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1 Executive Summary

Introduction

Whilst a great deal of R&D is carried out within National Measurment Laboratories (NMIs) to develop improved metrological capability with higher accuracy, there is a clear need to disseminate improved accuracy through new metrological instrumentation throughout industry and society. In particular, significant improvements in the provision and measurement of time and frequency (T&F) at NMIs have been made in recent years, The transfer and use of this high accuracy T&F capability in industry is strongly dependent on the development of suitably compact instrumentation with low size, weight and power (SWaP). This project has addressed the issue of adapting leading edge T&F techniques that can be efficiently incorporated into novel instrumentation for use in both microwave and optical time and frequency applications.

The Problem

Global high technology sectors such as telecommunications, aerospace, navigation, defence and security all rely on timing synchronisation between accurate time and frequency references. Frequency standards with stability and accuracy at the level required for these industrial applications already exist in well-controlled laboratory environments, with the best of these today being capable of fractional frequency reproducibilities equal to or better than 10^{-15}, significantly beyond what is required for most industrial applications. These laboratory frequency standards are generally bulky, have high electrical power consumption and can only be operated by highly trained personnel. The development of industrial versions of high performance time and frequency standards will always involve a trade-off between NMI lab performance and size, weight and power (SWaP) requirements for operation in relatively hostile environments and conditions. They are also not designed for extended operation in demanding industrial environments such as space, aerospace, ground-based mobile communications and base stations, where temperature fluctuations and vibration levels are likely to be at least an order of magnitude worse than in a typical laboratory environment. This project has focussed on the development of low SWaP optical and microwave frequency standards and local oscillators which take advantage of techniques developed for high-accuracy laboratory clocks and adapt them for future industry standards.

The Solution

This JRP set out to develop low SWaP near infra-red optical frequency standards as stand-alone references for optical communications at 1.5 μm wavelengths, and sensing applications across the 1 μm to 2 μm region using gas-filled and sealed hollow core fibre (HCF) cells. Results for the acetylene-filled 1.5 μm HCF systems have shown fractional frequency stabilities in the range of 10^{-11} at 1 second averaging, and fractional frequency accuracies between 10^{-9} and 10^{-10}.

The project also set out to develop high-stability optical local oscillators (OLOs) capable of operating in non-ideal and hostile environments offer increasing opportunities for space clocks, satellite navigation, deep space ground stations, and multi-telescope arrays such as the Square Kilometre Array. using transportable vibration-insensitive optical reference cubic cavities, and achieved fractional frequency instabilities below $5x10^{-15}$ between 1 and 100 seconds. The technology has since been licensed to an SME.

Microwave local oscillators (MLOs) also play a very significant role in industrial applications of timing and synchronisation such as high bandwidth communications, navigation and timing, aerospace and high resolution radar. Our research demonstrated optical-to-microwave down-conversion from OLOs withlower instabilities and frequency noise figures than the best microwave devices. A range of techniques designed to optimise the constituent processes to achieve the low noise down-conversion to the microwave region have been developed. Free-running quartz microwave local oscillators are widely-used industry-standard oscillators with good short term stabilities, and where their longer term drift is controlled by reference to external timing systems such as GPS. For GPS-denied situations, local Cs or Rb atomic microwave standards are needed to maintain synchronisation and holdover during the GPS outage, especially for mobile communications scenarios. The project investigated two compact atomic clock options, targetting different regimes of 10^{-11} and 10^{-13} frequency stabilities. The first focussed on developing effcient filling of a compact HCFphysics package thermal caesium atoms, and demonstrated this via high contrast spectrally narrow Cs optical signals from the HCF. The second activity involved the characterisation of a prototype clock based on cold rubidium trapped atoms on a chip (TACC), where excellent instabilities of less than 10^{-14} after several hours averaging were achieved.

Impact

The project's outputs were disseminated to the metrology, scientific, industrial time & frequency communities by various routes. The project so far has contributed 15 publications and 59 presentations. A presentation on the results of project was made to the IEC TK86 Swiss Committee concerned with fibre optics, with the goal of making people aware of the new coming technologies that may impact the photonics community. In addition a presentation to UK Ministry of Defence stakeholder group on optical and microwave micro-clocks was given. The technologies developed in the project were demonstrated at the industrial showcase event in Neuchatel late June 2015, with over 80 participants.

The industrial take-up and eventual industrial impact on all these parallel developments rests upon the further refinement of system and device designs, and the evaluation of frequency stability and drift. Some of the early work by partners on robust cavity designs and low-noise microwave generation has resulted in EU and national funded collaborations being set up between separate partners and MenloSystems GmbH, a major femtosecond comb supplier. Further, activities on hollow core fibre systems for both IR optical reference standards and microwave clocks are contributing to ESA and defence-related applications respectively. In the former case, ESA is interested in small IR wavelength standards at ~ 2 μm as on-board reference for satellite monitoring of atmospheric carbon dioxide concentrations. In the latter, there is interest in small clocks with suitable accuracies for use in mobile defence scenarios. Finally, significant activity by some of the partners on the development of robust optical cavities is contributing strongly to ESA technology development of space versions of these cavities, as was demonstrated in the ESA design studies of the cosmic vision STE-Quest mission proposal, a mission designed to answer a range of questions in fundamental physics. There has also been significant take-up of the optical oscillator cubic cavity design in an ESA engineering model build of a high stability laser stabilised to the cubic cavity, as an integral part of the development of space equipment for gravity mapping from space. As mentioned above, the cubic cavity development has also led to licensing discussions with an industrial SME for the provision of high resolution spectroscopic instrumentation. In all these cases, it is necessary to demonstrate increased technology readiness levels (TRLs) for prototype systems before full industrial take up can be fully implemented. Achieving high TRL levels for space and defence applications inevitably requires substantial and costly development outside the scope of EMRP projects, especially for equipment destined for space, aerospace, defence and telecoms.

2 Project context, rationale and objectives

Introduction and context

This project focussed on the translation of bulky, power-hungry NMI-based frequency standards technology, typically only operable in well-controlled laboratory environments, into a new generation of high performance, compact, portable, robust and turn-key instruments, well-suited for operation in industrial environments. The technology and industrial prototypes developed within the project targeted the limitations of existing industrial frequency standards in market sectors that include telecommunications, instrument manufacture, gas sensing, space, aerospace, defence and navigation. The evolution of such frequency standards into prototypes suitable for industrial operation underpins the establishment of a wider quantum sensor and clock industry within Europe, and some European companies are already taking on board the technology developed within the project, with follow-on projects and licensing of prototypes.

