Digital output compensation for precise frequency transfer over commercial fiber link*

CI Cheng (慈骋)[1], WU Hong (吴虹)[1], TANG Ran (唐然)[1], LIU Bo (刘波)[1,2], CHEN Xing (陈星)[3], ZHANG Xue-song (章学松)[1], ZHANG Yu (张瑜)[1], and ZHAO Ying-xin (赵迎新)[1]**

1. *Tianjin Key Laboratory of Optoelectronic Sensor and Sensing Network Technology, Institute of Electronic Information and Optical Engineering, Nankai University, Tianjin 300071, China*
2. *Key laboratory of Optical Information Science and Technology, Ministry of Education, Nankai University, Tianjin 300071, China*
3. *Institute of Quantum Electronics, School of Electronics Engineering and Computer Science, Peking University, Beijing 100871, China*

(Received 27 September 2017; Revised 13 November 2017)

An ultra-highly precise and long-term stable frequency transmission system over 120 km commercial fiber link has been proposed and experimentally demonstrated. This system is based on digital output compensation technique to suppress phase fluctuations during the frequency transmission process. A mode-locked erbium-doped fiber laser driven by a hydrogen maser serves as an optical transmitter. Moreover, a dense wavelength division multiplexing system is able to separate forward and backward signals with reflection effect excluded. The ultimate fractional frequency instabilities for the long-distance frequency distributed system are up to 3.14×10^{-15} at 1 s and 2.96×10^{-19} at 10 000 s, respectively.
Document code: A **Article ID:** 1673-1905(2018)02-0109-5
DOI https://doi.org/10.1007/s11801-018-7220-0

Due to the need for long-distance highly stable frequency transfer, radio frequency transfer via fiber links has attracted growing research interests in recent years[1-7]. Its prerequisite is to considerably improve the frequency stability of atomic clock serving as the frequency reference[8-10]. Moreover, compared with free-space radio frequency transfer, fiber-optic links are more desirable for their low attenuation and high reliability[11,12]. And the key issue is to employ electrical-optical converters in long-distance frequency transfer fiber links. In these techniques, since periodic optical pulses could provide highly accurate repetition rate and high signal-to-noise ratio, mode-locked lasers (MLLs) are normally used as optical transmitters[2-4,7]. Therefore, precise radio frequency transfer has been widely applied in various cutting-edge scientific as well as engineering areas, from microwave and optical communications[13-16] to optical frequency metrology for accurate positioning and navigation applications[11,17,18].

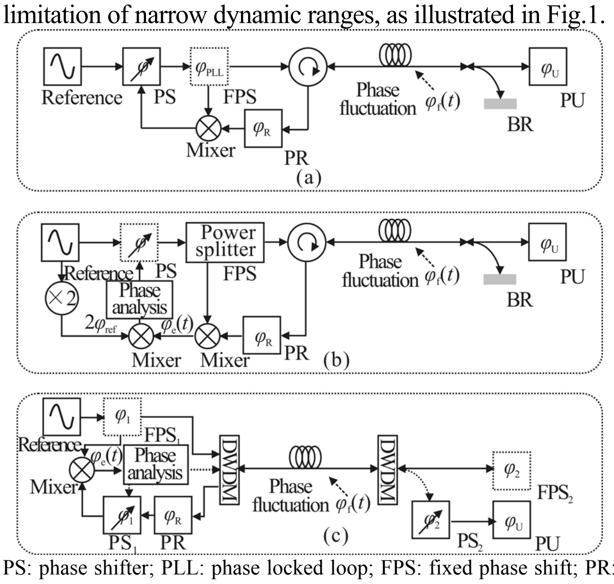
Although fiber link transfer is an attractive approach for topological distribution, the greatest challenge is environmental perturbation, such as physical vibration and temperature changes, which will result in phase fluctuation during the frequency transmission process. A variety of efficient methods, including optical group delay[1,2] and electronic compensation techniques[3-7], have been proposed in recent years to suppress phase noises caused by environment perturbation. O. Lopez et al[1] utilized optical delay lines for different dynamic ranges to correct fast as well as slow phase perturbations, by which frequency dissemination could be achieved over an 86-km urban optical link with a fractional frequency instability of 1.3×10^{-15} at 1 s integration time. Giuseppe Marra et al[2] demonstrated a transfer compensation model with a fiber stretcher and a thermally controlled spool, which helped to achieve a 1 s fractional transfer instability of 5×10^{-15} over 86 km fiber link. The optical group delay method is limited by its narrow dynamic range. For longer fiber link systems, phase drift during the frequency transfer process may accumulate over the compensation range. Moreover, the measurement precision is limited by increased fiber length introduced by the fiber stretcher or delay line. To resolve this issue, electronic compensation techniques have been proposed based on phase detectors and phase shifters[3-7]. Bo Ning et al[3] employed pump power modulation technique in combination with a phase shifter to precisely control phase shift within a wider dynamic range, and the frequency instability reached 6.6×10^{-18} at 16 000 s. However, all of the aforementioned methods are based on fiber splicing without introduction of interconnectors, which allows for reflection at remote end with an optical circulator at the local end to separate the

