Metrol. Meas. Syst., Vol. 27 (2020) No. 3, pp. 441–450
DOI: 10.24425/mms.2020.134586

METROLOGY AND MEASUREMENT SYSTEMS
Index 330930, ISSN 0860-8229
www.metrology.wat.edu.pl

A MAINTENANCE-FREE SOLUTION FOR OPTICAL FREQUENCY TRANSFER

Przemysław Włodarczyk, Przemysław Krehlik, Łukasz Śliwczyński

AGH University of Science and Technology, Faculty of Computer Science, Electronics and Telecommunications, al. A. Mickiewicza 30, 30-059 Kraków, Poland (✉ *pwl@agh.edu.pl*, +48 12 617 30 20, *krehlik@agh.edu.pl*, *sliwczyn@agh.edu.pl*)

Abstract

This paper focuses on automatic locking of tracking filters used in optical frequency transfer systems. General concept of such a system is briefly described and the problems with its automatic startup, originating in the use of the analog phase locked loop to filter weak, received signal, are discussed. A supervisory circuitry and algorithm to solve these problems is proposed. The frequency of the signal to be filtered is measured indirectly and the output frequency of the tracking filter is monitored. In the case of lack of synchronism (*i.e.* after the startup) a significant difference of these frequencies is measured and the supervisory algorithm forces the filter to tune into the right frequency and then allows it to synchronize. A system with the proposed solution was implemented and tested experimentally on a fiber optic link with high attenuation and multiple optical connectors. Transient signals during locking were recorded to investigate the system's behavior in real environment. The system was evaluated in the link causing synchronization losses every 17 min on average. During measurements over 3 days, the whole system was synchronized for over 99.98% of time despite these difficult conditions.

Keywords: fiber-optics, optical frequency transfer, tracking filter, automatic startup.

1. Introduction

Optical atomic clocks are used in the construction of the most accurate frequency references [1]. Some of them, like the single ion atomic clock, can achieve systematic uncertainty of the order of 10^{-18} [2]. As modern frequency references are among the most technically advanced systems built by humans, their complexity and price make them possible to be realized only in a few research centers. Therefore, in order to allow for comparisons between the references and access to precise frequency signal to a wider group of users, there is a need for a system allowing distribution of such a signal with lowest possible degradation [3]. There are several methods to accomplish this goal. Among these, fiber-optic based solutions with transfer of optical frequency allow to obtain precision greater than systems based on transfer of signals in the radio frequency range [4]. Therefore, in recent years much work has been put into the development of systems for the phase-stabilized transfer of laser light, both in optical fibers [5–11] and in free space [12, 13].

Although a first industrial grade coherent fiber link for optical frequency standard dissemination has already been reported [14], most of today's optical frequency transfer systems require human intervention from time to time.

Usually these systems use auxiliary circuits for accurate narrow-band signal filtration, which, utilizing phase lock loops, are not able to start properly without aid because of possibility of false locking. This problem is addressed below.

2. General concept of the stabilized optical frequency transfer system

Figure 1 shows a block diagram of the considered stabilized optical frequency transfer system based on the scheme proposed by Ma *et al.* [15]. The optical frequency signal ν_{IN} intended for transmission is directed to a coupler which splits it into two signals. The main signal is transmitted through a circulator to an *acousto-optical modulator* (AOM1) and then through an optical fiber to the remote station. At the remote end the signal passes through a second modulator AOM2. Acousto-optical modulators are controlled by signals of frequencies f_L and f_R and shift the light frequency, thus the frequency at the remote end of the system is:

$$\nu_{OUT} = \nu_{IN} + f_L + f_R\,. \tag{1}$$

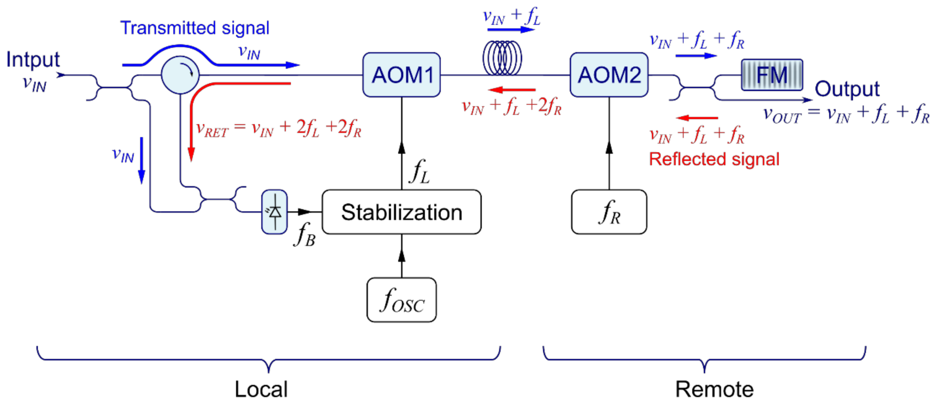

Fig. 1. Block diagram of the optical-frequency transfer system.

