

User Guide

Novoptel

EPS1000 Polarization Scrambler/Transformer



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Revision history

Version	Date	Remarks	Author
0.1.0	28.10.2011	Draft version	B. Koch
0.1.1	30.08.2012	Draft version	B. Koch
0.1.2	15.04.2013	Description of external voltage allocation (Registers 50...65)	B. Koch
0.1.3	23.07.2013	Support of multiple wavelength bands	B. Koch
0.1.4	07.05.2014	Description of PDL measurements	B. Koch
0.1.5	21.07.2014	Footnotes of USB register table added/corrected	B. Koch
0.1.6	26.06.2015	Updates due to GUI rev. 1.4.2.0	B. Koch
0.1.7	09.06.2016	For EPS Firmware \geq 1.1.0.0: Scrambling speed tables added	B. Koch
0.1.8	27.09.2016	Register description complemented	B. Koch
0.1.9	23.10.2017	LAN (TCP/IP) communication added	B. Koch
0.2.0	19.03.2018	Nominal scrambling speed explanation clarified, correction of table dwell time	R. Noe, B. Koch
0.2.1	20.04.2018	Rotation matrices and orientation angle of waveplates added	R. Noe
0.2.2	07.03.2019	Footnote (3) of Control Registers corrected (1828, not 1829)	B. Koch
0.3.0	22.06.2020	Description of firmware-embedded PDL measurement (firmware \geq 1.2.0.0)	B. Koch
0.3.1	15.11.2021	Description of scrambling type and target speed (firmware \geq 1.2.0.7)	R. Noe
0.3.2	18.08.2021	Description of optional SOP tracker	B. Koch

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Rear panel

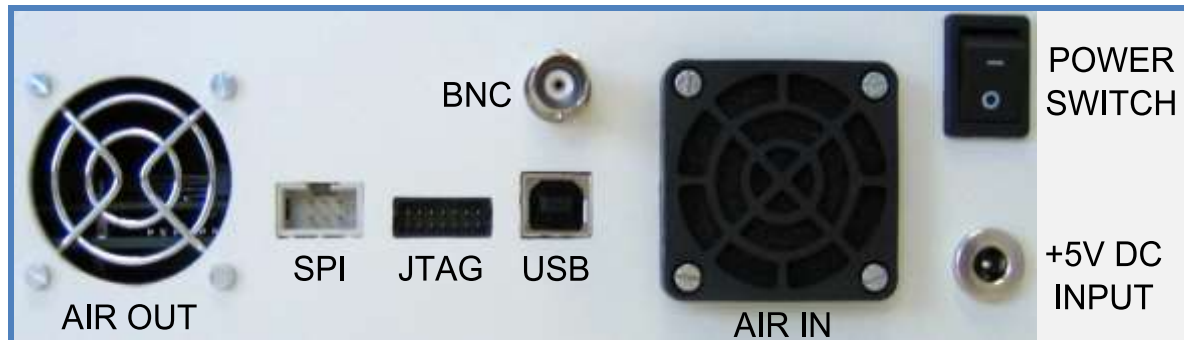


Fig. 1: EPS1000 rear panel

Operation of the instrument via front control panel

Power the instrument with the provided power supply and switch it on. The scrambler firmware provides a cyclic menu, which is shown on the LCD or OLED display. The menu structure is

WELCOME
Scrambling/PDL mode
QWP0
QWP1
QWP2
HWP
QWP3
QWP4
QWP5
Optical Frequency
Wavelength Band
LAN Configuration
Save Configuration

Menu points QWP0 and QWP5 are missing in scrambler configurations with only four quarter wave plates. The menu point *Wavelength Band* is missing if the scrambler supports only a single wavelength band. The menu point *LAN Configuration* is missing if the scrambler is not equipped with a LAN interface. The menu point *Scrambling/PDL mode* is missing if the scrambler is not equipped with an optical detector.

The control buttons *UP* and *DOWN* let you to navigate through the menu. The control buttons *LEFT* and *RIGHT* changes a selected setting or selects a decimal place, which can afterwards be changed with the buttons *UP* and *DOWN*.

For each waveplate, you can choose between *DISABLED*, *FORWARD* and *BACKWARD* operation of the wave plate and set the desired nominal scrambling speed. For the quarterwave plates, nominal scrambling speed is given in in rad/s

between 0 and +999,999.99 rad/s. For the halfwave plate, it is given in krad/s between 0 und 20,000.00 krad/s. For actual scrambling speeds see p. 8.

The range for the optical frequency is at least C and L band, usually 182.9 THz (1639.1 nm) to 198.5 THz (1510.3 nm).

Operation of the instrument via graphical user interface

The instrument communicates by a USB IC FT232R from FTDI (Future Technology Devices International Limited, <http://www.ftdichip.com>).

The Novoptel EPS1000 Graphical User Interface (= GUI) is compiled on a Microsoft Windows 10 64 Bit system. It is recommended to set the DPI scaling to 100%.

Installing the USB driver

Execute the installation program of the provided USB driver (*CDM21228_Setup.exe*). You will find more detailed information about the driver at <http://www.ftdichip.com/Support/Documents/InstallGuides.htm>.

Connecting the instrument

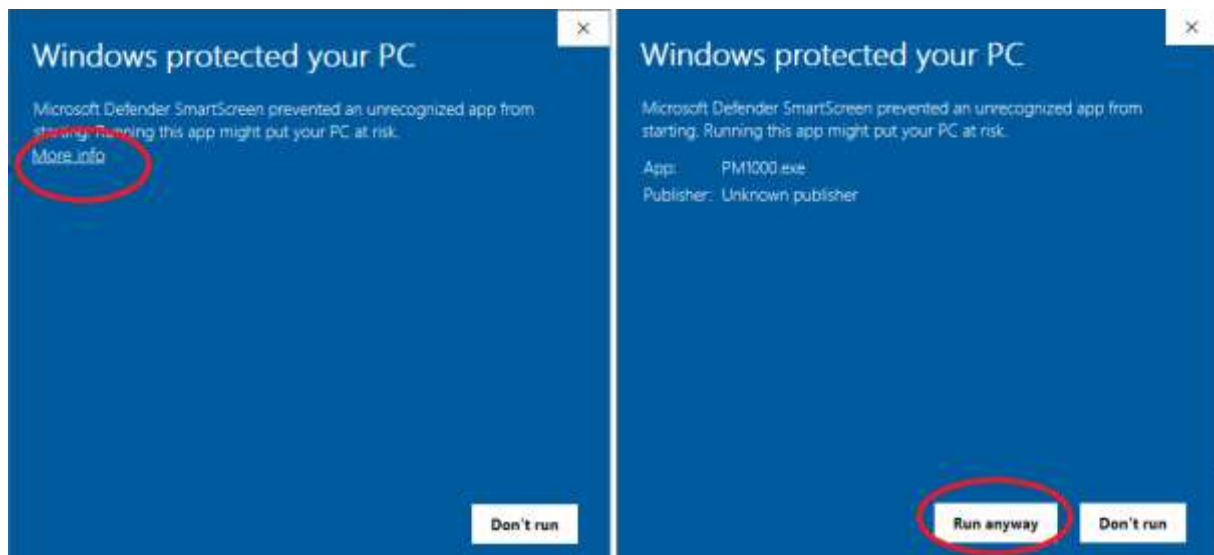
After the driver is installed successfully, connect PC and instrument using the provided USB cable. Wait until Windows has recognized the USB device and shown an acknowledgement message. Power the instrument with the provided power supply and switch it on.

Installing the GUI

Any previous version of the graphical user interface has to be uninstalled first. For installation, execute *setup.exe* in the folder *EPS1000_XXXX*, where *XXXX* refers to the GUI versions. Follow the instructions of the installation dialogue.

If not found on the PC, Microsoft .NET Framework 4.5 will be installed during installation of the GUI.

