Experimental investigation of interoperability in optical frequency transfer

Łukasz Śliwczyński
AGH University
Krakow, Poland
sliwczyn@agh.edu.pl

Przemyslaw Krehlik
AGH University
Krakow, Poland
krehlik@agh.edu.pl

Łukasz Buczek
AGH University
Krakow, Poland
lbuczek@agh.edu.pl

Harald Schnatz
Physikalisch-Technische Bundesanstalt (PTB)
Braunschweig, Germany
harald.schnatz@ptb.de

Jochen Kronjäger
Physikalisch-Technische Bundesanstalt (PTB)
Braunschweig, Germany
jochen.kronjaeger@ptb.de

Krzysztof Turza
Poznan Supercomputing and Networking Center
Poznań, Poland
kturza@man.poznan.pl

Artur Binczewski
Poznan Supercomputing and Networking Center
Poznań, Poland
artur@man.poznan.pl

***Abstract*— In this paper we investigate the interoperability of two different designs of repeater laser stations in inhomogeneous optical frequency transfer link. Such stations are used to regenerate weak optical signals and are key components of any long-distance link. We propose to use an acousto-optic modulator with appropriately selected shift to bridge the frequency gap between the two repeater laser stations. Experimental investigation showed that such a solution works correctly and does not degrade the transfer performance.**

Keywords—optical frequency, frequency transfer, repeater laser station, fiber optic, interoperability, acousto-optic modulator

I. Introduction

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) terminating the link segments, connected with 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 (see Fig. 1).

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 available from different commercial vendors turns out to be important. This raises the question about the interoperability of such an inhomogeneous network.

II. Interoperability Requirements

In an interoperable system, a seamless coexistence of devices using different design or technology to provide the same functionality is expected. In case of optical frequency transfer networks, it means delivering the frequency signal to the far link end with a minimum of noise degradation as a primary requirement, and, as a secondary requirement, an automatic, human intervention free (re)synchronization of the entire link after powering up, recovery from power failure or fiber break/disconnection.

In an optical frequency transfer/dissemination network, both OBA and RLS devices are used to regenerate the optical signal weakened by the fiber attenuation. OBA, however, is a passive device in the sense that it does not change the frequency of the processed signals. This way various OBA designs can be considered inherently interoperable, even when using different physical principle to achieve optical gain (e.g. based on stimulated emission in a doped fiber or using nonlinear fiber behavior through Brillouin or Raman stimulated scattering).

RLS can be considered as a device with two bi-directional optical ports, called the uplink and downlink ports. It regenerates the optical signal by offset-locking its external-cavity semiconductor laser diode (ECLD) to the weak optical signal incoming via the uplink port (having the frequency of ν_{Uin}). It is then sent back via the uplink port to

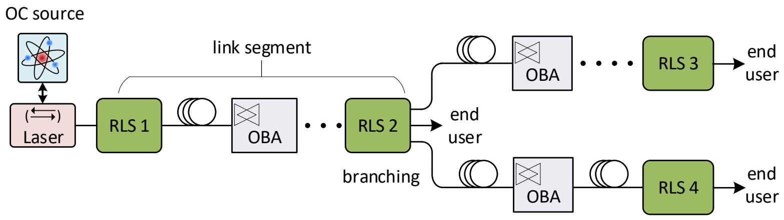

Fig. 1. General concept of optical frequency dissemination/transfer network.

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.

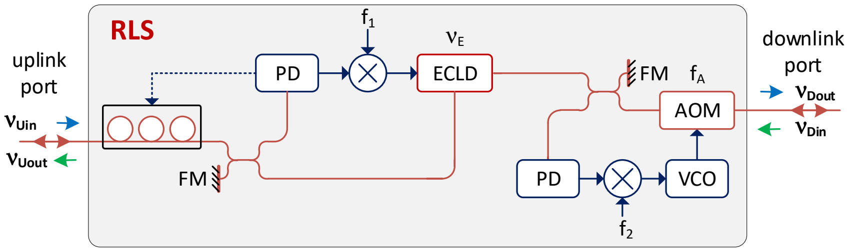

Fig. 2. Generic RLS structure.

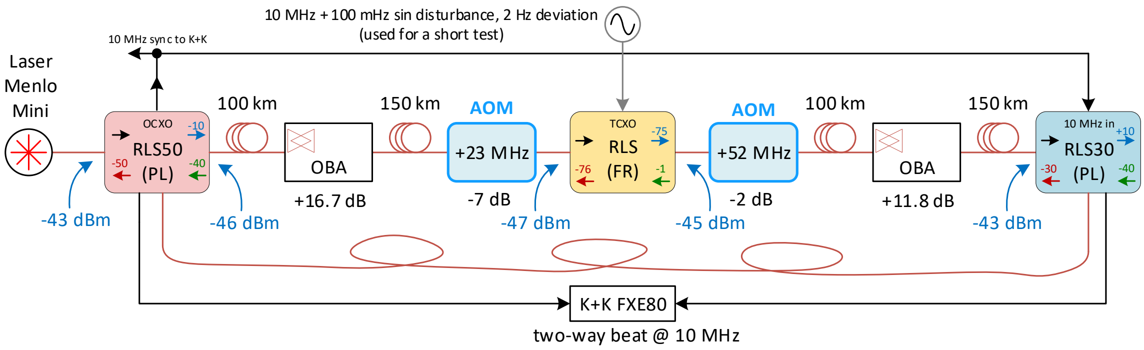

Fig. 3. Generic setup used in the interoperability experiments.

the previous RLS in the chain (with the frequency shifted to ν_{Uout}), and also via the downlink port to the next RLS (with the frequency shifted to ν_{Dout}). To close the feedback loop necessary for the fiber noise cancellation, the RLS must receive the correct optical frequency ν_{Din} from the next RLS via its downlink port. The generic internal structure of the RLS is shown in Fig. 2.