Identification of issues and problems for industrial frequency standards

Industry requires a range of increasingly stable and reproducible optical and microwave frequency standards for applications in a wide range of sectors including telecommunications, instrument manufacture, gas sensing, aerospace, defence and navigation. These frequency standards must be compact, portable and turn-key, with reasonably low power consumption.

In telecommunications, requirements for more accurate optical frequency standards are driven by demands for rapid data transfer via optical fibre. This is an important market area for Europe, which is home to seven of the largest ten telecommunications operators in the world. In 2008, revenues in the electronics communications sector amounted to €351 Bn in the EU. The optical telecoms industry requires both increasingly rapid data transfer per channel and also a larger number of channels. It is anticipated that the International Telecommunications Union (ITU) will increase the number of channels in the 1.5 µm telecomms band by reducing the channel spacing from 100 GHz to 25 GHz [1], and eventually arrange for wider spectral coverage away from the 1.5 µm narrow band. These drivers mean that the industry will require the capability to make both higher-accuracy frequency measurements over a larger wavelength range in the field.

Extended wavelength coverage with such optical frequency standards also broadens market applicability of the technology. ESA and space companies involved in Earth observation have significant industrial interest in frequency references at around 2 µm, useful both for calibration of optical instruments such as wavemeters or for space-based LIDAR technology to monitor atmospheric CO_2 concentrations. Monitoring atmospheric gases such as CO_2, CH_4 or H_2O is important improving our understanding of long-term climate change and global warming.

Navigation and timing synchronisation applications are further strong drivers for the development of a new generation of compact frequency standards. Many time and frequency referencing applications in telecommunications, aerospace and satellite navigation consist of a quartz local oscillator or low specification atomic clock, steered to an external eg GPS reference signal. Loss of accuracy and traceability occur, in mobile applications or if the external signal is deliberately degraded or denied. Thus there is a major industrial need, vital for both civil and military applications, for autonomous clock operation to provide synchronisation holdover in the event of loss of GNSS signal access, and faster acquisition of high-accuracy navigation solution once the satellite signals are re-acquired. A recent UK Royal Academy of Engineering report identified several % of GDP as dependent on satellite navigation-based services. Other navigation applications, such as radar, increasingly rely on high-resolution short-term frequency stability, pointing to the need for improved low-SWaP local oscillators with superior phase noise over current commercially available oscillators.

Improved frequency standard and clock performance is also required in wireless communications as we move to 5G capability, in which timing synchronization between network clocks is vital for error-free transfer of ever-increasing data levels.

Several of these key applications will ultimately require space-based frequency standards. For such applications, new frequency standards will not only need to be compact, low SWaP, portable and turn-key, but the technology will also need to be capable of space qualification, and able to withstand the extreme accelerations experienced during launch. In all these respects, national defence agencies and space agencies are key early adopters of improved industrial frequency standards, with a much wider high-technology manufacturing and user community close behind.

Project objectives pursued to provide advanced industrial frequency standards solutions

The project set out to develop robust low-SWaP optical frequency standards as optical communication references for dense wavelength division multiplexing (DWDM) channel calibration at 1.5 µm and similar infra-red references for gas sensing in the 1 µm to 2 µm wavelength region, based on novel gas cell technology using hollow core fibres filled with absorbing molecular gases. This involved studies to better understand HCF transmission properties, methodologies for filling and sealing the HCFs and coupling to single mode fibre. Electronics for stabilising semiconductor lasers to the sealed HCF cells were developed, and a complete active HCF prototype 1.5 µm HCF–stabilised laser standard was characterised, demonstrating fractional frequency stabilities in the range of a few x 10^{-11}, and fractional frequency accuracy between 10^{-9} and 10^{-10}.

The project also looked to develop a compact, vibration-insensitive and transportable optical local oscillator, achieving a leading edge short term fractional frequency instability below 5×10^{-15} for term averaging times from 1–100 s, to provide industrially-compatible local oscillators for anticipated optical platform applications in space and aerospace, as well as the source for comb-based down-conversion to provide low phase noise microwave oscillators. The resulting portable vibration-insensitive cubic cavity design within an evacuated

[1] Telecommunication Standardization Sector (ITU-T) Recommendation ITU-T G 694.1 “Spectral grids for WDM applications: DWDM frequency grid“ (http://www.itu.int/ITU-T/studygroups/com15/otn/transport.html).

chamber was demonstrated at the final industry workshop and led to industrial take-up and licensing after the project conclusion.

As mentioned above, techniques for comb-based frequency down-conversion from the optical to microwave were developed within the project to provide ultra-low phase noise capability in the microwave region for the applications in defence and aerospace. The techniques included very low phase noise detection of optical signals, coupled with alternative methods of tight phase locking and transfer oscillator methodologies for comb stabilisation to the optical carrier. The tight phase lock technique has resulted in licensing to an SME. The transfer oscillator scheme demonstrated 3 x 10^{-15} instability at 1 second averaging, less than that of the optical oscillator itself, thereby not increasing noise levels. Comb repetition rate multiplication techniques using fibre spool interferometers further reduced phase noise by minimising unwanted low frequency comb mode intensities. The totality of these optical-to-microwave down-conversion techniques have demonstrated low phase noise microwave synthesis at a level that the microwave industry can now benefit from in the short to medium term.

Finally, the project has developed techniques for miniature and compact microwave atomic frequency standards to address the need for industrial applications that require autonomous operation free of a requirement for an external reference signal. Techniques for filling hollow core fibres with Cs vapour were investigated as a preliminary to developing clock frequency stability and accuracy in the 10^{-10} – 10^{-12} range, with potential use as miniature clocks for mobile communications for defence, security and aerospace. Low SWaP designs involved coherent population trapping of thermal Cs atoms by means of microwave modulated laser light transmitted through the fibre. It did not prove possible to investigate the CPT technique within the project timescale, but good contrast Doppler-free saturated absorption signals from the Cs-loaded HCF demonstrated the viability of the approach.

A second approach to compact microwave clocks, targeting frequency stability and accuracy performance in the 10^{-12} – 10^{-13} range, offered potential solutions for use as master clocks such as those needed for telecommunications networks and satellite navigation systems. This approach centred on the frequency characterisation of a prototype clock using laser-cooled rubidium atoms magnetically trapped above a 5 cm^3 microchip physics package, in stark contrast to the highest accuracy Cs fountain microwave clocks that comprise a physics package of ~ 2 m^3. This prototype demonstrated excellent fractional frequency stability reaching 6×10^{-15} after 30 000 seconds averaging. In both cases, compactness and low power consumption are a significant objective.

