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The measurement of time / La mesure du temps

Frequency and time transfer for metrology and beyond using telecommunication network fibres

Transfert d'une référence de temps ou de fréquence par fibre optique pour la métrologie et au-delà

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ABSTRACT

The distribution and the comparison of an ultra-stable optical frequency and accurate time using optical fibres have been greatly improved in the last ten years. The frequency stability and accuracy of optical links surpass well-established methods using the global navigation satellite system and geostationary satellites. In this paper, we present a review of the methods and the results obtained. We show that public telecommunication network carrying Internet data can be used to compare and distribute ultra-stable metrological signals over long distances. This novel technique paves the way for the deployment of a national and continental ultra-stable metrological optical network.

RÉSUMÉ

La distribution et la comparaison d'étalons de fréquence optique ultra-stables et d'échelle de temps ont été grandement améliorées depuis dix ans par l'emploi de fibres optiques. La stabilité de fréquence et l'exactitude des liens optiques fibrés surpassent les méthodes bien établies fondées sur les communications satellitaires. Dans cet article, nous présentons les méthodes et les résultats obtenus pendant cette décennie. Nous montrons que les réseaux de télécommunication publics transportant des données Internet peuvent être utilisés pour

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comparer et distribuer des signaux métrologiques sur de grandes distances. Ceci ouvre la voie au déploiement d'un réseau métrologique à l'échelle nationale et continentale.

1. Introduction

Frequency metrology has developed considerably over the past ten years and has benefitted from scientific advances in the areas of atomic laser cooling and femtosecond frequency combs. Today cold-atom microwave frequency standards routinely reach a fractional accuracy approaching 10^{-16} [1–3]. Trapped-ion or neutral-lattice optical clocks have already demonstrated accuracy in the low 10^{-17} and stability down to 10^{-18} or better in several laboratories [4–8]. This outstanding performance makes them ideal tools for laboratory tests of the validity of General Relativity (see for instance [7,9,10]). Among them, the comparison of different types of clocks is used to detect possible temporal variations of fundamental physical constants [11–13]. More generally, accurate time and frequency transfer is essential for relativistic geodesy, high-resolution radio astronomy, and is the basis of almost every type of precision measurement.

Until recently, the conventional means for remote frequency transfer was based on the processing of satellite radio-frequency signals, the Global Navigation Satellite System (GNSS), or dedicated satellite transfer [14]. Optical fibre links have shown potential to transfer frequency with much better accuracy and stability. The use of intensity modulated optical carriers around 1.55 μm (telecommunication window) to transfer radio-frequency or microwave signals have already been successfully demonstrated up to hundreds of kilometers over dedicated fibre routes [15–20]. A significant leap forward can be achieved using the optical phase of the optical carrier at 200 THz (1.55 μm) to transfer an extremely accurate and ultra-stable frequency reference over long distances. The high sensitivity detection of the optical phase using heterodyne methods in conjunction with spectrally very pure lasers, are the basic tools to achieve low-noise optical frequency transfer. In the last decade, several experiments in Europe, USA and Japan have explored the limits of this method, paving the way for a new generation of ultra-stable optical networks [18,21–31]. A ground-breaking frequency transfer has been demonstrated on a record distance of 920 km and even 1840 km on a dedicated fibre network [27,32]. The outcome of such a technique leads to high resolution comparisons between remote clocks in conjunction with the use of femtosecond frequency combs [26,33–37].

In this paper, we will review nearly one decade of progress in optical carrier frequency transfer with optical fibres focusing on the use of public networks to achieve a scalable, continental-wide optical frequency distribution network with fibre links for science and industry.

2. Optical carrier phase fibre link for frequency metrology: principle of operation

We will focus now on optical carrier frequency transfer. The purpose of an optical link is to reproduce the frequency of an ultra-stable signal (seeded at the input end of the fibre) with the best fidelity at the output end. However, the optical phase is disturbed by the fluctuations of the optical path arising from the fibre temperature fluctuations and mechanical vibrations. To overcome this limitation, we need to measure and compensate for such fluctuations.

The first reported solution to this problem appeared in the mid-90s with the so-called "Doppler cancellation scheme" [38]. Fig. 1 depicts the operation principle of a stabilized fibre link [39]. The light makes a round trip in the same fibre in order to experience twice the perturbations along the optical path. At the input end, one compares the input phase and the round-trip signal phase. The phase difference gives the fluctuations arising from the round-trip propagation in the fibre. It can be used to generate a correction signal at the input end, assuming that the forward single trip fluctuation is exactly half of the total round-trip fluctuations. Thus, this compensation set-up requires a high degree of symmetry between forward and backward paths since only reciprocal/symmetric phase fluctuations are corrected. It is worth noting that the

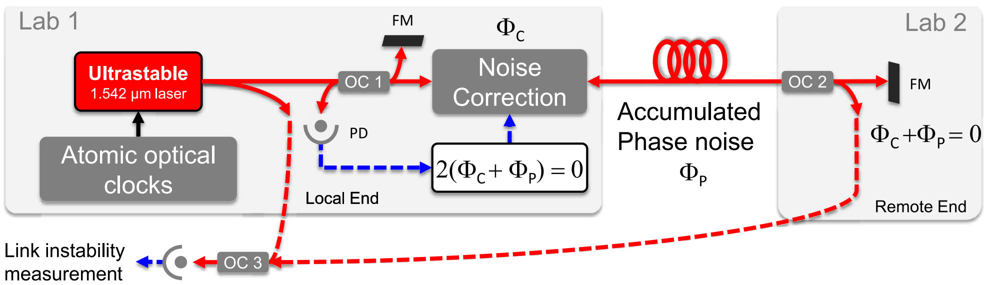

Fig. 1. (Colour online.) Principle of an active-noise-compensated link. The propagation phase noise is detected using the round-trip signal and an active correction is implemented at the link input. The end-to-end beat note signal is detected to evaluate the link stability and accuracy. FM: Faraday mirror, OC: optical coupler, PD: photodiode.