



# Interoperability in optical frequency transfer fiber optic links

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**Abstract:** The paper addresses the interoperability problem in heterogeneous optical frequency transfer fiber links, which requires the coexistence of equipment with different designs. As we point out, a key component is the repeater laser station, which, for its operation, requires ensuring design-specific relationships between the frequencies of the optical signals at its ports. Ensuring their interoperability requires dedicated optical frequency shifters that adapt to existing differences. The second aspect of interoperability relates to the ability to recover without human intervention after a link failure, e.g., a loss of power or a fiber break. Both aspects were investigated experimentally using two different repeater laser station designs in a 500 km laboratory fiber link, demonstrating the interoperability of the tested devices in various configurations. Transfer stability and frequency inaccuracy were comparable to those obtained in homogeneous chains, reaching  $10^{-20}$  at averaging times of around  $10^4$  seconds.

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## 1. Introduction

Optical frequency standards (also known as optical clocks) have nowadays reached a maturity and reliability level that transformed them from being the object of interest of the researcher teams working towards their further improvement into instruments that can serve a much broader community of users (see e.g. [1–4] and the REFIMEVE [5] or NLPQT [6] webpages). The progress made recently in the field of optical clocks technology [7–13] pushed the General Conference on Weights and Measures (CGPM) in 2022 to promote the idea of the new definition of the SI unit of time, the second, and to undertake activities towards the acceptance of this definition in 2030 [14]. The recent works have already demonstrated the capability of optical clocks to generate a time scale [15,16] and discussed implementation roadmaps [17].

To operate and maintain an optical clock, however, highly qualified staff and appropriate conditions are still required, making these devices relatively uncommon, located usually in designated laboratories of National Metrological Institutes (NMI). In recent years transportable optical clocks (TOC) have also reached a level of maturity (see, e.g. [18,19]) and a small number of these devices is currently used, mainly in the experiments related to the chronometric levelling and general relativity. Exploitation of optical clocks is supported by an appropriate and reliable distribution infrastructure, which can guarantee sending an optical clock signal to the user without degrading its stability and accuracy. Such an infrastructure is also necessary in regular optical clock operation, requiring comparison with other clocks, usually situated in a neighbouring country or even further. Required distances range from hundreds to more than a thousand kilometres. Optical fibers have emerged as a standard tool in such applications [20,21],

being a natural medium to transmit optical signals and allowing to span long distances. However, environmentally induced phase noise (due to e.g. temperature variations or vibrations, resulting in fiber delay changes) has to be compensated, otherwise it would seriously degrade the quality of the optical clock signal, causing large phase noise and cycle slips.

The required compensation is performed by a pair of link terminals (see Fig. 1) forming a feedback system [21]. The phase noise cancellation is provided by an acousto-optic modulator (AOM), which is fine tuned to keep the total round-trip frequency shift, detected as a beat note in the local module, at a constant value  $f_L$ . In the example shown in Fig. 1, this is achieved using a phase-locked loop based on a mixer and voltage-controlled oscillator (VCO). Generally, a fixed frequency shift, for example using a second AOM (marked with a dashed line in Fig. 1), is applied at the remote end of the link to mitigate the impact of Rayleigh backscattering. It can be proved [23] that, assuming the symmetry of the phase changes for the forward and backward signals propagating in the same fiber, the frequency at the output of such an arrangement is  $\nu_{out} = \nu_{in} \pm f_L/2$  (the sign depends on the feedback loop design), so is not affected either by the fiber-coupled noise nor any noise or offset introduced by the remote-end AOM. Although the result does not depend explicitly either on  $f_{AL}$  nor  $f_{AR}$  it is worth mentioning that these values cannot be chosen freely due to the rather limited tuning range of typical AOMs (about  $\pm$  a few MHz), so additionally the condition  $f_L \approx 2f_{AL} + 2f_{AR}$  has to be fulfilled by the nominal values of  $f_{AL}$  and  $f_{AR}$ . Two Faraday mirrors ( $FM_L$  and  $FM_R$ ) are used to align the polarization states of the optical signals incident on the photodiode (PD) to obtain a stable beat note, which otherwise would undergo random fading due to polarization changes within the fiber (for a more thorough explanation see e.g. [22], section 2).

