Fibre Laser Based Ultra-Low Phase Noise LO

Michael J. Staniforth, Ph.D.
ESL Defence Ltd.
16-17 Compass Point, Ensign Way,
Hamble.

Abstract

A concept architecture has been designed to use the advantages of fibre based laser technology in the technique of deriving an RF LO source from ultra stable lasers. The architecture consolidates the advances of key technologies to produce a compact, useable and rugged system, commensurate with more general defence applications as compared with solid-state free-space laser. The design concept addresses the need for ease of proliferation by simplifying the system for lower cost and by focussing on key design parameters to reduce laser power requirements. The design of key assessment experimentation has been completed to aid the development of a technical demonstrator.

Introduction

Previous work[1] has examined the use of mode-locked lasers to divide optical frequency standards to useful microwave/electronic levels. However, the technology at that time was based upon solid-state lasers mode-locked via complex and non-robust free-space optical schemes. Further, the driving of these lasers was inefficient resulting in extreme cooling requirements, generally using chilled water. Femtosecond-fibre lasers (FSFL) systems could address a number of these problems. Fibre lasers guide the light produced by the core of the waveguide. There is no need to use external free-space mirrors as these are written into the glass of the fibre (a technique developed in the telecoms boom to reduce cost). Thus, there are no first order external influences on the path of the laser light; environmental control becomes simple. Further, fibre lasers can be pumped directly from multi-mode diodes and the efficiency is high, reducing cost and cooling requirements. The extended geometry of the fibre laser gives high surface-to-volume ratios; no water cooling is required. Susceptibility to vibration is much reduced as long as robust input and output engineering is employed. However, we wish to enhance overall specification/performance by exploiting fibre technology throughout the system. To this end, we have designed a concept to include the use of laser standards (which the mode-locked laser will divide) based on single-frequency CW fibre lasers. This technology marries with the femtosecond pulsed laser on a physical and system level. Not only does it offer fibre connectivity but also the colour of operation is matched, simplifying the operation of the locking mechanism. Previous laser standards were designed at different colours and would have needed to be converted to that of the femtosecond laser. Another key advantage of fibre lasers is their match to non-linear optical technologies, which helps to configure the division process. Both photonic crystal fibre and highly non-linear fibre (HNLF) technologies continue to advance, leveraged by massive investment from the commercial and, increasingly, military markets. Both markets recognise that brightness is a key quality of systems aimed at communications and sensing.

Concept Architecture

The LO phase noise performance level this work is aimed at is approximately -160 dBc/Hz @ 1 kHz offset referenced to a 10 GHz carrier frequency. This represents nearly 60 dB improvement over high specification crystal based oscillators. Similar improvements closer in to carrier specifications are also expected. The basis for this performance is the use of very narrow linewidth lasers and advanced femtosecond lasers to divide the optical frequency to electronic whilst maintaining phase noise performance (the division ratios provide in some cases 100 dB of phase noise enhancement).
To assess the system in a likely, realisable technology, i.e. fibre lasers, a concept design has been researched.

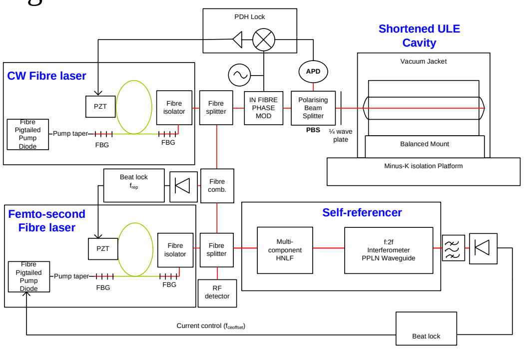

Figure 1 – Concept design architecture

The oscillator architecture, as depicted in Figure 1, incorporates a single CW fibre laser frequency locked to a high-finesse Fabry-Perot etalon cavity, which is the top half of the system, and a mode-locked femtosecond fibre laser locked to the stable CW laser by means of beat frequency detection and a self-referencing locking technique. The architecture thus maintains a fibre based approach in both the femtosecond laser-divider section and the CW laser section. This has clear benefits for the ruggedness and portability of the system.

The use of a new CW laser using the same technology as the FSFL provides a common colour (1550 nm) which significantly reduces the complexity of the overall system. Further, rapid improvement of the efficiency of commercially available HNLF and interferometer technologies has reduced the power output requirements for the FSFL such that an additional optical amplifier is not required.
An informative example of the nature of fibre laser based technology is depicted in Figure 2. The photograph is of a CW fibre laser suitable for possible use in the ULPNLO system demonstrator.