3 Research results

The research achievements with respect to the project objectives are described below in sections 3.1 – 3.4

3.1 Optical frequency standards

For the most accurate optical frequency standards in the 1.5 µm telecommunications band, NMIs use frequency-stabilized lasers based on acetylene gas cells, which are generally designed and constructed by NMI personnel. Such NMI-designed standards are typically reproducible at the 10^{-11} level however commercially available turn-key alternatives are typically only stable at the 10^{-8} level. These commercial systems are not based on molecular or atomic references and are susceptible to long-term frequency drift and require periodic re-calibration. Industry needs more stable turn-key optical frequency standards for spectral purity in telecommunications and gas sensing. This will allow more accurate narrow channel characterisation of wideband multiplexed fibre communication systems, leading to more efficient DWDM channel control and calibration, and faster analysis and higher resolution of trace gas spectra in sensing applications.

3.1.1 Properties of HCF, gas cells structures and related technologies

HCF fibres exist in a large variety of forms and structures, each one having its own specificity. One of the first objectives of the project was to evaluate the properties of a series of HCF fibres provided by our partners NKT and Chylas, in order to identify the best suited one, and also to investigate different possible configurations of all-fibre gas cells allowing to achieve the best possible performances, not only in term of optical and spectral properties, but also regarding compactness and long term stability. All-fibre gas cells essentially consist in a piece of HCF, which is filled with a reference gas at a pressure level depending on the targeted application. Sealing of the HCF and efficient light coupling with singlemode input and output fibre ports need to be provided, as shown in Figure 1.

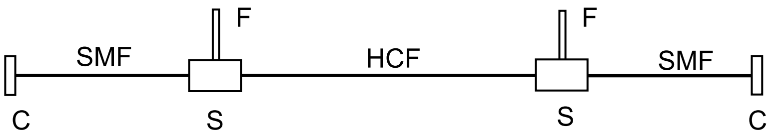

Figure 1: Basic structure of an all-fibre gas cell. HCF is the hollow core fibre, which will be filled with gas. SMF are the input and output fibre ports, S are the sealing and light coupling units, C is the optical connectors and F are the gas inlets.

These topics were extensively investigated within the project in collaboration between DFM, NPL, METAS and CSIC and the most relevant results are summarised here below.

Modal properties and gas-light interaction in the HCF core

In the project it was demonstrated that the wavelength dependent modal filtering occurring at the HCF–SMF junction in a fibre gas cell leads to spurious modulation of the transmitted light, which can be very large compared to the size of the spectral absorption feature of interest. This makes the application of large core multimode HCF problematic, despite of the fact that they would lead in a reduced transit-time broadening. HCF are also prone to surface modes, which are mostly due to inhomogeneities in the microstructure. These modes contribute to the same kind of spurious modulations as in the multimode case. The project also demonstrated that this effect can be strongly reduced by increasing the length of the HCF (
Figure 3). Three different types of HCF were evaluated by performing a polarization selective analysis of the output near field profile. Figure 2 shows the modal distribution measured on three different HCF, labelled respectively HC7_1, HC7_2 and HC7_PM1. The first two ones show a bimodal behaviour, together with significant surface modes all around the fibre core. The last fibre is essentially singlemode and with reduced surface modes and demonstrates the major improvement of the fibre properties achieved during the project.

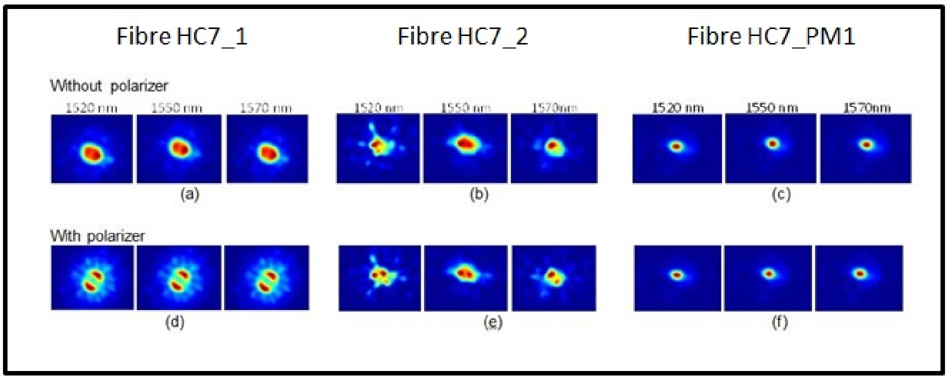

Figure 2: Modal distributions (near field profile) measured at the output of the three HC7 fibre samples. Fibre HC7_1 shows a bimodal (LP01 + LP11) behaviour throughout the wavelength domain of interest. Fibre HC7_2 shows a mixed contribution of higher order and of surface modes beyond 1550 nm and is not properly guiding at lower wavelengths. Fibre HC7_PM1 shows a much better Gaussian like near field pattern, despite of a small amount of ellipticity.

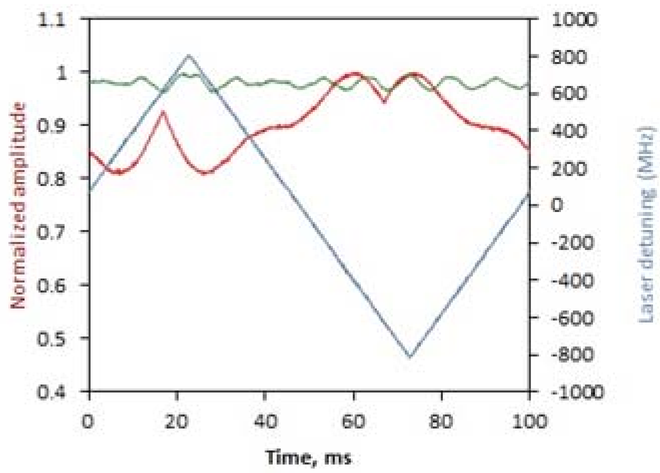

Figure 3: Relative power fluctuations measured at the output of an empty HCF cell built according to Figure 1. The signal is measured during a frequency sweep of the laser for two different lengths of the HCF. In red: 0.8m long HCF, in green 7.8m long HCF. The green 7.8m long HCF. The graph clearly shows the reduction of the modulation depth when the HCF length is increased.

The transit-time broadening limitations arising from the small fibre core diameters, compared to classical bulk gas cells were also investigated. For that purpose, frequency stability measurements of a fibre laser locked to the Doppler free P(16) line of a series of acetylene-filled HCF with different core diameters were performed at DFM. They allowed confirming that the best short term stabilities are obtained with large core diameter HCF, due to the reduced transit-time broadening, and that better long term stabilities are achieved with singlemode HCF, due to the reduced parasitic contribution of higher order and surface modes, as shown in Figure 4.