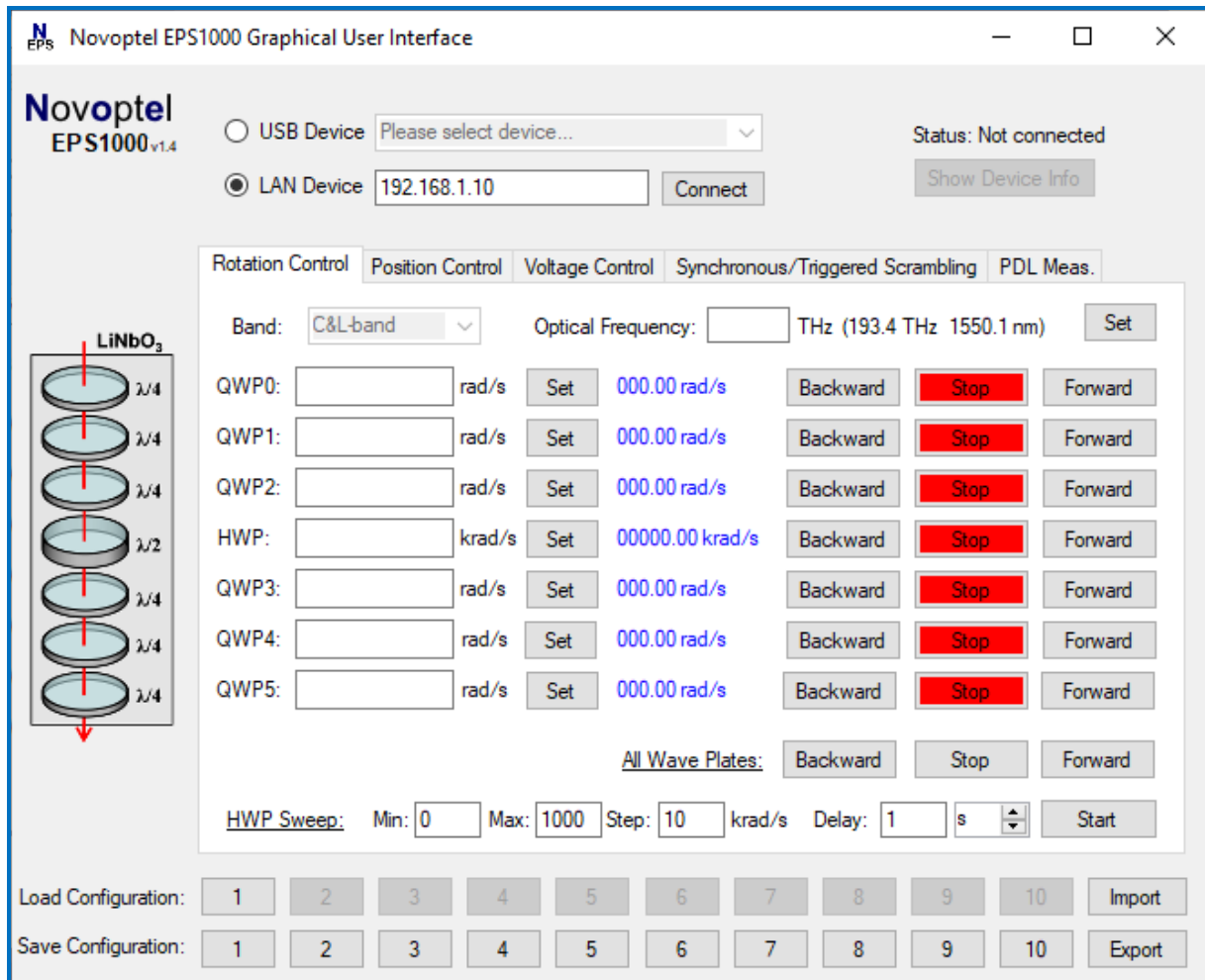
While installing a recently released GUI on Windows 10, you may receive a SmartScreen warning:



Microsoft Windows SmartScreen may flag newly uploaded files that have not built up a long enough history. You can install the GUI by clicking “More info” and then “Run anyway”.

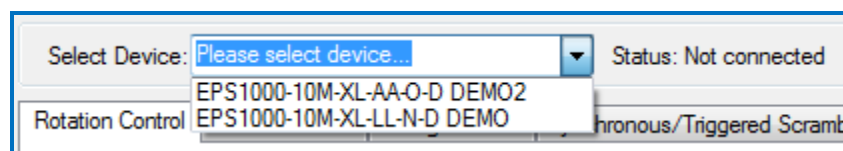
First steps with the GUI

The software launches automatically after installation. If you want to launch the software later manually, select *Programs\Novoptel\EPS1000* from the Windows Start Menu.

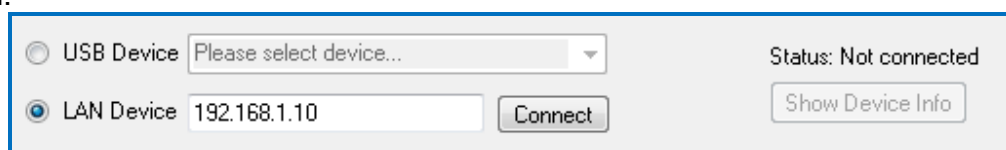


Selecting one of the instruments attached via USB or LAN

If you have attached only one Novoptel polarization scrambler/transformer, the GUI automatically selects this one. If you have attached more than one instrument, select the desired one from the drop-down menu.



If a device is connected via LAN, enter the IP address in the field below and click "Connect". The GUI will preload the IP address and the connection type at the next launch.



Subsequently, you can launch further instances of the GUI and connect them to further instruments.

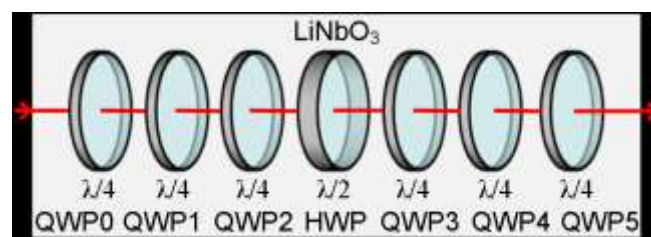
Setting the optical frequency

Type the optical frequency in THz with up to one position after decimal point into the field besides *Optical Frequency*.

Band: C&L band Optical Frequency: 193,5 THz (193,5 THz 1549,3 nm) Set

The valid range is at least C and L band, usually 182.9 THz (1639.1 nm) to 198.5 THz (1510.3 nm). Click the button *Set*. Retardations of the wave plates are fine-tuned to the given optical frequency.

Setting the nominal scrambling speed



The LiNbO₃ polarization transformer inside the EPS1000 can be configured such that it contains cascaded electrooptic waveplates, 3 quarterwave plates (QWP0, QWP1, QWP2), 1 halfwave plate (HWP), 3 more quarterwave plates (QWP3, QWP4, QWP5). Each electrical period of waveplate voltages corresponds to half a mechanical turn of a waveplate. **As the nominal scrambling speed we define that speed on the Poincaré sphere which occurs if a waveplate generates rotating linear polarization.** This is the case with circular polarization at the input of a QWP or linear polarization at the input of the HWP.

For the QWPs, nominal scrambling speed is given in rad/s between 0 and 999,999.99 rad/s. The angular eigenmode rotation speed ($d\zeta/dt$) of a QWP equals its nominal scrambling speed. For input polarizations having ellipticity angle magnitudes $<\pi/8$ the polarization change speed of a QWP is up to $\sqrt{2}$ times the nominal scrambling speed, which is the achievable scrambling speed. For equidistributed input polarization the root-mean-square (rms) speed is $2/\sqrt{3} = 1.15$ times as large as for circular input polarization.

For the HWP, the nominal scrambling speed is given in krad/s between 0 and 20,000.00 krad/s. The angular eigenmode rotation speed ($d\zeta/dt$) of the HWP equals half its nominal scrambling speed. The maximum achievable scrambling speed of the HWP equals its nominal scrambling speed. For equidistributed input polarization the rms speed is $\sqrt{2/3} = 0.816$ times as large.

