Mode-locked lasers for remote intercomparison of frequency standards over optical fibre networks

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Abstract

Frequency transfer via optical fibre networks provides a promising method for the remote comparison of optical frequency standards at the highest levels of stability and accuracy. The use of mode-locked pulse trains is attractive because it offers the prospect of transmitting microwave and optical frequencies simultaneously. We have studied the suitability of a mode-locked Cr:YAG laser for this purpose, investigating both the free-running noise properties of the laser system and the noise added in the transmission of the pulse train over an in-house fibre testbed.

Optical frequency standards based on trapped ions and cold atoms are reaching the point at which they are becoming competitive in accuracy with caesium primary frequency standards and exceeding them in stability. Comparison of optical frequency standards developed at various NMIs currently depends on femtosecond optical frequency comb measurements of their frequency relative to primary caesium or hydrogen maser microwave standards, together with satellite time-transfer to relate the latter. Although optical frequency standards can currently reach a fractional frequency stability better than 1×10^{-15} within a few minutes, satellite comparison methods, such as two-way satellite time transfer (TWSTT) or GPS carrier phase, require at best around 20 days to reach an uncertainty at this level [1]. It is unlikely that these techniques can be improved to match the ultimate anticipated stability of optical frequency standards.

Frequency transfer via optical fibre offers the potential to greatly improve on this performance but is only economically feasible if it can be performed using installed optical fibre networks. In addition to this top-end application, it also offers the prospect of dissemination of rf timing signals for precise network synchronisation or of optical frequency standards for applications such as remote calibration of telecommunications band wavelength standards.

Three approaches to frequency transfer via optical fibre networks are the subject of current research: transfer of an rf or microwave frequency by amplitude modulation of a cw optical carrier frequency; transfer of an optical frequency using a cw source; and simultaneous transfer of rf and optical frequencies using a mode-locked optical source. These techniques have recently been the subject of a major review article [2]. The major demonstration of microwave frequency transfer has been the 88 km round trip fibre link between LNE-SYRTE and the Laboratoire de Physique des Lasers (LPL) in Paris [3]. Despite the success of these experiments, it may be preferable to transmit an optical frequency directly. This will inevitably have to be the frequency of a ultrastable laser in the 1.5 µm band. Comparison of optical frequency standards would be achieved using femtosecond combs to make optical frequency ratio measurements at each end of the fibre link. Experiments at both the LNE-

SYRTE/LPL link [4] and a shorter (6.8 km round trip) link between JILA and NIST (Boulder) [5] show a significant improvement in frequency stability using optical frequency transfer, whilst a small-scale network linking stabilised laser sources over a broad range of wavelengths has been demonstrated at NIST [6]. Work on cw optical frequency transfer at 1.5 µm is planned at NPL.

The approach studied in this work is to transmit the pulse train from a mode-locked laser, offering the possibility of simultaneous transmission of a microwave frequency (the pulse repetition rate) and a comb of optical frequencies. The JILA group have demonstrated a fractional frequency instability of 9×10^{-15} $(\tau/\mathrm{s})^{-1/2}$ in transmission of a high harmonic of the pulse repetition rate of a mode-locked Er:fibre laser over their link to NIST [7] and have demonstrated remote synchronisation of mode-locked femtosecond lasers [8]. In this paper we report on the transmission properties of a mode-locked pulse train through in excess of 25 km of standard single mode optical fibre, with emphasis on the study of noise processes which may degrade the stability of the transmitted pulse repetition frequency.

As part of its absolute optical frequency metrology infrastructure, NPL is using a femtosecond optical frequency comb based on a mode-locked Er:fibre laser [9]. After amplification, the fibre laser generates ~1 nJ, 100 fs pulses at 100 MHz repetition rate with a spectral bandwidth of about 100 nm. The output of the fibre laser is broadened in highly nonlinear fibre to generate a comb spanning a full octave in optical frequency in the mid-infrared (1 µm – 2 µm). There are a number of disadvantages in using such a relatively low repetition rate source for fibre transmission experiments. The high peak power may give rise to unwanted nonlinear processes in the fibre. For optical frequency applications, such as remote calibration of telecommunications wavelength standards, the 100 MHz comb mode spacing is too small to allow for easy mode identification. In this work, a passively modelocked femtosecond Cr^{4+}:YAG laser with a pulse repetition rate of 2.5 GHz is used. This frequency is compatible with current telecommunications systems and is sufficiently high to enable mode identification to be achieved using a commercial wavemeter. The output wavelength from the laser centred at 1540nm is also well matched to the current transmission wavelength of many optical networks.

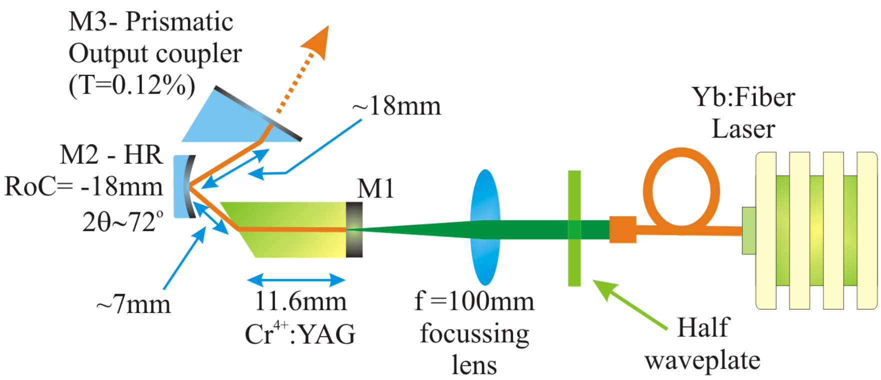

Figure 1 Schematic of the compact mode-locked Cr:YAG laser.