Figure 2 – 1kHz linewidth 1550 nm single frequency laser

Femtosecond-fibre lasers will soon be available in similar topologies and are already in relatively small form factors.
The impact that this form of laser has on the system is seen when working out the volume of a solid-state laser system as compared to a fibre laser system – a few litres for the fibre based system as compared to 100's of litres for the solid-state system.
A second major conceptual aim is to remove the requirement of a power amplifier laser. This is enabled by improving the non-linear components in self-referencing system (this system locks the comb divider). A number of technologies are currently being developed to enable low power optical second harmonic generation (SHG) and supercontinuum generation (SCG). These technologies aim to increase non-linearity coefficients and the threshold field intensity required to operate. This means we can specify a few milliwatts of average power

in the femtosecond laser rather than hundreds of milliwatts as in present systems. This is a significant cost driver in a productionised system.

Experimental Validation

As part of this year of risk reduction, a detailed consideration and design of experiments to validate the technology has been conducted. The main concern for the measurement of ultra low phase noise LO is that of providing a reference to measure against. In general, two systems are required, which at least match each other's performance. NPL possess more than one femtosecond comb system and a number of ultra narrow linewidth lasers, which have been developed and used to probe the ultra fine transitions of optical atomic clocks. Thus, a set of experiments can be configured to assess the performance of a fibre laser based RF signal generator with a solid-state laser equivalent.

Laser standard test

Firstly, the experiments assess the laser standard to which the femtosecond combs are locked (the comb essentially divides the optical frequency standard to microwave frequencies). Two separate extremely narrow linewidth lasers are used (Hz class at 450 THz). The outputs of each will be beat together to determine noise between the standards. The output can be compared with a relatively low phase noise RF synthesizer (the optical phase noise is much worse than that achieved at RF after the comb division system and therefore this is a relatively simple measurement). The optical frequency drift over longer time intervals will be compensated for in the RF synthesiser. Referencing the results for this experiment from the optical to RF will provide assessment of the best performance possible after the comb division (20 dB/decade improvement factor).

Comb System Test

Each single comb system will be then configured. During this, each will be measured against an RF high stability reference (H-Maser). This will provide a first assessment of the comb's phase noise (with an FFT analyser) and stability (with a frequency counter). This is limited by the phase noise and stability of the H-Maser to relatively poor levels (the short-term phase noise of which is dominated by its crystal oscillator based synthesiser). The absolute frequency of the laser will be slow locked to the RF reference to maintain constant zero offset in the phase noise assessment.

Comb against comb test

The main experiment is designed to provide measurement of the potential performance of the systems in that two references aimed at similar performance will be compared against each other. Firstly a solid-state Ti:Sapphire based femtosecond comb and a fibre laser based comb will be locked to a single optical reference. Again, the frequency of one of the combs will be locked to other, long term, in the phase noise assessment.

Finally, each comb will be referenced to separate laser references to allow comparison of two complete systems, i.e. optical reference and femtosecond comb clock-divider.

Ancillary measurements in the programme are to include the assessment of any additional phase noise added to the CW laser standard by optical fibre transfer. The laboratories in which the CW standards and the femtosecond combs are housed are separate and therefore must be linked optically. This is more than just experimentally relevant; it could also help design optical reference remote transfer systems.

CW laser performance

Another, experimental phase will introduce 1550 nm CW laser standards based on fibre lasers. This will begin with the use of a COTS single frequency fibre laser. These lasers use short pieces of fibre to form an etalon structure the length of which is used to control the frequency (frequency selective mirrors form the cavity to select the particular mode formed by the etalon). Thermal, mechanical length and diode pump tuning can be used as stabilisation methods. In isolation, the single frequency laser will achieve sub kHz linewidths, but by stabilisation to an external etalon, this will be brought down to Hz level performance (this translates to micro-hertz level line widths at microwave).

Summary

The definition of a technology demonstrator architecture has concluded that fibre laser technology is an apt technology for the development of an ultra low phase noise local oscillator based on the femtosecond comb optical frequency dividers. Further, the conversion of optical standards to 1550 nm using fibre lasers is commensurate with the aims of providing solutions for a military context and reducing cost. A set of experiments have been considered and designed to explore the capabilities and possibilities for the technology.

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[1] Staniforth EMRS DTC precursor study 2003.