Suspended core fibres provided by Chylas and different other types of solid-core micro-structured fibres were also evaluated by CSIC and by METAS, but were not selected, due to the low gas-light interaction, and due to the large inherent transit-time broadening.

Based on these evaluations the best out of all tested fibres is a single mode HCF, with a core diameter of about 8 μm, and showing a minimum of residual surface modes. This core diameter results in la transit-time broadening of about 45 MHz.

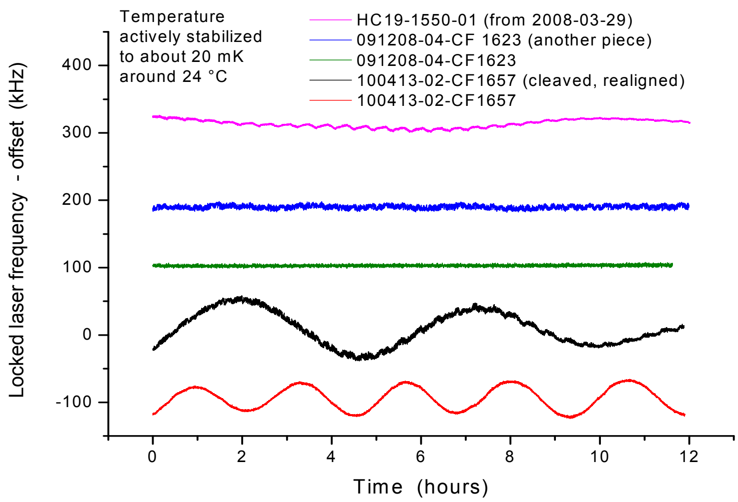

Figure 4: Frequency deviation of a fibre laser locked to different HCF fibres: Trace (HC19-1550-01: large core, multimode HCF) shows the best short time stability, due to a reduced transit-time broadening. The long term stability degrades, due to the spurious modulation induced by higher order modes. In the contrary, Traces

(091208-04-CF: small core HCF, singlemode) show a degraded short term stability, due to the increased transit-time broadening but a better long term stability, due to the singlemode behaviour.

<u>Gas cell structure and related technologies</u>

Different structures of all-fibre gas cells were developed and demonstrated, with the main goal to minimize internal Fabry-Perot effects and insertion losses and to achieve long term stability of the gas pressure.

The first one was demonstrated by METAS and consists in making the junction between the HCF and the input and output SMF ports using a dedicated butt-coupling method with minimized Fresnel back reflection. The butt-coupling is achieved using connector, almost similar to those used in classical optical fibre systems. The junction between the connectors is achieved using a gas-tight connector adapter, which allows to simultaneously perform the coupling of light between the SMF and the HCF with low reflections, and to have access to the HCF core for evacuating and gas filling. This technique takes benefit from well-established technologies and makes it easy to combine HCF components with classical components and systems as used in the telecommunications industry. Residual back reflections down to -25 dB were obtained, depending on the HCF fibre type. Figure 5 shows one picture of the prototype connector adapter, which was developed in this project and also one typical gas cell built using this technique.

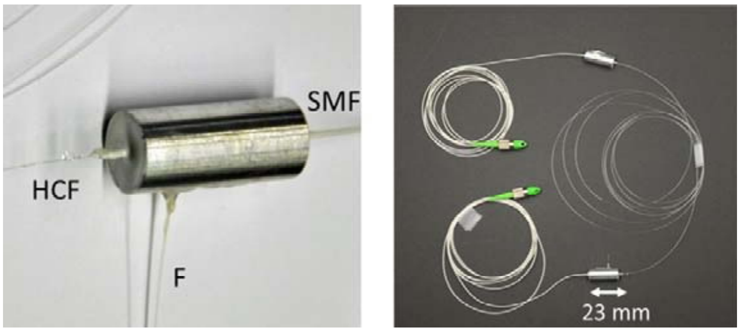

Figure 5: Left: Gas tight connector adapter. SMF is the input singlemode fibre , HCF is the hollow core fibre, F is the gas capillary, which allows to perform the filling of the HCF core. Right: shows one fully functional gas cell built using this technology.

A different method, based on lensed glass micro cavities was demonstrated by DFM. The cavities are used to seal both HCF ends and to give access to the HCF core for evacuating and gas filling. Light coupling in and out of the HCF is performed through the termination lens, which is antireflection coated for reduced intra-cavity Fabry-Perot effects. The basic structure of the micro cell and an example of all fibre gas cell built using this technique are shown in Figure 6.

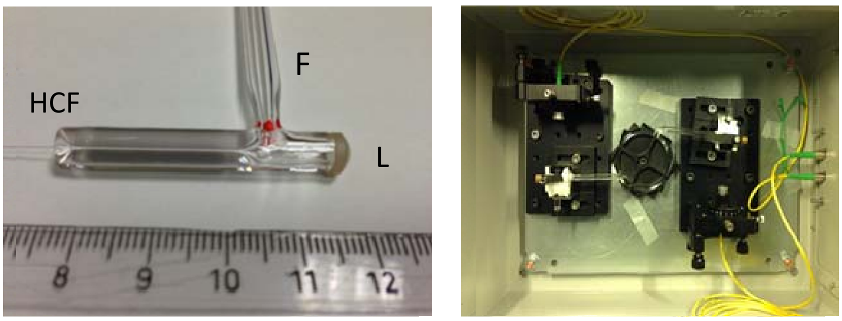

Figure 6: Left: Lensed glass micro cavity. HCF is the hollow core fibre, F is the gas inlet, which allows to perform the filling of the HCF core, L is the A.R. coated coupling lens. Right: shows one fully functional gas cell built based on this technology.

A third method, based on the direct splicing between HCF and the SMF fibres was tested by NPL and METAS. This method is very elegant and simple, but requires more complex gas filing techniques, since the gas needs to be put in the HCF before splicing. Moreover, 4 % Fresnel reflections at the SMF-HCF interface are unavoidable, due to the impedance mismatch between the HCF and SMF cores. This leads in unwanted distortions of the measured absorption lines. This drawback may be attenuated by applying dedicated phase modulation and signal processing techniques during spectroscopic measurements with the gas cell.

It was decided for the project to take the option of reducing the spurious modulations as far as possible and to concentrate mostly on the first two structures of gas cells.

3.1.2 Fabrication of gas cells and spectroscopy measurements

This part of the project allowed successfully demonstrating the fabrication of a series of HCF-based gas cells using, either a gas-tight connector adapter (METAS approach) or a glass micro cavity (DFM approach). The project also succeeded in performing a series of inter-comparisons and in-situ test by industry partners, which demonstrated the good performances of these all-fibre gas cells.