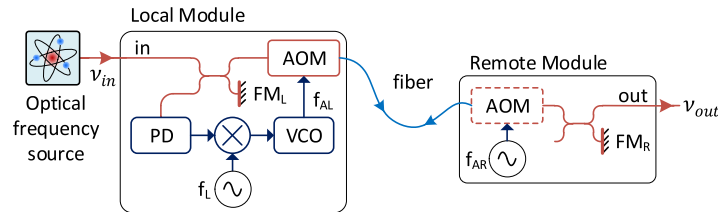


**Fig. 1.** A basic setup for optical frequency distribution, suitable for short-distance links (PD – photodiode, FM – Faraday mirror, VCO – voltage-controlled oscillator, AOM – acousto-optic modulator).

Such a simple system is suitable for short links only, connecting the premises located not further than about 100 km apart, e.g. laboratories situated on the same campus. For long distance links, several hundreds of kilometres long, means to regenerate the bi-directional optical signals are required to compensate for signal loss caused by the attenuation of the optical fiber. This can be achieved passively (i.e. with no intentional change of the transmitted optical frequencies) by optical bi-directional amplifiers (OBA) [23–32] or actively (where the optical frequencies are intentionally changed) in more demanding situations using devices commonly named repeater laser stations (RLS) [33–37].

Typical long-distance optical frequency transfer link uses some number of RLSs interleaved with OBAs. An RLS can perform several different functions: it can simply terminate the link, serve as an access point for an end-user or split the signal into a few branches (see Fig. 2). It also helps splitting long links into shorter segments, improving the effectiveness of noise cancellation as its bandwidth scales inversely with the link length. It also improves the compensational gain, which scales inversely with the square of the length [21]. The number of devices used in a particular network will depend on the number of planned access points, distances and availability of huts along the links to place the necessary equipment.

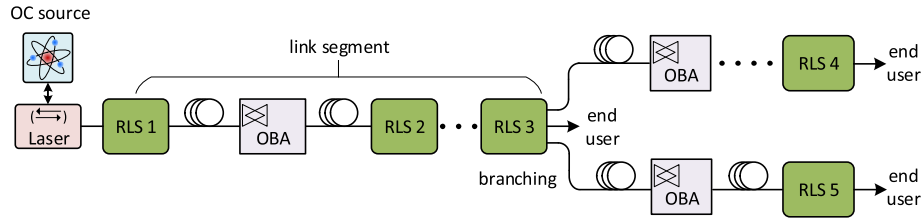


**Fig. 2.** General concept of a long-distance optical frequency dissemination/transfer network.

In the context of the envisaged pan-European clock distribution network (as worked out in the framework of the CLONETS [38] and CLONETS-DS [39] EU projects and currently tested as a Pathfinder pilot link [40,41] connecting PTB in Braunschweig, Germany, and KL FAMO in Toruń, Poland, using the fiber infrastructure provided by Gigabit European Academic Network (Geant) and the transmission equipment developed by the PSNC and AGH), the problem of connecting sub-networks using equipment developed in various countries and/or available from different commercial vendors turns out to be a vital one. This raises the natural question about equipment interoperability in such an inhomogeneous network, which is a requirement for its continuous and reliable operation.

## 2. Generic link building blocks

As shown in Fig. 2, there are two main building blocks in a considered optical frequency distribution network: OBA and RLS.

OBA implemented in typical links usually exploit a piece of Er doped fiber to obtain desired amplification simultaneously in both directions [23–28], although other techniques based on fiber nonlinearity, like stimulated Brillouin (SBS) [29–31] or Raman scattering (SRS) [32], have also been reported. The processing of bi-directional optical signals inside the OBA is limited to just providing the gain, so assuming the OBA design is fully symmetric (i.e. the forward and backward signals share the same fibers) and the link is correctly designed (i.e. the total gain of all OBAs is well suited for the particular link attenuation and is adequately distributed along it so as not to cause intense double Rayleigh backscattering or Brillouin excitation), these devices, in principle, would neither affect the signals stability nor its accuracy.

The second main block required in a long-distance optical frequency distribution link is an RLS, which has a feature to regenerate the weak optical signals decreased by fiber attenuation and other losses [34,35,37]. It contains in a single device the functionality of both the local and remote modules as shown in Fig. 1. A generic RLS structure is presented in Fig. 3. It has two bi-directional optical ports: an uplink port and a downlink port, which are used to connect to the previous and next link segments, respectively. The corresponding optical frequencies are marked as  $\nu_{in}^U, \nu_{out}^U$  and  $\nu_{in}^D, \nu_{out}^D$  for the up- and downlink ports, respectively. The first part of the RLS connected to the uplink port is responsible for the regeneration of the optical signal, which is typically provided by a low-noise external cavity semiconductor diode laser (ECDL), acting as the source of signals for both the uplink and downlink outputs. The ECDL is locked to the incoming uplink signal with a frequency offset  $f_1$  by comparing the beat note produced in PD<sub>1</sub> with the local stable electrical oscillator. The polarization controller (PC) together with the Faraday mirror (FM<sub>1</sub>) solves the problem of random polarization changes in the uplink fiber connecting the RLS with the source of the transferred optical frequency (see description of the basic setup shown in Fig. 1).