The waveplates are depicted among each other in the sequence in which they are traversed by the light. Type the desired speed with up to two positions after decimal point into the box beside the wave plates. To obtain a uniform distribution of the polarization states on the Poincaré sphere, the nominal scrambling speeds of the waveplates should be incommensurate with each other. See Section III. of

<http://ieeexplore.ieee.org/document/7507007/> for application examples. Bipolar nominal scrambling speeds (forward and backward, in the following marked by the sign) generally yield broader polarization speed distributions on the Poincaré sphere than unipolar speeds.

A Rayleigh-like speed distribution is for example obtained by setting QWP0, QWP1, QWP2, HWP, QWP3, QWP4, QWP5 to nominal scrambling speeds of 8387, -3766.8, 13363, 9840, -7062.6, 14800, -11677 rad/s, respectively. The observed rms scrambling speed is 37.3 krad/s.

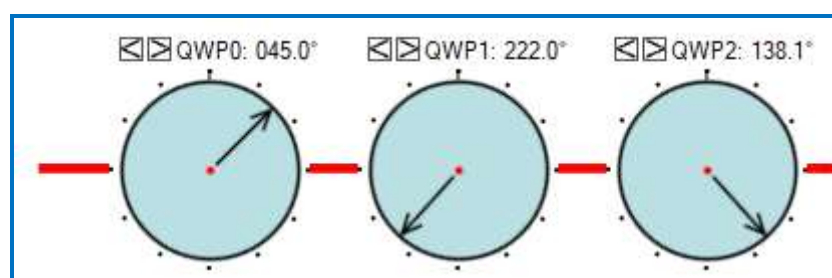
A peaked speed distribution, useful for accelerated performance or outing testing, is for instance obtained by the nominal speeds 119.28, -53.57, 190.04, 70000, -100.45, 210.5, -166.07 rad/s, respectively. It is peaked around 70 krad/s. Given the dominance of the HWP speed it is useful to say: QWP0 to QWP2 scramble the unknown input polarization. Dependent on this, the HWP generates circles in parallel planes of the Poincaré sphere with radii between 0 and 1. QWP3 to QWP5 reorient these circles arbitrarily.

QWP2:	<input type="text" value="999999.99 rad/s"/>	<input type="button" value="Set"/>	999999.99 rad/s	<input type="button" value="Backward"/>	<input type="button" value="Stop"/>	<input type="button" value="Forward"/>
HWP:	<input type="text" value="20000.00 krad/s"/>	<input type="button" value="Set"/>	20000.00 krad/s	<input type="button" value="Backward"/>	<input type="button" value="Stop"/>	<input type="button" value="Forward"/>

Click the button *Set*. This will transfer the entered value to the value in blue. Only the blue value is the actually applied rotation speed. Select the rotation direction by clicking "*Forward*" or "*Backward*" (or "*Stop*", to stop the waveplate).

Setting a certain state of polarization

This function allows setting a fixed state of polarization or adjusting the input- and output polarization of a rotating wave plate. Select the tab *Position Control*. Each waveplate is depicted as a rotary knob. An arrow marks the eigenmode orientation angle ζ of the waveplate on the equator of the Poincaré sphere. The eigenmode orientation angle is shown above the waveplate in degrees.



To rotate the waveplate, click on one knob and move the mouse with pressed mouse button around the center of the knob. In case that the wave plate was configured to rotate with a given speed, it will be halted automatically. You can start the rotation again using the tab *Rotation Control*.

Physically, waveplates can be described by their rotation matrices G of the normalized Stokes vector. These are

$$\mathbf{G} = \begin{bmatrix} (1 + \cos(2\zeta))/2 & \sin(2\zeta)/2 & \sin\zeta \\ \sin(2\zeta)/2 & (1 - \cos(2\zeta))/2 & -\cos\zeta \\ -\sin\zeta & \cos\zeta & \cos\delta \end{bmatrix} \text{ for the QWPs,}$$

$$\mathbf{G} = \begin{bmatrix} \cos(2\zeta) & \sin(2\zeta) & 0 \\ \sin(2\zeta) & -\cos(2\zeta) & 0 \\ 0 & 0 & -1 \end{bmatrix} \text{ for the HWP.}$$

The eigenmode orientation angle ζ on the equator of the Poincare sphere is also the physical electrostatic field orientation angle inside the waveguide. It equals twice the orientation angle of a mechanical waveplate. The angular eigenmode rotation speed in the foregoing subchapter is $d\zeta/dt$.

The total normalized Stokes vector rotation matrix or polarization transformation of the EPS1000 is obtained by cascading (multiplying) the rotation matrices of the 7 waveplates.

Store and load a configuration

You can save and recall up to ten configurations. Both nominal scrambling speeds and fixed positions of all wave plates are considered thereby.

Load Configuration:	1	2	3	4	5	6	7	8	9	10	Import
Save Configuration:	1	2	3	4	5	6	7	8	9	10	Export

Click on a numbered button beside *Save Configuration* to save the configuration to one of the memory locations. Click on a button beside *Load Configuration* to recall a configuration from a memory location. Unused memory locations are faded out. Instances of the Software which are launched in parallel share the memory locations.

The configuration can also be imported from and exported to text files (*.dat). The files consist of 66 lines, for register addresses 65 down to 0 (in this order). Each line of the text file simply contains the register address and the corresponding 16 Bit register value, separated by a space character (blank). The register addresses cover configuration of electrode voltages, waveplate positions, rotation speeds and rotation directions of the waveplates (see section *Control Registers*).

Operation of the instrument using register access

The polarization scrambler is controlled by reading from and writing to internal control registers. The register address line is 12 bits wide, while each register stores 16 bits. The connection host, e.g. the program running on the connected PC, initiates all communication.

Access the USB driver

The USB driver (CDM21228_Setup.exe) has to be installed on your system and the scrambler needs to be connected using a USB cable.

Support for Matlab

Matlab needs a header file like *ftd2xx.h* from FTDI to access the driver. Novoptel provides the header version *matftd2xx.h*, in which the data types are modified to become compatible with current Matlab versions.

The different functions of the driver can be seen from the header file. Information about each function is provided at

<http://www.ftdichip.com/Support/Knowledgebase/index.html>

You will find help about communicating to a driver at

<http://www.mathworks.com/help/techdoc/ref/loadlibrary.html>

Example Matlab scripts for USB data transfer are available from Novoptel upon request.

Operation of the instrument using other programs

The USB vendor <http://www.ftdichip.com/Support/Knowledgebase/index.html> provides examples for USB access using other programs, for example LabVIEW®. A rudimental example of a LabVIEW-VI (virtual instrument) is available from Novoptel upon request.

Example programs for Python can be downloaded from

https://www.novoptel.de/Home/Downloads_en.php.

USB Settings

The following settings have to be applied to enable USB communication:

Baud Rate	230400 baud
Word Length	8 Bits
Stop Bits	1 Bit
Parity	0 Bit

To speed up sequential read and write operations, we recommend setting:

USB Latency Timer	2 ms
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USB Transfer protocol

Writing to a register requires a 9 byte data packet. Each byte represents an ASCII-coded character. The packet starts with the ASCII-code 0x57 (for "W") and ends with the ASCII-code 0x0D for *carriage return*.

Send write data packet

„W“	A(2)	A(1)	A(0)	D(3)	D(2)	D(1)	D(0)	^CR
-----	------	------	------	------	------	------	------	-----

The 12 bit register address A is sent using 3 bytes, each containing the ASCII-character of the hexadecimal numbers 0 to F which represents the 4 bit nibble. The character of the most significant nibble is sent first. The 16 bit data, which should be written into the register, is sent with 4 bytes using the same coding as the register address.

Reading data from a register requires the host to send a *request data* packet to the instrument. The packet starts with the ASCII-code 0x52 (for "R"), followed by the register address coded the same way as in *write data* packets.