The remote station is equipped with a coupler which directs part of the light to the output port of the transfer system. The rest is reflected back by the Faraday mirror and returns to the local station via both modulators and the optical fiber. The returned signal passes through each of the modulators twice, each time being shifted in frequency. Thus the returned light beam has optical frequency

$$\nu_{RET} = \nu_{IN} + 2f_L + 2f_R\,. \tag{2}$$

Assuming that the optical path behaves symmetrically for both directions, both transmitted and reflected signals experience the same phase perturbations [15]. Thus phase variation of the returned signal in the local station is twice the phase variation in the remote station. Furthermore, if the phase perturbations are actively compensated in the local station, the remote station's light phase will also be stabilized.

In the local station, the returned signal is separated by the circulator and combined with the reference optical frequency signal. The two signals, when shone on the photodetector, generate the beat note with frequency f_B which equals the frequency difference between transmitted and returned signals

$$f_B = \nu_{RET} - \nu_{IN} . \tag{3}$$

Basing on (1), (2) the beat note frequency f_B may be expressed as:

$$f_B = 2f_L + 2f_R . \tag{4}$$

The phase of the obtained beat note follows the phase disturbance of the optical frequency signal transmitted through the loop (roundtrip). It is stabilized by applying a correct control signal to the AOM1. If the stabilization works correctly, the frequency f_B is equal to f_{OSC}.

The second modulator (AOM2) is used to avoid the influence of backward scattering in the fiber, although links without this modulator have also been considered for short-distance uses [16]. The light resulted from Rayleigh scattering which returns to the stabilization block passes only through the AOM1, so the resulting, harmful beat note has the frequency of two times f_L, and can be removed by a simple electrical band-pass filter.

The block diagram of the electronics used to stabilize the transfer of the optical frequency is shown in Fig. 2. Components in the signal path from receiver input to AOM1 are part of the main *phase lock loop* (PLL) which stabilizes the phase of received beat note and thus the phase of the optical frequency signal at the remote end of the link.

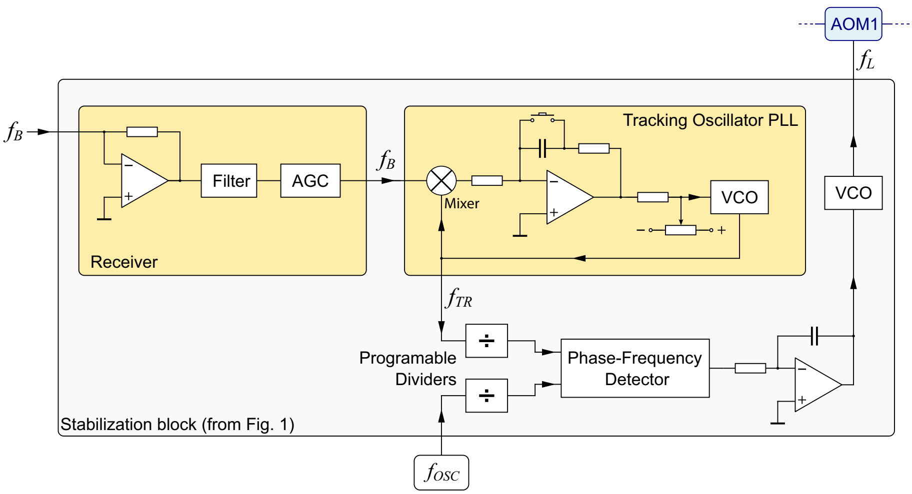

Fig. 2. Block diagram of the optical frequency stabilization block (f_B – frequency of the received beat note, f_L – frequency of signal driving the local modulator AOM1, f_{TR} – output frequency of the tracking oscillator).

