Polarization Control for Continuous Optical Frequency Transfer

P. Krehlik, Ł. Buczek and Ł. Śliwczyński
Faculty of Computer Science, Electronics and Telecommunications
AGH University of Science and Technology
Kraków, Poland
e-mail: krehlik@agh.edu.pl

Krzysztof Turza
Poznan Supercomputing and Networking Center (PSNC)
Poznań, Poland

***Summary*—In this work we present a solution for controlling the polarization state of the signal reaching the remote laser station terminating the optical frequency transfer link (or its section). The proposed controller eliminates the occasional fading of the beat note between the laser and the incoming signal, which is typically observed due to random wandering of the state of polarization of the signal traveling down an optical fiber. The efficiency of the solution is demonstrated for optical frequency transfer via an optical path consisting of real outdoor fibers, as well as fibers on spools and also polarization scramblers speeding up natural polarization fluctuations.**

***Keywords*—optical frequency transfer; polarization control; fiber-optic networks**

I. Introduction

Fiber-optic systems for phase-stabilized distribution of ultra-stable optical frequency reference signal disciplined to an optical atomic clock has been developing rapidly in last years, facilitating both the progress in the clocks development and their applications. In this situation human-intervention-free and continuous undisturbed operation of these systems become crucial.

One of the problems limiting continuous operation is the occasional fading of the beat note between the local and remote optical signals, which is typically observed due to random wandering of the state of polarization of the signals traveling down an optical fiber (see Fig. 1).

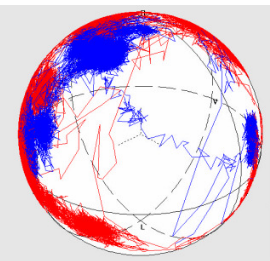

Fig. 1. An example of the random wandering of the polarization state in a real 2000 km-long outdoor fiber link. Both periods of relatively constant polarization and also rapid polarization changes may be noticed.

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In the early solution for the stabilized distribution of the optical frequency reference this problem was overcome by use of Faraday mirrors (i.e. mirrors rotating the polarization by 90 deg.), which allows to guarantee the polarization consistency of the signals beating in a photodiode [1, 2]. But in last years the long-distance links usually exploit somehow different solution, with phase-locked laser stations used along the link for signal regeneration and improving the phase noise cancellation efficiency [3, 4] – see Fig. 2. In this arrangement one can still benefit from the Faraday mirrors, but additionally an active polarization control is also needed, as depicted in Fig. 2.

II. Polarization Control

Basically, the polarization control may be obtained by some kind of polarization-affecting actuator, driven by the algorithm oriented on maximizing the strength of the beat note. In our case there are three main challenges for practical realization of the controller. First is that the weak remote signal entering the laser station is corrupted by various noises, which causes that also the beat strength indicating signal becomes noisy. The most specific and characteristic kind of noise in the long-haul optical frequency distribution system is the interferometric noise, arising from multiple back-reflections and backscattering which destructive impact is intensified by bidirectional optical amplifiers located along the link. The second challenge is that unpredictable trajectory of the polarization wandering may "lead" the polarization correcting algorithm to the end of the tuning range of the actuator, and so losing the ability for further proper polarization correction [5, 6]. The third problem is that

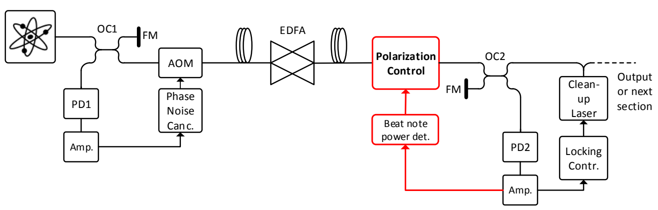


Fig. 2. Simplified scheme of the stabilized optical frequency transfer with the clean-up laser terminating the link or its section.

polarization-affecting actuators introduce also unwanted optical phase changes, so some trade-off between polarization stability and additional phase noise should be taken into account.

In our solution we use a four-section actuator with piezo fiber squeezers by General Photonics. The developed algorithm is based on applying a test voltage steps on each piezo section to determine the desired correction of the control voltages. The algorithm may operate continuously, or may be activated occasionally for short periods when the beat-note power is noticeably reduced.

