Ultrafast polarization handling

EPC1000 Polarization Controller/Demultiplexer 100 krad/s (p. 2)
Polarization and Phase Controller for QKD, 20 krad/s (p. 4)
EPS1000 Polarization Scrambler/Transformer 20...50 Mrad/s (p. 5)
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PM1000 Polarimeter 100 MS/s, memory 64 MS (p. 9)
LU1000 Laser Unit (p. 12)

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German Pavilion

- Pictured: Fastest or by far fastest polarization products of their class on the market
- By far lowest cost per krad/s-Mrad/s-MS/s-MS
- Available as desktop units, module cards, and IP cores
- Low power consumption, small PCB sizes, wide temperature range
- Operation stand-alone or via USB, LAN and Windows GUI, Matlab™, Labview™, Python
- Used by major telecom suppliers and carriers since 2010
- EPC1000 has achieved in 2010 a world record for highest symbol rate 50 Gbaud in realtime, polarization-agile (40 krad/s) 4 bit/symbol transmission (200 Gb/s PDM-QPSK, 430 km).

Novoptel GmbH, Paderborn, Germany (full info: page 12 bottom); info@novoptel.com (or info@novoptel.eu)
EPC1000 Polarization Controller/Demultiplexer

- **Guaranteed endless tracking (control) speed**: 40, 60 or 100 krad/s on Poincaré sphere
- To our knowledge, Novoptel's endless polarization tracking speed is at least 100 times as high as that of competitor products. If you are aware of something better then please inform us so that we can correct this statement.
- Extremely reliable: More than 350 Gigarad were tracked in several extended tests.

**Configuration example:**
EPC1000 with interference detection for demultiplexing of polarization-multiplexed DQPSK or QAM signals. Everything is mounted on controller card (see above).
Results obtained with EPC1000

In 2010, world’s highest symbol rate in polarization-agile realtime transmission with 4 bit/symbol: 50 Gbaud, 200 Gb/s, 430 km polarization-multiplexed DQPSK transmission with 40 krad/s polarization tracking (IEEE PTL 22(2010)9, pp. 613-615)


Complementary distribution function 1−F(RIE) of relative intensity error (RIE) for 1 hour at 0.1, 20, 40, 60, 80 krad/s, and for 64 hours at 100 krad/s scrambling speed (18 Gigarad in total). The zero point (RIE = 0) is determined without light.

Wide endless optical polarization control bandwidth: 1 THz at 70 krad/s speed
Best extinction: 40 dB at 1 krad/s speed
Temperature-independent operation: -15°C...60°C (70°C testing if desired)
Two-sided endless polarization control: 15 krad/s at input, 200 rad/s at output


Customer feedback

"Novoptel's polarization tracking device EPC1000 is probably the only commercially available equipment that is capable of demultiplexing two orthogonal states of polarization with a tremendously high tracking speed (~60 krad/s). We have evaluated extensively the EPC1000 module and have confirmed its performance to be fully satisfactory and just as claimed. Prof. Reinhold Noe and Dr.-Ing. Benjamin Koch are the well-known pioneers and leaders in this field. With their team they have achieved remarkable progress and tracking speed records over the years. I am so happy to see Novoptel offer these polarization controllers to the lightwave communication community as affordable subsystems for coherent detection."

Dr. David Tzeng, Measurement Analysis Corporation, USA
Polarization and phase control for quantum key distribution

- **Worldwide unique product**: Endless optical polarization and phase (difference) control
- Not only an unknown variable incoming polarization is transformed into a fixed output polarization (2 degrees-of-freedom), but also the phase difference (3rd degree-of-freedom) between this polarization and its orthogonal is controlled, endlessly (without any interruption).
- **Indispensable for continuous fiberoptic quantum key distribution (QKD) based on BB84 or similar protocol implemented in the polarization domain.**
- Pilot signals (0°, 45°)
  - in the frequency/wavelength domain (WDM) or
  - in the time domain (TDM), with complete pilot laser extinction and with clock recovery for QKD window timing. Very PMD-tolerant! Very advantageous.
- **Whole normalized Stokes space of the probe signal is stabilized.**
- Endless tracking speed 20 krad/s (typically)

Stabilization of normalized Stokes space of the probe signal, under 20 krad/s polarization scrambling. Perfekt for QKD with BB84

Traditional polarization control, does not work for QKD with BB84

Stabilization of normalized Stokes space of the probe signal, under 20 krad/s polarization scrambling, with 35 ps of PMD. Time division multiplex (TDM) version.