The remaining part of the RLS is responsible for the compensation of the noise of the fiber connected to the downlink port, which is very similar in its structure and operation to the local module of the basic link shown in Fig. 1. By multiplying the number of ports of the splitter at the

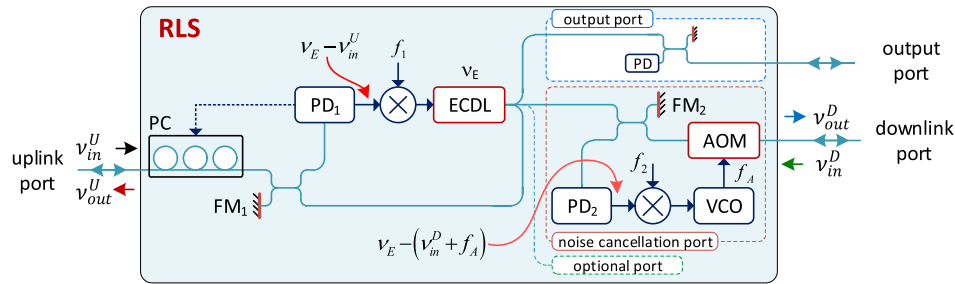


**Fig. 3.** Generic block diagram of the RLS.

ECDL output and replicating the components associated with the beat note generation (FM<sub>2</sub>, PD<sub>2</sub>) and/or phase noise compensation (AOM, VCO and the related electronics) the number of output/downlink ports can be increased and the range of available functionalities tailored forming what is known as a multi-branch laser station (MLS) [37].

During the RLS operation specific relations exist between the frequencies of the optical signals at its up- and down-link ports. These can be written based on the generic RLS structure (Fig. 3):

$$v_{out}^U = v_E = v_{in}^U + f_1, \quad (1)$$

$$v_{out}^D = v_E + f_A, \quad (2)$$

$$v_E - (v_{in}^D + f_A) = f_2, \quad (3)$$

where  $\nu_E$  is the optical frequency generated by the ECDL,  $f_A$  is the AOM driving frequency and  $f_{1,2}$  are internally generated RF frequencies derived from the same electronic reference oscillator. Equations (1) and (2) define the frequency shifts generated internally by the ECDL locking circuitry and by the AOM, respectively, whereas (3) results from the operation of the fiber phase noise cancellation feedback loop (analogous to the basic setup shown in Fig. 1). The above relations are summarized in a generic, port-level RLS model shown in Fig. 4 together with its defining equations. The proposed model uses only three parameters  $\alpha$ ,  $\beta$  and  $\gamma$ , which are simply the frequency differences between the optical frequency  $\nu_{in}^U$  entering the RLS uplink port and the optical frequencies  $\nu_{out}^U$ ,  $\nu_{out}^D$  and  $\nu_{in}^D$ , respectively. The values of  $\alpha$ ,  $\beta$  and  $\gamma$  are constant by design for a particular RLS type and they can be either directly provided by the RLS manufacturer or, alternatively, they can be determined basing on the RLS technical documentation.

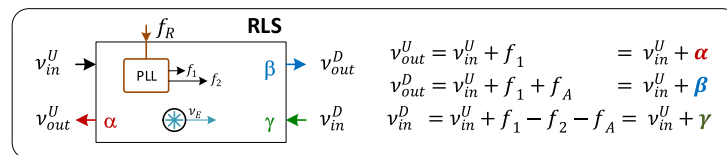


**Fig. 4.** RLS model with its defining equations. The reference frequency  $f_R$  (either external or internal) is used to drive all RLS internal blocks.

In practice, as usually  $\nu_{in}^U \neq \nu_{out}^D$ , two RLS versions differing with the internal frequency schemes are necessary to avoid permanent shifting of the output optical frequency in one direction if connected in a cascade. Additional constraints are usually also imposed on the RLS design to mitigate the problem of corrupting the transferred optical frequency by the phase noise of the internal electronic oscillator via  $f_1$  and  $f_2$  [35]. All such details can be conveniently combined in the  $\alpha$ ,  $\beta$  and  $\gamma$  parameters. If they are known the design of the heterogeneous and interoperable RLS chains becomes possible as will be discussed in detail in the next section.

