Pathfinder Update

Krzysztof Turza

1st SIG-TFN meeting
Amsterdam, Netherlands
16-17.10.2024

61-139 Poznan
ul. Jana Pawła II 10
phone: (+48 61) 858-20-01
fax: (+48 61) 852-59-54
office@man.poznan.pl
www.psnc.pl

Pathfinder - Deployment and First Results

Agenda

- Brief Recap
- General Overview
- Multiple Signals in Single Fiber
- Transmission Equipment
- First Result
- Installation Tips

Brief Recap

OFTEN		OTFN
November 2023 Public Tender Announcement		**NOW** ...nk testing ...ning experience

... Pan Eu...

Geographical Overview

2 dark fibres

Overall fibre length:

~690 km

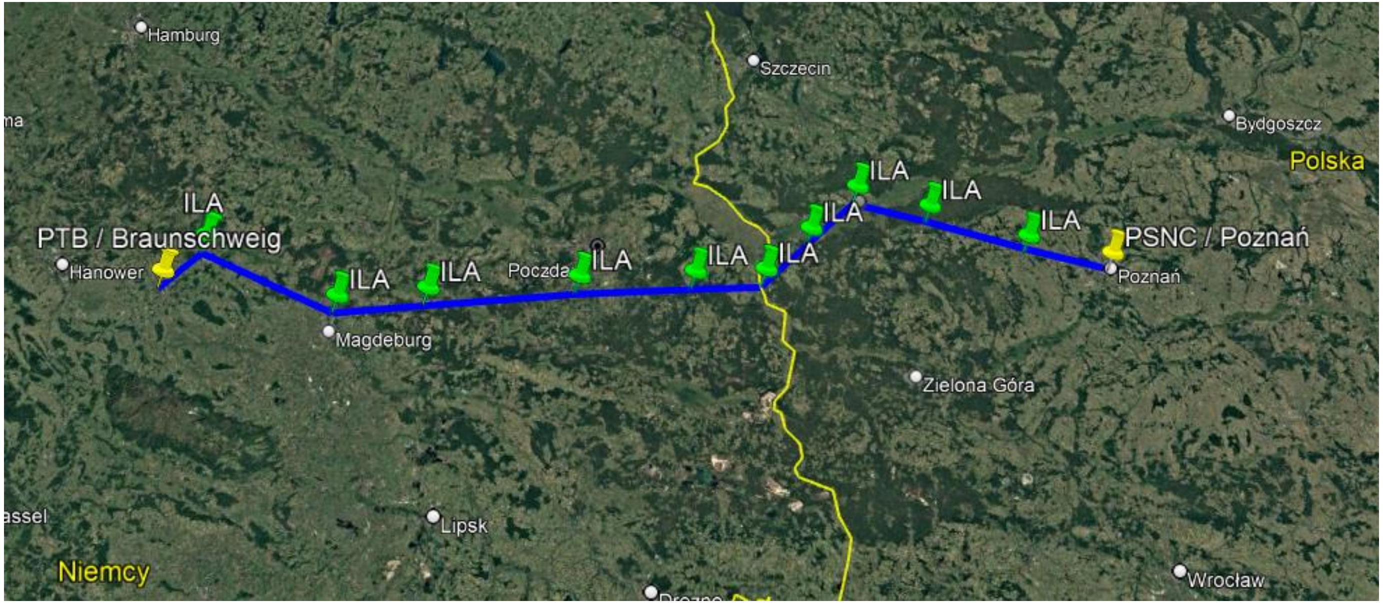
(270 km in Poland; Pionier/PSNC)
(420 km in Germany; Geant)

10 ILA points

(5 in Poland)
(5 in Germany)

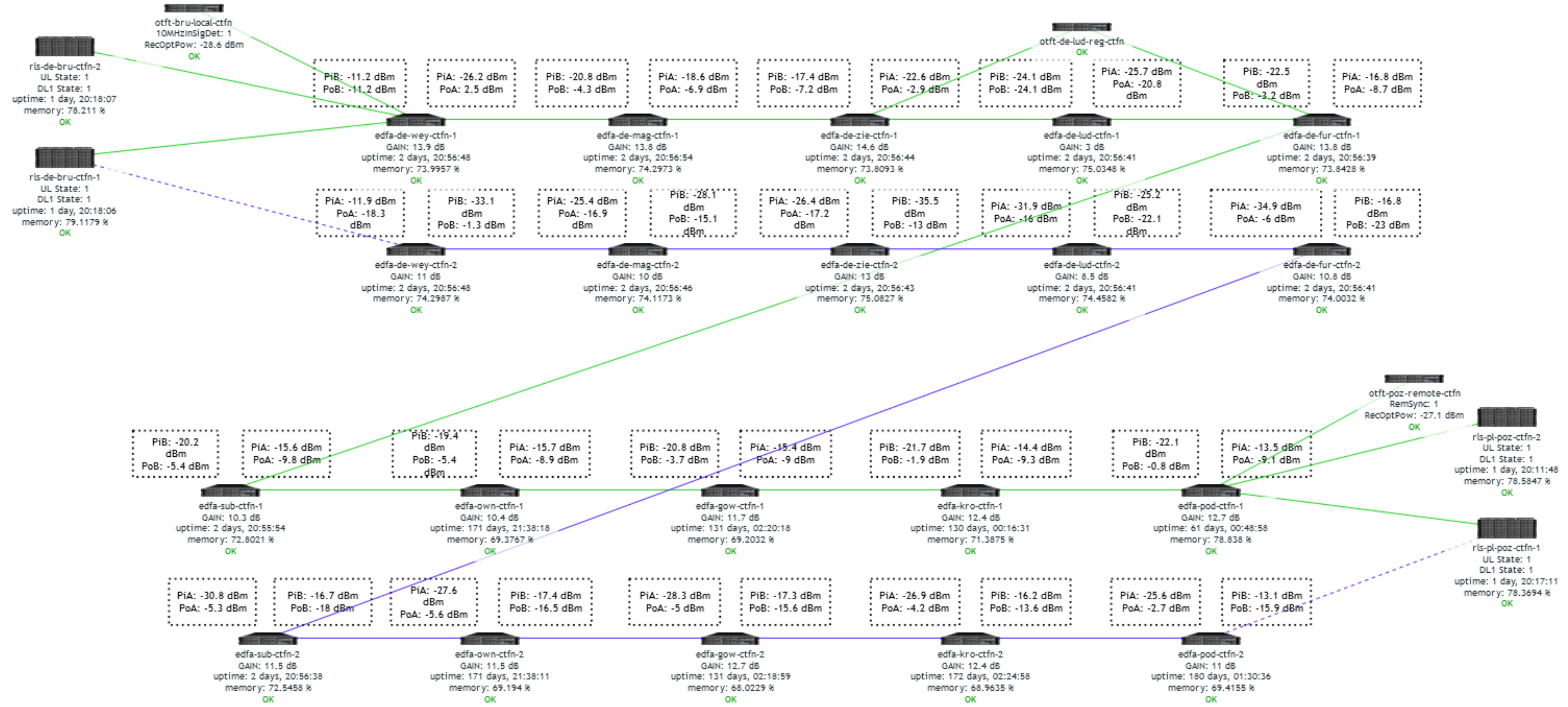
The longest section between ILAs:

106,7 km / 22,6 dB

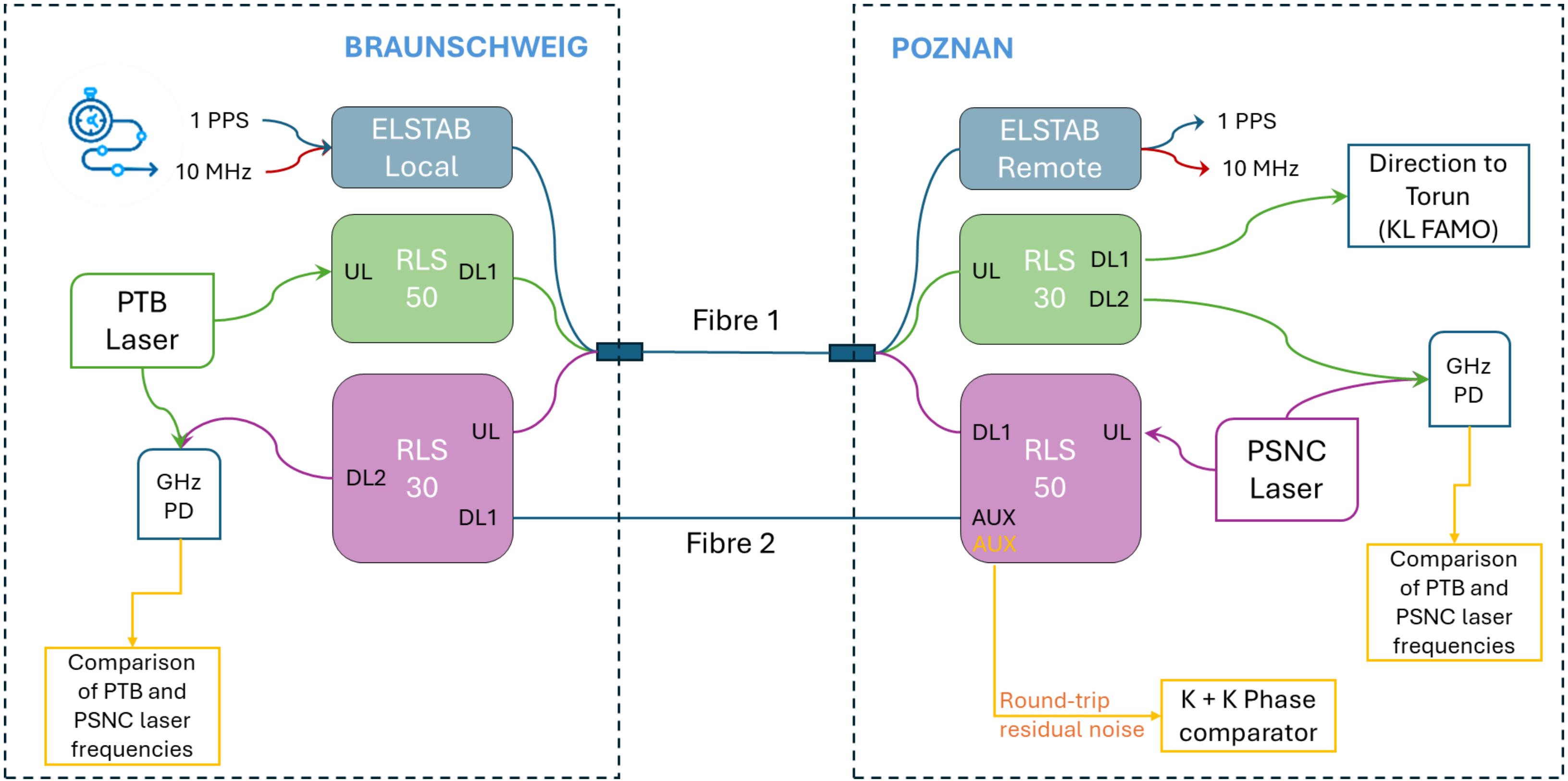


Monitoring Snapshot

C-TFN pathfinder PTB-PSNC



Three signals in a single fiber (2 x OC, T&RF)



Multiple signals in a single fiber? How is this possible? (1)

A. Wavelength Division Multiplexing (CWDM/DWDM)

- The method very well known for many years.
  Individual signals can be demuliplexed (separated) with appropriate filters.

- In pathfinder, WDM is used to separate management channels from T/F signals (CWDM method, at each node) and ELSTAB system signals from OC signals (at the ends of the link).
- No negative effect was observed when ELSTAB and OC signals are separated by only 100 GHz of the optical spectrum

- From a practical point of view, the easiest option is to buy filters with a 100 GHz grid (or wider: 400 GHz, 800 GHz).
- Transmitted signals would allow using a 50 GHz or even 25 GHz grid separation. However, the purchase of such filters is VERY expensive - there is no economic justification.