Gas cell fabrication

An important effort was placed in the development of the necessary fabrication processes, including evacuation and gas filling systems and procedures. These methods were successfully demonstrated and documented at DFM, METAS and NPL. The long term stability of the gas cell pressure is an important aspect, which was mostly investigated by DFM. Very well controlled gluing techniques and thorough drying of the cell before filling the cell with gas need to be achieved, in order to obtain the required performances. Pressure stabilities were estimated by measuring the change in width of the Lamb dip as a function of time. Values ranging from (14 ± 21) Pa/year to (207 ± 10) Pa/year were obtained, depending on gas cell and on the fabrication process.

A series of three different reference gas cells were successfully built within the project, with the main goal to analyse and compare their performances and to evaluate their usefulness towards an industrial application. DFM built one low pressure gas cell for nonlinear spectroscopy. The fibre was a singlemode HCF with a fibre core diameter of about 8 μm and the fibre length is of about 2.5 m. The cell was filled with $^{13}C_2H_2$ at a pressure level of about 13 Pa. METAS built a second low pressure as cell, based on a similar HCF but with a length of about 2 m and a gas pressure of about 50 Pa. A high pressure gas cell for linear spectroscopy measurements was also built at METAS for linear spectroscopy purposes. The fibre was filled with $^{12}C_2H_2$ at a pressure level of 400 Pa.

Spectroscopic characterization and inter-comparisons

Low pressure gas cells were measured using saturated absorption technique using different systems, which were implemented at DFM, METAS and MIKES. DMF and METAS systems use classical phase modulation schemes. MIKES developed a different approach using a self referenced optical frequency comb-based optical synthesizer to perform saturated absorption measurements and implemented a novel technique based on laser power modulation and a piezo modulation of the fibre to minimize parasitic interference effects during measurement. The project succeeded in performing an inter-comparison between DFM and MIKES by measuring the P(16) line of the gas cell provided by DFM at both laboratories. First very promising results allowed confirming agreement around 200 kHz (10^{-9} relative) on the determination of the central wavelength, although the more accurate measurements at DFM showed that 20 kHz reproducibility (10^{-10} relative) is feasible.

The high pressure HCF gas cell fabricated by METAS was successfully tested by our industrial partner Agilent. Extensive comparisons with a NIST bulk reference cell were performed (Figure 7) and allowed confirming the possible application of HCF gas cells as internal reference in wavelength measuring instruments.

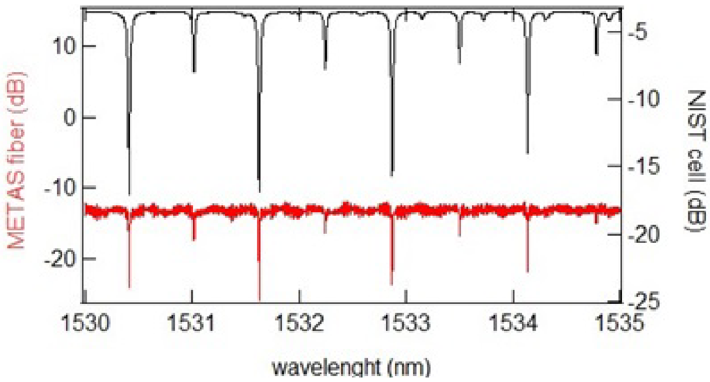

Figure 7: Spectrum of $^{12}C_2H_2$ as measured with a bulk cell from NIST (in black) and with a fibre cell fabricated by METAS (in red) and showing comparable spectral features.

The project succeeded in demonstrating the applicability of HCF-base gas cells for linear and for non-linear spectroscopy applications at the industry level. This was only possible thanks to the common effort of all participants.

All demonstrated technologies and principles have proved to be promising. Nevertheless an effective industrial application will require further optimizations and better controls of the fabrication processes in order to guarantee the required long term stabilities of such standards.

3.1.3 Active wavelength standards

In this part of the project, fibre lasers locked to the P(16) line of low pressure acetylene HCF-based gas cells by saturated absorption spectroscopy were successfully demonstrated at DFM and at METAS. Their structures are identical to those used for the evaluation of the gas cells reported in the previous section. With its laser, DFM achieved fractional frequency instabilities of a few 10^{-11}, as shown in Figure 8.

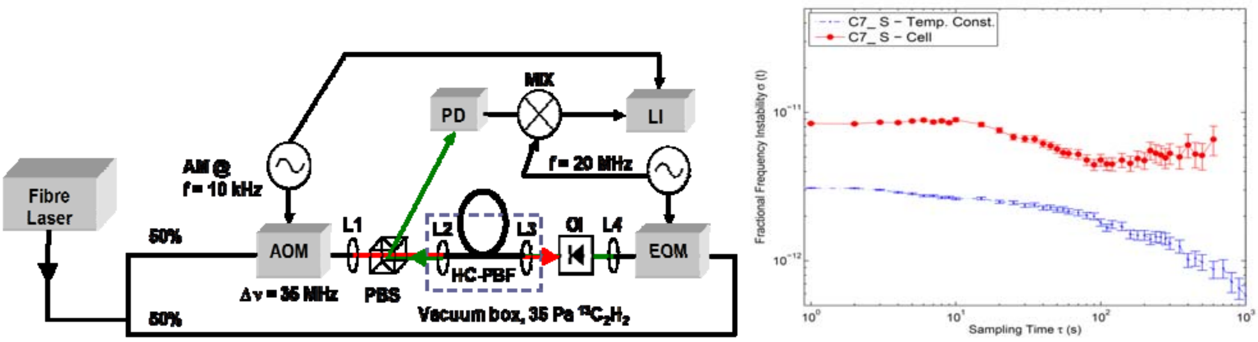

Figure 8: Left: Basic structure of the fibre laser developed at DFM. Right: Stability of the laser locked to the P(16) line of a low pressure HCF-based gas cell (red trace) measured by comparison to a reference laser with instabilities below $5{\cdot}10^{-13}$. A typical fractional instability of a few 10^{-11} was obtained

The project succeeded in demonstrating a stabilized fibre laser locked to a HCF-based gas cell reaching a fractional accuracy which could be measured between 10^{-9} (inter-comparison) and 10^{-10} and a fractional instability in the low 10^{-11}.