* This work has been supported by the National Natural Science Foundation of China (Nos.61571244 and 61501262), the Science and Technology Project of Tianjin (No.16YFZCSF00540), and the Natural Science Foundation of Tianjin (No.15JCYBJC51600).
** E-mail: zhaoyx@nankai.edu.cn

feedback signal and the emission signal. This scheme may not be applicable for the commercial fiber distribution system presented in this work.

We have proposed and experimentally demonstrated an ultra-highly stable and long-term phase-locked loop system for synchronization of an optical frequency comb laser to a hydrogen maser in our previous work[8]. In this letter, the mode-locked erbium-doped fiber laser (MLEDFL) is still used as a radio-to-optical wave converter without stability loss. And we will demonstrate a radio frequency dissemination system over a 120-km commercial urban fiber distribution link based on digital output compensation (DOC) technique. Moreover, dense wavelength division multiplexing (DWDM) system, bi-directional erbium-doped fiber amplifier (EDFA) system and data transceiver module have been also utilized in our system for frequency dissemination.

In our previous work, by using optical delay line and fiber stretcher, we have employed the optical group delay technique to suppress the phase fluctuations induced by environmental perturbations during frequency dissemination process. However, the phase drift over the 120-km commercial fiber link is over the compensation ranges of the above two devices. In successive experiments, an electronic compensation system is employed to overcome the limitation of narrow dynamic ranges, as illustrated in Fig.1.



PS: phase shifter; PLL: phase locked loop; FPS: fixed phase shift; PR: phase of return signal; BR: back reflector; PU: phase at user end; DWDM: dense wavelength division multiplexing

Fig.1 Schematic diagrams of (a) basic phase compensation system, (b) feedback phase compensation system, and (c) improved DOC system

Fig.1(a) shows the schematic diagram of basic phase compensation system[4,19]. A reference source with the initial phase of φ_{ref} is firstly shifted by $\varphi_{PS}(t)$ using an electronic phase shifter and then a fixed phase shift of φ_{PLL} is applied by employing mode-locked fiber laser. Phase fluctuation $\varphi_f(t)$ is introduced into the signal during the frequency dissemination process. At remote end, the backward reflection signal is generated through a back reflector. The phase shift for each process when the source signal transits from the source to its destination could be expressed as

$$\varphi_L(t)=\varphi_{ref}+\varphi_{PS}(t)+\varphi_{PLL}, \quad (1)$$

$$\varphi_U(t)=\varphi_{ref}+\varphi_{PS}(t)+\varphi_{PLL}+\varphi_f(t), \quad (2)$$

$$\varphi_R(t)=\varphi_{ref}+\varphi_{PS}(t)+\varphi_{PLL}+2\varphi_f(t), \quad (3)$$

where $\varphi_L(t)$, $\varphi_U(t)$ and $\varphi_R(t)$ denote the phases for local site, user end and returned site, respectively. In consideration of the bi-directional propagating signal through the same fiber link[20], according to Eq.(3), the phase fluctuation for the round trip fiber link is $2\varphi_f(t)$. By mixing $\varphi_L(t)$ and $\varphi_R(t)$, we can obtain the phase fluctuation $\varphi_f(t)$ after a low-pass filter using a phase detector[4]. In order to stabilize the user end signal, according to Eq.(2), the relationship between $\varphi_{PS}(t)$ and $\varphi_f(t)$ could be simply expressed as

$$\varphi_{PS}(t)+\varphi_f(t)+\text{Constant}=0. \quad (4)$$

In this way, the phase correction value could be acquired to eliminate the phase fluctuation during the frequency dissemination process. However, the error signal calculation method has so serious drawback that the relationship between the phase and the voltage retrieved from the error signal is nonlinear. Hence, it is rather difficult to acquire the exact phase error signal for compensation. Even though other phase analysis system has been proposed to calculate the phase, such difficulties as uncertain amplitude and low voltage-phase resolution also make it hard to estimate the exact phase error signal[20]. In this case, we need to set up a new compensation structure instead.