Multiple signals in a single fiber? How is this possible? (2)

B. Optical spectrum scanning

- We assume that the OC signals are so close to each other that separating them with optical filters is not technically feasible (at a distance closer than the width of a single WDM channel).
- Adjusting to the appropriate optical frequency (locking the local laser to the remote one) is done by scanning the optical spectrum (analogous to radio).
- Is this something new? NO, but there are some challenges:
  - How to lock to the correct OC signal?
  - How to do it automatically, without human intervention?
  - How not to interrupt the already operational transmissions during the scanning process?

… How to do it right without additional problems?
The answer how it was done in pathfinder on the next slides

Two OC signals in a single channel #44

How is this solved in pathfinder link?

- The RLS's used in the pathfinder (manufactured by PSNC) allow the scanning bandwidth to be narrowed down and center to a selected optical spectrum in software. This makes it possible to lock to a selected OC signal without causing interference to other signals.

- In the current hardware configuration, the safe optical distance between OC signals should be >2GHz.
  In Pathfinder, this is currently ~2.4GHz.

- In the future, it will be possible to reduce this distance to a few hundred MHz. However, this requires to develope additional hardware and software features to guarantee security/continuity of transmission.

Pathfinder Equipment – RLS [(1)]

PSNC's Laser Station (RLS)

NOTE: terminology is not equivalent to Exail's solution.

- Dedicated to building connections in a tree topology
- The UL (UpLink) port is used to connect to a reference signal (reference laser) or a previous RLS station (n-1)
- The UL port is equipped with a polarization controller that maintains the optimal polarity of the input signal continuously (no dead time for polarization correction, no interruptions in transmission)
- Automatic signal relocking after beatnote loss
- Software selection of the scanning range and center frequency of the internal laser

Pathfinder Equipment – RLS (2)

PSNC's Laser Station (RLS)

NOTE: terminology is not equivalent to Exail's solution.

- The 3 DL (Down Links) ports allow flexible configuration according to user needs. They can be used for:
  - connecting by a stabilized link to another RLS station (n+1),
  - a stabilized link to a remote end terminal,
  - local unstabilized or stabilized connection using the internal interferometer and external stabilization system (OUT and PD ports available).
  - a return connection to the RLS (n-1) station for monitoring residual phase changes in the fiber.
- Noise monitoring with Low and High Frequency Noise separation (helpful in optimizing EDAFs' Gains).
  It is possible to automatically search for optimal gains based on LF and HF - an algorithm developed and described by the AGH team:
  https://opg.optica.org/oe/fulltext.cfm?uri=oe-31-8-12083&id=528573

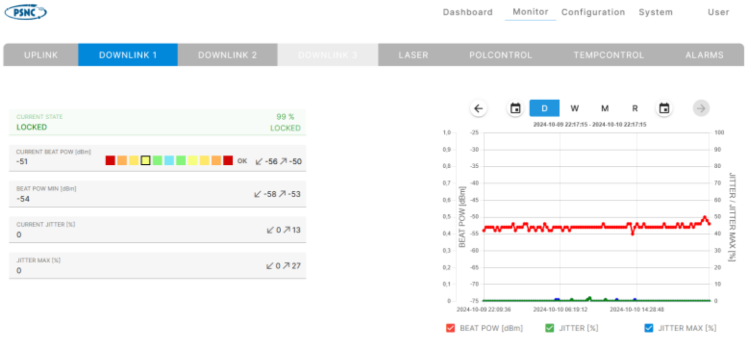
AGH

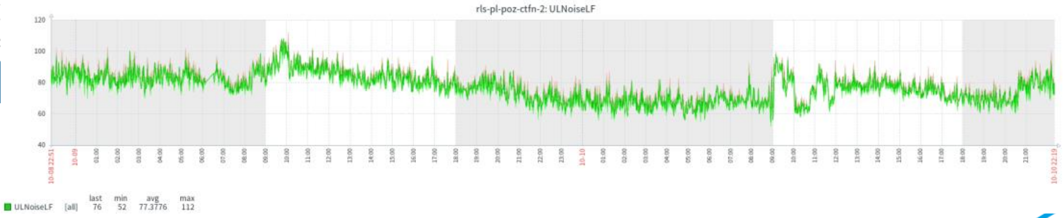
PSNC

Pathfinder Equipment – RLS [(3)]

PSNC's Laser Station (RLS)