3.1.4 Electronics for laser stabilization

Parallel to the optical developments, the project also investigated the realization of possible compact and turnkey electronics for implementation in stabilized lasers by taking advantage of commercially available FPGA (Field-Programmable Gate Array) structures. INRIM built a fully functional system for laser stabilization at 1st, 3rd and 5th harmonics, with relock-relock capability, which could be successfully tested for the stabilization of a Nd:YAG/I_2 laser. Figure 9 shows the internal structure of the controller and the realized prototype system.

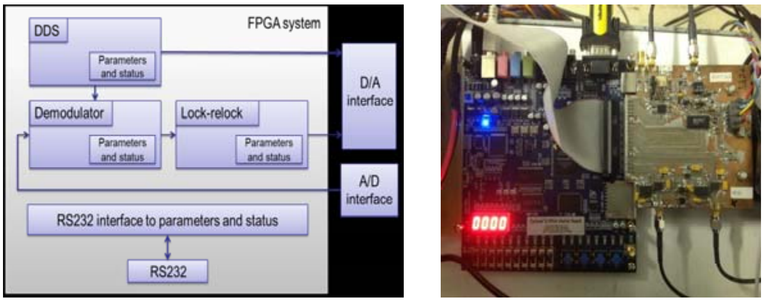

Figure 9: FPGA based system for laser stabilization developed at INRIM.

Another FPGA based system for Pound Drever Hall stabilization was also developed at NPL and is now operational.

3.1.5 Gas cells at other wavelengths.

A possible application of HCF-based gas cells for spectroscopy purposes at other wavelengths was successfully investigated by MIKES, DFM and NPL. One of the achieved objectives was to simulate absorption spectra of several potential gases using the HITRAN 2012 database to find best-suited references transitions around 1310 nm and 1550 nm. Methane proved to be a promising candidate for wavelengths around 1310 nm.

A laser setup for realizing a frequency reference at 2051 nm by locking the laser to carbon dioxide (CO_2) spectrum was built and characterized at DFM. This wavelength has importance in e.g. measurement of atmospheric carbon dioxide from satellites.

3.1.6 Summary and conclusions

The optical frequency standards results achieved within the project have clearly shown the viability of compact gas cell standards based on gas-filled and sealed hollow core fibres with application to optical telecoms frequency standards, gas sensing, and length metrology in the visible to near infra-red region. The activities carried out involved 6 members of the consortium and external collaborators, both on the HCF manufacturing side and the telecoms manufacturing side. The magnitude and extent of the results would not have been possible for a single metrology laboratory to achieve. The leading results achieved are:

- Enhanced insight into modal and transmission properties of hollow core fibres provided by manufacturers (eg NKT Photonics, Chylas SA)
- Development of a number of novel HCF cell filling techniques for molecular gases and subsequent sealing arrangements to provide stand-alone portable HCF gas cells.
- Doppler-limited and saturated absorption spectroscopic comparisons of compact and portable HCF cells against conventional bulk gas cells at telecoms wavelengths, with final comparisons carried out by the industrial telecoms provider, Agilent.
- Development of active optical frequency standard prototypes, with telecoms lasers frequency stabilised to sealed acetylene-filled hollow core fibre cells.
- Development of prototype FPGA-based frequency stabilisation electronics for compact industrial control circuitry
- Demonstration of active HCF prototypes with fractional frequency stabilities in the range of a few x 10^{-11}, with a few x 10^{-12} at 1 second averaging when the HCF cell is held within a vacuum enclosure.
- Demonstration of active HCF prototypes with fractional frequency accuracy between 10^{-9} and 10^{-10}.
- Investigation of other wavelength options for gas-filled HCF, pointing to methane at 1310 nm both for telecoms and gas sensing, and carbon dioxide at 2050 nm for references for atmospheric CO_2 concentration monitoring from space.

3.2 Optical local oscillators

The best commercially available optical local oscillators (lasers) have linewidths in the sub-kHz region over timescales of a few milliseconds. Future high accuracy optical atomic clocks will need lasers with sub-Hz linewidths over timescales of 1-100 seconds for both optical and down-converted microwave applications in satellite navigation, deep space ground stations, multi-telescope arrays such as the Square Kilometre Array and high resolution radar. This will allow improved and more resilient position, navigation and timing data availability in these high technology areas. This performance has so far only been demonstrated in extremely well controlled laboratory environments and needs to be demonstrated in harsher industrial environments such as space, aerospace and mobile defence arenas to be useful in future space science & earth observation missions, satellite navigation programmes, and in rapidly expanding high-data-rate communications.

3.2.1 Design and build of a high-performance optical cavity setup

The optical local oscillator is based on a design concept that minimises vibration sensitivity in three dimensions together with a tight mounting arrangement that allows the cavity to be operated in any orientation whilst undergoing translational and rotational movement, and/or within environments with enhanced levels of vibrational and thermal noise. This is necessary for any device that is intended for use outside stable laboratory environments and especially in the field or in space and aerospace applications. The cavity comprises an ultra-low-expansion (ULE) spacer cube of 5-cm edge dimension with truncated vertices. The cube is held by means of four of the vertices, providing a symmetrical tetrahedral arrangement. Three orthogonal bores are cut into the ULE cube centred on the mid-points of two opposite faces of the cube, with the bores intersecting at the centre of the cube. The optical cavity axis is set up along one bore by optically contacting two very-high-finesse cavity mirrors centred symmetrically on the bore at the relevant cube face centres. Finite element analysis has shown that vibration sensitivity of the cavity structure is minimized by achieving a fully symmetric structure and mounting arrangement. The cavity mirrors with 12.7 mm diameter x 4 mm thickness ULE substrates are coated for operation at 1064 nm, to give a design finesse of 240,000 and 150 μm TEM_{00} waist. The ULE spacer material had a specified coefficient of thermal expansion (CTE) that crosses zero at ~ 36 ^{0}C, thereby potentially allowing the temperature of vacuum chamber to be stabilized by TEC's a little above room temperature.