The improved feedback phase compensation system is proposed[5,6], as illustrated in Fig.1(b). In this scheme, the PLL-locked laser is not utilized. Consequently, after mixing $\varphi_L(t)$ with $\varphi_R(t)$, the error signal $\varphi_e(t)$ passing through a band-pass filter could be described as

$$\varphi_e(t)=2\varphi_{ref}+2\varphi_{PS}(t)+2\varphi_f(t). \quad (5)$$

In the meantime, the reference signal is doubled by using a frequency multiplier to acquire a phase signal of $2\varphi_{ref}$. By mixing the two signals and processing by a low-pass filter, the final error signal could be expressed as $2\varphi_{PS}(t)+2\varphi_f(t)$. In this way, Eq.(4) could be satisfied through maintaining the final error signal constant, so that the user end signal is stabilized accordingly.

However, all of the aforementioned reflection methods are not applicable for the complex commercial urban fiber distribution system presented in this work, as the introduction of interconnectors at the fiber splicing may cause signal reflection and interference to transmissions. In this case, an improved DOC structure is proposed, as shown in Fig.1(c). Instead of using reflection methods, a DWDM system is utilized for transferring forward and backward signals. Moreover, phase-locking technique has been used for synchronization of the MLEDFL to a hydrogen maser without stability loss. In Fig.1(c), φ_1 and φ_2 denote the fixed phase shifts in the phase-locking system. Besides, $\varphi_{PS1}(t)$ and $\varphi_{PS2}(t)$ denote two electronic phase shifters utilized in this method. One is used for feedback compensation of the round trip fiber link, while the other is used for digital output compensation at the user end. The phase shift for each section of this system could be expressed as

$$\varphi_L(t)=\varphi_{ref}+\varphi_1, \quad (6)$$

$$\varphi_U(t)=\varphi_{ref}+\varphi_1+\varphi_f(t) \ +\varphi_{PS2}(t), \quad (7)$$

$$\varphi_R(t)=\varphi_{ref}+\varphi_1+\varphi_2+2\varphi_f(t). \quad (8)$$

The return signal in Eq.(8) passes through an electronic phase shifter at local site and is mixed with the local signal in Eq.(6). Afterwards, the error signal is processed by a low-pass filter and could be simply expressed as

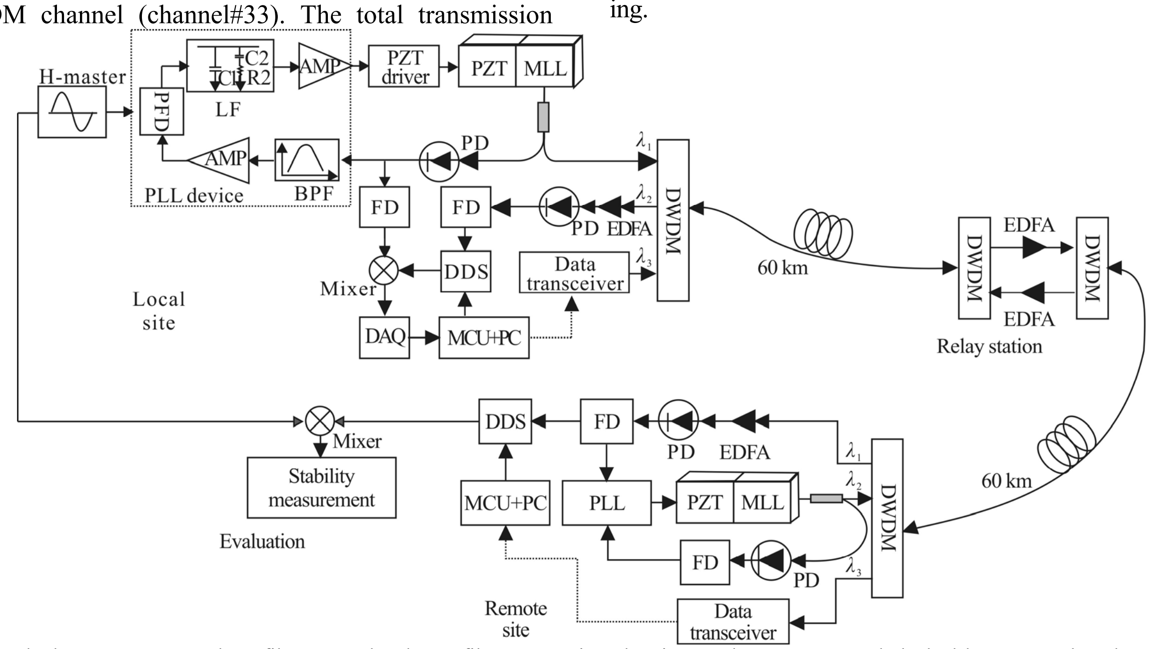
$$\varphi_e(t)=\varphi_2+\varphi_{PS1}(t) \ +2\varphi_f(t). \quad (9)$$