Send request data packet

„R“	A(2)	A(1)	A(0)	„0“	„0“	„0“	„0“	^CR
-----	------	------	------	-----	-----	-----	-----	-----

After receiving the *request data* packet, the instrument sends the requested data packet to the host:

D(3)	D(2)	D(1)	D(0)	CR
------	------	------	------	----

TCP/IP (LAN) Communication

The user can set the IP address, gateway and subnet mask via the front buttons. After the next power-up, the EPS1000 will open a TCP/IP socket using the entered settings and wait for a connection.

TCP/IP Settings

Port	5025
Input buffer	8192 Bytes

TCP/IP Transfer protocol

write data packet

In contrast to USB communication, writing to a register via TCP/IP requires only a 5 byte data packet. The packet starts with the ASCII-code 0x57 (for "W").

„W“	A(11..8)	A(7..0)	D(15..8)	D(7..0)
-----	----------	---------	----------	---------

The 12 bit register address is sent first in two bytes, followed by the 16 bit register data in another two bytes.

Reading data over TCP/IP requires the program to send a *request data* packet of 3 bytes to the instrument. The packet starts with the ASCII-code 0x52 (for "R"), followed by the register address coded the same way as in *write data* packets.

Send request data packet

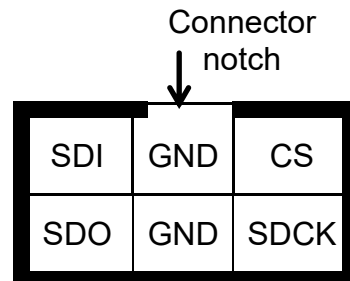
„R“	A(11..8)	A(7..0)
-----	----------	---------

After receiving the *request data* packet, the instrument sends the requested data packet to the host:

D(1)	D(0)
------	------

Operation of the instrument using SPI

All control registers can also be accessed by SPI. The SPI interface allows communication with a simpler protocol and shorter delays than USB. The SPI connector at the backside of the device provides the following connection:



Transmission starts with falling edge of CS and ends with rising edge of CS. After falling edge of CS, the command is transmitted. SDI is sampled with rising edge of SCK. Maximum SCK frequency is 500 kHz. Command and data word length is 16 bit each. MSB of command and data word is sent first, LSB last. If a valid *register read* (RDREG) command is received, the SDO output register shifts with falling edge of SCK to transmit the requested data word. Otherwise SDO remains in high impedance state. Data transfer to the device continues directly after transmitting a *register write* (WRREG) command.

Serial interface (SPI) commands

Command	Code	Data	Function
RDREG	0XXXh	OUT	Read register XXXh (for definition see <i>USB section</i>)
WRREG	1XXXh	IN	Write register XXXh (for definition see <i>USB section</i>)

Serial interface (SPI) timing

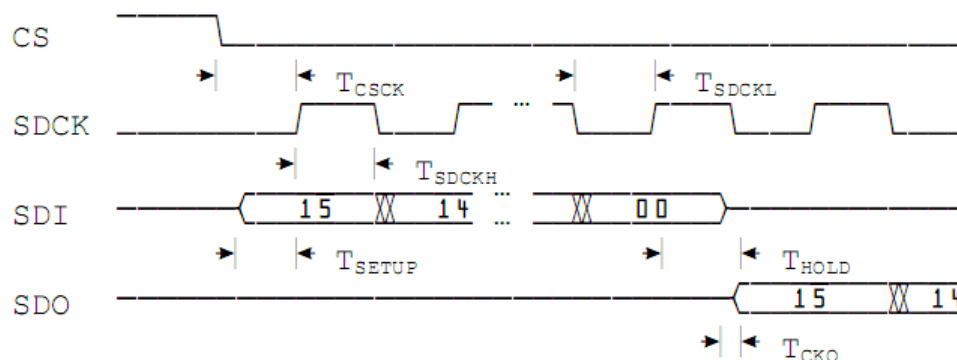


Fig. 2: Timing of SPI port.

Symbol	Description	Min	Max	Units
T_{CSCK}	CS low to SDCK high	120	–	ns
T_{CKCS}	SDCK low to CS high	120	–	ns

T _{SDCKL}	SDCKL low time	1	–	μs
T _{SDCKH}	SDCKL high time	1	–	μs
T _{SETUP}	SDI egde to SDCK high (setup time)	30	–	ns
T _{HOLD}	SDCK to SDI edge (hold time)	30	–	ns
T _{CKO}	SDCK edge to stable SDO	–	100	ns

Control registers

The following table describes all control register used to operate the scrambler:

Register address	Bit(s)	Read/ Write	Function
0	0	R/W	HWP rotation enable(1) or disable (0)
	1	R/W	HWP direction backward(1) or forward(0)
1	0	R/W	QWP0 rotation enable(1) or disable (0)
	1	R/W	QWP0 rotation direction backward(1) or forward(0)
2	0	R/W	QWP1 rotation enable(1) or disable (0)
	1	R/W	QWP1 rotation direction backward(1) or forward(0)
3	0	R/W	QWP2 rotation enable(1) or disable (0)
	1	R/W	QWP2 rotation direction backward(1) or forward(0)
4	0	R/W	QWP3 rotation enable(1) or disable (0)
	1	R/W	QWP3 rotation direction backward(1) or forward(0)
5	0	R/W	QWP4 rotation enable(1) or disable (0)
	1	R/W	QWP4 rotation direction backward(1) or forward(0)
6	0	R/W	QWP5 rotation enable(1) or disable (0)
	1	R/W	QWP5 rotation direction backward(1) or forward(0)
9	15..0	R/W	HWP nominal scrambling speed Bits 15..0 ⁽¹⁾
10	15..0	R/W	HWP nominal scrambling speed Bits 31..16 ⁽¹⁾
11	15..0	R/W	QWP0 nominal scrambling speed Bits 15..0 ⁽²⁾
12	15..0	R/W	QWP0 nominal scrambling speed Bits 31..16 ⁽²⁾
13	15..0	R/W	QWP1 nominal scrambling speed Bits 15..0 ⁽²⁾
14	15..0	R/W	QWP1 nominal scrambling speed Bits 31..16 ⁽²⁾
15	15..0	R/W	QWP2 nominal scrambling speed Bits 15..0 ⁽²⁾
16	15..0	R/W	QWP2 nominal scrambling speed Bits 31..16 ⁽²⁾
17	15..0	R/W	QWP3 nominal scrambling speed Bits 15..0 ⁽²⁾
18	15..0	R/W	QWP3 nominal scrambling speed Bits 31..16 ⁽²⁾
19	15..0	R/W	QWP4 nominal scrambling speed Bits 15..0 ⁽²⁾
20	15..0	R/W	QWP4 nominal scrambling speed Bits 31..16 ⁽²⁾
21	15..0	R/W	QWP5 nominal scrambling speed Bits 15..0 ⁽²⁾
22	15..0	R/W	QWP5 nominal scrambling speed Bits 31..16 ⁽²⁾
23	15..0	R/W	Target speed of distribution in multiples of 10 rad/s; Bits 15..0 ⁽⁸⁾
24	15..0	R/W	Scrambling type; Bits 31..30 3 = Rayleigh 2 = Peaked 0, 1 = User Target speed of distribution in multiples of 10 rad/s;