The beat note is received by a transimpedance amplifier equipped with an *automatic gain control* (AGC). As phase deviation of the optical frequency signal accumulated in a practical optical path can easily exceed one period, a frequency divider is used to reduce fluctuations at the phase-frequency detector input to an acceptable level to prevent cycle slips. In order to ensure reliable operation of the divider and avoid its metastable behavior, the signal is thoroughly filtered and formed. Initial filtration is carried out by an LC filter in the receiver. However, for accurate narrow-band signal filtration an auxiliary PLL, the so-called tracking oscillator, is used.

The tracking oscillator is a classic PLL in which an analogue mixer is used as a phase detector. In this way, unlike the main loop with a digital phase-frequency detector, the tracking oscillator can tolerate a significant level of input noise [17]. The error amplifier, implemented with the operational amplifier as an integrating circuit to achieve zero phase error, controls the *voltage controlled oscillator* (VCO).

Unfortunately, this type of PLL has a much smaller capture range than the tracking range. After switching the power supply on, when the whole system is not yet synchronized, the frequencies at the input and output of the tracking oscillator usually differ significantly. In such a situation the low frequency component of the mixer's output voltage, which constitutes the error signal, is practically equal to zero. The error amplifier, therefore, integrates the offsets of the operational amplifier and the mixer and, depending on the sign, which is unpredictable, can tune the VCO away from the intended locking point.

What more, a false lock can occur in the tracking oscillator. When the input and VCO frequencies differ, then the mixer's output signal contains a component of the difference in these frequencies. This component causes the VCO frequency modulation, so the output signal contains multiple sidebands. If any of these bands is close to the tracking oscillator's input frequency, it can generate an error signal strong enough to prevent synchronization and keep the loop in a false lock [17].

The effects described cause a situation in which, after switching the power supply on, it is unlikely that the tracking oscillator will lock with the correct frequency. Thus the entire optical frequency transfer system is unlikely to lock automatically.

So far the described problem has usually been solved with an integrator of the tracking oscillator equipped with a switch enabling zeroing the charge on the capacitor. At the same time, the VCO is adjusted in such a way, that when the error amplifier is zeroed (the switch is closed), the output frequency is close enough to the desired frequency of the beat note to allow the tracking oscillator to synchronize. This method is not very convenient because it requires a user's intervention every time the system is turned on as well as in the case of a loss of synchronism caused by temporary disturbances in the link. Moreover, in the case when system conditions change, $e.g.$ as a result of aging or thermal drifts, it may need to be re-adjusted.

3. Tracking oscillator locking mechanism

The problems described in the previous section can be solved by using a supervisory mechanism which measures the tracking oscillator's output frequency f_{TR} and the frequency f_L of the AOM1 control signal at the local station. Note that the frequency to which the tracking oscillator should be locked, f_B, cannot be measured directly because the received signal is weak and noisy. However, according to (4), $f_B = 2f_L + 2f_R$. Since the frequency of the signal driving the AOM2 at the remote station f_R is fixed and known, the actual beat note frequency f_B can be determined at the local station by measuring f_L. (See Fig. 1 for f_B, f_L, f_{OSC}, f_R and Fig. 2 for f_B, f_L, f_{OSC}, f_{TR}).

Knowing the f_{TR} and f_B, it is possible to determine whether the f_{TR} frequency generated by the tracking oscillator's VCO is too high or too low and force its change in the right direction. If the output frequency of the tracking oscillator f_{TR} matches the beat note frequency f_B with the given accuracy ε it can be assumed that the tracking oscillator is synchronized. It is worth noting that f_B and f_{TR} do not have to be exactly equal even when the loop is synchronized, as there can be momentary deviations due to perturbations in the link. The accuracy ε needs to be chosen within the tracking oscillator capture range, so even if it was not synchronized it will lock when f_B and f_{TR} differ by less than ε.

Metrol. Meas. Syst., Vol. 27 (2020), No. 3, pp. 441–450
DOI: 10.24425/mms.2020.134586

The block diagram of the tracking oscillator with the supervisory mechanism working on the given principle is shown in Fig. 3. It contains a microcontroller, which measures the frequencies f_L, f_{TR}, calculates f_B, and determines whether the loop is synchronized. In the case of lack of synchronism, the FREQ_UP or FREQ_DOWN signal is activated and turns an appropriate transistor in the charge pump on for a while. While the transistor is on, the charge is injected thorough the resistor R into the error amplifier. It forces the tracking oscillator's VCO to change its f_{TR} frequency in the desired direction and make the loop synchronize.

