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Comparison of Optical Polarization-Dependent Loss Measurement Methods

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***Abstract*—A number of polarization-dependent loss (PDL) measurement methods has been proposed for the characterization of optical devices. These use all polarization states or only 0°, 45°, 90° and circular or tetrahedron vertices or equivalent configurations on the Poincaré sphere. They determine PDL alone or the complete Mueller matrix and potentially polarization mode dispersion. They need no calibration or need polarimeter(s). Speed is also an issue. We compare performance and features of these 5 PDL measurement methods. A fast polarization scrambler with LiNbO3 device generates the test polarizations.**

Keywords— polarization, polarization-dependent loss, PDL, Lithium Niobate, polarimetry

I. INTRODUCTION

Polarization-dependent loss (PDL) is an important property of fiberoptic components. Various measurement methods have been reported:

(A) **All polarization states** are sequentially generated and applied to the device-under-test (DUT) [1, 2]. Minimum and maximum output intensities are recorded. Measurement time is very long.

(B) B. Nyman has sequentially applied **0°, 45°, 90° and circular polarizations** to the DUT [2-4]. The topmost line of the Mueller matrix is determined. To generate the linear polarizations precisely, a mechanically rotated polarizer may be employed. That one is very slow, and subject to wear.

(C) **Complete Mueller matrix** [5] measurement of the device-under-test (DUT) is fast. At least 4 polarization states are needed, preferably the corners of a tetrahedron. The Mueller-Jones matrix with only 7 degrees-of-freedom is subsequently calculated and delivers PDL.

(D) In the **sqrt(3)** method [6], a depolarized, usually finite sequence of statistically independent polarization states is generated and applied to the DUT. The peak (up and down) variation of the output intensity from its arithmetic mean therefore equals $\sqrt{3}$ times the standard deviation.

(E) In the (obvious) **extinction method** a search algorithm applies and finds those two polarizations for which minimum and maximum output intensities are obtained [6].

(F) At least 4 arbitrary, possibly **floating polarizations** are measured before the DUT and allow calculating PDL from intensity samples measured behind the DUT.

We compare performance and features of these 5 PDL measurement methods. In all cases, a polarization transformer/scrambler is needed.

II. EXPERIMENTAL SETUP

All methods can be realized by subsets of this setup (Fig. 1): A laser source is connected to a bandpass filter (BPF). The BPF was found to be helpful when measuring highest PDL. The spectrally cleaned laser signal is fed to a polarization scrambler, which can also be configured as polarization state synthesizer or polarization controller. Our polarization scrambler contains a LiNbO$_3$ polarization transformer. The overall scrambler response time (< 200 ns) is much shorter than that of fiber squeezers or liquid crystal components, leave alone mechanical stepper motors. This is crucial for achieving short measurement times.

Before and behind a DUT, polarimeter and low-PDL photodiodes allow measuring the polarization and/or the signal power. Four DUTs were assessed:

- Simple patchcord (should have no PDL)
- PDL device 1 with PDL set to about 1.5 dB
- PDL device 2 with PDL set to about 14.8 dB
- Inline polarizer

The polarizer was specified with an extinction ratio (ER) of 25 dB. The ER includes the polarization misalignment (PER) of the PMF and the connector with respect to the eigenmodes of the polarizer. The PDL itself is usually much higher than the ER, as will be seen for this polarizer.

Two manual polarization controllers (MPCs) are put in front of and behind the DUT to explore polarization dependency of the PDL measurement. These have fiber loop diameters of 60 mm to minimize associated PDL.

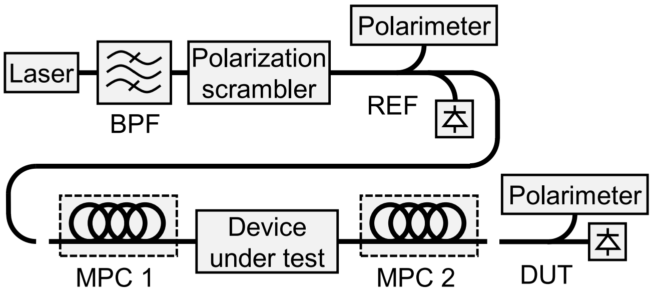

Fig. 1: Setup which contains all parts needed for the 5 PDL measurement methods (A...E). Manual polarization controllers (MPC) for error evaluation purposes are dashed.