For the endless polarization control we introduced a „penalty term" into the algorithm preventing the section voltages from saturating (going towards their hardware limit), and resulting algorithm jamming. Thanks to the redundancy offered by the four-section actuator, reducing of the extreme voltage on one section can be compensated by the other sections. Experiments with actively scrambled polarization show that the penalty term introduces some imperfectness of polarization stabilization resulting in app. 1 dB beat-note power fluctuation, but completely eliminate the risk of the beat note fading resulting from the controller clinching.

III. Experimental Results

Basing on the experimental setup containing optical path consisting of real outdoor fibers, fibers on spools and also polarization scramblers speeding up natural polarization fluctuations, we optimized the parameters of the controller and evaluate it operation in various conditions.

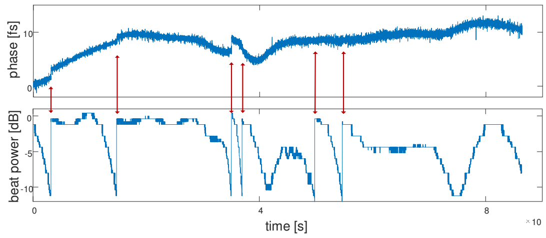
In particular, using a testbed containing 120 km of outdoor fiber, 150 km of fiber on spools and a bidirectional optical amplifier, we verified good operation of the controller for extremely noisy beat note, both in case of very weak optical signal (-70 dBm), and also in case of strong interferometric noise caused by backscattering and reflections around the amplifier. We determined that for best performance in case of very noisy beat note the algorithm speed should be sacrificed to some extend by introducing beat-note power averaging and decreasing the gain factor.

We also compared the usually applied strategy of occasional polarization corrections with continuous operation of the controller. We determined that continuous operation allow to avoid rapid phase/frequency changes characteristic for triggered operation (see Fig. 3). In case of occasional polarization adjustments some phase jumps are sometimes observed, which is related to the fiber birefringence. The stability (Modified Allan Deviation) seems to be very similar for both cases (see Fig. 4). The main difference is however that in the case of continuous polarization adjustments the beat power is permanently close to the maximum value because the proper polarization is maintained at the photodiode. So we believe the risk of the beat note fading in case of the rapid polarization perturbation is reduced, as the controller reacts immediately to any noticeable beat-not power decreasing.

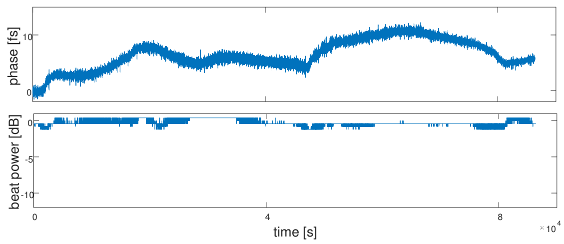
The controller was finally tested in a 600 km-long link in the Polish PIONIER optical network. Five bidirectional amplifiers were placed along the link. The link had a form of geographical loop, i.e. the „local" and „remote" devices were located in the same lab. In the registration period of seven days four cycle slips of unknown origin occurred, and the fluctuation of beat-note power was below 2 dB. The stability (see Fig. 5) was at the level of 6×10^{-20} .

IV. Conclusion

In this work we presented the solution of polarization controller preventing the fading of the beat note and therefore allowing continuous, human intervention free operation of the optical frequency transfer system. Continuous operation allow to avoid rapid phase excursions, which are characteristic for triggered operation, and to obtain nearly constant power of the beat note.



(a)



(b)

Fig. 3. Optical phase and beat power fluctuation in case of occasional (a), and continuous (b) polarization control.

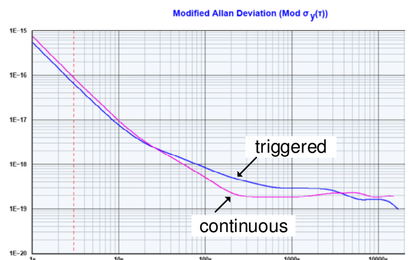


Fig. 4. Frequency transfer stability in case of occasional and continuous polarization control.

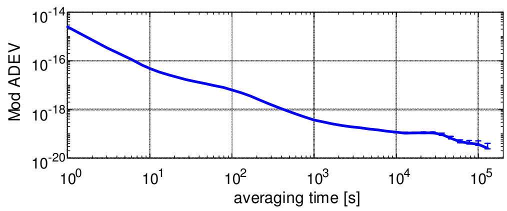


Fig. 5. Frequency transfer stability obtain in the final experiment.

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