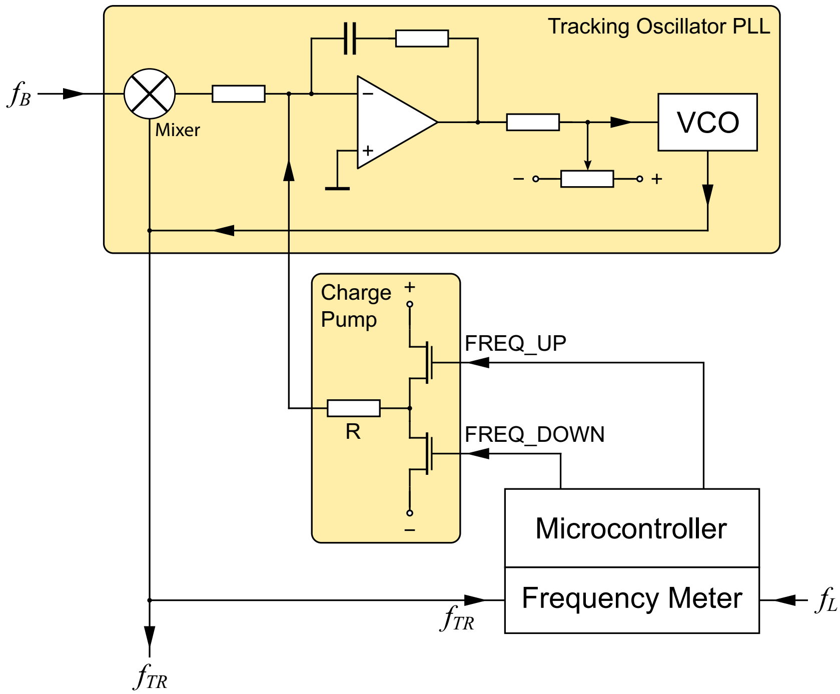

Fig. 3. Diagram of the proposed tracking oscillator monitoring circuit (f_B – frequency of the received beat note, f_L – frequency of signal driving local modulator AOM1, f_{TR} – output frequency of the tracking oscillator).

The value of resistor R is selected to provide sufficient current to overcome the circuit offsets and false lock error signal. On the other hand, in order to avoid VCO frequency hopping back and forth around the desired value, it should be small enough to change the VCO frequency by less than the given accuracy ε before next frequency measurement.

4. The algorithm of the supervisory mechanism

Each millisecond the supervisory mechanism determines the frequencies f_L, f_{TR} and f_B, and takes the action according to the state diagram shown in Fig. 4. The state machine can be in one of four states: frequency monitoring state (ST_MONITOR), frequency comparison state (ST_COMP), state of frequency decrease (ST_DEC) and state of frequency increase (ST_INC). After the startup, it enters the ST_MONITOR state. The frequencies f_B and f_{TR} are compared in this state. If they are equal with the given accuracy ε, then it is assumed that the tracking oscillator is synchronized and the algorithm remains in the ST_MONITOR state.