The cavity finesse was measured by ring-down measurements. These identified a measured finesse of 150,000, but on the TEM_{02} mode (see ring-down measurement in figure 10 below). The TEM_{00} mode gave a finesse of a few tens of thousand only. As a result, the 1064 nm mirrors were de-contacted from the spacer and substituted with a pair of available 1550 nm mirrors at PTB. These mirrors were larger than the originals (25.4 mm diameter x 7 mm fused silica substrates with plane and 100 cm radius of curvature). The effect of the change from ULE mirror substrates to fused silica substrates with different CTE results in the depression of the combined zero CTE for the ULE spacer and fused silica mirror combination to a temperature below 0 ^{0}C. As a result, additional ULE annular rings (25.4 mm outer and 10 mm inner diameter and 7 mm thickness) are contacted to the rear of the fused silica mirrors, which raised the zero CTE point to more manageable

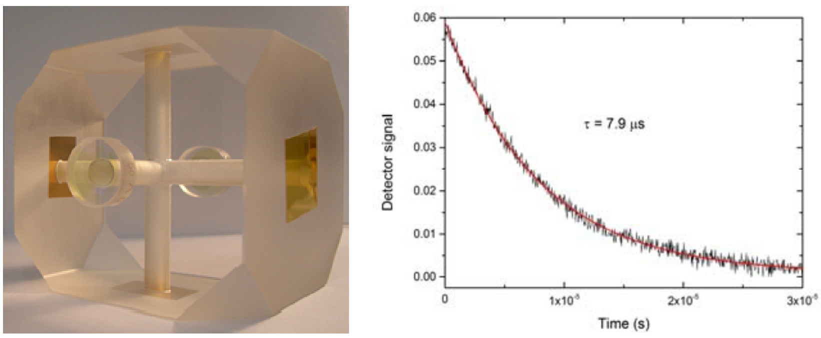

Figure 10: a) cubic cavity showing ULE spacer with high finesse mirrors contacted to two opposite faces, and b) ring down measurements from which the cavity finesse is determined

temperatures close to the original ULE spacer temperature. As per NPL calculations, the 1064 nm ULE cavity mirrors were replaced at PTB by larger 1550 nm fused silica mirrors (fused silica mirrors - plane and

100 cm ROC) with ULE compensating rings (25.4 mm outer and 10 mm inner diameter and 7 mm thickness). Prior to the change of mirrors, finite element analysis calculations were carried out at NPL to ensure that the change of mirror dimennsions and annular ring additions did not comrpromise the low vibration sensitivities expected.

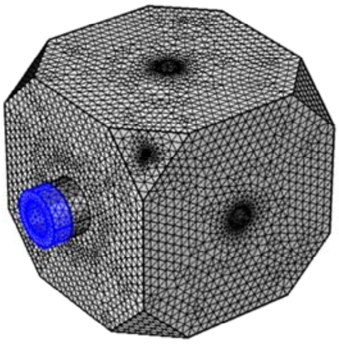

Figure 11: Finite element modelling of vibration insensitivity

3.2.2 Design and build of cavity mounting frame and vacuum chamber

The revised cavity arrangement was mounted at PTB in a cubical frame by means of adjustable holding pins with viton hemispherical ends bearing on the centre of the 4 vertices with equal and opposite forces towards the centre of the cavity applied to all 4 mounting pins. In order to ensure the mounting pins maintained contact with the cube vertices at all times under accelerations of up to 50 g, this required a 130 N minimum pre-stressing onto the vertex support points. Further, the maintenance of cavity and cube symmetry within the mounting frame required an accuracy of alignment of the centre of the viton support pads to the axis between vertices through the centre of the cube to a level in the 50 µm range. In this way, the resulting equal and opposite force symmetry through cavity centre gives rise to insensitivity to inertial forces due to linear and rotational accelerations. Thus the cavity is constrained against displacement in 3 dimensions, and against rotation due to tangiental friction.

The cubic cavity and mounting frame, together with 2 layers of thermal shields within a vacuum chamber designed and constructed at PTB according to their “shoe box” design. This chamber was all-aluminum with indium and lead vacuum seals and bakeable to 125 °C, and evacuated to 2×10^{-7} mbar pressure by a 2 l/s miniature ion pump. The inner shield was passive, with the outer shield actively controlled by thermo-electric coolers (TECs) to a temperature of 35 ^{0}C. The temperature stability of this shield was held at better than 1 mK for weeks. Vacuum viewports and internal windows were coated with for broadband operation between 1064 nm and 1550 nm. A RIO narrow-linewidth fibre-coupled semiconductor laser was then frequency locked to the cavity using an analogue Pound-Drever-Hall (PDH) lock box. Figure 12 shows the PTB thermal shield and outer vacuum chamber arrangement.

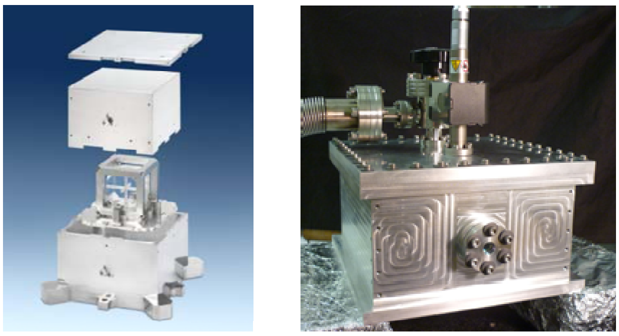

Figure 12: cubic cavity thermal shield and vacuum chamber

The cavity-stabilised 1550 nm laser frequency was compared to an ultra-stable laser locked to a cryogenic silicon cavity, with a reference instability floor of 1 x 10^{-16}. The comparison showed an frequency instability of less than 5 x10^{-15} for averaging times between 0.2 and 100 s, in full compliance with the target stability requirement.

The vibration sensitivity of the cavity frequency was measured to be 7.0 x10^{-11} per g, 2.4 x10^{-11} per g, and 0.9 x10^{-11} per g parallel and orthogonal to the cavity axis without optimization. The worst case is x2.5 above the value measured in the original arrangement at NPL (Webster and Gill Optics Lett. **36** 3572-4, 2011).

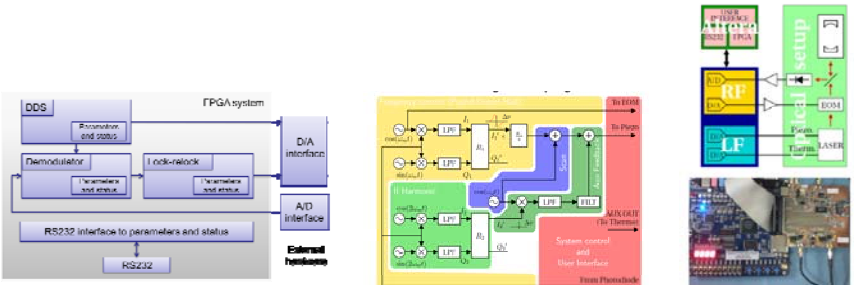

Figure 13: Cavity-stabilised electronic control design developed by INRIM

The electronic control system developed at INRIM to frequency stabilise the RIO laser to the cubic cavity comprised an Altera Cyclone II FPGA board plus daughter board with two 100ks/s 16 bit DA, 50 Ms/s AD and 12 bits DA, with a direct digital synthesis of 500 kHz for the electro-optic modulator to povide the PDH modulation of the laser frequency, and demodulation after signal sampling.