			<p>Bits 29..16⁽⁸⁾</p> <p>Target speed (Bits 29..0) is limited to 1000000 (Rayleigh, 10 Mrad/s) or 2000000 (Peaked, 20 Mrad/s). Limiting takes place when register 24 is written and scrambling type is Rayleigh or Peaked. To avoid accidental target speed truncation, write register 23 first, then write register 24.</p>
25	15..0	R/W	Optical Frequency Index I ⁽³⁾
40	15..0	R/W	HWP position Index I ⁽⁴⁾
41	15..0	R/W	QWP0 position index I ⁽⁴⁾
42	15..0	R/W	QWP1 position index I ⁽⁴⁾
43	15..0	R/W	QWP2 position index I ⁽⁴⁾
44	15..0	R/W	QWP3 position index I ⁽⁴⁾
45	15..0	R/W	QWP4 position index I ⁽⁴⁾
46	15..0	R/W	QWP5 position index I ⁽⁴⁾
47	15..0	R/W	Table Dwell Time (multiples of 40 ns) as stored in the table, Bits 15..0
48	15..0	R/W	Table Dwell Time (multiples of 40 ns) as stored in the table, Bits 31..16
50	13..0	R/W	LiNbO ₃ section 1 electrode 1 voltage ⁽⁵⁾
51	13..0	R/W	LiNbO ₃ section 1 electrode 2 voltage ⁽⁵⁾
52	13..0	R/W	LiNbO ₃ section 2 electrode 1 voltage ⁽⁵⁾
53	13..0	R/W	LiNbO ₃ section 2 electrode 2 voltage ⁽⁵⁾
54	13..0	R/W	LiNbO ₃ section 3 electrode 1 voltage ⁽⁵⁾
55	13..0	R/W	LiNbO ₃ section 3 electrode 2 voltage ⁽⁵⁾
56	13..0	R/W	LiNbO ₃ section 4 electrode 1 voltage ⁽⁵⁾
57	13..0	R/W	LiNbO ₃ section 4 electrode 2 voltage ⁽⁵⁾
58	13..0	R/W	LiNbO ₃ section 5 electrode 1 voltage ⁽⁵⁾
59	13..0	R/W	LiNbO ₃ section 5 electrode 2 voltage ⁽⁵⁾
60	13..0	R/W	LiNbO ₃ section 6 electrode 1 voltage ⁽⁵⁾
61	13..0	R/W	LiNbO ₃ section 6 electrode 2 voltage ⁽⁵⁾
62	13..0	R/W	LiNbO ₃ section 7 electrode 1 voltage ⁽⁵⁾
63	13..0	R/W	LiNbO ₃ section 7 electrode 2 voltage ⁽⁵⁾
64	13..0	R/W	LiNbO ₃ section 8 electrode 1 voltage ⁽⁵⁾
65	13..0	R/W	LiNbO ₃ section 8 electrode 2 voltage ⁽⁵⁾
78	6	R/W	Ext. gating of QWP5 rotation en-/disable ⁽⁷⁾
	5	R/W	Ext. gating of QWP4 rotation en-/disable ⁽⁷⁾
	4	R/W	Ext. gating of QWP3 rotation en-/disable ⁽⁷⁾
	3	R/W	Ext. gating of HWP rotation en-/disable ⁽⁷⁾
	2	R/W	Ext. gating of QWP2 rotation en-/disable ⁽⁷⁾
	1	R/W	Ext. gating of QWP1 rotation en-/disable ⁽⁷⁾
	0	R/W	Ext. gating of QWP0 rotation en-/disable ⁽⁷⁾
79	6	R/W	Ext. gating of QWP5 active high (1) or low (0) ⁽⁷⁾
	5	R/W	Ext. gating of QWP4 active high (1) or low (0) ⁽⁷⁾
	4	R/W	Ext. gating of QWP3 active high (1) or low (0) ⁽⁷⁾
	3	R/W	Ext. gating of HWP active high (1) or low (0) ⁽⁷⁾
	2	R/W	Ext. gating of QWP2 active high (1) or low (0) ⁽⁷⁾

	1	R/W	Ext. gating of QWP1 active high (1) or low (0) ⁽⁷⁾
	0	R/W	Ext. gating of QWP0 active high (1) or low (0) ⁽⁷⁾
84	15..0	R	Firmware version
91	15..0	R	Serial Number
123	15..0	R	Dark current of ADC sample (optional photodetector)
124	15..0	R	Optical power at upper ADC range limit in μW
126	1	R/W	(1) automatic or (0) manual switching between two optional photodetectors
	0	R/W	Manual switch position or polarity of automatic switching according to Bit 1
128	15..0	R	Integer part of ADC sample
129	9..0	R/W	Averaging Time Exponent (ATE) for ADC sampling
130	15..0	R/W	Address of internal sampling memory
131	15..0	R	Data-Out of internal sampling memory
132	0	R/W	Triggered WP rotation enable (1) or disable (0)
133	15..0	R	Fractional part of ADC sample, frozen at each reading of register 128
134	15..0	R/W	Memory stop-address for measurements (max. $2^{16}-1$)
135	15..0	R	Next sampling memory address bits 15..0
136	15..0	R/W	Measurement delay in multiples of 20 ns ⁽⁶⁾
137	15..0	R/W	Memory Averaging Time Exponent (MEMATE) for memory trigger ⁽⁶⁾
138	2..0	R/W	Control of optional electrical switches ⁽⁶⁾
139	0	R	Next sampling memory address bit 16 ⁽⁶⁾
140	15..0	R/W	Number of cycles to be skipped during measurements ⁽⁶⁾
141	3..0	R/W	With a value A in this register, 2^A samples will be stored per waveplate position ⁽⁶⁾
150	0	R/W	(0): Define WP rotation by registers 9...22 (1): Define WP rotation by registers 151...157
151	15..0	R/W	HWP eigenmode rotations per 10.7 s
152	15..0	R/W	QWP0 eigenmode rotations per 10.7 s
153	15..0	R/W	QWP1 eigenmode rotations per 10.7 s
154	15..0	R/W	QWP2 eigenmode rotations per 10.7 s
155	15..0	R/W	QWP3 eigenmode rotations per 10.7 s
156	15..0	R/W	QWP4 eigenmode rotations per 10.7 s
157	15..0	R/W	QWP5 eigenmode rotations per 10.7 s
218	0	R/W	Table execution in row (1) or table (0) mode
219	9..0	R/W	Table memory input address
220	0	R/W	Enable (1) or disable (0) continuous table execution
221	15..0	W	Table memory write trigger. Must be reset to "0" in firmware < 1.0.7.0! Bit 0: Write table memory vector 00, 01, and 02 Bit 1: Write table memory vector 03 Bit 2: Write table memory vector 04

			.. Bit 15: Write table memory vector 17 In firmware <1.0.7.0, Bit 0 writes all table memory vectors.
222	15..0	R/W	Int. trigger period in mult. of 40 ns, Bits 15..0
223	15..0	R/W	Int. trigger period in mult. of 40 ns, Bits 31..16
224	0	R/W	External trigger input enabled (1) or disabled (0)
225	1	R/W	Enable (1) or disable (0) trigger by ATE counter
	0	R/W	Enable (1) or disable (0) internal trigger counter
226	1	R/W	Configure BNC port as output (1) or input (0)
	0	R/W	1: Enable BNC trigger signal output
227	1..0	W	Bit 0: "1" will launch a trigger event (manual trigger) Bit 1: "1" will reset the table to the first entry
228	9..0	R/W	Length of current table in table memory
229	6..0	R/W	Fixed waveplate positions are defined by registers (0) or by table memory (1) Bit 6: QWP0 Bit 5: QWP1 Bit 4: QWP2 Bit 3: HWP Bit 2: QWP3 Bit 1: QWP4 Bit 0: QWP5 Note: In firmware < 1.0.7.0, Bit 0 defines the status for all waveplates.
239	1..0	R/W	Table mode. "01": Waveplate positions "10": Waveplate nominal scrambling speeds "11": Electrode voltages Note: This and all table memory registers are described for firmware >=1.1.0.0. For earlier firmwares please refer to User Guide rev. 0.1.6.
250..267	15..0	R/W	Table memory input vector 00 to 17. See section "Table memory".
270..287	15..0	R	Table memory output vector 00 to 17
340	0	R/W	"1": Optional SOP tracking mode enabled. Requires optional error detector or digital error signal interface.
	1	R/W	"1": Enable SOP tracking
341	15..0	R/W	Control gain (100 by default)
342	0	R/W	Error signal minimization ("0") or maximization ("1"). Maximization is only recommended for checking the error signal range, not for enduring control
343	3..0	R/W	Averaging time exponent (ATE). Although function is more complicated than this one may define an equivalent averaging time which is roughly $80 \text{ ns} * 2^{\text{ATE}}$. Fundamental control speed changes like $1 / (80 \text{ ns} * 2^{\text{ATE}} + 100 \text{ ns})$. High ATE (= low control