Proper frequency planning assures that the noise of local f1 and f2 RF references 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 allow coexistence of two different RLS designs, it is sufficient to insert an appropriate optical frequency shifter (AOM) in-between. Stability and accuracy of the frequency driving the AOM is not critical – it adds to the fiber phase noise so is compensated in the feedback loop by the RLS (within the constraints set by the propagation delay [3].

III. Interoperability Tests

Interoperability of two different RLS types was investigated: one (marked RLS(FR)), available commercially from Exail/iXblue, is based on the design developed originally at Laboratoire de Physique des Lasers (LPL) and LNE-SYRTE and is used mostly in the French REFIMEVE+ infrastructure [1]. The second one (marked as RLSxx(PL), where xx is either 30 or 50 and indicates the uplink frequency shift $\nu_{Uin} - \nu_{Uout}$ in MHz) was developed recently by the PSNC/AGH group and is used in the Polish NLPQT network [2].

The generic setup used in our experiments is presented in Fig. 3. It included three RLS devices, two Er doped OBA, a set of acousto-optic frequency shifters and 500 km of spooled G.652 fibers. We used a Menlo ORS-Compact ultra-stable laser as a source of optical signal. During the experiments we interchanged the positions of RLS devices, so all three possible setups were tested in total:

- RLS50(PL)-AOM(+23)-RLS(FR)-AOM(+54)-RLS30(PL),
- RLS(FR)-AOM(+54)-RLS30(PL)-RLS50(PL),
- RLS30(PL)-RLS50(PL)-AOM(+23)-RLS(FR).

To suppress the influence of the noise picked up by the patchcords when measuring the transfer instability, we set up a two-way measurement, where two beat notes at both ends of the link were observed. The average of the two measurements then represents the frequency transfer error across the chain of RLS. In all cases, the modified Allan deviation (ModADEV) dropped quite quickly with a slope close to -2, reaching a level of about 10^{-19} after 10^2 s, where influence of laboratory air-conditioning was noticeable in the form of a bump. Then, for averaging times longer than 10^3 s, the level of 10^{-20} was reached. A representative result of a nine-days long measurement is shown in Fig. 4.

Apart from long measurements of the frequency transfer instability, we also performed short tests where the reference 10 MHz frequency of the "middle" RLS was disturbed by applying a 100 mHz sinusoidal modulation with 2 Hz deviation to observe its potential influence on the transfer stability. As expected, no evidence of the "middle" RLS reference frequency modulation was observed, proving that this kind of disturbance is not transferred to the optical

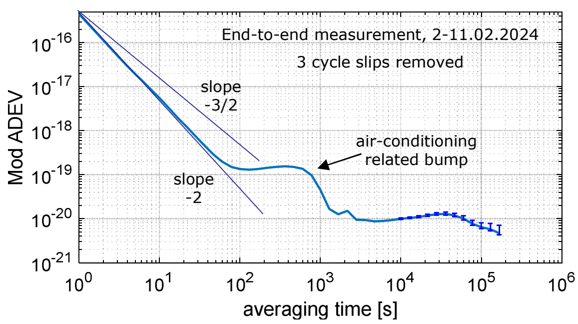

Fig. 4. Example measurement showing instability of tested setups.

frequency, just like in a homogenous link.

Tests of link re-synchronization showed that in most cases the link is able to recover within an acceptable time of a few minutes. In some cases this time was longer or the re-synchronisation failed. This problem was caused by the ECLD of one RLS locking while the previous RLS in the chain was still trying to achieve its lock, so that the optical frequency entering the RLS via its uplink port was still changing. This problem was identified and fixed by modifying the algorithm controlling the ECLD in RLS(PL).

IV. Conclusion

We have performed experiments showing that inhomogeneous links for optical frequency dissemination can be made interoperable by implementing the necessary frequency shift in the optical domain using a simple AOM.

Tests in three different link setups have been undertaken with the order of RLS interchanged. All measurements showed good fiber noise suppression, reaching the level of 10^{-19} after less than 1000 seconds. These 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. In addition, emulation of power up failure or fiber break showed that the inhomogeneous link can recover its lock in an acceptable time without a human intervention.

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/

[3] P. A. Williams, W. C. Swann, und N. R. Newbury, “High-stability transfer of an optical frequency over long fiber-optic links”, J. Opt. Soc. Am. B 25, p. 1284, 2008, https:/doi.org/10.1364/JOSAB.25.001284.