### 3. Interoperability requirements

Interoperability is a notion where devices with the same or similar functionality, but of different design/manufacture, can work seamlessly, or with only a limited human intervention, in a larger system. It can also be extended to the capability of a particular piece of equipment to be replaced with one of different design but having identical functionality. Interoperability in a distribution network requires considering all the aspects related to the optical frequency distribution in the first place, but also the capability of the installed devices to recover automatically after a failure (like a loss of the power supply or a break of an optical path). This second aspect is especially important in case of links forming a large network, where reliable operation of the entire system depends on the interaction of many individual devices.

The RLS is a key component for interoperability as it actively modifies the processed optical frequencies and requires specific dependencies between them. OBAs, on the other hand, can be regarded to be inherently interoperable, at least with respect to their main functionality, i.e. providing the optical gain in both directions. Some differences between specific designs concerning, e.g., the range of available gain, noise level or amplification bandwidth can be expected. Also the method of OBA gain control can be different - it can either be stabilized and independent from the character of signals amplified, or set just by adjusting the pump power. Such details may seriously affect the process of setting up the link. Nevertheless, OBAs of different design/manufacture can be in principle interleaved in the same link and successful coexistence of SBS- and Er-based amplifiers has already been presented [36].

RLS intended to operate over the same link should be regarded as not interoperable unless the frequency shifts defined by respective  $\alpha$ ,  $\beta$  and  $\gamma$  parameters fulfil the condition  $\alpha(n) = \gamma(n-1) - \beta(n-1)$ , where  $n$  is the number of the RLS in the chain. If this is not the case, suitable frequency adaptors have to be added at the up- and/or down-link ports to compensate existing frequency differences (see Fig. 5). As all frequency distribution fiber optic links in Europe universally use channel C44 (194.4 THz) [5,6,33–35,40] it can be safely assumed that the ECDL inside the RLS( $n$ ) will be able to tune to the incoming frequency  $\nu_{in}^U(n)$  entering its uplink port. The required adaptor should thus be able to match the  $\nu_{in}^D(n-1)$  of the preceding RLS to the  $\nu_{out}^U(n)$  of the next one in the chain. As the adaptors have to operate bi-directionally over the same fiber, the frequency shift between  $\nu_{out}^D(n-1)$  and  $\nu_{in}^U(n)$  also needs to be taken into account. Using the model from Fig. 4 and the diagram shown in Fig. 5 this can be expressed as:

$$\nu_{in}^U(n) = \nu_{in}^U(n-1) + \beta(n-1) + f_A, \quad (4)$$

$$\nu_{in}^U(n) + \alpha(n) + f_A = \nu_{in}^U(n-1) + \gamma(n-1), \quad (5)$$

where  $f_A$  is the frequency shift provided by the adaptor. Equations (4) and (5) allows expressing directly the required frequency shift as :

$$f_A = \frac{\gamma(n-1) - \alpha(n) - \beta(n-1)}{2} \quad (6)$$

Such a frequency shift can be provided by a an AOM driven by a constant frequency oscillator. As the adaptor AOM is inserted in series with the fiber interconnecting the two RLSs involved so any noise of its driving oscillator will simply add to the fiber noise. As being in the common feedback path it will thus be compensated by the noise cancellation loop (similarly as the noise introduced by the remote module AOM in the diagram in Fig. 1). In practice any frequency synthesis circuit based on TCXO or OCXO is expected to be sufficient. The location of the interfacing AOM can be, in principle, arbitrary, however placing it close to one of the RLS is a natural choice.

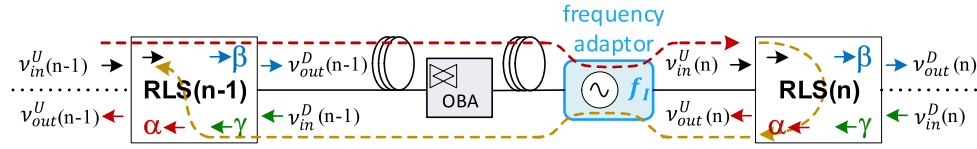


Fig. 5. An illustration of a chain with inherently not interoperable RLSs.

#### 4. Interoperability tests and experimental results

We performed tests of the interoperability of two different RLS designs in a laboratory at PTB. One of the designs, further referred to as  $\text{RLS}_{\text{FR}}$ , is currently commercially available from Exail (see [42]) and is based on a design originally developed at the Laboratoire de Physique des Lasers (LPL) and LNE-SYRTE. These devices are routinely implemented in the French REFIMEVE + infrastructure [5]. The second design, in the following referred as  $\text{RLS}_{\text{PL}}$ , has been produced recently by the PSNC/AGH group and is currently being implemented in the Polish NLPQT network [6].