			speed) tolerates higher time constant of error signal and is good for averaging of noisy error signal. Low ATE (= high control speed) requires low time constant of error signal. Permissible time constant of control signal is roughly $40 \text{ ns} * 2^{\text{ATE}}$. When using digital feedback interface to the PM1000, minimum ATE is 2. 0000h = least averaging, highest speed 0001h = more averaging, reduced speed ... 000Fh = most averaging ($2^{000Fh} = 2^{15}$), lowest speed
344	12..0	R/W	Error signal delay (deadtime, risetime), given as multiples of 20 ns. Default value for digital feedback interface to PM1000 is 41.
345	2..0	R/W	Dither amplitude. Small dither is recommended if error signal is of good quality. Large dither is needed if error signal is noisy. Register determines percentage of nominal dither amplitude. Default value is 0002h = 50%. 0000h = 0% 0001h = 25% 0002h = 50% 0003h = 75% 0004h = 100% 0005h = 125% 0006h = 150% 0007h = 175%
346	3..0	R/W	Strength with which voltages are pulled back to zero during tracking. Default = 1. Tracking fast, endless trajectories may require higher values.

- (1) The HWP speed index I (32 bit integer) is calculated from the nominal HWP scrambling speed SHWP (in krad/s) by $I = \text{round}(\text{SHWP} \cdot 100)$.
- (2) The QWP speed index I (32 bit integer) is calculated from the nominal QWP scrambling speed SQWP (in rad/s) by $I = \text{round}(\text{SQWP} \cdot 100)$.
- (3) The optical frequency index I is calculated from the optical frequency F (in THz) by $I = \text{round}(F \cdot 10 \cdot 1828)$.
- (4) The position index I is calculated from Position P (in degrees) by $I = \text{round}(P \cdot 65536 / 360)$.
- (5) Only applicable since firmware 1.0.2.0
- (6) Only applicable since firmware 1.0.6.0
- (7) Only applicable since firmware 1.0.8.1
- (8) Only applicable since firmware 1.2.0.7. In older firmwares the individual WP speeds must be set. To find possible settings, activate Peaked or Rayleigh distribution in the GUI, set a target speed and read individual WP speeds and rotation directions.

Table memory

The table memory registers are described for firmware $\geq 1.1.0.0$. For earlier firmware versions please refer to User Guide rev. 0.1.6.

The first two vectors of a table define the dwell time of the table entry:

Vector	Meaning
--------	---------

00	Table dwell time in multiples of 40 ns, minus 1, Bits 15..0
01	Table dwell time in multiples of 40 ns, minus 1, Bits 31..16

For a dwell time of 200 ns, a value of 4 must be written into Vector 00, since $(4+1)*40\text{ns}=200\text{ns}$.

The meaning of all other vectors depend on the table mode:

Waveplate positions:

The waveplate positions are given in integer numbers between 0 and $2^{16}-1$, where 2^{16} means a full revolution.

02	Position of HWP
03	Position of QWP0
04	Position of QWP1
05	Position of QWP2
06	Position of QWP3
07	Position of QWP4
08	Position of QWP5
09..17	reserved

Waveplate nominal scrambling speeds:

The nominal scrambling speeds are given in rad/s/100 for the quarterwave plates and in krad/s/100 for the halfwave plate.

02	HWP nominal scrambling speed Bits 15..0
03	Bits 4..0: HWP nominal scrambling speed Bits 20..16 Bit 14: Enable (1) or disable (0) HWP rotation Bit 15: HWP rotation direction backward (1) or forward (0)
04	QWP0 nominal scrambling speed Bits 15..0
05	Bits 10..0: QWP0 nominal scrambling speed Bits 26..16 Bit 14: Enable (1) or disable (0) QWP0 rotation Bit 15: QWP0 rotation direction backward (1) or forward (0)
...	...
14	QWP5 nominal scrambling speed Bits 15..0
15	Bits 10..0: QWP5 nominal scrambling speed Bits 26..16 Bit 14: Enable (1) or disable (0) QWP5 rotation Bit 15: QWP5 rotation direction backward (1) or forward (0)
16..17	reserved

Electrode voltages:

The 16 electrode voltages (8 sections, 2 voltages per section) are given as integer number between $2^{15}-6000$ and $2^{15}+6000$.

02	Voltage 1 of section 1
03	Voltage 2 of section 1
04	Voltage 1 of section 2
05	Voltage 2 of section 2
...	...
16	Voltage 1 of section 8

17	Voltage 2 of section 8
----	------------------------

Firmware upgrade

Via the JTAG port the user can upgrade the firmware, if ever needed. Note that the upgrading firmware must be obtained from Novoptel on a per-module basis because the firmware is encrypted and authenticated.

The schematic and timing of the JTAG port correspond to that detailed in Spartan-3 Generation Configuration User Guide UG332 (v1.6) October 26, 2009 from Xilinx (www.xilinx.com).

Synchronous/Triggered Waveplate Rotation

In normal scrambling mode, waveplates are rotated continuously. Quasi-steady polarization changes are thereby achieved. For some applications, the polarization should be fixed for a defined time interval to allow accurate SOP sampling within it. This can be done with the synchronous/triggered waveplate rotation function: The waveplates will be kept rotating internally, but the corresponding electrode voltages will be updated only upon a trigger event.

Trigger Source

Several different trigger sources are available:

Manual: Trigger events can be manually released by pushing the *Manual Trigger* button.

Internal: The scrambler is triggered by an internal clock. The *Internal Trigger Period* can be adjusted in multiples of 40 ns. Minimum *Internal Trigger Period* is 200 ns

ATE: Internal trigger synchronous to the averaging time of the optional photodetector. The trigger event will be launched every $80 \text{ ns} \cdot 2^{\text{MEMATE}}$.

External: Triggering by a LVCMOS33 (0 V / +3.3 V) signal that is applied to the BNC connector at the rear panel of the device.

Continuous: Only applicable for synchronous/triggered table execution: The scrambling table is executed continuously.

The internal triggers can optionally be fed out to the BNC connector at the rear panel of the device if the box *Trigger (OUT) BNC* is activated.

Fig. 3: “Synchronous/Triggered Scrambling” tab

Synchronous/Triggered Table Execution

The scrambler can put all waveplates to specified positions or even put all electrode voltages to specified values which are stored in a table. Each row of the table contains the positions of the 7 waveplates, followed by the 16 corresponding electrode voltages and a dwell time (= subsequent delay) in nanoseconds. The dwell time must be a multiple of 40 ns. Minimum dwell time is 200 ns.

Tables can be created using the GUI. They can be stored to and loaded from a file. This way, tables can also be generated by an external program and, afterwards, loaded into the scrambler. For a better understanding of the corresponding registers, please also refer to Application Note 2.

Since firmware 1.1.0.0 of the scrambler, three separate table modes exist for waveplate positions, nominal scrambling speeds and electrode voltages. The first row of a text file defines the table mode using the syntax *table_mode='mode'*, where *'mode'* is one of *'position'*, *'speed'* and *'voltage'*.

In the positions table, the positions of the 7 waveplates are given as integer numbers between 0 and $2^{16}-1$, followed by the dwell time as described above. In the speeds table, the first 7 numbers define the status (on/off, Bit 0) and the direction (forward/backward, Bit 1) of the waveplates, followed by the 7 nominal scrambling speeds and the dwell time. The nominal scrambling speeds are given in rad/s/100 for the quarterwave plates and in krad/s/100 for the halfwave plate. In the voltages table, the 16 electrode voltages are given as integer number between $2^{15}-6000$ and $2^{15}+6000$, followed by the dwell time.

The trigger sources are the same as described in the previous section “Synchronous/Triggered Waveplate Rotation”. There are two basic trigger modes, row or table:

Row Trigger Mode

In row trigger mode, the rows of the stored table are executed one-by-one upon a trigger event. After the last table row, the counter starts over from the first table row.