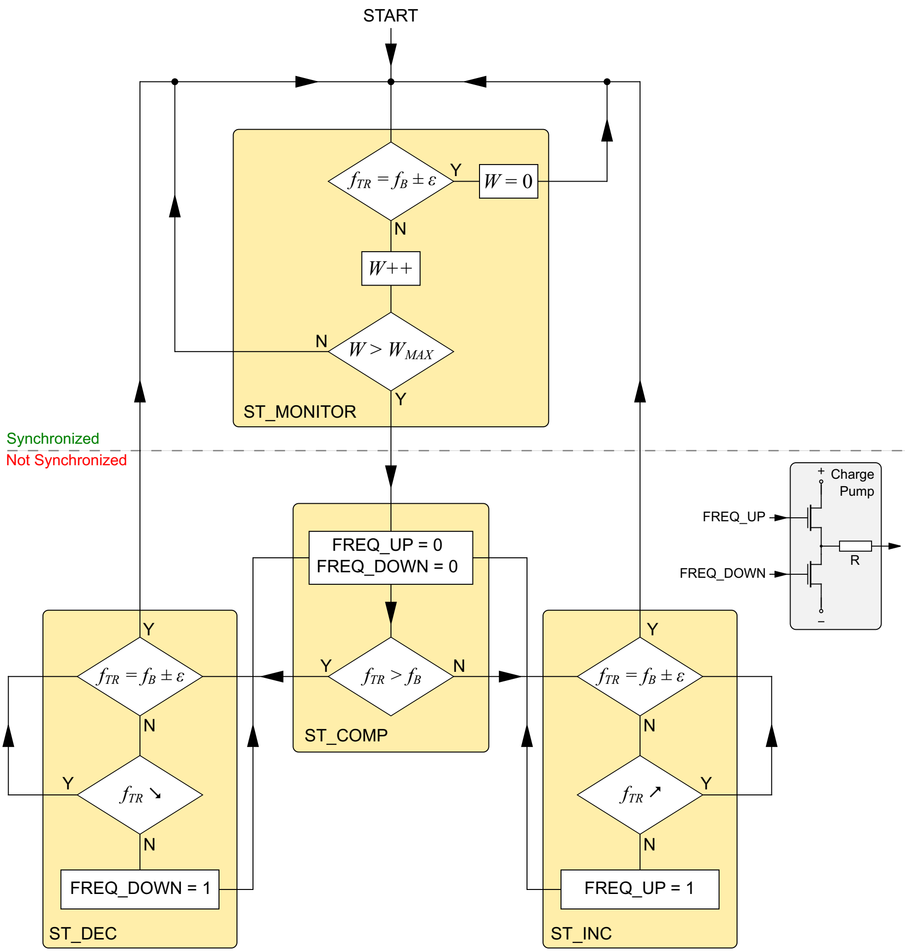

Fig. 4. Algorithm supervising operation of the tracking oscillator. During normal operation the oscillator is synchronized and the algorithm stays in the ST_MONITOR state. In the case of lack of synchronism the algorithm loops between ST_COMP and ST_DEC (or ST_INC) state and activates the charge pump to retune the oscillator.

When the frequencies f_B and f_{TR} do not match, the value of a time counter W is increased, but the algorithm remains in the ST_MONITOR state until the value of the counter exceeds the preset value W_{MAX}. If the frequencies f_B and f_{TR} match before the counter W reaches this limit, it is assumed that the tracking oscillator remains synchronized and the disturbance was temporary. In this case it will be ignored and the counter W will be reset. Thanks to this, temporary disturbances in the operation of the entire system are ignored. As each frequency measurement and each algorithm step takes one millisecond, the counter W reaches the limit when the frequencies f_B and f_{TR} do not match for more than W_{MAX} milliseconds. In this case the state machine recognizes that the loop is not synchronized and goes to the ST_COMP state.

Then, to achieve synchronism, the algorithm loops between ST_COMP and ST_DEC (or ST_INC) states setting the FREQ_DOWN (or FREQ_UP) variable which activates the charge pump and retunes the tracking oscillator until it is synchronized.

www.czasopisma.pan.pl PAN www.journals.pan.pl
Metrol. Meas. Syst., Vol. 27 (2020), No. 3, pp. 441–450
DOI: 10.24425/mms.2020.134586
POLSKA AKADEMIA NAUK

In the ST_COMP state, it is checked if the current output frequency of the tracking oscillator f_{TR} is higher or lower than f_B. Depending on the result of the comparison, in the next step, the machine changes state to ST_DEC or ST_INC.

If the output frequency of the tracking oscillator f_{TR} is higher than f_B, then in order to achieve synchronism it should be lowered. In this case the machine goes to the ST_DEC state when the frequencies of f_{TR} from the current and previous steps of the algorithm sre compared to determine whether the f_{TR} decreases or increases. If the f_{TR} decreases then it is a change in the desired direction and no additional action is needed. The algorithm remains in the ST_DEC state in this case, until the f_{TR} and f_B frequencies are equal with the required accuracy ε. As ε is within the lock-in range, it is assumed that when the f_{TR} and f_B match, the tracking oscillator will synchronize automatically and the algorithm will enter the ST_MONITOR state. However, if the algorithm is in the ST_DEC state and the f_{TR} increases, then the FREQ_DOWN signal is activated, which forces the tracking oscillator's VCO to lower its f_{TR} frequency. After the next frequency measurement the algorithm enters the ST_COMP state and the charge pump is turned off. If the f_{TR} is still too high then the algorithm will enter the ST_DEC state again to check if the frequency changes in the desired direction and activate the charge pump if needed. The cycles will be repeated until $f_{TR} = f_B \pm \varepsilon$.

If the algorithm is in the ST_COMP state and it turns out that the f_{TR} is too low then it enters the ST_INC state. Then its operation is analogous to the operation in the ST_DEC state, but it is focused on increasing the f_{TR} frequency.