**Below**: Setup with TDM pilot signals. Includes miniature modulation boards for commercially available ECLs.

**Stabilization and phase control setup**:

- Polarization scrambler 1
- ECL
- Polarization scrambler 2
- SMF 63 km
- DGD 35 ps
- FPGA-based controller
- LiNbO₃ polarization transformer
- PBS + photodiodes
- Demux
- 90°
- 135°
- Polarimeter

EPS1000 Polarization Scrambler/Transformer

- Ultrafast endless optical polarization scrambling at up to 20 Mrad/s (or 50 Mrad/s with less waveplates)
- 10 ns clock cycles (= updating intervals) assure continuous, quasi steady polarization changes even at high scrambling speeds (e.g., in 0.01 rad steps at 1 Mrad/s) and minimize deviations from desired smooth time-dependence of trajectory, for meaningful assessment of polarization/PMD tracking(trackers).
- 3 electrooptic quarterwave plates (QWP) + 1 halfwave plate (HWP) + 3 QWPs with adjustable rotation speeds (QWP: −2000000.00 ... +2000000.00 rad/s; HWP: −20000.00 ... +20000.00 krad/s)
- Optical frequency can be preset for most accurate waveplate operation, at least from C band to L band (186.2 ... 196.0 THz, 1529 ... 1610 nm). Optional: S band, 1310 nm
- Insertion loss ~1.7...2.5 dB. Power consumption ~12 W (+5 V power supply 100-240 V included)
- Differential group delay (DGD) sections consisting of polarization-maintaining fibers (PMF) available for highly realistic PMD emulation, using several EPS1000 and DGD sections.
- Available as a desktop unit, module or intellectual property core
- Interfaces for computer (USB, LAN) or controller (SPI, UART, digital hardware lines)
- Standalone operation of desktop unit via control buttons. Several units can be controlled simultaneously by graphical user interface (GUI; see next page), Matlab™, Labview™ or similar. Speeds of rotating and positions of stopped waveplates and electrode voltages can be set, saved and loaded.
- Serial Peripheral Interface (SPI) permits realtime operation; e.g., direct setting of waveplate voltages.
- In synchronous scrambling mode, user-generated tables with sets of waveplate positions or speeds can be loaded. Following an external trigger event (3.3 V LVCMOS signal applied at BNC connector, or SPI command) the sets are executed sequentially at specified instants (granularity: 40 ns; minimum delay until next execution instant: 200 ns). For recirculating loop experiments and emulation of lightning strikes.
- In triggered scrambling mode, the sets are executed cyclically one by one upon external trigger events or USB commands (minimum delay until next execution instant: 200 ns). Application examples: polarization-dependent loss (PDL) and Mueller/Jones matrix measurements.
- Optional photodetectors enable accurate PDL and loss measurements
- NEW: Depolarization in 960...360 ns interval, based on 50 Mrad/s version with 3 rotating waveplates
- EPX1000 = cost-saving desktop unit with combined functionalities of EPS1000 and 40...100 krad/s polarization controller/demultiplexer EPC1000
- PMS1000 = combination of EPS1000 with ultrafast (100 MHz) polarimeter PM1000

Exemplary output trajectories on Poincaré sphere

60-V step at HWP settles completely within 50 ns (20 ns/div). Small-signal response is a lot faster.
Left: Frequently used operation modes of USB- or LAN-operated graphical user interface. Other operation modes are:
- Voltage Control: Direct setting of 16 electrode voltages
- Device Testing (optional): Intensity recording for PDL and loss measurement

Pseudorandom state generation

Above: 20 vertices of dodecahedron, measured at the ends of 640 ns symbols.
Below: Transients visualized, 1 ms symbols

Customer feedback

“We have used the EPS1000 endless polarization scrambler in our record-breaking coherent transmission experiments (see our site www.optcom.polito.it) and it has performed flawlessly. We have particularly appreciated its very low insertion loss and its flexibility. Thanks to the EPS1000 endless polarization scrambler our recirculating-loop experimental results have become stable, repeatable and reliable.”