Table Trigger Mode

In table trigger mode, the scrambler starts over from the first table entry upon every trigger. Subsequent rows are executed after the dwell time delay specified in each row. After the last table row, the row counter is halted until the next trigger event occurs.

In *Row Trigger Mode* the *Internal Trigger Period* must be chosen at least as long as the longest *Dwell Time*. In *Table Trigger Mode* the *Internal Trigger Period* must be chosen at least as long as the sum of all *Dwell Times*.

Table Mask

With the table mask, selected waveplates can be excluded from the table execution. The mask is given as an integer number that represents a 7 Bit vector. The most significant bit corresponds to the first waveplate (QWP0) and so on. Position and nominal scrambling speeds of waveplates excluded from table execution can be used as in normal operation mode.

External electrode voltage allocation

Since firmware 1.0.2.0 (release 15.04.2013), the EPS1000 allows external allocation of the 16 LiNbO₃ electrode voltages via USB, LAN or SPI. This increases flexibility when searching for a defined polarization state: 16 instead of 7 degrees of freedom are thereby provided. The external voltage setting overwrites any nominal speed or position setting of the corresponding waveplate when writing to one of the registers 50 to 65, see register description. The voltage value is given as an unsigned integer with an offset of 8192. Positive integers generate positive voltages. The register value is limited to 8192 ± 6000 , referring to a voltage range from -48V to +48V. In the GUI, the offset is not shown.

The screenshot shows the 'Voltage Control' tab of the EPS1000 GUI. At the top, there are five tabs: 'Rotation Control', 'Position Control', 'Voltage Control' (selected), 'Synchronous/Triggered Scrambling', and 'PDL Meas.'. Below the tabs, there is a 'Step size' input field set to '10'. The main area contains 16 rows of controls for electrode voltages, labeled U01 through U72. Each row consists of a text label (e.g., 'U01:'), an input field (containing '0'), a label '(-6000)', a 'Set' button, and two buttons labeled '-' and '+'. The rows are arranged in two columns: U01-U51 on the left and U02-U72 on the right.

Fig. 4: Allocation of registers corresponding to 16 electrode voltages.

The given value is written into the digital-to-analog converter (DAC) directly after it appears in the register. When using SPI, the delay between the last SPI command bit and the internal DAC complete output flag is <100 ns. Initial electrooptic response is typically obtained in <100 ns more.

PDL measurement

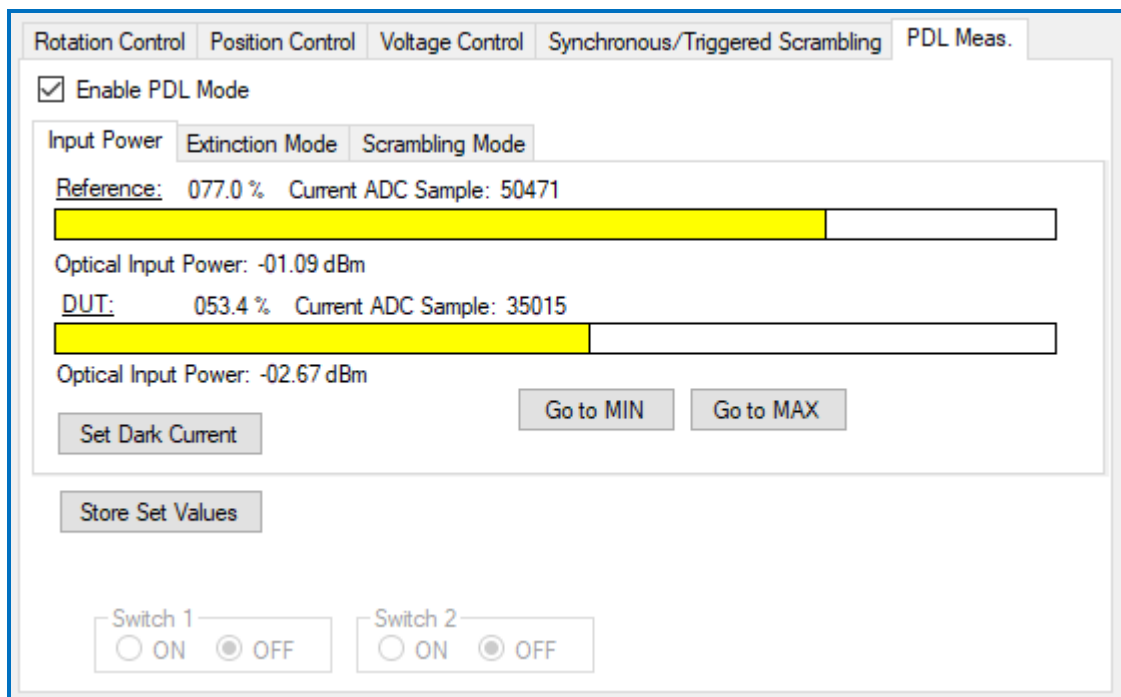
Polarization-dependent loss (PDL) can be measured by Mueller matrix evaluation with Novoptel's polarimeter PM1000 and the EPS1000. In contrast, **non-polarimetric** methods for PDL (and loss) measurement are covered here.

We recommend

- either the **extinction method**, i.e. the searching of polarizations with maximum and minimum transmission,
- or the **scrambling method**. This requires a sequence of polarizations states, whose correlation matrix of normalized Stokes vectors is 1/3 times the identity matrix. Such a sequence is applied to the device under test (DUT) and the output power P is measured for each applied polarization state. Maximum and minimum output power are given by $\langle P \rangle \pm \sqrt{3}\sigma_P$. The PDL in dB is given by $10\log_{10}\left(\frac{\langle P \rangle + \sqrt{3}\sigma_P}{\langle P \rangle - \sqrt{3}\sigma_P}\right)$. Here $\langle P \rangle$ is the mean output power and σ_P is the standard deviation of P . Examples for suitable polarization state sequences are the corners of diamond, cube and other polyhedrons, or simply equidistributed polarizations. The latter will automatically be applied and analyzed when using the *Scrambling Mode* of the PDL measurement feature.

PDL measurement with the GUI

Only if the EPS1000 is equipped with one or two photodetectors, the tab *PDL Meas.* will appear in GUI.



When the *Enable PDL Mode* checkbox is checked, an internal optical switch switches the light path from the EPS1000 scrambling output to an internal 3 dB coupler. The first output of the coupler serves as internal reference path, connected to the reference detector. The second output of the coupler and the input of the DUT detector are fed to the instrument's front, for the user to place his DUTs for PDL measurements there.

Two bars are shown in the *Input Power* tab of the GUI, corresponding to the optical powers detected in the reference path and in the DUT path. Optical power at the input of the EPS1000 can be adjusted according to the displayed power of the reference path (low values decrease accuracy).

Recalibration of the photodetector's dark currents can improve measurement accuracy, especially at high PDL. This can be done by the button *Set Dark Current*. To store the new dark current values permanently, click the button *Store Set Values*.

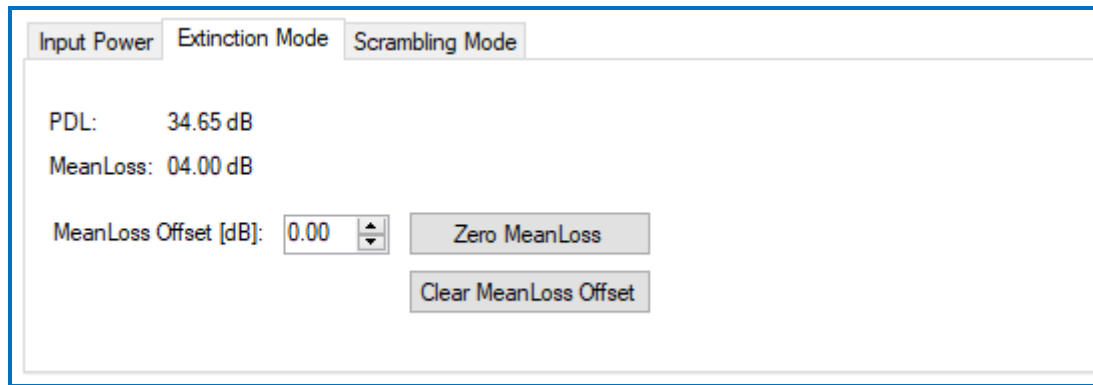
If the user clicks *Go to MIN* or *Go to MAX*, the EPS1000 will perform a gradient step algorithm to adjust the SOP to minimum or maximum transmission through the DUT. The search takes less than 50 ms. After the search, the algorithm will stop.