Method	DUT	Mean PDL	Total PDL Span (MPCs moved)	Standard Deviation of PDL (MPCs halted)	Duration, calibration
(A)ll polarization states	Patchcord	0.141 dB	−0.0166 dB; +0.0195 dB	−0.0019 dB; +0.0019 dB	83.9 ms, **no**
	PDL device 1	1.512 dB	−0.0809 dB; +0.101 dB	−0.0019 dB; +0.0019 dB	
	PDL device 2	14.72 dB	−0.131 dB; +0.147 dB	−0.0150 dB; +0.0151 dB	
	Polarizer	34.71 dB	−3.44 dB; +36.60 dB	−0.899 dB; +1.13 dB	
(B). Nyman, 0°, 45°, 90°, circular	Patchcord	**0.016 dB**	**−0.0100 dB; +0.0085 dB**	−0.0010 dB; +0.0010 dB	**4 ms**, yes
	PDL device 1	1.508 dB	−0.0309 dB; +0.0239 dB	−0.0039 dB; +0.0039 dB	
	PDL device 2	14.70 dB	−0.519 dB; +0.572 dB	−0.0298 dB; +0.0300 dB	
	Polarizer	29.61 dB	−8.09 dB; +43.40 dB	−0.669 dB; +∝ dB*)	
(C)omplete Mueller matrix	Patchcord	0.026 dB	−0.0162 dB; +0.0165 dB	−0.00066 dB; +0.00066 dB	**4 ms** (1.92 µs tested), yes
	PDL device 1	1.500 dB	−0.0326 dB; +0.0430 dB	−0.00179 dB; +0.00180 dB	
	PDL device 2	14.81 dB	−0.209 dB; +0.148 dB	−0.0029 dB; +0.0029 dB	
	Polarizer	**69.12 dB**	**−6.28 dB;** +15.50 dB	**−1.51 dB**; +2.34 dB	
(D)epolarization, sqrt(3)	Patchcord	0.040 dB	−0.0153 dB; +0.0091 dB	**−0.00058 dB; +0.00058 dB**	83.9 ms, **no**
	PDL device 1	1.500 dB	−0.0300 dB; +0.0267 dB	−0.00131 dB; +0.00131 dB	
	PDL device 2	14.94 dB	−0.374 dB; +0.447 dB	−0.00327 dB; +0.00327 dB	
	Polarizer	30.09 dB	−6.14 dB; +29.91 dB	−0.0548 dB; +0.0555 dB	
(E)xtinction	Patchcord	0.025 dB	−0.0147 dB; +0.0146 dB	−0.0008 dB; +0.0008 dB	24 ms (6 ms tested), **no**
	PDL device 1	1.500 dB	**−0.0245 dB; +0.0214 dB**	**−0.0003 dB; +0.0003 dB**	
	PDL device 2	14.86 dB	**−0.0311 dB; +0.0236 dB**	**−0.0021 dB; +0.0021 dB**	
	Polarizer	59.91 dB	−3.90 dB; +3.58 dB	−1.01 dB; +1.32 dB	

*) Standard deviation was > mean.

Table 1: PDL measurement results obtained with various methods. Highlights are shown in boldface.

III. RESULTS

PDL, its mean and its deviations will be calculated as, or from, quotients of transmitted intensities. These linear units are then converted into dB. This explains why ± standard deviation of linear units does not mean ± the same dB value. For instance, an ideal polarizer transmits mean, maximum and minimum intensities of 0.5, 1 and 0, respectively. This set of linear units 0.5±0.5 corresponds to losses of 3 dB + {−3 dB; +∝ dB}. The BPF is always in place, unless otherwise noted.

