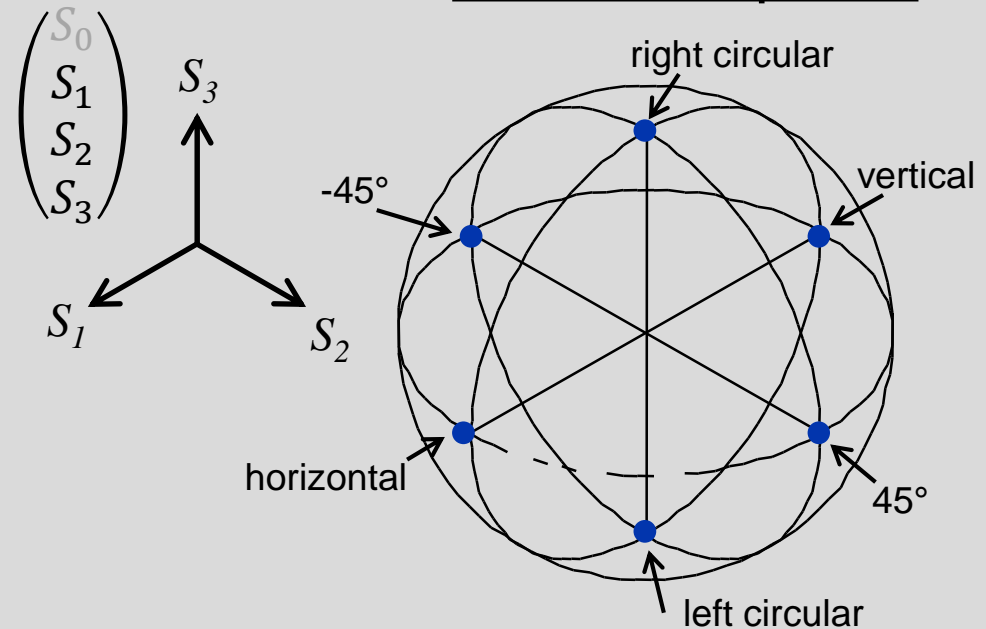
# Stokes vectors

- General Stokes vector with 4 parameters:

$$\vec{S}' = \begin{pmatrix} S_0' \\ S_1' \\ S_2' \\ S_3' \end{pmatrix} = \begin{pmatrix} \overline{|\underline{E}|^2} \\ \overline{|\underline{E}|^2 \cdot \cos 2\epsilon \cdot \cos 2\vartheta} \\ \overline{|\underline{E}|^2 \cdot \cos 2\epsilon \cdot \sin 2\vartheta} \\ \overline{|\underline{E}|^2 \cdot \sin 2\epsilon} \end{pmatrix}$$

- Degree of polarization (DOP):