The experimental setups used (see Fig. 6 for details) consisted of one  $\text{RLS}_{\text{FR}}$  and two  $\text{RLS}_{\text{PL}}$ , connected in three possible configurations using two 250 km long segments of G.652 spooled fiber and additional Er-doped OBAs to compensate for the fiber and the adaptor AOM losses. The values of  $\alpha$ ,  $\beta$  and  $\gamma$  for the RLSs used are collected in Table 1. The  $\text{RLS}_{\text{PL}}$  comes in two versions,  $\text{RLS}_{\text{PL}}\text{-30}$  and  $\text{RLS}_{\text{PL}}\text{-50}$ , which are designed to be cascaded and consequently do not require any adaptor frequency shifter between them. To match the uplink of the  $\text{RLS}_{\text{FR}}$  to the downlink of the  $\text{RLS}_{\text{PL}}\text{-50}$ , the frequency shift obtained from eq. is +23 MHz. To match the downlink of the  $\text{RLS}_{\text{FR}}$  to the uplink of the  $\text{RLS}_{\text{PL}}\text{-30}$ , the frequency shift obtained from Eq. (6) is +52 MHz. In all tested combinations, the first RLS was supplied with the optical frequency obtained from a Menlo ORS ultrastable cavity-stabilized laser. The tests included both the stability/accuracy assessment and the link recovery after interventions including a fiber break and a power supply loss.

Table 1. RLS frequency shift values

|          | $\text{RLS}_{\text{FR}}$ | $\text{RLS}_{\text{PL}}\text{30}$ | $\text{RLS}_{\text{PL}}\text{50}$ |
|----------|--------------------------|-----------------------------------|-----------------------------------|
| $\alpha$ | −76 MHz                  | −30 MHz                           | −50 MHz                           |
| $\beta$  | −75 MHz                  | +10 MHz                           | −10 MHz                           |
| $\gamma$ | −1 MHz                   | −40 MHz                           | −40 MHz                           |

##### 4.1. Assessment of the dissemination stability and accuracy

The measurement of the frequency dissemination stability was performed by counting beat notes between the respective ECDL using auxiliary measurement ports present in each RLS (these are equipped with a fiber interferometer and a photodiode, similarly to a regular downlink port, but without the AOM and associated electronics). The auxiliary ports were connected by short fiber pathcords (~2 m long), which allowed measuring two beat notes at both sides using a multichannel K + K FXE phase recorder (running in a  $\Lambda$ -counting mode). This approach is necessary to remove the influence of the uncompensated patchcords on the stability assessment, even though the measurements were undertaken in an air-conditioned laboratory – see an example shown in Fig. 7. The dissemination stability was obtained then by analysing a two-way beat  $f_B = (f_{Bxy} + f_{Byx})/2$ , where  $x$  and  $y$  equal to 1, 2 or 3 depending on the location of the measurement points (see Fig. 6). In addition, the FXE, the first and last RLS were referenced to a common time base. The second RLS (i.e. the middle one), as well as the interfacing AOM, was intentionally