A. All polarization states

For method (A), no polarimeters are needed. In other words, it works without calibration. The scrambler was configured to generate a scrambling speed distribution with a peak at about 42 krad/s. The aim was to reach a dense coverage of the Poincaré sphere. Details are described in [6] where the same configuration was applied to realize method (D). During a measurement time of 83.9 ms, intensity samples were taken with the photodiode behind the DUT at a sampling rate of 781.3 kS/s. From the 2^{16} samples, the minimum and maximum were chosen for PDL calculation. Accuracy at low PDL is mainly limited by PDL of the scrambler (<0.1 dB), measurement noise and intensity fluctuations of the laser. While the former can add to or subtract from PDL of the DUT (if there is one), the latter two will always add. This is substantiated by the fact that even without scrambling, a PDL of 0.04 dB was calculated from the taken samples. Dark current of the sampling ADC was calibrated with the mean of the samples taken without light. With the patchcord as DUT, we measured a mean PDL of 0.141 dB (instead of the desired 0.000 dB), by far the highest among all 5 methods (Table 1). When the MPCs were moved the PDL varied up to −0.0166 dB and +0.0195 dB. With PDL device 1, a mean PDL of 1.512 dB and much higher variations up to −0.0809 dB; +0.101 dB were observed when moving the MPCs. With PDL device 2, we measured a mean PDL of 14.72 dB with variations of up to −0.131 dB and +0.147 dB. When testing the polarizer, the minimum sample taken during measurement was always smaller than the mean of the samples taken during dark current calibration. This led to infinite (or complex) PDL results. To avoid that, we set the dark current value to the minimum sample without light instead of the mean. After this modification, mean PDL of the polarizer was calculated as 34.71 dB, with variations of up to −3.44 dB and +36.6 dB when moving the MPCs.

It should be noted that for method (A) we did not use the reference photodiode, other than for the faster method (E). This way we may have underestimated somewhat the accuracy of method (A). But the 0.04 dB value measured without scrambling is a limit, higher than those of the other methods.

B. B. Nyman, 0°, 45°, 90°, circular

For method (B), the scrambler, now configured as a polarization state generator, generated the necessary 0°, 45°, 90° and circular polarizations with help of the reference polarimeter in front of the DUT. Correct electrode voltages for the various polarization states are initially found in a short search routine. Behind the DUT, we measured with the single photodiode like before, but now synchronized to the polarization switching of the scrambler, between only 4 states. This relaxed the timing considerably compared to method (A). It allowed extending the sample averaging time from 1.28 µs to 40.96 µs. Dwell time at each of the 4 polarization states was extended to 1 ms. In total, the PDL measurement time was reduced from 83.9 ms to 4 ms. Since the reference polarimeter before the DUT was necessary anyway, we used its intensity samples for compensation of scrambler PDL. When measuring synchronously with the scrambler and DUT photodiode, even laser intensity fluctuations were compensated.

With patchcord and with PDL device 1 as DUTs, PDL span and standard deviation were smaller than with method (A), thanks to the added compensation possibilities and longer averaging time. But with the PDL device 2 and with the polarizer, the PDL measurement values were worse than with method (A). With the polarizer, measured mean PDL was only 29.61 dB. Reason is that calculation of high PDL corresponds to the estimation of very low intensities which have not necessarily been measured, since the reference polarizations can be away quite a bit from the polarization with lowest transmission.

C. Complete Mueller matrix

Methods (C) and (B) have identical timing. The big difference of method (C) from method (B) is that the SOP / Stokes vector is measured, not just the intensity. For (C), we have chosen the 4 corners of a tetrahedron as the test polarizations. This is the theoretical optimum when using 4 polarization states. The two polarimeters allowed measuring the SOP in reference and DUT paths simultaneously, for compensation of intensity fluctuations and PDL at the output of the scrambler. Both polarimeters were also electrically connected to the scrambler for synchronization. We kept the dwell time of 1 ms for each polarization state. So, measurement still completes in 4 ms. Using a polarimeter behind the DUT allows one to obtain the complete Mueller matrix of the DUT. If only one polarimeter is available, it is possible to measure the reference path once and then switch or plug in the various DUTs. With the patchcord as DUT, the measured PDL deviated by up to −0.0162 dB and +0.0165 dB from the mean value 0.026 dB. The observed PDL span can be explained by PDL of coupler and connectors as well as finite calibration accuracies of the two polarimeters. When not moving the MPCs, standard deviation of the PDL value was just ±0.00066 dB. For PDL device 2, movement of the MPCs varied the PDL by up to −0.209 dB and +0.148 dB with respect to the mean value 14.81 dB. With the polarizer, measured PDL deviated by up to −6.28 dB and +15.5 dB from the mean value of 69.12 dB. Standard deviation of the PDL value was −1.51 dB and +2.34 dB, regardless of whether the MPCs were moved or not. To our surprise, the BPF was not necessary in method (C) to measure high PDL.