$$p = \sqrt{S_1'^2 + S_2'^2 + S_3'^2} / S_0'$$

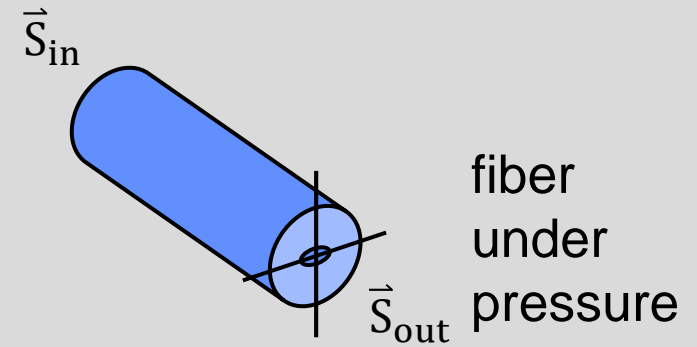
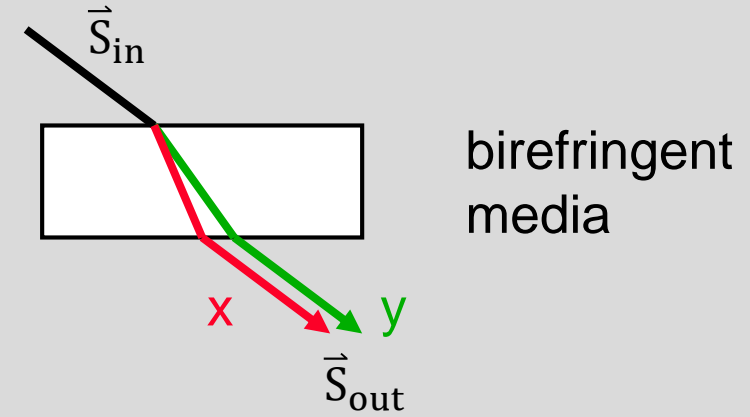
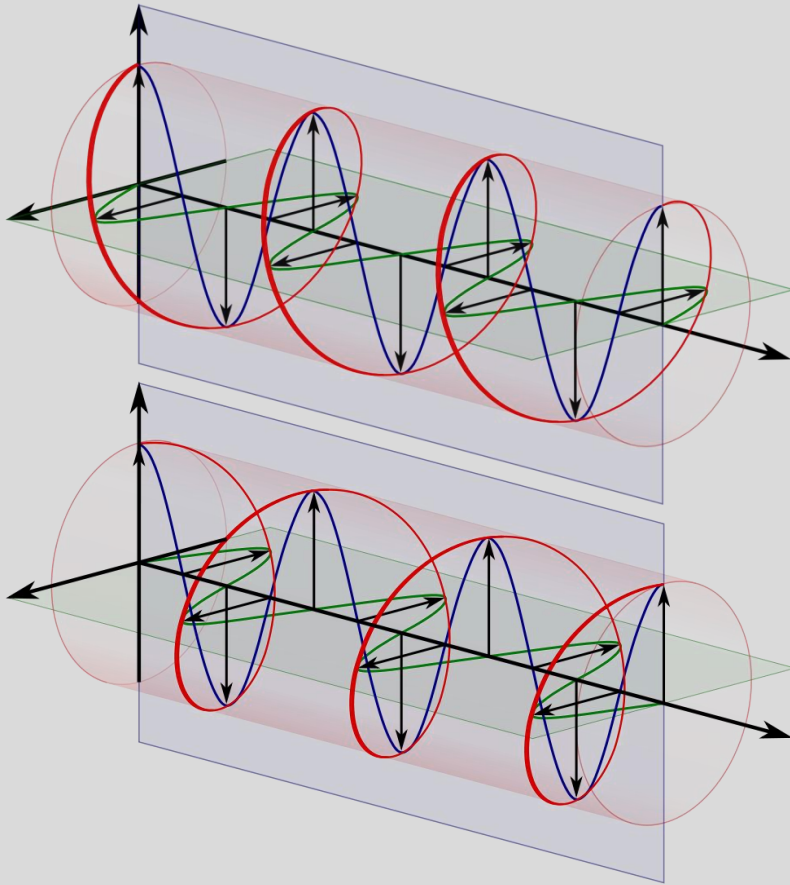


# Stokes vectors

Normalization types in PM1000:

- *Standard normalization*
  - Stokes vectors are normalized to unity length (surface of the sphere)
- *Non-normalized*
  - Stokes vector length corresponds to the power. On Poincaré sphere, surface is reached at defined power level.
- *Exact normalization*
  - Stokes vector length corresponds to degree of polarization (DOP). On Poincaré sphere, surface is reached at  $DOP=1$ .