It should be noted that the charge injected into the error amplifier is small enough so that the f_{TR} adjustment in a single step is less than ε. Thanks to this, the f_{TR} frequency always reaches f_B from one side and it is not possible to alternate between ST_DEC and ST_INC states continuously.

5. Experimental results

The proposed locking algorithm was implemented using an ARM based microcontroller. The frequencies f_L and f_{TR} were measured using the microcontroller's counters. The accuracy of such a measurement is sufficient as it is much better than accuracy ε. We have proved that in our system false locks appear at about 1.5 MHz difference between f_L and f_{TR} and that the locking range is around ±500 kHz. Then the ε was chosen to be 100 kHz, which is well in the locking range of the tracking oscillator PLL.

The W_{MAX} limit can be chosen deliberately. A low value causes excessive sensitivity to link perturbations and leads to unnecessary actions of relocking, while a large W_{MAX} extends the response time after a loss of lock. In this implementation $W_{\mathrm{MAX}}$was chosen to be 200 ms. We carried out experiments with several values of W_{MAX} and determined that values larger than 100 ms can be safely used (this value can also be obtained by analyzing results in Fig. 6).

The optical frequency transfer system equipped with the described automated locking facility was tested on a fiber optic link with a length of about 110 km. The link consisted of 60 km of optical fiber running through the city and suburban areas around Krakow and 50 km of optical fiber on a spool. In case of vibrations, the fiber on the spool is subjected to them over the entire length, while in a real link the vibrations affect only a certain fragment of the fiber. For this reason, the fiber on the spool is more sensitive to vibration than the fiber in the field. It can be, therefore, assumed that the conditions in the test link used in the experiment are more stressful than it can be expected in a real fiber optic network. In order to control the transmission conditions and how frequent synchronization loss episodes occur, an adjustable optical attenuator was inserted into the optical path. The total attenuation of the optical path was around 28 dB.

A 1560 nm NKT Photonics laser with 100 Hz line width was used as an optical frequency source. The first modulator AOM1 was configured to increase the light frequency by f_L = 40 MHz and the second one (AOM2) to decrease its frequency (f_R = −60 MHz). The f_{OSC} was set to 40 MHz, so, with the stabilization working correctly, the beat note frequency f_B was equal to 40 MHz.

In order to verify the operation of the proposed mechanism, its software was temporarily modified so it cyclically activated FREQ_DOWN or FREQ_UP signal for time long enough to lose synchronization (by forcing the tracking oscillator to generate wrong frequency). Then the described supervision algorithm was run. It was experimentally verified that the proposed method and algorithm were able to recover synchronization of the tracking filter after each such disturbance. The average time needed for the tracking oscillator's re-synchronization was about 260 ms, of which 200 ms was an arbitrarily chosen delay, corresponding to the value of the counter W_{MAX} = 200. This observation time prevents the supervisory algorithm from taking control of tracking oscillator in the case of small disturbances when the tracking oscillator is able to resynchronize itself.

Typical examples of the tracking oscillator synchronization processes are shown in Fig. 5. Figure 5a shows a case in which the algorithm starts with the minimum frequency of the tracking oscillator VCO f_{TR}, whereas Fig. 5b shows the opposite situation, *i.e.* when the initial output frequency of the tracking oscillator f_{TR} has a maximum value. In the drawings, an arrow marks the moment when the supervisory algorithm is started from the ST_MONITOR state. After 200 ms a lack of synchronism is detected and the supervisory mechanism takes control to re-synchronize the PLL. As soon as the frequency f_B reaches f_{TR} with sufficient accuracy ε, the tracking oscillator locks and tracks the received beat note signal. This enables the main loop to synchronize over the