The robust results allow further reduction of the measurement time. For accurate assessment of effects, the MPCs were not moved when the measurement time was changed. PDL device 2 was the DUT. We shortened the dwell time and observed a rising standard deviation that, beginning at ±0.0029 dB at a dwell time of 1 ms, reached ±0.0147 dB at a dwell time of 0.48 µs (1.92 µs for a complete Mueller matrix measurement).

The separate Mueller matrix measurements can as well be taken continuously, if the scrambler keeps switching and the polarimeters keep recording over a longer time. We recorded the polarization states for 4000 Mueller matrices in one continuous scan and got similar standard deviations as in the case of single measurements.

Approximate PMF length (DUT)	Differential group delay (DGD)	
	mean	standard deviation
0 mm (no PMF)	3 fs	1 fs
7 mm	12 fs	1.5 fs
25 mm	34 fs	3 fs
49 mm	66 fs	3 fs
580 mm	801 fs	2 fs
780 mm	1032 fs	2 fs
2600 mm	3540 fs	3 fs
7000 mm	9432 fs	3 fs

Table 2: PMD measurement results obtained with method (C) and a laser tuned in 96 steps of 50 GHz each

If the laser frequency is swept during the measurement, then the Mueller matrices allow calculating the polarization mode dispersion (PMD) of the DUT. Our laser could not sweep continuously. It switched frequency in 96 discrete steps of 50 GHz. With 50 GHz frequency steps, DGDs up to 1/(2·50 GHz) = 10 ps can measured unambiguously. The optical power drop during the channel switching allowed automatic assignment of the measurement data to the correct laser frequencies when evaluating the data. We tested different pieces of polarization maintaining fiber (PMF) as DUTs, 6 times each. To vary polarization transformations from one measurement to the next, always one SMF connector was disconnected, rotated by different multiples of 360° and reconnected. With a patchcord as DUT, we measured a mean DGD of 3 fs with a standard deviation of 1 fs (Table 2). A 7 mm long PMF with an expected DGD of ~9.4 fs was already clearly detected. The PMF DUTs had measured DGDs between 12 fs and 9432 fs with standard deviations between 1.5 fs and 3 fs.

D. Depolarization, sqrt(3)

We return to pure PDL measurement. For method (D), the scrambler emulates rotating waveplates, aiming for an equal distribution over the Poincaré sphere. No polarimeter is required, just the 2 photodiodes. We measured a residual degree of polarization (DOP) of 0.0117 within the measurement time of 83.9 ms. From the intensity samples taken during this time simultaneously in front of and behind the DUT, PDL is calculated [6]. For small PDL, mean PDL and polarization dependency is comparable to methods (C) and (E). For large PDL, the PDL results gets imprecise. An advantage is the low cost, like for methods (A) and (E).

E. Extinction

For method (E), the 2 photodiodes were kept and the polarization scrambler executed a gradient search algorithm for minimum and maximum intensity at the photodiode behind the DUT. One iteration of the gradient search algorithm took about 30 µs. After 400 iterations (= 12 ms), the polarization state was reliably at minimum or maximum transmission, regardless of input polarization and orientation of the DUT. After the last of the 400 iterations, the algorithm measured intensities at both photodiodes over a time of 82 µs and started over with search for the opposite pole. PDL was derived from the 4 intensities (DUT and REF at minimum and maximum transmission). A complete PDL measurement took little more than 24 ms (≈ 2·(12 ms + 82 µs)).

At low PDL, measurement errors are dominated by the small PDL of the photodiodes (about up to 0.03 dB) which can add up. At high PDL, offset or dark current calibration of the photoreceivers, especially the one measuring behind the DUT, is necessary for good accuracy. Also, reflections and laser side modes are crucial since they can reduce the degree of polarization (DOP) and thereby limit extinction. The BPF proved helpful in this respect.

While moving the MPCs with no other DUT, the mean PDL 0.025 dB of the patchcord varied by −0.0147 dB and +0.0146 dB, slightly better than with method (C). When not moving the MPCs, we measured a standard deviation 0.0008 dB of the PDL.

With the PDL device 2, the mean PDL of 14.86 dB varied by −0.0311 dB and +0.0186 dB. Standard deviation of PDL when testing the 2 PDL devices and not moving the MPCs was lowest for method (E).