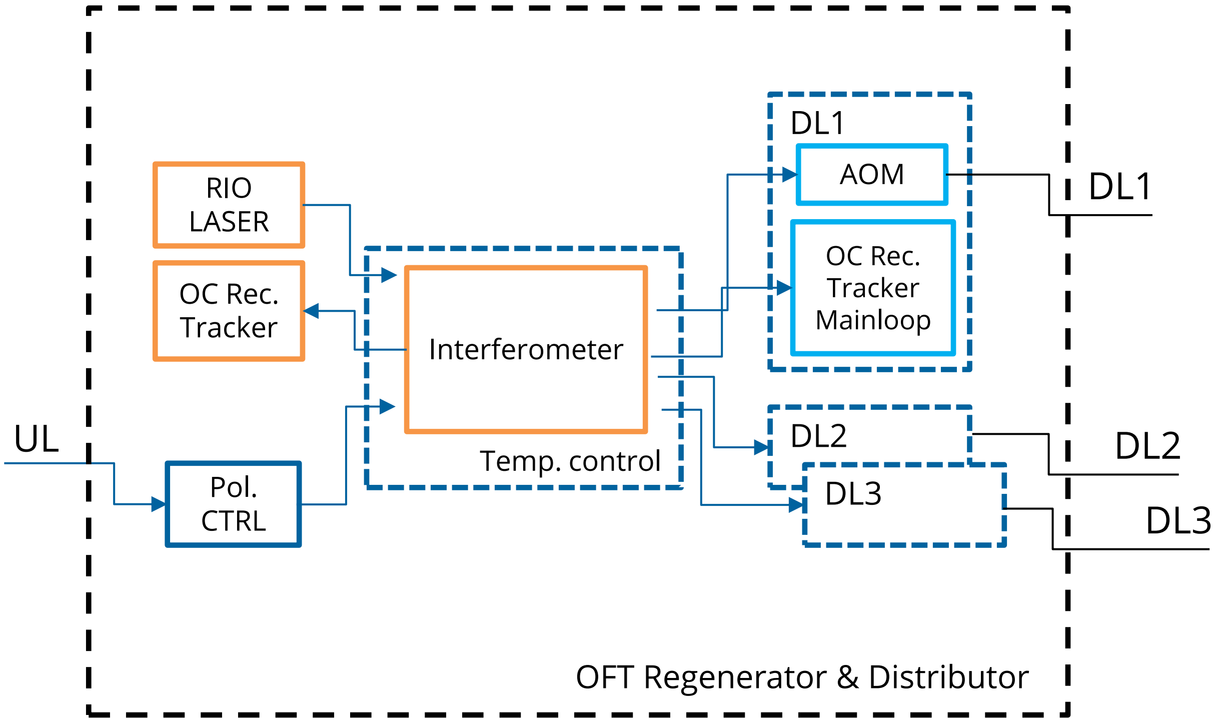
Management system: SNMP, WEB-gui, CLI





Pathfinder Equipment – RLS (4)

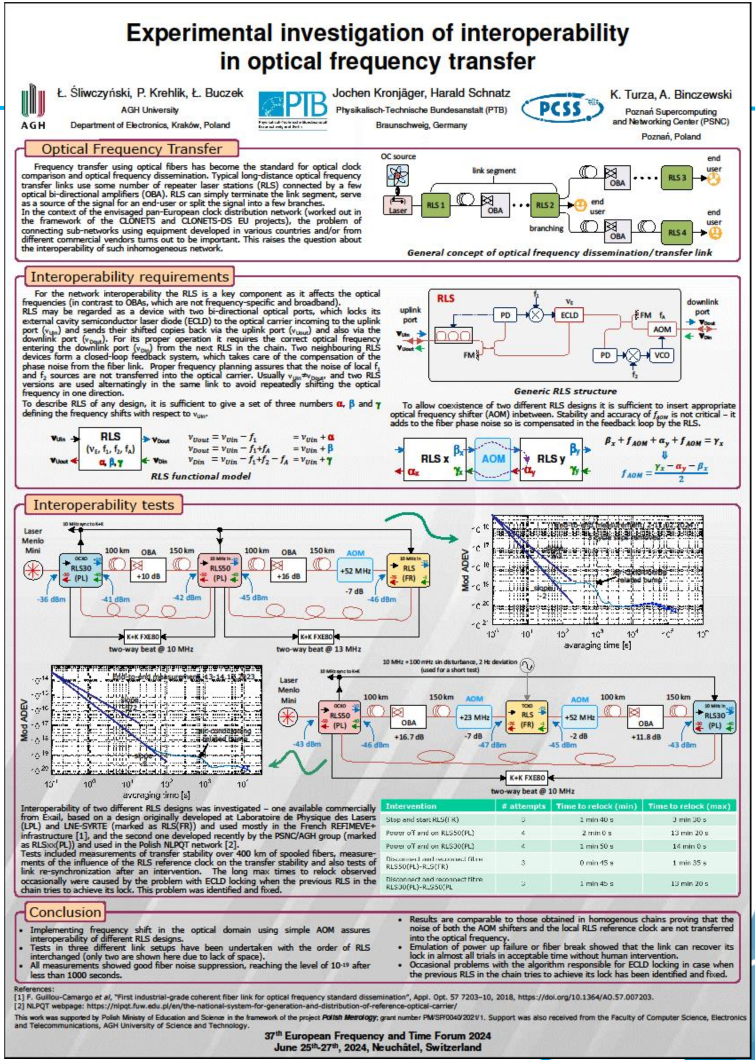
PSNC's Laser Station (RLS)



Pathfinder Equipment – RLS (4)

RLS Compatibility

Interoperability of Exail's RLSs and those used in the pathfinder link (developed by the PSNC/AGH group) was presented at the recent EFTF.


Experimental investigation of interoperability in optical frequency transfer

Ł. Śliwczyński, P. Krehlik, Ł. Buczek
AGH University
Department of Electronics, Kraków, Poland
Jochen Kronjäger, Harald Schnatz
Physikalisch-Technische Bundesanstalt (PTB)
Braunschweig, Germany
K. Turza, A. Binczewski
Poznań Supercomputing and Networking Center (PSNC)
Poznań, Poland

Optical Frequency Transfer

Frequency transfer using optical fibers has become the standard for optical clock comparison and optical frequency dissemination. Typical long-distance optical frequency transfer links use some number of repeater laser stations (RLS) connected by a few optical bi-directional amplifiers (OBA). RLS can simply terminate the link segment, serve as a source of the signal for an end-user or split the signal into a few branches.
In the context of the envisaged pan-European clock distribution network (worked out in the framework of the CLONETS and CLONETS-DS EU projects), the problem of connecting sub-networks using equipment developed in various countries and/or from different commercial vendors turns out to be important. This raises the question about the interoperability of such inhomogeneous network.

General concept of optical frequency dissemination/transfer link

Interoperability requirements

For the network interoperability the RLS is a key component as it affects the optical frequencies (in contrast to OBAs, which are not frequency-specific and broadband). RLS may be regarded as a device with two bi-directional optical ports, which locks its external cavity semiconductor laser diode (ECLD) to the optical carrier incoming to the uplink port (ν_{Uin}) and sends their shifted copies back via the uplink port (ν_{Uout}) and also via the downlink port (ν_{Dout}). For its proper operation it requires the correct optical frequency entering the downlink port (ν_{Din}) from the next RLS in the chain. Two neighbouring RLS devices form a closed-loop feedback system, which takes care of the compensation of the phase noise from the fiber link. Proper frequency planning assures that the noise of local f_1 and f_2 sources are not transferred into the optical carrier. Usually $\nu_{Uin} \neq \nu_{Dout}$, and two RLS versions are used alternatingly in the same link to avoid repeatedly shifting the optical frequency in one direction.
To describe RLS of any design, it is sufficient to give a set of three numbers α, β and γ defining the frequency shifts with respect to ν_{Uin}.

