C. R. Physique 16 (2015) 524–530

Contents lists available at ScienceDirect

Comptes Rendus Physique

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Optical frequency dissemination for metrology applications

Dissémination de fréquences optiques pour applications métrologiques

Stefan Droste[a,*], Thomas Udem[a], Ronald Holzwarth[a,b],
Theodor Wolfgang Hänsch[a,c]

[a] *Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, 85748 Garching, Germany*
[b] *Menlo Systems GmbH, Am Klopferspitz 19a, 82152 Martinsried, Germany*
[c] *Ludwig-Maximilians Universität, Schellingstrasse 4, 80799 München, Germany*

ARTICLE INFO

Article history:
Available online 8 April 2015

Keywords:
Optical fiber link
Frequency transfer
Optical atomic clock
Lasers

Mots-clés :
Fibre optique
Transfert de fréquence
Horloge atomique
Lasers

ABSTRACT

With the progress in the development of optical frequency standards grows the demand for the dissemination of stable optical frequencies. To date, optical fiber links constitute the most promising medium to bridge large geographical distances while still maintaining a high degree of frequency stability and accuracy. We investigated the transfer of an optical frequency along different fiber links during the past years and achieved a fractional instability and uncertainty at a level lower than 10^{-19} using fiber links with lengths of up to almost 2000 km. We give an overview of different techniques and methods that can be used in combination with optical fiber links to achieve a stable frequency transfer. The results of different fiber links are summarized and an outlook of future links is given.

RÉSUMÉ

Avec les progrès réalisés dans le développement de standards de fréquences optiques, les besoins en matière de dissémination de fréquences optiques stables augmentent. À ce jour, la fibre optique constitue le moyen le plus prometteur pour relier de grandes distances géographiques tout en maintenant une haute exigence en matière de stabilité et de précision en fréquence. Nous avons étudié le transfert d'une fréquence optique par différentes fibres au cours des dernières années et avons atteint une instabilité fractionnelle et une imprécision à un niveau inférieur à 10^{-19} pour des fibres optiques couvrant une longueur de presque 2000 km. Nous donnons un aperçu de différentes techniques et méthodes qui peuvent être utilisées en combinaison avec des fibres optiques pour obtenir un transfert de fréquence stable. Les résultats obtenus pour différentes fibres optiques sont résumés et un aperçu des futurs développements du transfert par fibre est donné.

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[*] Corresponding author.
E-mail address: stefan.droste@nist.gov (S. Droste).

http://dx.doi.org/10.1016/j.crhy.2015.03.011

1. Introduction

Precise frequency references constitute the corner stone for many precision measurements in modern science. This is due to the fact that no other physical quantity can be measured with a better accuracy than frequencies. To take advantage of this, the measurement variables of various experiments are converted into a frequency whenever possible, which is then determined by comparing it to a well-known reference. The most stable frequency references are generated by frequency standards that use atomic transitions as an oscillator. Nowadays, the precision and instability of these frequency references approaches 1×10^{-18} if an optical transition is chosen [1–6]. Experiments that require the highest degree of precision directly profit from these impressively stable and accurate references [7,8].

Some applications, as for instance in the telecommunication industry, require a relative frequency precision of $\approx 1 \times 10^{-8}$ for the synchronization of base stations [9]. These requirements are routinely met by commercial cesium or rubidium frequency standards that can be operated on site [10]. More stringent requirements to the frequency reference are set by high-precision experiments that demand a frequency uncertainty on the order of $\approx 1 \times 10^{-14}$ or below [11]. For these applications, commercial active hydrogen masers are often used that provide a frequency reference with an instability of about 1×10^{-15}. Due to the high costs of those devices, hydrogen masers are mostly found in major precision measurement laboratories. State-of-the-art optical clocks to date generate frequencies with fractional uncertainties of below 1×10^{-17} and instabilities of a few parts in 10^{18} [1–3]. Optical clocks as well as atomic fountain clocks are not commercially available and mostly require a laboratory environment due to their complexity and sensitivity. For the same reason, they can hardly be transported.

To still be able to take advantage of these stable oscillators, it is desirable to transfer the frequency information from the clock location to distant sites. With the availability of satellites and the invention of global satellite navigation, stable frequencies can be transferred to basically every point on the surface of the earth [12]. The microwave transfer between satellites and ground stations, however, is limited to an instability and accuracy of $> 10^{-16}$ [13]. It therefore supports most microwave frequency sources, but is inadequate for the dissemination of optical clock signals. In the past years, optical frequency transfer using fiber links has gained substantial attention due to the ability to deliver optical frequencies with instabilities and accuracies of a few parts in 10^{19} [14–17]. It should be pointed out, however, that despite this good performance, a comparison of optical clocks on the level of 10^{-18} first requires a precise determination of the gravitational potential difference between the clock locations to verify that potential deviations between the clock outputs do not originate from relativistic effects [7]. In this report, we give an overview of the principles and methods of carrier-wave-fiber-based frequency transfer. The fiber links investigated in our group are briefly reviewed, while the longest link is discussed in more detail. We also show a prediction for the expected frequency instability of future long-distance fiber links.

2. Principles of fiber based frequency transfer

For the last several years, experiments on the transfer of frequencies via optical fibers have been performed with ever-increasing performance and fiber lengths. Different methods using optical signals for the transfer of frequencies have been investigated. An optical signal provided by a continuous wave (cw) laser can be amplitude modulated before it is sent through a fiber link [18], thereby transferring a microwave frequency. A combined transfer of microwave and optical frequencies can be achieved by transmitting pulses from a mode-locked laser [19]. Femtosecond pulses can also be used in combination with an optical cross-correlation technique to deliver a stable timing signal to a remote location [20,21]. Furthermore, an optical carrier wave can be disseminated by transferring the light of a stable cw laser. While for short distances up to a few tens of kilometers, all four methods show formidable performances, the latter one has been demonstrated to achieve excellent results in long-distance frequency transfer, due to the high carrier frequency and since no dispersion management is required.

In addition to the higher oscillating frequency, it is nowadays possible to generate optical frequencies with extremely low fractional instabilities below 10^{-15} in 1 s [22,23]. Furthermore, the telecommunication industry did tremendous pioneering work by investigating the transmission of light through glass fibers. The well-developed countries in Western Europe feature a large and dense glass fiber network that is mainly used for Internet data traffic. Therefore, using glass fibers to coherently transmit an optical carrier is an obvious approach.

In contrast to sending light over free-space [20], light that is transmitted through fibers experiences less perturbations, which enables better performance. Nevertheless, deployed fibers are, to some extent, inevitably subject to the environment that can affect the properties of the light that travels through them. The most prominent perturbations on optical fibers are thermal fluctuations and acoustic vibrations. Those perturbations lead to variations of the physical fiber length and to fluctuations of the fiber's refractive index. This in turn changes the optical path length and causes phase shifts often referred to as Doppler noise. These phase fluctuations set limits on the achievable stability and accuracy of the transmitted signal. If an optical frequency of 194 THz is transmitted through a 1000-km-long standard single-mode fiber (as in our experiments) that is affected by a temperature variation of 1 K during the course of one day, a fractional frequency shift of about 4×10^{-13} is introduced. Consequently, the fiber-induced phase fluctuations have to be detected and compensated in order to achieve a high stability and accuracy of the transferred frequency.

A simplified setup for the optical-fiber-based frequency transfer is shown in Fig. 1. An optical oscillator that consists of a cw laser operating at a wavelength of 1542 nm generates a stable optical signal. The light of this laser enters a Michelson