Prof. Dr. Pierluigi Poggiolini, Politecnico di Torino, Italy
Emulation of lightning strikes in fiber with EPS1000-20M

Circular retardation vs. time with 2 ns temporal resolution for scrambling 3 different speed profiles, all having the same peak retardation of 4.8 rad.

The polarization scrambler EPS1000 has been used to demonstrate lightning protection https://www.infinera.com/ice5-innovation/ of coherent optical data transmission at the OFC2018 exhibition.

Exemplary polarization speed distributions obtained with EPS1000

Peaked (for fastest assessment of coherent RX)  Quasi-Rayleigh  Triangular

Scalable software examples (Python, Matlab) available for speed setting. Many other choices

EPS1000-50M Depolarizer

- 50 Mrad/s version with 2 QWPs (8 Mrad/s) + 1 HWP (40 Mrad/s)
- Sets of periodic electrode voltages with integer relative driving frequencies, for instance [2, 3, –2]
- Depolarization in 960...360 ns interval
- Independent of input polarization

Mean and maximum degree-of-polarization (DOP) obtained with 1000 random input polarizations
PMDE1000 Polarization Mode Dispersion Emulator

- $N+1$ polarization scrambler modules (boards) EPS1000 with speeds up to 20 Mrad/s (or 50 Mrad/s) and $N$ differential group delay (DGD) sections are integrated into one case. (Standard: 19 inch rack-mount)
- Section DGDs can be switched.
- Typical configuration: 3 EPS1000, 2 DGD sections (switchable, e.g., 15 ps, 50 ps, ..., or external)
- Applications: Polarization mode dispersion (PMD) emulator for coherent fiber links (400 Gb/s 80 km ZR, transoceanic links, Tb/s links, ...). PMD equalization (with user-supplied control signals).

![Exemplary differential group delay profile](image)

Exemplary differential group delay profile, with overall first-order PMD being equal to sum of individual DGD or PMD vectors

![PMD emulator diagram](image)

PMD emulator with $N$ DGD sections (indices 1...N) placed between $N+1$ retarders/scramblers SCR (indices 0...N)

Example: PMDE1000 with 3 EPS1000 and 2 switchable DGD sections

**Reasoning:**


We have shown in [https://www.novoptel.de/Control/Literature/getPDF4.annot.pdf](https://www.novoptel.de/Control/Literature/getPDF4.annot.pdf) (Section V.) that the physical DGD section model (distributed or discrete) of PMD displayed above is the only one which makes sense because it approximates natural PMD best. (Higher-order PMD modeling based on a finite Taylor expansion of the PMD vector is unphysical because it inevitably predicts infinite PMD far off the optical reference frequency.) In [https://www.novoptel.de/Control/Literature/70EF9388d01.annot.pdf](https://www.novoptel.de/Control/Literature/70EF9388d01.annot.pdf) (Section II.A) is described why this is much more reasonable than the usage of variable DGD sections. PMD is emulated highly realistically by the usage of several EPS1000 and DGD sections in the PMDE1000
PDLM Polarization Dependent Loss Multimeter

- Usage mode or extension of EPS1000 polarization scrambler, with built-in photodetector(s).
- Polarization-dependent loss (PDL) and mean loss are calculated in firmware.
- PDL measurement interval <100 ms
- PDL measurement range 0.05...50 dB
- Optical power meter function
- Extinction method (superb especially for large PDL) and sqrt(3) method
- Polarization scrambler functionality is kept with optional switch.
- Fully programmable (USB, LAN, GUI, Matlab, Python, C, ...)

Left: Standard configuration of EPS1000 with PDLM function. DUT = device under test. An optical switch can be built in, which makes the polarization scrambler EPS1000 accessible without coupler insertion loss.

Below: PDL measurements (extinction mode, <100 ms for each of 100 measurements, 2 PDLM units tested) of patchcord (left) and partial polarizer (right) as DUT while polarization before and behind DUT is changed.