Generic RLS structure

To allow coexistence of two different RLS designs it is sufficient to insert appropriate optical frequency shifter (AOM) inbetween. Stability and accuracy of f_{AOM} is not critical – it adds to the fiber phase noise so is compensated in the feedback loop by the RLS.

$\nu_{Uout} = \nu_{Uin} - f_1 = \nu_{Uin} + \alpha$
$\nu_{Dout} = \nu_{Uin} - f_1 + f_A = \nu_{Uin} + \beta$
$\nu_{Din} = \nu_{Uin} - f_1 + f_2 - f_A = \nu_{Uin} + \gamma$

RLS functional model

$\beta_x + f_{AOM} + \alpha_y + f_{AOM} = \gamma_x$

$f_{AOM} = \frac{\gamma_x - \alpha_y - \beta_x}{2}$

Interoperability tests

Interoperability of two different RLS designs was investigated – one available commercially from Exail, based on a design originally developed at Laboratoire de Physique des Lasers (LPL) and LNE-SYRTE (marked mostly in the French REFIMEVE+ infrastructure [1], and the second one developed recently by the PSNC/AGH group (marked as RLSxx(PL)) and used in the Polish NLPQT network [2].
Tests included measurements of transfer stability over 400 km of spooled fibers, measurements of the influence of the RLS reference clock on the transfer stability and also tests of link re-synchronization after an intervention. The long max times to relock observed occasionally were caused by the problem with ECLD locking when the previous RLS in the chain tries to achieve its lock. This problem was identified and fixed.

Intervention	# attempts	Time to relock (min)	Time to relock (max)
Stop and start RLS(FR)	3	1 min 40 s	3 min 30 s
Power off and on RLS50(PL)	4	2 min 0 s	13 min 20 s
Power off and on RLS30(PL)	4	1 min 50 s	14 min 0 s
Disconnect and reconnect fibre RLS50(PL)-RLS(FR)	3	0 min 45 s	1 min 35 s
Disconnect and reconnect fibre RLS30(PL)-RLS50(PL)	3	1 min 45 s	13 min 20 s

Conclusion

- Implementing frequency shift in the optical domain using simple AOM assures interoperability of different RLS designs.
- Tests in three different link setups have been undertaken with the order of RLS interchanged (only two are shown here due to lack of space).
- All measurements showed good fiber noise suppression, reaching the level of 10^{-19} after less than 1000 seconds.
- Results are comparable to those obtained in homogenous chains proving that the noise of both the AOM shifters and the local RLS reference clock are not transferred into the optical frequency.
- Emulation of power up failure or fiber break showed that the link can recover its lock in almost all trials in acceptable time without human intervention.
- Occasional problems with the algorithm responsible for ECLD locking in case when the previous RLS in the chain tries to achieve its lock has been identified and fixed.

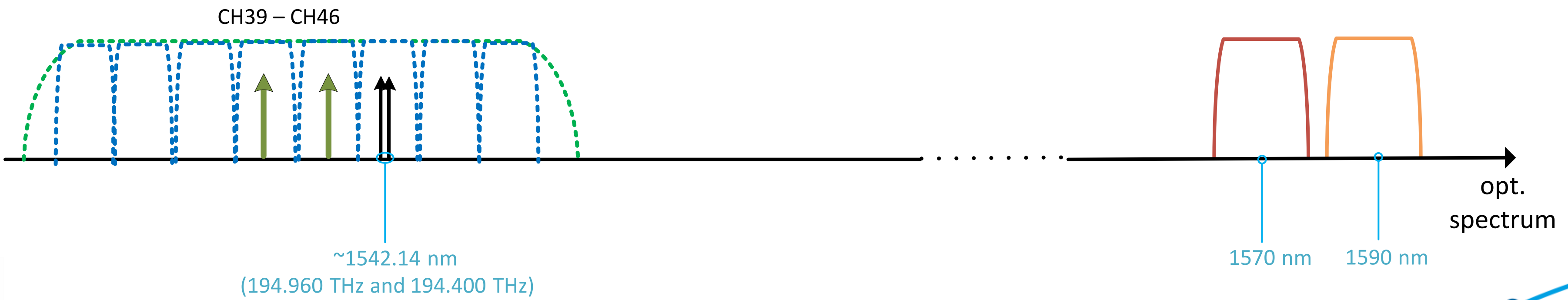
References:
[1] F. Guillou-Camargo et al, "First industrial-grade coherent fiber link for optical frequency standard dissemination", Appl. Opt. 57 7203–10, 2018, https://doi.org/10.1364/AO.57.007203.
[2] NLPQT webpage: https://nlpqt.fuw.edu.pl/en/the-national-system-for-generation-and-distribution-of-reference-optical-carrier/

This work was supported by Polish Ministry of Education and Science in the framework of the project Polish Metrology, grant number PM/SP/0040/2021/1. Support was also received from the Faculty of Computer Science, Electronics and Telecommunications, AGH University of Science and Technology.

37th European Frequency and Time Forum 2024
June 25th-27th, 2024, Neuchâtel, Switzerland

Pathfinder Equipment – bidirectional EDFA (1)

Optical Spectrum



Pathfinder Equipment – bidirectional EDFA (2)