The feedback compensation loop detects the phase fluctuations and sends the digital error value to the phase shifter at the remote site. Afterwards, we set the compensation phase value at the user end to half of the one at the local site. Thus we have

$$\varphi_{PS1}(t)=2\varphi_{PS2}(t). \quad (10)$$

In this way, the phase relationship between $\varphi_{PS2}(t)$ and $\varphi_f(t)$ could be obtained. By keeping the final error signal in Eq.(9) as a constant, Eq.(4) could be satisfied and the user end signal in Eq.(7) could be stabilized to realize output phase compensation.

Fig.2 shows the schematic diagram of the improved DOC frequency transfer system. At local (emission) site, a highly reliable H-maser with a frequency instability of 1.5×10^{-15} at 10 000 s is utilized as the reference to generate 10-MHz radio frequency signal. An MLEDFL with a repetition rate of 100 MHz and an average output power of 22 mW serves as a radio to optical converter for frequency transfer over a long distance fiber link. In the meanwhile, a PLL-device synchronizes the laser output signal to the reference. 1% of the laser output signal is fed into a low-noise photodetector (Newport 1611FC-AC) for frequency locking and phase compensation, while the remnant signal is coupled into a DWDM channel (channel#33). The total transmission loss measured for the fiber link is about 40 dB. And a relay station is settled at the center of the 120-km fiber link for simultaneous amplification of the forward and backward propagating signals. We set up a bidirectional EDFA structure at the relay station, which consists of two low-noise EDFAs and two identical DWDM components. At remote (user) site, the laser output signal is received in channel#33 by a DWDM coupler, which will pass through a MCU-controlled DDS (AD9910) to recover and transfer signals to the user end. In the meanwhile, the received signal is used as the reference to synchronize another MLL through the PLL device. Afterwards, the new locked laser output signal is coupled into channel#34 of the DWDM for backward frequency dissemination. Furthermore, a data transceiver module is introduced at both ends of the transmission loop. Once the phase fluctuations are detected at local site, an optical communication will be established for transferring the digital error by using a pair of standard small form pluggable (SFP) optical transceivers at both sites. Since it is far away from the main frequency dissemination channels, channel#36 is selected to avoid possible inter-channel crosstalk. In order to evaluate the performance of the proposed system, local site and remote site are settled at the same laboratory in LB town. In the meanwhile, the relay station is placed in another city, KT town, which is connected by a pair of 60-km long underground fibers as shown in Fig.2. For evaluation, the reference signal from the H-maser and the laser output signal at the user end are mixed together to test the frequency instability. A pre-amplifier (SR560) is used after the mixer to filter out the unwanted high-order harmonic frequency component and to amplify the direct current (DC) signal as well. Afterwards, a DAQ card (NI 6251) logs the DC signal at the sampling rate of 100 Hz and sends the data to the PC for future processing.



H-maser: hydrogen maser; LF: loop filter; BPF: band-pass filter; PZT: piezoelectric transducer; MLL: mode-locked laser; PD: photodetector; FD: frequency divider; EDFA: erbium-doped fiber amplifier; DDS: direct digital synthesizer; DAQ: data acquisition; MCU: micro control unit; PC: personal computer

Fig.2 Experimental setup of the high-precision frequency transfer system with improved DOC technique

For typical telecommunication fiber links, the temperature coefficient of propagation delay is about 38 ps/(km·K)[21], which will lead to about 4.56 ns/K propagation delay in the 120 km commercial fiber link. It is obvious that without compensation the fiber temperature change will cause slow but dominant phase variations in our proposed system. Consequently, in order to verify the compensation performance, we employ another DDS device (DDS_1 shown in Fig.3(a)) to introduce phase jitter artificially. The output of the mixers could reflect the phase difference between the H-maser and signals at remote site. As shown in Fig.3(b), the output of $mixer_1$ is within −2.5 V and 2.5 V, which represents the phase difference between the H-maser and uncompensated signal. For comparison, the output of $mixer_2$ is almost close to zero, which indicates the compensation is effective.