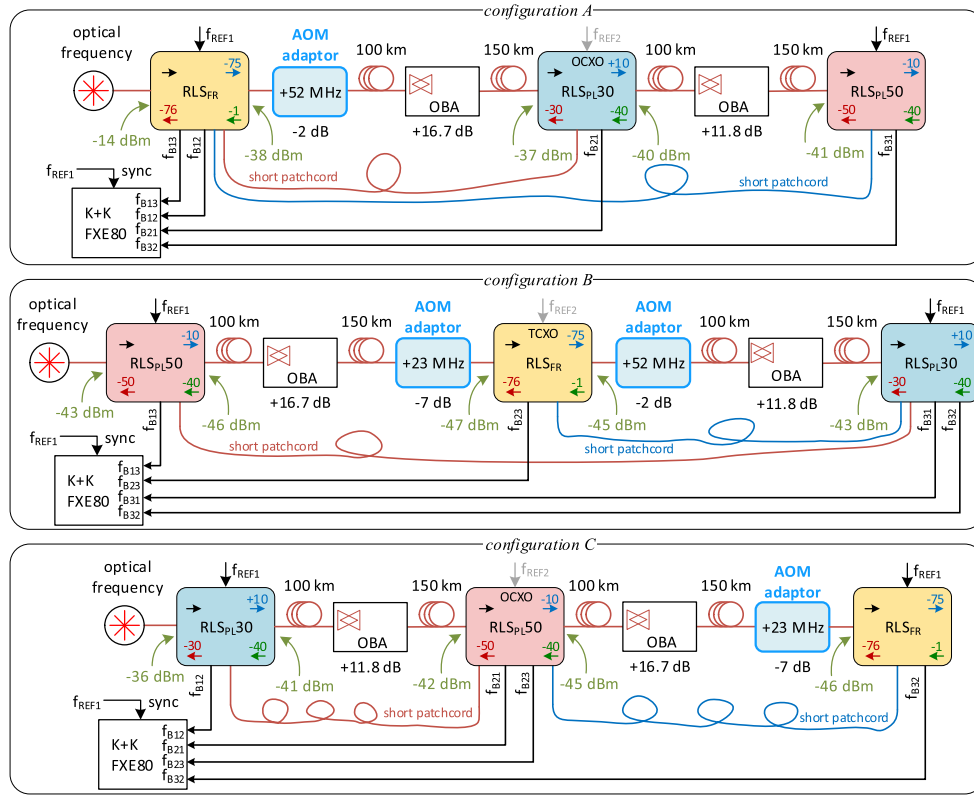


**Fig. 6.** Three test setups used in the interoperability experiments. The number “30” or “50” in the  $RLS_{PL}$  symbols refers to the frequency shift existing at the RLS uplink port. Colour and black lines are used to distinguish between fiber and electrical connections. The optical power levels incident on the RLS ports are shown in light green.

driven from a different RF source, to examine whether its instability affects the end-to-end transfer of the optical frequency.

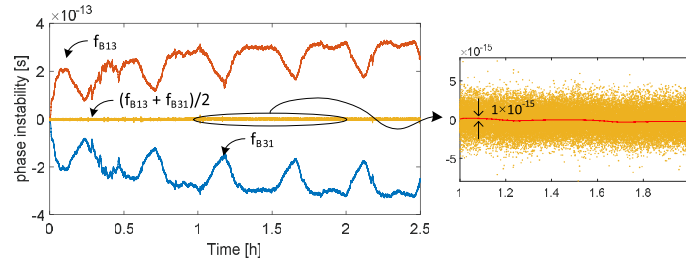


**Fig. 7.** Effect of the two-way stability assessment: residual phase of individual beat notes reveal large fluctuations with about 30 min periodicity due to laboratory air-conditioning. The inset zoomed in a 60 min long part showing the fluctuations greatly suppressed (red curve showing the noise average over 10 min) when using a two-way beat. The sampling time was 1 second for all the curves shown.

The results of the stability assessment are collected in Fig. 8. In all the configurations tested the end-to-end stability (blue curves, measured between the first and the third RLS in the chain) approaches a floor of  $10^{-20}$  after about  $10^3$  s with the slope close to  $\tau^{-2}$ , where  $\tau$  is the averaging

time. The bump noticeable slightly below  $10^3$  s can be related to the residual phase fluctuations visible in the inset in Fig. 7, which reveals a small influence of the temperature on the equipment tested, probably through the fiber interferometers in  $RLS_{PL}$  devices, as their thermal shields temperature stabilization had not yet been implemented during our experiments.

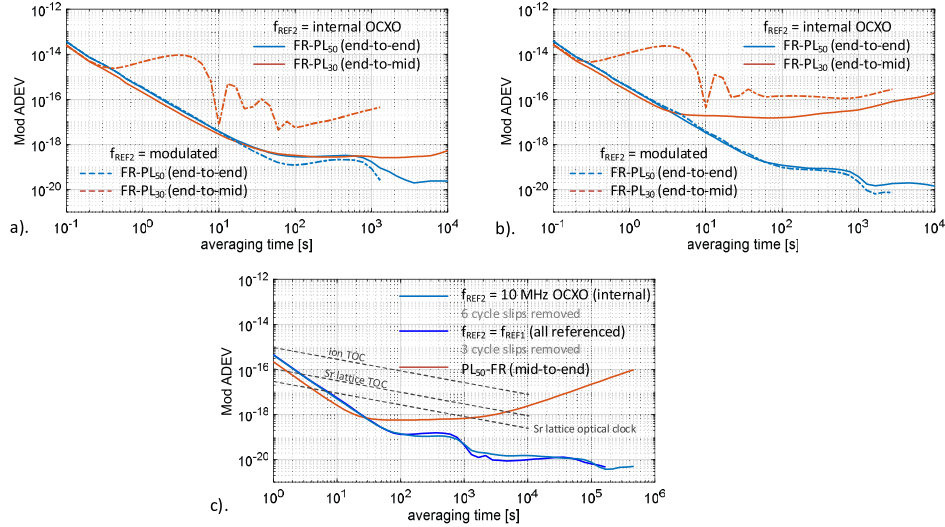


**Fig. 8.** Results of stability assessment: (a) for configuration A, (b) for configuration B and (c) for C. In (c) the dashed lines are drawn representing the fractional instability of a single ion TOC, Sr lattice TOC and the stationary state-of-the-art Sr lattice optical clock.