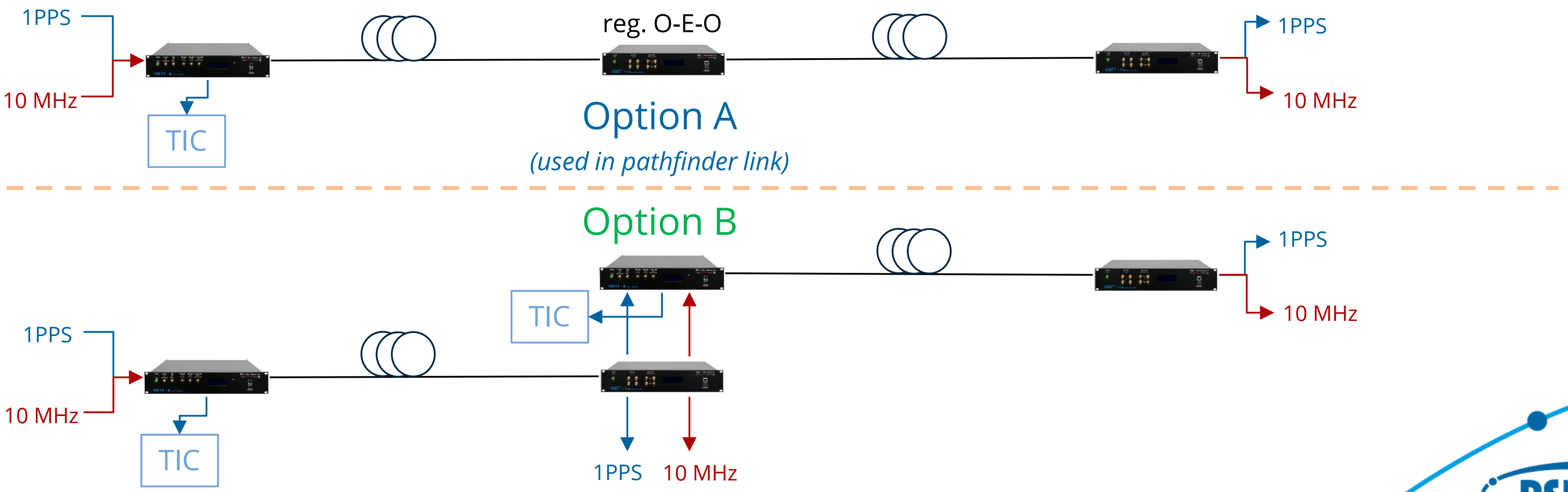
Technical Description

- EDFA bi-directional amplifier
  - Amplifier operating spectrum limited to eight channels (8skip0 filter). In pathfider channels from #39 to #46).
  - Gain range up to 24 dB
  - True gain (not pump power) control (also for non-modulated signals - e.g. OC) - gain is independent on power and/or number on signals launched
- Management
  - Management SNMP, WEB-gui, CLI
  - Management „in fibre" is implemented using a pair of CWDM channels in the L-band 1570/1590 nm (1Gbps).
  - Commercial Layer 3 switch is built into the amplifier (simple routing protocols can be configured). Management of the switch is independent of the rest of the amplifier.

Pathfinder Equipment – ELSTAB (OSTT)

Practical information

- System for distributing time (1PPS) and frequency (10 MHz).
  Well documented and commercially available.
  Frequency transfer stability: ADEV < 3×10^{-13}@1s, < 3×10^{-17}@10^5s
  https://piktime.com/offer/ostt-4/



What does the patfinder make possible?

Optical Carrier

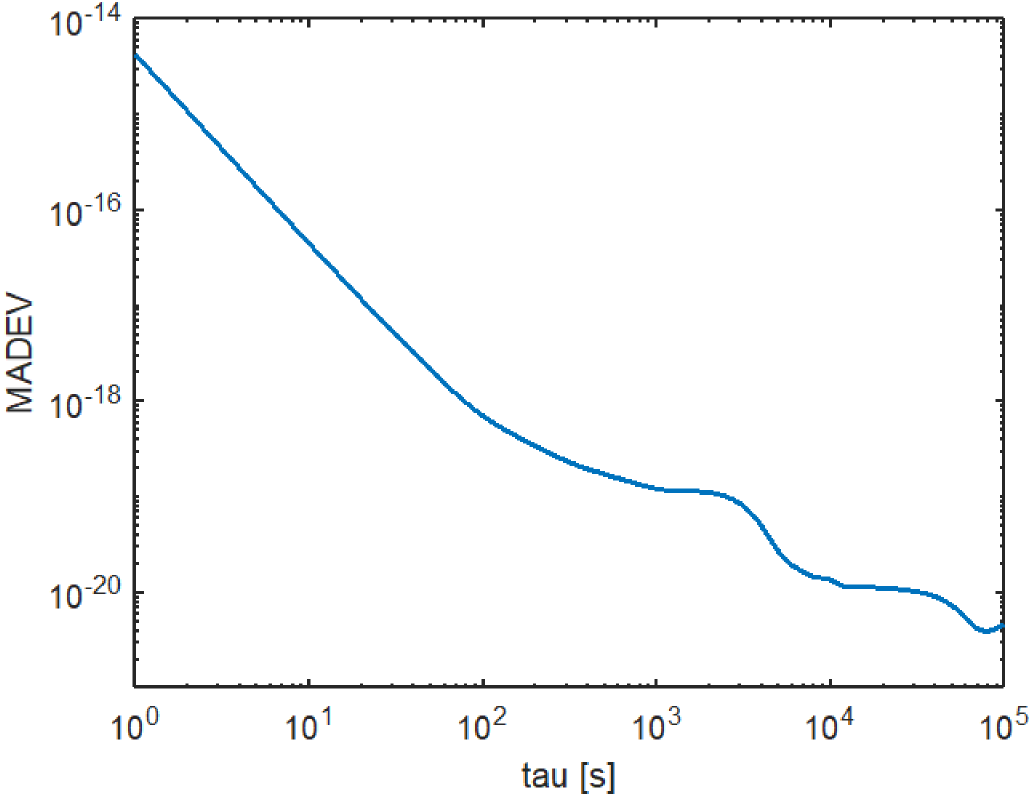
- Polish Optical Clocks (KL FAMO) added to network of European comparisons
- Possibility of international cooperation with institutions affiliated within the Polish NLPQT project

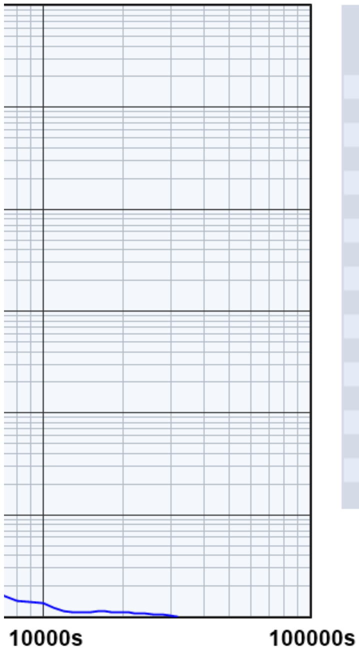
10 MHz and 1 PPS (UTC_PL)