This Cr^{4+}:YAG laser is a Kerr lens mode locked femtosecond laser developed at the University of St Andrews [10,11]. The modelocked laser cavity features a compact, three-element design (Figure 1). It is important to note that, in general, the pulse repletion frequency of a passively modelocked laser is defined by the cavity round trip time and hence the cavity length. In order to achieve GHz pulse repetition frequencies, the cavity length is reduced far below that normally associated with femtosecond laser systems which results in a large reduction in the intensity of the laser pulses used for the non-linear effects on which the modelocking is based. This gives rise to significant challenges in laser design and gain material selection. Similar cavity designs, at lower repetition rate, have previously been demonstrated by Mellish [12] and Tomaru [13]. The laser is pumped at 1064 nm by a cw Yb:fibre laser focussed into the laser cavity using a simple 3-element optical system. The laser cavity is formed by the plane facet of the plane-Brewster cut Cr:YAG crystal, which is coated for broad-band high reflectivity at the lasing wavelength (high transmission for the pump wavelength), and the rear facet of the Littrow prism, which is coated as a 0.12% output coupler at 1540 nm. The Littrow prism provides dispersion compensation, whilst the $r = -18$ mm curved cavity fold mirror creates a stable cavity mode. The laser head is packaged as a robust engineered prototype with a footprint of only 215 mm × 106 mm. The entire cavity is cooled using a single thermoelectric cooler to minimise the drift of individual cavity components and optimise the output frequency stability.

Stable mode-locking is achieved at a pump power of around 5 W, generating 50 pJ pulses at a repetition rate of 2.5 GHz. The temporal pulse width is around 70 fs, measured by intensity correlation. The pulse spectrum has a full width at half maximum of about 45 nm at a centre wavelength tuneable around 1540 nm. This corresponds to a time bandwidth product (assuming $sech^2$ pulse shape) of ~0.32 indicating that the laser generates chirp-free pulses.

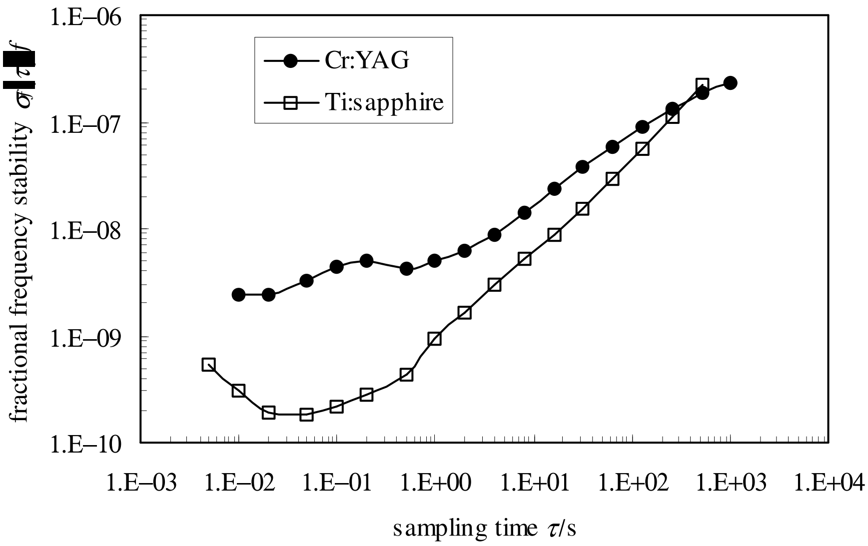

Figure 2 Fractional frequency stability of the Cr:YAG laser repetition rate, compared to that of a Kerr mode locked Ti:sapphire laser.

At very short timescales, the repetition rate of a Kerr mode locked laser can show very high intrinsic stability, since the Kerr effect tightly couples all modes of the frequency comb. At longer timescales, the stability is principally limited by thermal drift and acoustic noise. Figure 2 illustrates the stability of the Cr:YAG laser repetition rate compared to that of a free-running Kerr mode locked Ti:sapphire laser. This Ti:sapphire laser has a linear cavity and a pulse repetition rate of 90 MHz. The Cr:YAG laser used in these experiments currently has no provision for active stabilisation of the pulse repetition frequency. However, the propagation time through a typical 100 km silica fibre link is around 0.5 ms, so it is only stability over this timescale which is significant for these experiments as this dictates the limit to the servo bandwidth available for compensation of phase noise in the fibre.

The pulse repetition rate of the Cr:YAG laser corresponds to a temporal pulse separation of 400 ps. The chromatic dispersion of standard single mode fibre (in this case Corning SMF-28e+) at 1550 nm is 16.4 ps nm^{-1} km^{-1}; consequently pulses with a spectral FWHM of 44 nm are temporally dispersed to the point at which they overlap after propagating through only 0.5 km of fibre. It is therefore interesting to study the extent to which the coherence of the mode structure is preserved after propagation through long (25 km – 100 km) lengths of fibre. The overall dispersion of a fibre link can be reduced to near zero by the insertion of a matched length of dispersion compensating fibre (DCF). A comparison of the added noise in transmission over SMF spools in a laboratory environment with and without DCF will be presented.

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