With a polarizer as the DUT, mean PDL was 59.91 dB and varied by up to −3.9 dB and +3.58 dB, depending on the positions of the MPCs. Without the BPF, measured PDL varied between 32 and 39 dB. Also for PDL device 2, standard deviation of PDL increased when the BPF was taken away. Seemingly extinction was then limited by optical signal components off the main laser frequency.

We have also tried to shorten the 24 ms measurement time of method (E) by speeding up the iterations of the search algorithm by factors of 2. When measuring within 12 ms, results were still comparable. With a measurement time of 6 ms, a PDL of not more than about 40 dB was measured for the polarizer (while the true PDL is on the order of 60 dB). So, in terms of measurable extinction, method (E) (no calibration) beats method (B) (needs polarimeter/calibration) even when execution times are comparably short.

F. Floating polarizations

In order to apply method (C) to a WDM demultiplexer with 96 ports, 96 polarimeters would be required. Clearly, for WDM demultiplexers and other multiport devices, cost-effective PDL measurement requires that intensity detectors be used like in method (B). Fortunately there is a synopsis of these two methods. One polarimeter at the scrambler output measures the reference polarizations. Arbitrary, even **floating polarizations** are permissible, since these test polarizations are constantly measured.

At least $n = 4$ polarization states with Stokes vectors $\mathbf{S}_i$ ($i = 1...n$) are generated by the polarization scrambler. They form the columns of a $4\times n$ matrix $\mathbf{S} = [\mathbf{S}_1, \mathbf{S}_2, ..., \mathbf{S}_n]$. In principle the $\mathbf{S}_i$ are arbitrary. Only their normalized Stokes vectors need to form a body of non-zero volume inside the Poincaré sphere. Wavelength dependence of the polarization scrambler can be easily calibrated away.

For best PDL measurement accuracy it is desired to make the condition number of **S** as small as possible. The smallest possible condition number $\sqrt{3}$ is obtained if the normalized Stokes vectors form the corners of a tetrahedron like we used in method (C), diamond, cube or similar. In that case the covariance matrix of the normalized Stokes vectors equals 1/3 times the identity matrix. The small condition number is advantageous compared to the traditional method (B) where the condition number ≈3.23 is almost twice as large.

Based on polarimeter readings the $\mathbf{S}_i$ are optimized initially. They can be applied again, cyclically with high repetition rate, during subsequent PDL measurements. It hardly matters if the $\mathbf{S}_i$ float or drift or if they vary during an optical frequency scan because the polarimeter can always measure them accurately.

The DUT forms a partial polarizer. The topmost line $\mathbf{M}_0 = [m_{00}, m_{01}, m_{02}, m_{03}]$ of its Mueller matrix yields arithmetic mean transmission m_{00} and peak (up or down) variation $m_{00} g = \sqrt{m_{01}^2 + m_{02}^2 + m_{03}^2}$ from the arithmetic mean transmission, with $0 \le g \le 1$. The normalized peak transmission variation is

$$g = \frac{\sqrt{m_{01}^2 + m_{02}^2 + m_{03}^2}}{m_{00}} . \tag{1}$$

Minimum transmission is $T_{\min} = m_{00}(1-g)$. Maximum transmission equals $T_{\max} = m_{00}(1+g)$. In a passive DUT it holds $T_{\max} \le 1$. PDL in dB is easily calculated as

$$\begin{aligned} PDL_{\mathrm{dB}} &= 10\log_{10}\frac{T_{\max}}{T_{\min}} = 10\log_{10}\frac{1+g}{1-g} \\ &= 10\log_{10}\left(m_{00} + \sqrt{m_{01}^2 + m_{02}^2 + m_{03}^2}\right) . \\ &\quad -10\log_{10}\left(m_{00} - \sqrt{m_{01}^2 + m_{02}^2 + m_{03}^2}\right) \end{aligned} \tag{2}$$

Upon excitation with input polarization state $\mathbf{S}_i$, an output intensity I_i is measured behind the DUT. The output intensities measured for all $\mathbf{S}_i$ can be written into a row vector $\mathbf{I} = [I_1, I_2, ..., I_n]$. It holds $\mathbf{I} = \mathbf{M}_0\mathbf{S}$, or, with column vectors,

$$\mathbf{I}^T = \mathbf{S}^T\mathbf{M}_0^T \tag{3}$$

where ^{T} means transposition. For $n > 4$ it is convenient to eliminate the excess degrees-of-freedom by a matrix multiplication from the left,

$$\mathbf{B}\mathbf{I}^T = \mathbf{B}\mathbf{S}^T\mathbf{M}_0^T . \tag{4}$$

Here, **B** is a suitably chosen $4\times n$ matrix. A simple natural choice is $\mathbf{B} = \mathbf{S}$. The length of vectors $\mathbf{B}\mathbf{I}^T$ and $\mathbf{M}_0^T$ is 4. The 4×4 matrix $\mathbf{B}\mathbf{S}^T$ is easily invertible.