- Link to UTC laboratories (UTC-PL, UTC-AOS)
- Signals for VLBI and LOFAR stations (3 in Poland)
- Linking Lithuania into European T/F network

Results (1)

Stability of the link PSNC->PTB->PSNC (two times 690 km)



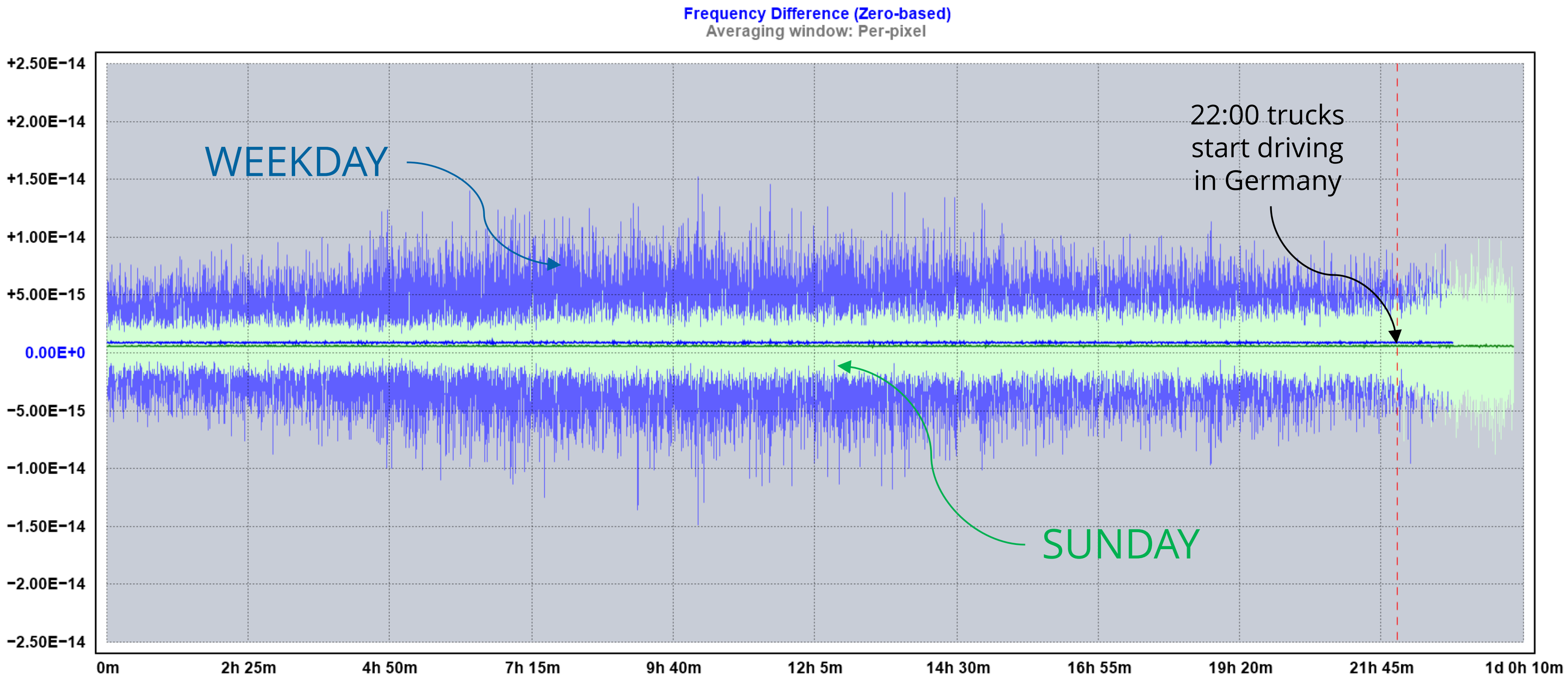


Tau	Sigma(Tau)
1s	4.26E-15
2s	1.08E-15
4s	2.72E-16
8s	6.89E-17
10s	4.46E-17
20s	1.16E-17
40s	3.18E-18
80s	9.63E-19
100s	7.01E-19
200s	3.40E-19
400s	1.95E-19
800s	1.33E-19
1000s	1.20E-19
2000s	1.10E-19
4000s	4.97E-20
8000s	1.44E-20
10000s	1.35E-20
20000s	1.10E-20

nterval	Duration
	5d 21h 14m 51s

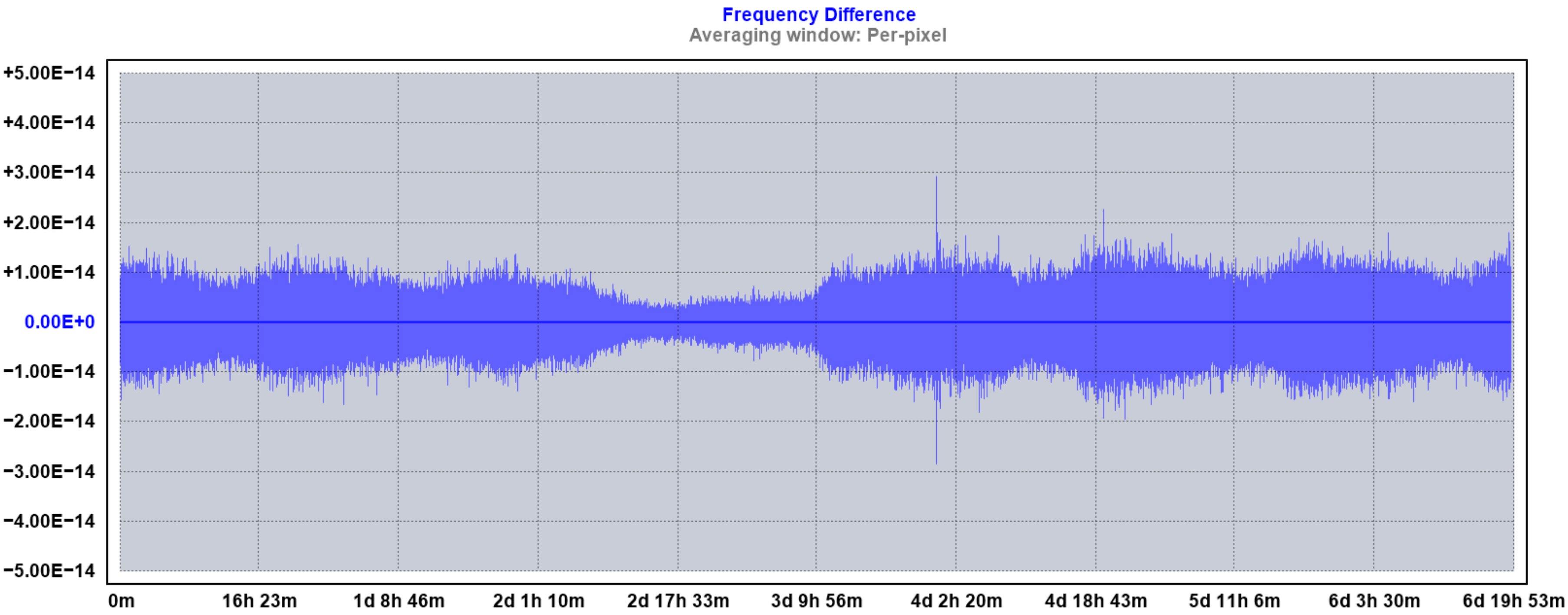
Results (2)