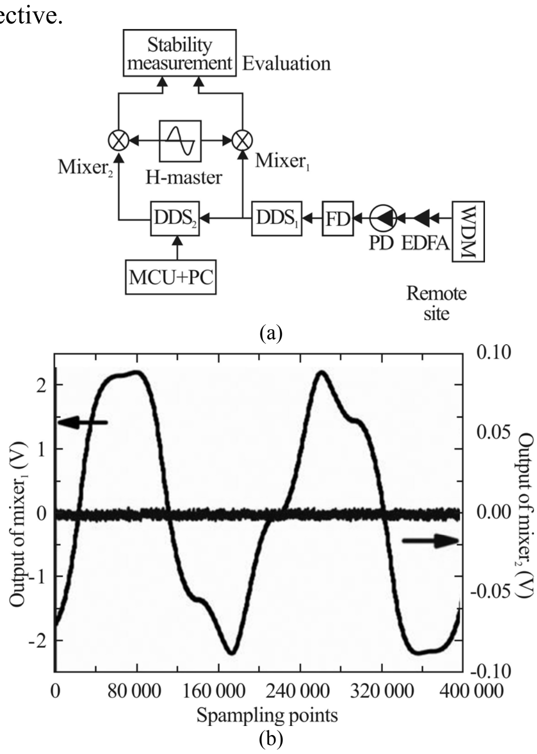


Fig.3 (a) Experimental setup for stability measurement; (b) Evaluation results of phase compensation

The commercial urban fiber distribution system adopted in this work is complex, and traditional reflection method based on optical circulators is not applicable due to the Fresnel reflection caused by the interconnectors. We have proposed the high precision frequency transfer system based on the following considerations: firstly, a PLL device is employed to lock the laser output signal for reference frequency stabilization rather than direct transfer of laser generated pulses[5,6]; secondly, a DWDM system is introduced into the dissemination loop, which could produce 0.8-nm-spacing DWDM channel signals and suppress Fresnel reflection; moreover, the bidirectional EDFA at the relay station and the MLL at the remote site would help to improve signal-to-noise ratio for accurate and long distance frequency transfer; finally but most importantly, the DOC system is set up to detect the phase error generated by the close feedback loop and recover the phase signal at the user end through the data transceiver model.

All of the aforementioned points are acceptable and the fractional frequency instability is described in overlapping Allan deviation[22], as illustrated in Fig.4.

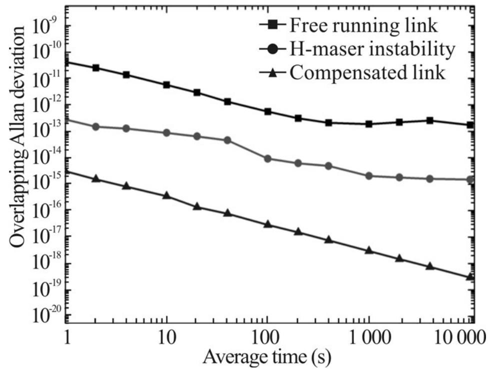


Fig.4 Measured fractional frequency instability of the DOC frequency transmission system

As frequency reference, the frequency instabilities of the H-maser are 2.84×10^{-13} and 1.5×10^{-15} at 1 s and 10 000 s, respectively. Meanwhile, the fractional frequency instabilities of our long-term frequency transmission system over 120 km commercial fiber link are experimentally proved to be 3.14×10^{-15} at 1 s and 2.96×10^{-19} at 10 000 s, respectively. For comparison, the measured fractional frequency instability of frequency transmission fiber link without compensation is just 4.2×10^{-11} at 1 s and 1.72×10^{-13} at 10 000 s, which indicates that our DOC structure works efficiently to ensure a long-term stability of frequency transmission system over a long distance commercial urban fiber link.

In summary, we have proposed a frequency transmission system with ultrahigh precision and long-term stability. In this system, a phase-locked MLEDFL is utilized as an optical transmitter. Besides, DWDM technology is employed in our system for frequency dissemination, which is able to produce 0.8-nm DWDM channels and suppress Fresnel reflection. Most importantly, the transmission system is compensated by the DOC structure and the fractional frequency instability could be considerably improved. A frequency transmission system over a 120 km commercial urban fiber link has been established to acquire fractional frequency instabilities of 3.14×10^{-15} at 1 s and 2.96×10^{-19} at 10 000 s in overlapping Allan deviation. Experimental results indicate that our proposed DOC system has good long-term stability and high precision, which ensures its potential applications in high-precision radio frequency transfer.