The EPS1000 can optionally be equipped with one or more open-drain outputs. This way a load can be switched that is connected between output and the +5V terminal (or an external supply, up to +26 V). Namely, an external optical switch could select DUT vs. reference measurement by clicking on ON and OFF in one of the fields *Switch 1* and *Switch 2* in the figure above. If the EPS1000 is not equipped with such output(s), the corresponding fields are disabled.

PDL measurement with the extinction method

When the *Extinction Mode* tab is active, the EPS1000 will measure the powers in the DUT channel after alternately adjusting the SOP to minimum and maximum transmission. The difference of the two powers is displayed as PDL value in dB. Any PDL of the EPS1000 is compensated by simultaneous measurements in the reference path. Each search and consecutive measurement takes less than 50 ms. so that a complete PDL measurement finishes in less than 100 ms.

During the search of minimum and maximum transmission, the averaging time constant of the EPS1000 is about 5 μ s. If the optical delay of the DUT exceeds about 2 μ s, we recommend using the scrambling method instead.

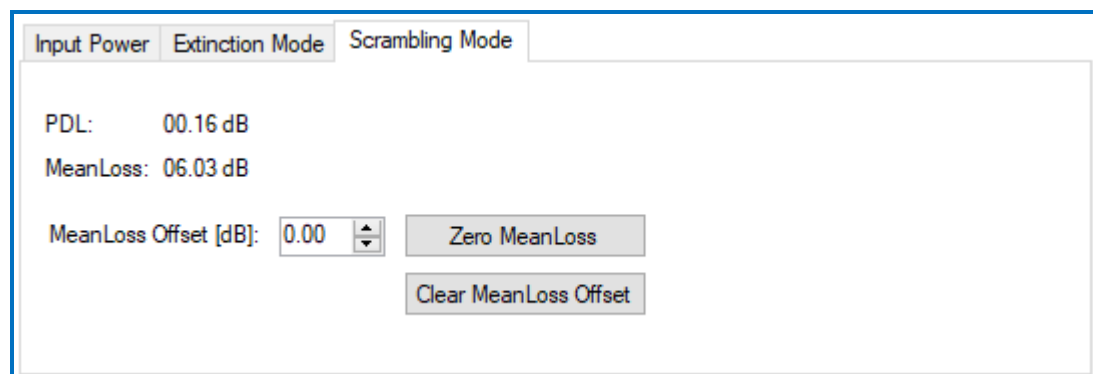


The screenshot shows the software interface with three tabs: 'Input Power', 'Extinction Mode' (which is selected), and 'Scrambling Mode'. The main display area shows 'PDL: 34.65 dB' and 'MeanLoss: 04.00 dB'. Below this, there is a 'MeanLoss Offset [dB]' field with a value of '0.00' and a small up/down arrow icon. To the right of this field are two buttons: 'Zero MeanLoss' and 'Clear MeanLoss Offset'.

From the difference of the reference and DUT measurements, mean loss is calculated. For calibration or comparison of different DUTs, the displayed mean loss value can be adjusted (by entering a value in the numerical box) or set to zero (buttons *Zero MeanLoss* and *Clear MeanLoss Offset*). The mean loss offset value can be stored permanently together with the dark currents with the button *Store Set Values*.

PDL measurement with the scrambling method

When the *Scrambling Mode* tab is active, the EPS1000 will apply equidistributed polarizations to the DUT and calculate PDL as described above.



The screenshot shows the software interface with three tabs: 'Input Power', 'Extinction Mode', and 'Scrambling Mode' (which is selected). The main display area shows 'PDL: 00.16 dB' and 'MeanLoss: 06.03 dB'. Below this, there is a 'MeanLoss Offset [dB]' field with a value of '0.00' and a small up/down arrow icon. To the right of this field are two buttons: 'Zero MeanLoss' and 'Clear MeanLoss Offset'.

The offset for the mean loss value can be adjusted the same way as in the *Extinction Mode*.

PDL measurement with the front control panel

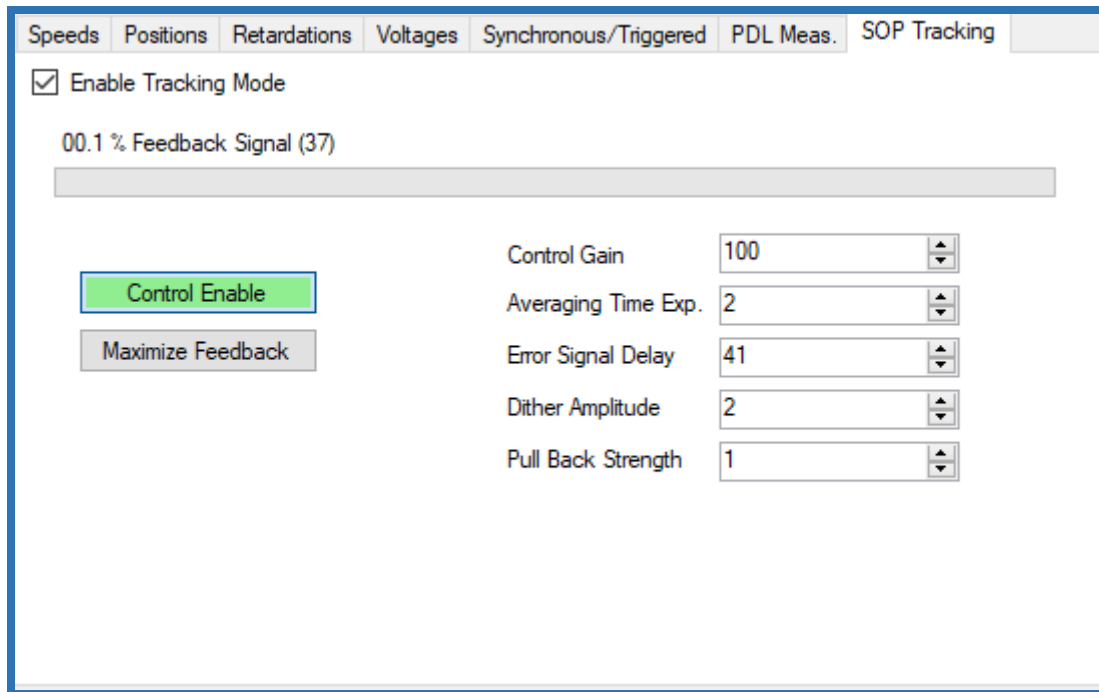
If the optional photodetectors are present, the front control panel allows switching from scrambling mode into the PDL measurement mode also without using the GUI. In the PDL measurement mode, the menu structure is

Scrambling/PDL mode
Input power
PDL (extinction method)
Min./Max. selection
PDL (scrambling method)
Set dark current
Zero mean loss
Save Configuration

The functions of the front control menu are equivalent to the functions in the GUI. In the menu point *Input power*, only the optical power in the reference path is displayed.

SOP tracking

The EPS1000 can optionally be equipped with an error detector or digital error feedback interface to a polarimeter PM1000 that allow polarization tracking. In this case, the “SOP tracking” tab of the GUI allows enabling the tracking mode of the EPS1000.



Control parameters can be set according to the description of registers 340 to 346.

Important: When using the digital feedback interface between EPS1000 and PM1000 it must be ensured that ATE of PM1000 exceeds ATE of EPS1000 only by a maximum of 1. For example, if ATE of EPS1000 is 2, ATE of PM1000 must be ≤ 3 .