Noise on Sunday vs. the rest of the week



Results (3)

Noise on Sunday vs. the rest of the week



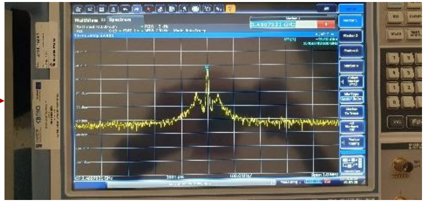
Trace	Sample Interval	Duration
PSNC -> PTB -> PSNC 10-17.10 (2 x 690 km)	1 s	6d 19h 35m 16s

Results (4)

PTB -> PSNC -> KL FAMO connection (>1000 km)

PTB laser
vs.
clean up and „flywheel" laser

PTB laser
vs.
PSNC (ORS Menlo)



Results (5)

PTB -> PSNC -> KL FAMO + clean up

Currently, the ultra-stable optical frequency signal being delivered from PTB to KL FAMO (Toruń) is used for final evaluation of cavity-stabilized lasers and clean-up systems, which is an initial step towards future comparison between German and Polish optical clocks.

Residual link noise, cavity drifts and clean-up bandwidth are being characterized and optimized.

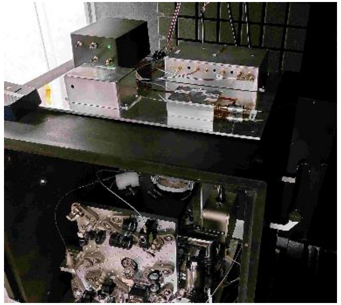
AGH

NICOLAUS COPERNICUS UNIVERSITY IN TORUŃ

Results (6)

PTB -> PSNC -> KL FAMO + clean up

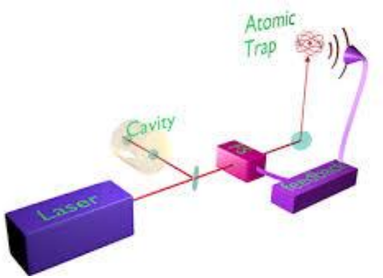
PTB



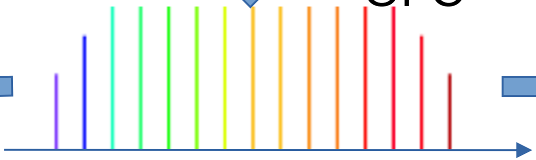
clean up laser@1542 nm

local „flywheel”
10 cm cavity @1542 nm

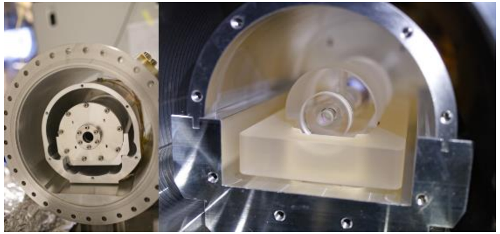
new ultra-stable lasers in construction



strontium clock line laser @698 nm



optical frequency comb for fundamental physics applications



Hg optical clock lines ultra-stable lasers @1062 and 908 nm

Installation tips (1)

What we have learned by installing pathfinder?

- Transmission of OC signals over a distance of ~700km without intermediate RLS is possible. It is also possible to transmit more than one OC signal in a single WDM channel (this has pros and cons).
- Automatic gain control is a MUST! Thanks to this, there is full freedom to turn on and off individual services. Link optimization is also MUCH simpler - correcting the gain of one amplifier does not affect the performance of the others.
- Noise monitoring in the end devices (RLSs) significantly helps optimizing amplifier gains (theoretical calculations are not always optimal). It also helps to daily link monitoring.
- Transmitting OC and Elstab signals in a single fiber requires taking into account the difference in optical budgets of ~50 dB vs ~25 dB (more demanding are Elstab or White Rabbit than „OC" systems).
- "In fiber" management strongly simplifies access to all devices.

Installation tips (2)

What we have learned by installing pathfinder?

- T/F link can be operated 24/7 (continuous OC signal polarization control needed) and can be ready to use at any time.
- Independent monitoring in the feedback link (by K+K) is useful - it shows acoustic noise caused by „human activity”, BUT problems with the comparator itself are not uncommon - note with proper interpretation of events.
- Cycleslips are rare in Pathfinder (we didn't observe any but we had a lot of problems with the comparator so we might have missed something). From a conservative standpoint, we estimate that cycleslips occur once a week.

PSNC

Poznan Supercomputing and Networking Center

61-139 Poznan
ul. Jana Pawła II 10
phone: (+48 61) 858-20-01
fax: (+48 61) 852-59-54
office@man.poznan.pl
www.psnc.pl