# Polarization changes



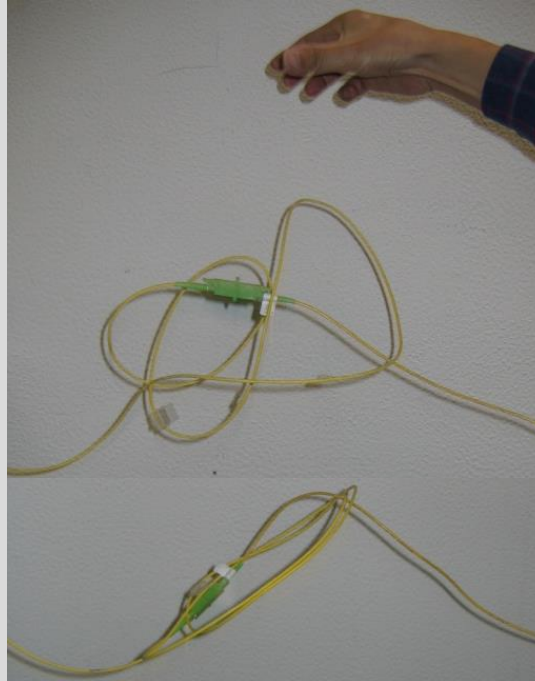
- In birefringent media, the wave is split into the two eigenmodes of the medium. The phases of the two waves are shifted in time with respect to each other: The polarization is changed. The differential phase shift is called retardation.
- Bending or squeezing of the fiber induces birefringence, because the fiber core is compressed one-sided.

# Polarization changes

temperature changes



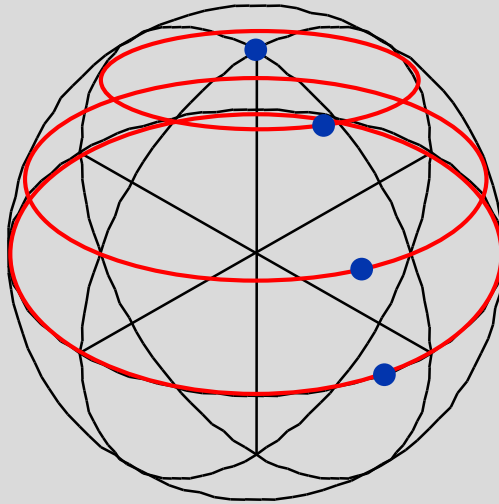
movement of fiber



Electrical discharge  
(lightning)



- Temperatur changes and movement (also shaking, vibrations) of the fiber create polarization changes
- Measured in rad/s (krad/s, Mrad/s) on the surface of the Poincaré sphere



## Example:

An event causes birefringence with circular eigenmodes ( $S_3 = \pm 1$ ), increasing retardation: The SOP is rotated around the  $S_3$ -axis. The absolute SOP change depends on the distance between the SOP and the eigenmodes axis, which is  $S_3$ .

- In principle, an SOP event can be missed if birefringence changes mainly in one pair of eigenmodes, and measured SOP is near to one of the eigenmodes.
- This can be avoided by measuring the **Mueller matrix** of the fiber instead of just polarization changes.

# Mueller matrix

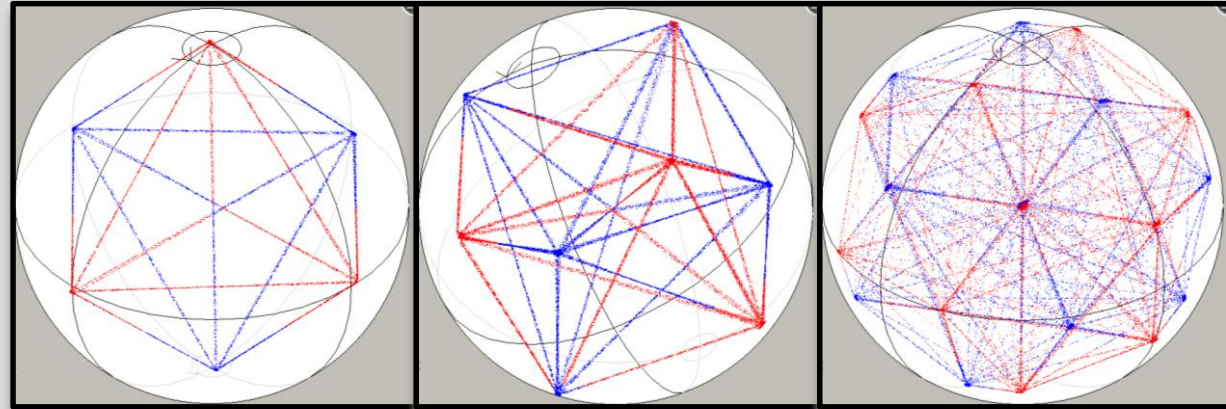
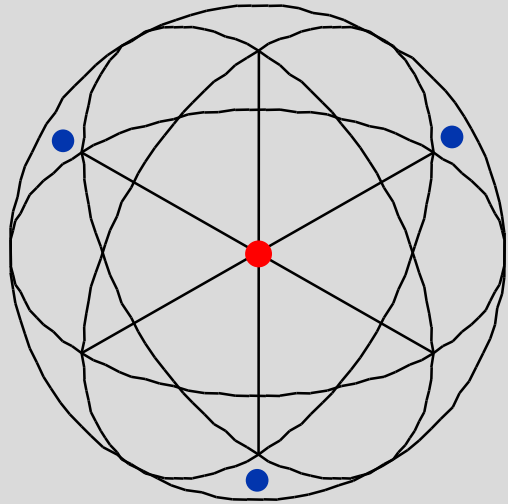
- Any effect of a particular optical element (e.g. a fiber link) on the Stokes vector can be expressed by the 4x4 Mueller matrix:

$$\vec{S}'_{\text{out}} = \mathbf{M} \cdot \vec{S}'_{\text{in}}, \quad \mathbf{M} = \begin{bmatrix} M_{00} & M_{01} & M_{02} & M_{03} \\ M_{10} & M_{11} & M_{12} & M_{13} \\ M_{20} & M_{21} & M_{22} & M_{23} \\ M_{30} & M_{31} & M_{32} & M_{33} \end{bmatrix}$$

- In lossless media, this simplifies to a 3x3 submatrix (often a rotation matrix)  $\mathbf{G}$ :

$$\vec{S}'_{\text{out}} = \mathbf{M} \cdot \vec{S}'_{\text{in}}, \quad \mathbf{M} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & G_{11} & G_{12} & G_{13} \\ 0 & G_{21} & G_{22} & G_{23} \\ 0 & G_{31} & G_{32} & G_{33} \end{bmatrix}, \quad \vec{S}_{\text{out}} = \mathbf{G} \cdot \vec{S}_{\text{in}}, \quad \mathbf{G} = \begin{bmatrix} G_{11} & G_{12} & G_{13} \\ G_{21} & G_{22} & G_{23} \\ G_{31} & G_{32} & G_{33} \end{bmatrix}$$

# Mueller matrix measurement



- Apply  $n \geq 4$  polarizations using a polarization state generator (EPS1000)
- Measure the  $n$  polarizations at fiber input ( $\mathbf{S}_{in,i}$ ) and fiber output ( $\mathbf{S}_{out,i}$ )
- Calculate Mueller matrix  $\mathbf{M}$ :  $\vec{S}_{out,i} = \mathbf{M} \cdot \vec{S}_{in,i}$ ,  $\mathbf{M} = \mathbf{S}_{out} \mathbf{S}_{in}^+ (\mathbf{S}_{in} \mathbf{S}_{in}^+)^{-1}$
- Mueller matrix contains maximum and minimum transmission, corresponding polarizations at input and output, polarization dependent loss (PDL), eigenmodes, retardation, polarization mode dispersion (PMD, if measured at several frequencies)

➡ polarization transformation known not for only one measured SOP, but **all!**

# Recording types



- Manual Recording:

Records 1 memory block and stops. Block size is defined by *Memory Exponent* (ME). Sampling time is defined by *Averaging Time Exponent* (ATE):  $t_s = 2^{ATE} \cdot 10 \text{ ns}$ ,  $f_s = 100 \text{ MHz} / 2^{ATE}$

- Triggered Recording:

Uses memory blocks as ringbuffers for continuous recording. Upon a defined trigger event, it continues recording in the current block for the amount of post-trigger samples. After that, it continues in the next block.

- (Endless) Dynamic Undersampling:

A sample is only recorded if it differs by the previous recorded sample by more than a defined threshold. Once a block is completed, the GUI/script can transfer it. The GUI/script marks transferred blocks so they can be overwritten with new data by PM1000.