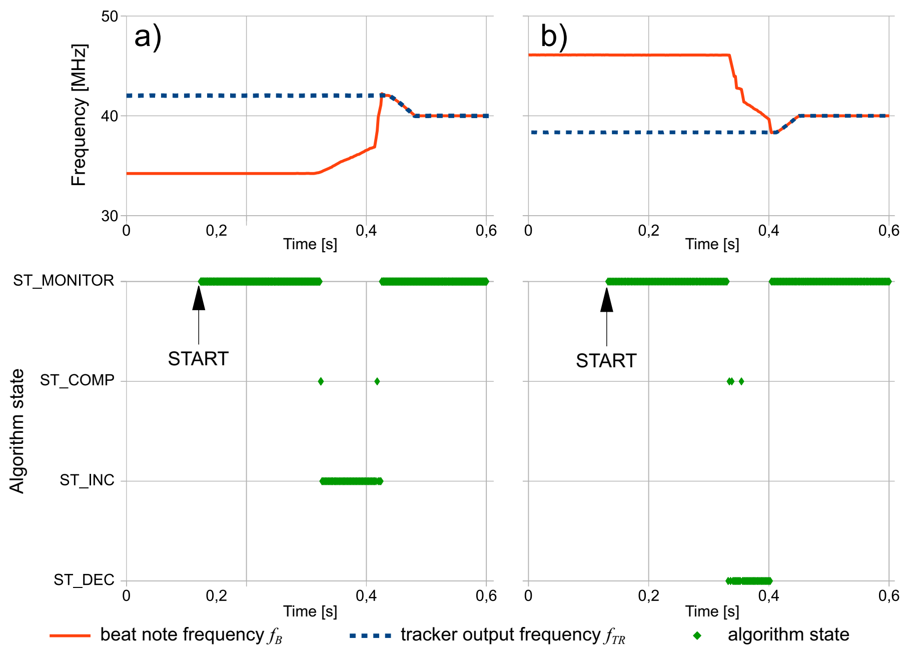

Fig. 5. Transient signals during synchronization. Arrows mark start of the supervisory algorithm.

Metrol. Meas. Syst., Vol. 27 (2020), No. 3, pp. 441–450
DOI: 10.24425/mms.2020.134586

next several dozen milliseconds. As soon as the main loop is synchronized, the optical frequency signal is stabilized and the frequency of the beat note f_B reaches exactly 40 MHz.

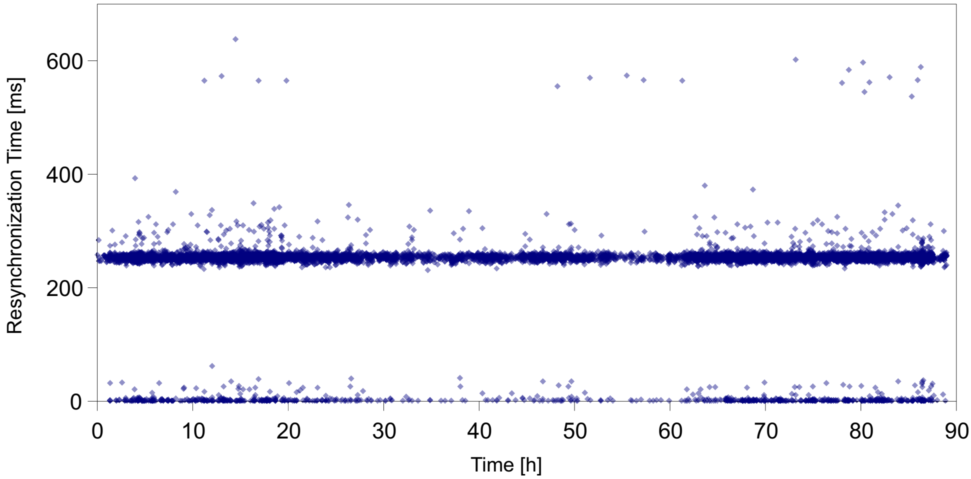

Fig. 6. Time needed for the link to resynchronize in the case of a disturbance. Each dot represents synchronization loss which occurred at some particular time instant.

After recording transients from Fig. 5 normal operation of the algorithm was restored. Then the attenuation in the optical path was increased to a get synchronization break every 50 s on average and the link remained turned on for the next three days. Fig. 6 shows the time needed for the link to resynchronize in each subsequent moment in which the loss of synchronization occurred. It can be seen that there are three categories of such episodes. In the case of small disturbances, the link is able to resynchronize without any additional action and such episodes last no more than several dozen of milliseconds, with majority of them lasting less than a few milliseconds. Just to avoid unnecessary resynchronization action in such cases, the $W_{\mathrm{MAX}} = 200$ ms observation time is implemented in the algorithm. If a disturbance is large, it causes a loss of synchronization. In this case, it is detected after 200 ms and the supervisory algorithm starts resynchronization which last around another 60 ms. In a few cases disturbances caused by human activity in the lab where strong and long which caused two subsequent runs of resynchronization. In these cases the synchronization time doubled and was around 500–600 ms.

Despite many synchronization loss episodes, the optical frequency was stabilized for 99.55% of the time due to the operation of supervisory mechanism. Next, the attenuation was reduced to the previous level, so that the average time between synchronization losses was approximately 17 min. With such a link configuration in measurements lasting another 3 days, the whole system was synchronized for over 99.98% of time.

