High-Accuracy Optical Frequency Metrology: traceability at the 1E-17 level

Abstract

The advancements achieved in measuring and disseminating optical frequency signals have benefited the realisation of metrological standards. In particular, atomic clocks based on optical transitions show performances that outperform those of the current primary standards that realise the definition of the second in the International Systems of Units (SI), based on the hyperfine microwave transition of the fundamental level of the Cs atom. A future redefinition of the second will be possible if accurate frequency measurements of optical clocks with respect to the current Cs primary standard are performed, as well as direct comparisons of optical clocks to characterise their ultimate uncertainty level.

High-accuracy optical frequency measurements have been made possible thanks to the development of optical frequency combs, which are based on femtosecond pulsed lasers whose frequency spectrum consists of a series of equispaced optical frequency modes. Being the separation between the comb modes a radio-frequency, frequency combs provide a direct link between the optical and microwave domain, allowing comparison of optical frequencies with respect to the Cs primary standard. Moreover, optical combs make feasible measurements of optical frequency ratios, so that comparisons between different species of optical clocks can be performed. In this case optical combs are used as transfer oscillators throughout the optical domain. In addition, the same technique can be used to perform spectral purity transfer of ultrastable optical sources.

When atomic clocks have to be compared between distant facilities, proper methods to disseminate time and frequency signals have to be found. In the case of optical frequencies, the technique that makes possible accurate dissemination is based on the frequency transfer over networks of phase-stabilised optical fibre links. Dissemination at the accuracy level achieved by optical clocks have been demonstrated over distances of thousands of km.

This thesis reports on the work carried out at the Istituto Nazionale di Ricerca Metrologica (INRiM), the Italian National Metrology Institute (NMI), and the activity performed as guest researcher at the National Physical Laboratory (NPL), the UK's NMI.

The work performed at INRiM focused on using an erbium-fibre frequency comb to enable spectral purity transfer of ultrastable lasers and optical frequency measurements of the ^{171}Yb optical lattice clock operating in our laboratories. Spectral purity transfer between the 1156 nm and 1542 nm spectral regions has been demonstrated with a residual instability of $5 \times 10^{-17}(\tau/\mathrm{s})^{-1/2}$ and accuracy of 3×10^{-19}. Two absolute frequency measurements of the ^{171}Yb clock have been performed by

using the erbium-fibre comb, one with respect to the INRiM Cs primary standard, achieving uncertainty of 5.9×10^{-16}, the other with respect to the International Atomic Time timescale (TAI), with uncertainty of 2.6×10^{-16}. Furthermore, the optical comb was used to measure the optical frequency ratio between the ^{171}Yb clock and a transportable ^{87}Sr optical clock developed at the German NMI (PTB), with uncertainty of 2.8×10^{-16}.

At NPL preliminary investigations on a novel technique that could be used for the phase-stabilisation of fibre links have been carried out, studying backreflection signals generated in optical fibres. The effect of spurious signals and chromatic dispersion in fibre spools has been characterised and a coherent detection scheme that could make possible to retrieve information about phase fluctuations experienced over optical fibres has been developed.