# Timestamps

During recording, timestamps may be added to the data, depending on recording type:

- Manual Recording: No timestamp
- Triggered Recording: 1 timestamp per event/block
- Dynamic Undersampling: 1 timestamp per sample
  - ... with 1PPS synchronization: ... + 1 timestamp per second

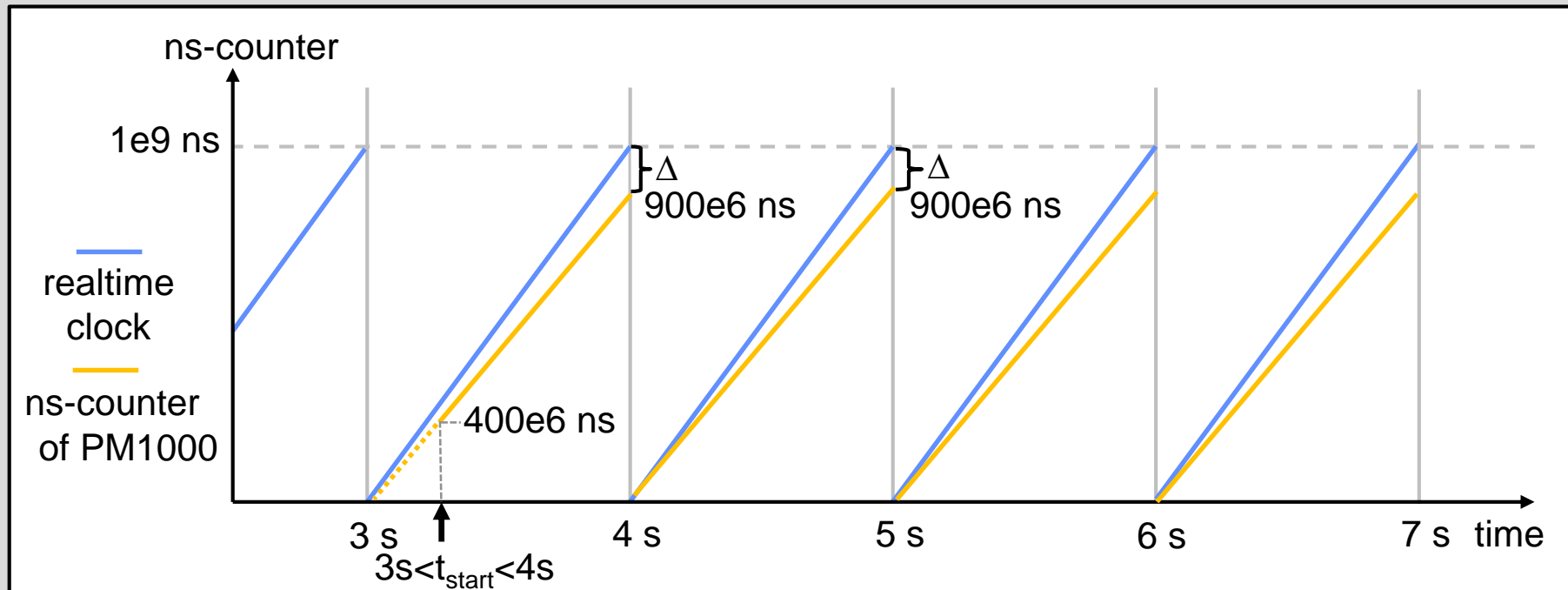
All data timestamps are relative to the starting time of the recording, which is stored in additional registers of the polarimeter. During long recording times, the internal clock of PM1000 may slowly drift away from the realtime clock. This can be compensated by providing a one-pulse-per second (1PPS) signal from a realtime clock source.

Due to latencies during sending the starting command, also the starting time has an uncertainty of several milliseconds, unless corrected by a 1PPS signal.

# Timestamp correction by 1PPS

Timestamp correction using 1PPS signal:

- Evaluate ns-counter at rising edges of the 1PPS signal



- Recording starts at a count of 400e6:  $t_{\text{start}} = 3.400 \text{ s}$
- Apply correction of  $\Delta$ :  $t_{\text{start}} = 3.444 \text{ s}$
- Apply correction of  $\Delta$  to every recorded relative timestamp between the 1PPS pulses (expected clock deviation is usually  $<10 \text{ ppm!}$ )

# Summary

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