Matrix equations (4) ($n > 4$) or (3) ($n = 4$) can be solved for $\mathbf{M}_0^T$. Matrix inversion is well suited for this.

$$\left(\mathbf{B}\mathbf{S}^T\right)^{-1}\mathbf{B}\mathbf{I}^T = \mathbf{M}_0^T . \tag{5}$$

But Gaussian elimination / LU decomposition with pivoting is preferred since computational effort is lower. The elements of $\mathbf{M}_0^T$ yield m_{00}, g, PDL and mean loss.

Method (B) is a special, suboptimal case of method (F). This PDL measurement with arbitrary, even drifting or floating test polarizations, like in method (A), generalizes method (B) to improve the condition number. Only the topmost line of the Mueller matrix is needed. The added polarimeter allows the test polarizations to be arbitrary. This is a decisive practical advantage because polarization transformers / scramblers depend on wavelength and may drift over time.

In method (C), polarizations have been measured even in 1.92 µs. So, method (F) requires a minimum of 1.92 µs per PDL measurement and promises at least the same accuracy as method (B) with correspondingly short intensity measurement intervals.

The following ingredients are available:

- Fast accurate polarimeters
- Fast polarization scramblers or transformers
- Hardware for fast solution of matrix equation (4), (3)
- Optical couplers with low PDL
- Photodetectors with low PDL

This means a fast PDL meter can readily be built. This way, PDL (and mean loss) measurements during a single optical frequency sweep become possible for a fast, cost-effective characterization of optical WDM demultiplexers etc.

IV. FURTHER DISCUSSION

Presumably the PDL span is always influenced by reflections and residual polarization adjustment errors. This is most obvious for the polarizer which has a large PDL.

In Table 1, highlights are shown in boldface. The patchcord is measured with lowest PDL and most accurately with method (B), and most reproducibly with method (D). The PDL devices are measured most accurately and reproducibly by method (E), followed by methods (C) and (A).

For the polarizer, which, if ideal, should have infinite PDL, it makes most sense to check how high the lowest obtained PDL is. Method (C) yields the highest such value 69.12 dB – 6.28 dB = 62.84 dB, and the same holds for the reproducibility 69.12 dB – 1.51 dB = 67.61 dB. Method (C) is closely followed by method (E). The lowest PDLs obtained with each of the 5 methods are listed in Table 3. They tell how high PDL can be measured reliably.

Methods (A), (D), (E) need no polarization calibration(s). Methods (B), (C) are fastest in our implementation.

Method	Lowest PDL obtained with polarizer as DUT
(A)ll polarization states	31.27 dB
(B). Nyman, 0°, 45°, 90°, circular	21.52 dB
(C)omplete Mueller matrix	62.84 dB
(D)epolarization, sqrt(3)	23.95 dB
(E)xtinction	56.01 dB

Table 3: Lowest PDL obtained with polarizer as DUT. Value tells how high PDL can be measured reliably.

V. CONCLUSION

Put in simple words, (C) and (E) are more accurate than (B), except for low PDL (patchcord).

With (E) and (C), extinctions on the order of 60 dB and even higher have been measured, whereas the other methods are limited to roughly 30 dB, with the traditional method (B) performing worst.

Methods (A), (D), (E) need no calibration, no polarimeter. Among these, the **extinction method** (E) has shown best performance and is faster.

Methods (C), (B) are fastest (4 ms, or even < 2 µs, at least for (C) where this was tried). Only method (C) yields the **complete Mueller matrix**, not just PDL, and therefore permits PMD measurement. Even when measuring highest PDL, method (C) was found to be robust against normal laser sidemodes / ASE noise.

Method (F) is very cost-effective for multiport devices and eliminates the wavelength-dependence problem of method (B).

Loss, PDL and potentially PMD measurement vs. optical frequency should preferably require only one frequency scan. $LiNbO_3$ polarization transformers / scramblers are best suited in this respect.

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