References

[1] O. Lopez, A. Amyklein, M. Lours, C. Chardonnet and G. Santarelli, Applied Physics B Lasers & Optics **98**, 723 (2009).

[2] G. Marra, R. Slavík, H.S. Margolis, S.N. Lea, P. Petropoulos, D.J. Richardson and P. Gill, Optics Letters **36**, 511 (2011).

[3] B. Ning, P. Du, D. Hou and J. Zhao, Optics Express **20**, 28447 (2012).

[4] D. Hou, P. Li, C. Liu, J. Zhao and Z. Zhang, Optics Express **19**, 506 (2011).

[5] J. Zhao, D. Li, B. Ning, S. Zhang and W. Duan, Optics Express **23**, 8829 (2015).

[6] J. Shen, G. Wu, L. Hu, W. Zou and J. Chen, Optics Letters **39**, 2346 (2014).

[7] X. Chen, J. Lu, Y. Cui, J. Zhang, X. Lu, X. Tian, C. Cheng, B. Liu, H. Wu and T. Tang, Scientific Reports **5**, 18343 (2015).

[8] C. Ci, X. Zhang, X. Li, X. Chen, Y. Cui, Y. Zhao, B. Liu and H. Wu, Applied Optics **55**, 6747 (2016).

[9] N. Hinkley, J.A. Sherman, N.B. Phillips, M. Schioppo, N.D. Lemke, K. Beloy, M. Pizzocaro, C.W. Oates and A.D. Ludlow, Science **341**, 1215 (2013).

[10] B.J. Bloom, T.L. Nicholson, J.R. Williams, S.L. Campbell, M. Bishof, X. Zhang, W. Zhang, S.L. Bromley and J. Ye, A New Generation of Atomic Clocks: Accuracy and Stability at the 10^{-18} Level, 2013.

[11] P.H. Dana, Real-Time Systems **12**, 9 (1997).

[12] F.R. Giorgetta, E. Baumann, W.C. Swann, L.C. Sinclair, I. Coddington and N.R. Newbury, Performance Analysis of Optical Free-space Two-way Time-frequency Transfer, Applications of Lasers for Sensing and Free Space Communications, 2013.

[13] B. Wang, C. Gao, W.L. Chen, J. Miao, X. Zhu, Y. Bai, J.W. Zhang, Y.Y. Feng, T.C. Li and L.J. Wang, Scientific Reports **2**, 556 (2011).

[14] M.T.L. Hsu, Y. He, D.A. Shaddock, R.B. Warrington and M.B. Gray, IEEE Photonics Technology Letters **24**, 1015 (2012).

[15] K. Jung, J. Shin, J. Kang, S. Hunziker, C.K. Min and J. Kim, Optics Letters **39**, 1577 (2014).

[16] S. Droste, F. Ozimek, T. Udem, K. Predehl, T.W. Hänsch, H. Schnatz, G. Grosche and R. Holzwarth, Physical Review Letters **111**, 1 (2013).

[17] G. Santarelli, F. Narbonneau, M. Lours, D. Chambon, S. Bize, A. Clairon, C. Daussy, O. Lopez and M.E. Tobar, High Performance Frequency Dissemination for Metrology Applications with Optical Fibers, Proceedings of the 2005 IEEE International Frequency Control Symposium and Exposition, 2005.

[18] K. Predehl, G. Grosche, S.M. Raupach, S. Droste, O. Terra, J. Alnis, T. Legero, T.W. Hänsch, T. Udem and R. Holzwarth, Science **336**, 441 (2012).

[19] G. Lutes, Development of Optical Fiber Frequency and Time Distribution Systems, DTIC Document, 1981.

[20] F. Narbonneau, M. Lours, S. Bize, A. Clairon, G. Santarelli, O. Lopez, C. Daussy, A. Amy-Klein and C. Chardonnet, Review of Scientific Instruments **77**, 064701 (2006).

[21] P. Krehlik, M. Lipiński and Ł. Śliwczyński, Measurement Science & Technology **21**, 075302 (2010).

[22] W.J. Riley, Handbook of Frequency Stability Analysis, NIST SP-1065, 1 (2007).