The brown curves show the stability measured to the middle RLS, which is in all cases worse than the end-to-end stability. The reason is that the mid-RLS reference frequency was free running, so any instability of this reference frequency reflects directly on the stability measurement. The level of the stability degradation depends directly on the quality of the reference source, showing to be better for OCXO used in  $RLS_{PL}$  design (configuration A and C) and slightly worse for TCXO used in  $RLS_{FR}$  design (configuration B). It was even much worse when intentional 100 mHz frequency modulation with 2 Hz deviation was applied to the mid-RLS reference input (dashed brown curves), which resulted in a large bump located at  $\tau \sim 4$  s.

It is important to say that the end-to-end stability (blue curves; solid for OCXO/TCXO and dashed for external modulated references, respectively) stays, however, unaffected. It was thus proved experimentally that the feature of the RLS design preventing the noise of its internal reference from coupling to the optical frequency transferred (which is related to the internal frequency planning – see [35] and the note at the end of section 2) is preserved in a heterogeneous RLS chain involving the interfacing AOMs. In addition, no other detrimental effects related to the instabilities of the frequencies controlling the interfacing AOMs were identified.

The measurements presented in Fig. 8 for configuration C focus on a long-term behavior of the tested setup obtained in two campaigns, one lasting for 23 days between December 19<sup>th</sup> 2023 to January 12<sup>th</sup> 2024 (light blue) and the second one for 10 days between 2<sup>nd</sup> and 12<sup>th</sup> of February 2024 (dark blue). The mid-RLS frequency reference was changed between the campaigns – internal OCXO was used in the first one, which was then switched to all devices using the same external frequency reference (apart from the interfacing AOM, which still relied on its internal oscillator). In those periods only a few cycle slips were registered (6 in the first period and 3 in the second one) – related data points were removed before the MDEV calculation. Careful analysis revealed that these slips occurred in the section involving  $RLS_{FR}$  – they resulted probably from the polarization controller in  $RLS_{FR}$ , which seeks for better conditions by switching between a

few polarization states after substantial polarization walk-off. The relative frequency inaccuracy calculated from the data collected are  $1.4 \times 10^{-21}$  and  $3.6 \times 10^{-22}$  for the first and the second measurement campaign, respectively.

#### 4.2. Link recovery

The second part of the interoperability tests included activities related to link recovery after an intervention, simulating power supply failure or fiber break. In all configurations a few attempts of each intervention were undertaken, measuring in each case the period of time required to recover stable operation of the link. For the RLS<sub>FR</sub> the manual turning-on of individual internal blocks via software is required, so in this case the device was restarted by sending a suitable command instead of just powering it off and on.

For the link to recover, each RLS in the chain must lock to the incoming optical signal. In the RLS locking phase the internal ECDL tunes, sending its frequency-varying light through the downlink port to the subsequent devices. The problem of locking the entire RLS chain is thus not a straightforward one as it relies on the philosophy behind the implemented software ECDL locking algorithms to a large extent. This is especially important when devices of different design are expected to coexist on a single link.

Reacquiring lock is passed towards the end of the link through successive devices, so a longer link recovery time may be expected the closer to the link start the affected device is located. This is confirmed by the results collected in Table 2 showing recovery times that are in general below 5 min if the intervention took place just at the beginning of the link, dropping to less than 2 min when the intervention approached the link end.

On a few occasions much longer times were observed (~15 min), which was identified as resulting from the specificity of the ECDL tuning algorithms implemented in the RLS<sub>FR</sub>. It also happened a few times that the link was unable to recover, which required taking another intervention to restart the recovery process. Closer analysis revealed that this was caused by the ECDL tuning algorithm in the RLS<sub>PL</sub>50, which accidentally can get stuck at the wrong side of the incoming optical frequency, disabling this way also locking of the subsequent devices. This problem, not observed previously, was identified and adequate countermeasures were undertaken. The modification that is now used in the RLS<sub>PL</sub> algorithm enables the ECDL locking only if the optical frequency entering the RLS uplink port is stable in a predefined time window, which allows identifying the situation when the preceding RLS in the chain is trying to acquire its lock. This finally allowed full link recovery to be achieved after each intervention, which was verified during a second visit at PTB at the end of February 2024.