6. Summary

The presented supervisory mechanism is a step toward the construction of a maintenance-free system for optical frequency transfer. It enables automatic synchronization of the system without the participation of the operator and automatic resumption of operation in the event of a temporary link failure. These events can be logged which allows to monitor the system condition history. It also allows to obtain long periods of correct operation of the system even in very noisy links.

Acknowledgement

This work was supported by the TiFOON 18SIB06 project. The TiFOON project has received funding from the EMPIR program co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation program.

References

[1] Ludlow, A.D., Boyd, M. M., Ye, J., Peik, E., Schmidt, P.O. (2015). Optical atomic clocks. *Reviews of Modern Physics*, 87(2), 637–701.

[2] Huntemann, N., Sanner, C., Lipphardt, B., Tamm, C., Peik, E. (2016). Single-ion atomic clock with 3×10^{-18} systematic uncertainty. *Physical Review Letters*, 116(6), 063001.

[3] Riehle, F. (2017). Optical clock networks. *Nature Photonics*, 11(1), 25–31.

[4] Foreman, S.M., Holman, K.W., Hudson, D.D., Jones, D.J., Ye, J. (2007). Remote transfer of ultrastable frequency references via fiber networks. *Review of Scientific Instruments*, 78(2), 021101.

[5] Williams, P.A., Swann, W.C., Newbury, N.R. (2008). High-stability transfer of an optical frequency over long fiber-optic links. *Journal of the Optical Society of America B*, 25(8), 1284–1293.

[6] Newbury, N.R., Williams, P.A., Swann, W.C. (2007). Coherent transfer of an optical carrier over 251 km. *Optics Letters*, 32(21), 3056–3058.

[7] Droste, S., Ozimek, F., Udem, T., Predehl, K., Hänsch, T.W., Schnatz, H., Grosche, G., Holzwarth, R. (2013). Optical-frequency transfer over a single-span 1840 km fiber link. *Physical Review Letters*, 111(11), 110801.

[8] Lopez, O., Haboucha, A., Chanteau, B., Chardonnet, C., Amy-Klein, A., Santarelli, G. (2012). Ultra-stable long distance optical frequency distribution using the Internet fiber network. *Optics Express*, 20(21), 23518–23526.

[9] Lopez, O., Kanj, A., Pottie, P. E., Rovera, D., Achkar, J., Chardonnet, C., Amy-Klein, A., Santarelli, G. (2013). Simultaneous remote transfer of accurate timing and optical frequency over a public fiber network. *Applied Physics B*, 110(1), 3–6.

[10] Krehlik, P., Schnatz, H., Śliwczyński, Ł. (2017). A hybrid solution for simultaneous transfer of ultra-stable optical frequency, RF frequency, and UTC time-tags over optical fiber. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 64(12), 1884–1890.

[11] Lopez, O., *et al.* (2015). Frequency and time transfer for metrology and beyond using telecommunication network fibres. *Comptes Rendus Physique*, 16(5), 531–539.

[12] Giorgetta, F.R., Swann, W.C., Sinclair, L.C., Baumann, E., Coddington, I., Newbury, N.R. (2013). Optical two-way time and frequency transfer over free space. *Nature Photonics*, 7(6), 434–438.

[13] Kang, H.J., Yang, J., Chun, B.J., Jang, H., Kim, B.S., Kim, Y.J., Kim, S.W. (2019). Free-space transfer of comb-rooted optical frequencies over an 18 km open-air link. *Nature Communications*, 10, 4438.

[14] Guillou-Camargo, F., *et al.* (2018). First industrial-grade coherent fiber link for optical frequency standard dissemination. *Applied Optics*, 57(25), 7203–7210.

[15] Ma, L.S., Jungner, P., Ye, J., Hall, J.L. (1994). Delivering the same optical frequency at two places: accurate cancellation of phase noise introduced by an optical fiber or other time-varying path. *Optics Letters*, 19(21), 1777–1779.

[16] Wang, G., Yao, Y., Yan, T., Bian, L., Meng, Y. (2019). A new optical frequency transfer method via fibre based on active phase noise compensation with single acousto-optic modulator. *Metrology and Measurement Systems*, 26(1), 115–124.

[17] Gardner, F.M. (1979). *Phaselock Techniques, Second Edition*. John Wiley & Sons, Inc.