PM1000 Polarimeter

- Measurement of all 4 Stokes parameters, display on Poincaré sphere and in oscilloscope mode. Also available: Normalized Stokes vector, degree-of-polarization (DOP)
- Three choices for the normalization of Stokes parameters/vectors:
  - Standard: Normalized Stokes vectors are normalized to unit length. Regardless of power and DOP, they appear at the surface of the Poincaré sphere.
  - Exact: Normalized Stokes vectors are normalized only with respect to optical power. For DOP < 1 (or DOP = 0) they appear inside (or in the center of) the Poincaré sphere.
  - Non-normalized: Display of the non-normalized Stokes parameters. This means, DOP and optical power determine the length of the displayed $S_1-S_2-S_3$ Stokes vector.
- 100 MHz polarization state sampling frequency. 64 M polarization states can be recorded.
- 30 MHz analog bandwidth. Averaging (10 ns, 20 ns, 40 ns, ... 2.68 s), triggering, gating
- Internal triggering on SOP or intensity events. Selectable pre-trigger data ratio. Perfectly suited for automated long-term assessment of polarization transients. Download while recording next events!
- Realtime Poincaré sphere display up to 100 MHz in graphical user interface (GUI) or 50 MHz on connected monitor (HDMI/DVI, 720p60 or WXGA+). Not a single sample is lost!
- 100 MHz memory view, zoom in oscilloscope mode, screenshots, numeric display
- Speed histogram, intensity histogram, software examples for Matlab™ and Labview™
- Hardware option: 2 sensitivity ranges extend usability to +4...-40 dBm.
- Full support of EPS1000 polarization scrambler/transformer and EPX1000 polarization controller/demultiplexer and scrambler/transformer for Mueller matrix, Jones matrix, PDL and PMD measurement. Optional lock-in detection. EPS1000 module can be plugged onto PM1000 module.
- Power consumption: ~5 W (+5 V from included power supply 100-240 V)
- Available as a standalone desktop unit, as a module card, and as an intellectual property (IP) core
- Realtime operation with Serial Peripheral Interface (SPI), trigger/gating input/output (BNC)
- Operation via control buttons of desktop unit, USB, LAN, SPI or graphical user interface (GUI)
- Available: C&L (standard), S, E, O bands. Tunable C&L band laser modules can be built in.
EPS1000 polarization scrambler, characterized with various settings and PM1000 averaging times.

Configurable (1 rad/s to >100 Mrad/s) internal trigger is used to record the polarization fluctuations caused by hitting a DCM cassette. Oscilloscope mode.

Polarization extinction ratio (PER) measurement while heating PMF (left) or tuning an ITLA (right). Tuning-induced polarization transients are excluded by setting intensity threshold.

PM1000 desktop unit comes with Windows GUI. Can be connected to monitor (HDMI/DVI; 720p60 or WXGA+) and used without extra computer!

Rich internal and external triggering possibilities.

Predecessors PM500 of the polarimeter PM1000 have been used by D. Charlton et al. for field measurements of state of polarization transients in optical ground wire, with time and location correlation to lightning strikes: https://www.osapublishing.org/oe/abstract.cfm?uri=oe-25-9-9689

The polarimeter https://www.novoptel.de/Polarimeter/Polarimeter_PM1000_en.php has also been used by F. Pittala et al. for "Laboratory Measurements of SOP Transients due to Lightning Strikes on OPGW Cables" https://doi.org/10.1364/OFC.2018.M4B.5.
PMS1000 Polarimeter and Polarization Scrambler/Transformer

- Combination of the PM1000 polarimeter with the EPS1000 polarization scrambler/transformer
- All functionalities and data of PM1000 and EPS1000
- Ideal for synthesis of desired polarization states and device under test (DUT) polarimetry
- Opto-mechanical 2x2 switch (optional) can connect output of LiNbO$_3$ polarization transformer directly to input of polarimeter. Insertion loss of each path is thereby increased by ~0.5 dB (<1 dB).
- Another opto-mechanical 2x2 switch (optional) can exchange output of LiNbO$_3$ polarization transformer and input of polarimeter, to determine DUT reciprocity by backward measurement.
- Power consumption (w/o optional lasers): ~17 W (+5 V from included power supply 100-240 V)
- Desktop units (combined PMS1000 or separate EPS1000 & PM1000) or module cards
- Switching between PM1000 and EPS1000 via control buttons, or parallel operation via USB