## 5. Conclusion

Coexistence of various RLS designs, which are a key component in building a heterogeneous optical frequency transfer/distribution network, is possible if assuring correct optical frequencies entering their up- and downlink ports. An AOM driven with the correct frequency can play the role of a suitable interface. The required frequency driving the interfacing AOM can be determined knowing the frequency shifts of up and down propagating optical signals with respect to the signal entering the uplink port. This was emphasized by proposing the generic RLS model, requiring no knowledge about the RLS internal structure or its internal frequency scheme.

The transfer stability in a heterogeneous RLS chain is similar to the stability in a homogenous chain using only homogenous devices. In our experiments the level of  $10^{-20}$  was reached after the averaging time of about  $10^3$  s. The results are independent of the RLS configuration tested. The end-to-end stability is affected neither by the frequency stability of the oscillators driving the interfacing AOMs nor the stability of the RF oscillator of the middle RLS. It was thus experimentally proved that the heterogeneous chain preserves the feature of RLS design, where the noise of its reference frequency is not transferred to the optical carrier. A relative frequency

Table 2. Results of the link recovery experiments

|                 | Intervention                                              | # of attempts | Time to relock (typical) | Comments                                        |
|-----------------|-----------------------------------------------------------|---------------|--------------------------|-------------------------------------------------|
| Configuration A | RLS <sub>FR</sub> restart                                 | 3             | 4 min 30 s               | Lock failure observed (RLS <sub>PL50</sub> )    |
|                 | RLS <sub>PL30</sub> power off/on                          | 2             | 2 min 20 s               |                                                 |
|                 | RLS <sub>PL50</sub> power off/on                          | 2             | 1 min 30 s               |                                                 |
|                 | RLS <sub>FR</sub> – RLS <sub>PL30</sub> fiber reconnect   | 4             | 1 min 30 s               | Lock failure observed (RLS <sub>PL50</sub> )    |
|                 | RLS <sub>PL30</sub> – RLS <sub>PL50</sub> fiber reconnect | 2             | 1 min 50 s               |                                                 |
| Configuration B | RLS <sub>PL50</sub> power off/on                          | 3             | 4 min 10 s               | $t_R \sim 14$ min observed (RLS <sub>FR</sub> ) |
|                 | RLS <sub>FR</sub> restart                                 | 3             | 1 min 40 s               |                                                 |
|                 | RLS <sub>PL30</sub> power off/on                          | 3             | 1 min 40 s               |                                                 |
|                 | RLS <sub>PL30</sub> – RLS <sub>FR</sub> fiber reconnect   | 3             | 2 min 0 s                |                                                 |
|                 | RLS <sub>FR</sub> – RLS <sub>PL50</sub> fiber reconnect   | 3             | 1 min 15 s               |                                                 |
| Configuration C | RLS <sub>PL30</sub> power off/on                          | 4             | 2 min 30 s               | $t_R \sim 14$ min observed (RLS <sub>FR</sub> ) |
|                 | RLS <sub>PL50</sub> power off/on                          | 4             | 2 min 0 s                | Lock failure observed (RLS <sub>PL50</sub> )    |
|                 | RLS <sub>FR</sub> restart                                 | 3             | 1 min 40 s               |                                                 |
|                 | RLS <sub>PL30</sub> – RLS <sub>PL50</sub> fiber reconnect | 3             | 1 min 45 s               |                                                 |
|                 | RLS <sub>PL50</sub> – RLS <sub>FR</sub> fiber reconnect   | 3             | 1 min 45 s               | $t_R \sim 13$ min observed (RLS <sub>FR</sub> ) |

inaccuracy at the level of  $10^{-21}$  was obtained in two measurement campaigns lasting for a dozen of days. The results of both campaigns are consistent, proving fully satisfactory operation of the RLS chain, without losing its lock or other negative symptoms.

In addition, no significant differences between using the internal middle RLS frequency reference and applying the common external frequency reference can be identified, showing once again the correct operation of the heterogeneous RLS chain.

A very important aspect of the interoperability is the capability of the heterogeneous link to recover without any human intervention after return from a supply failure or an optical path break. It depends not only on the hardware, but also on the philosophy of operation and design of the software algorithms responsible for the RLS internal ECDL locking. Modification of the locking software of RLS<sub>PL</sub> was necessary to assure fully automatic link recovery in the case of the RLSs tested, emphasizing the need for thorough interoperability testing.

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**Data availability.** Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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