- A number of polarization states is generated for the DUT. Subsequent calculations yield:
  - **Mueller matrix**, **Mueller-Jones matrix** (= Mueller matrix made non-depolarizing) and **Jones matrix**
  - **Eigenmodes**, retardation, mean loss, **PDL** (= polarization-dependent loss)
  - Decomposition of Mueller and Jones matrices into sequences SBA + PPPS + SBA. Definitions: PPPS = horizontal partial polarizer and phase shifter. SBA = Soleil-Babinet analog = retarder having a retardation between 0 and $\pi$ and eigenmodes anywhere on the $S_2$-$S_3$ great circle of the Poincaré sphere. An SBA does to horizontal polarization the same as a Soleil-Babinet compensator to circular polarization: mode conversion with adjustable phase shift.
  - **10 ns temporal resolution** of all time-variable component properties (Mueller matrix etc.)

- With LU1000 or available tunable laser(s), Mueller and Jones matrices can be measured as a function of optical frequency, and **PMD** is determined. Inverse scattering allows a **DGD profile** (= differential group delay profile) to be generated (JLT 21(2003)5, p. 1198, JLT 33(2015)10, pp. 2127-2138, 2015).

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**PMS1000A for measurement of Mueller and Jones matrices and PMD of a device under test (DUT). Optional components are shaded. C&L band tunable laser modules are available (usually in LU1000 laser unit). EPS1000 polarization scrambler/transformer and PM1000 polarimeter are individually accessible, even when they are combined into one unit.**

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**Measurements and Calculations**

- Time-resolved PDL of a rotating electrooptic halfwave plate (EPS1000) as a DUT, extracted from 1024 Mueller matrices recorded with 320 ns temporal spacing.
- Measured DGD profile in the PMD vector space of two concatenated, arbitrarily oriented PMFs, with DGDs of 4 and 6.6 ps. Not only the total 1st-order PMD vector but also the structure of the DUT becomes apparent.
LU1000 Laser Unit

- Up to 4 lasers, tunable continuously or in steps of 50 GHz (or tbd) according to ITLA MSA. Ultra-narrow linewidth (or tbd).
- Up to 18 dBm output power, adjustable.
- C & L band available, optionally with AM.
- Operation via control buttons or SPI, USB, LAN using Graphical User Interface, Matlab, Labview or similar.
- Desktop unit. **Fully compatible with EPS1000 and PM1000 for device characterization.**

All Novoptel products

- Temperature tested.
- Available as module cards, desktop units, 19" 1U rackmounts.
- USB, LAN, SPI available.
- Fully programmable (USB, LAN, GUI, Matlab, Python, C, ...)

**Novoptel fulfills your needs**

- Delivered items come with test protocols.
- Customer feedback and requests are taken into account during development and after purchase through free software updates. This has led to new features.
- Special developments upon customer request.

From an EPC1000 test protocol: Complementary distribution function $1 - F(RIE)$ of relative intensity error (RIE) during 3-hour polarization tracking with temperatures -15°C...+60°C at 40 krad/s scrambling.

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**About Novoptel**

Novoptel GmbH was founded by Dr.-Ing. Benjamin Koch and Prof. Dr.-Ing. Reinhold Noé in 2010 as a spin-off of the University of Paderborn, Germany, with the aim of developing and delivering novel optics and electronics for telecommunication. Leveraging decades of pioneer experience in optical polarization control plus knowledge about needs of the telecom industry, Novoptel has brought this technology to unprecedented maturity and has developed ultrafast optical endless polarization controllers, polarization scramblers, polarimeters and other products.

Prior to founding Novoptel, Reinhold Noé co-received the Innovation Award 2008 of the Land North Rhine-Westphalia in the category Innovation, for the first submitted/published synchronous QPSK transmission with DFB lasers (2006) and with polarization multiplex (2007). He has (co-)authored about 300 peer-reviewed journal and conference papers and 160 patent applications and patents.

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