After testing, the high finesse cubic cavity within its vacuum chamber was exhibited at the IND14 industry workshop in Neuchatel, June 2014.

3.2.3 Summary and conclusion

The optical local oscillator developed under this project objective was focussed on the achievement of a portable vibration-insensitive optical cavity capable of withstanding accelerations of the type encountered in eg a space satellite launch, but also able to operate with a frequency stability in advance of any previous portable system. In order to achieve these goals, two consortium partners combined to address different aspects of the system design, with NPL concentrating on the optical cavity design and build and PTB working on the cavity mounting structure and surrounding vacuum enclosure. Both partners brought their individual expertise to bear in developing a prototype portable optical local oscillator which went beyond the current state of the art, and has since resulted in licenses being granted to a European manufacturer. The particular achievements include:

- Enhancement of the original all-ULE cubic cavity design of Webster and Gill (2011), to comprise a ULE spacer with fused silica mirror substrates and compensating ULE ring annuli.
- Multi-level temperature control arrangement of cavity mounting structure within vacuum chamber.
- Vibration insensitivities in 3 orthogonal directions measured to be close to early measurements made on original all-ULE cubic cavity.
- Measured frequency stability of < 5 x 10^{-15} between 0.2 s and 100 s within the required specification.
- Optical cubic cavity system within vacuum chamber demonstrated at final industry workshop at Neuchatel (June 2014).
- European opto-electronics manufacturer Menlo Systems GmbH now agreed licenses for the cubic cavity arrangement.

3.3 Microwave local oscillators

The best commercially available microwave local oscillators are based on ultra-low-noise quartz crystals with frequency stabilities of around 8 × 10^{-14} at 1s. This stability limits performance in some leading-edge applications such as radar for the aerospace and defence sector. Higher-stability alternatives to quartz, such as cryogenic sapphire, are available but are unacceptable due to high maintenance costs associated with their fragility and large size and therefore compact and robust microwave local oscillators need to be developed.

3.3.1 Low noise microwave synthesis from optically referenced femtosecond combs

At present, the best commercially available microwave local oscillators are based on ultra-low-noise quartz crystal oscillators with frequency stabilities of around 8×10^{-14} at timescales of a few seconds. This limits performance in some leading-edge applications such as radar, but higher-stability alternatives such as cryogenic sapphire oscillators have unacceptably high maintenance costs. There is thus a requirement for improved local oscillators with frequency stability and phase noise superior to that of the best commercially available oscillators, but with acceptable size, complexity and power consumption.

In the optical region of the spectrum, highly stable frequency sources can be produced by stabilizing lasers to high finesse optical cavities, with laboratory devices based around room-temperature vibration-insensitive cavities demonstrating fractional frequency stabilities that are typically around 1×10^{-15} from 1 – 100 s or even better. This stability can be transferred to the microwave domain using a femtosecond optical frequency comb, which acts as a low-noise optical-to-microwave frequency divider. Pioneering work on this approach was carried out at NIST using a Ti:sapphire-based optical frequency comb, and has since been extended to demonstrate stabilities below 10^{-15} for timescales of a few seconds.

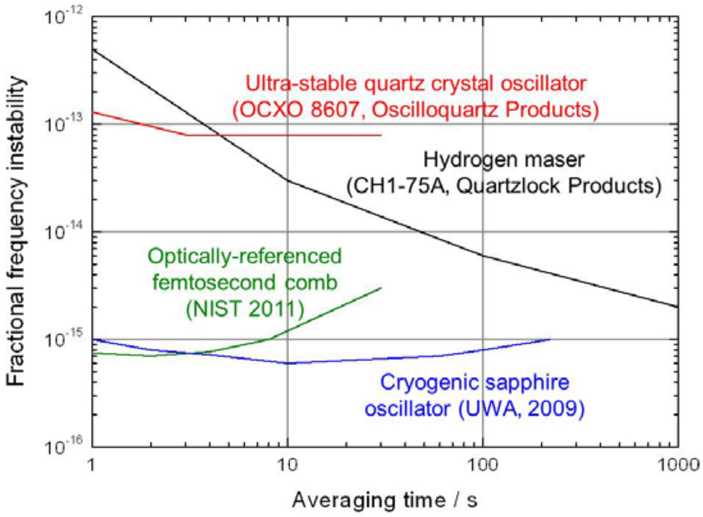

Figure 14: Comparison of several leading microwave generation technologies, clearly demonstrating the potential of optically referenced femtosecond combs to outperform commercially available microwave local oscillator technologies.

It is evident from Figure 14 that optically referenced femtosecond combs can have noise properties far superior to the best commercially available microwave sources. However Ti:sapphire-based combs are relatively large, power-hungry, and do not have sufficiently good long-term operational reliability for most applications. Translating this performance from the laboratory to an industrial environment poses additional challenges, which have been tackled within the project. The project has focussed mainly on using fibre-based femtosecond combs, which are much better suited for continuous operation than Ti:sapphire-based combs. As a result of the work performed, a new toolbox of components for low-noise microwave synthesis from optically referenced femtosecond combs has been produced, which can be configured to provide systems of reduced size and complexity, with performance levels appropriate for particular applications. The components developed can be classified into three main areas: schemes for microwave extraction, different approaches to locking the optical frequency comb, and methods for reducing high frequency phase noise.

3.3.2 Microwave extraction schemes

Transfer of frequency stability from the optical to the microwave domain using a femtosecond optical frequency comb is based on the synchronization of the pulse repetition rate of the femtosecond laser to the optical frequency of an ultrastable laser, and the subsequent detection of the optical pulse train.

Photodetection

The most commonly employed detection system is a fast photodetector. However when an optical pulse train from an optically referenced femtosecond comb is detected using a fast photodetector, excess phase noise is generally observed in the demodulated electronic signals at the fundamental repetition rate and its harmonics, and this can limit the residual stability of the microwave frequency generation. The main cause of this additional phase noise is the amplitude-to-phase (AM-PM) conversion in the saturated photodiodes, which transfers power fluctuations of the femtosecond mode-locked laser into phase fluctuations of the electronic signals generated at harmonics of the pulse repetition rate.

Experiments performed within the project have shown that the phase of the microwave signals relative to the optical pulse train depends on the optical energy per pulse, or equivalently the average optical power. Detailed studies of this dependence have been carried out for InGaAs p-i-n photodiodes operating at 1550 nm, and the energy per pulse to microwave phase conversion (EPC) coefficient has been found to oscillate between positive and negative values as the pulse energy increases, thus exhibiting several vanishing points at specific pulse energies, as illustrated in Figure 15.

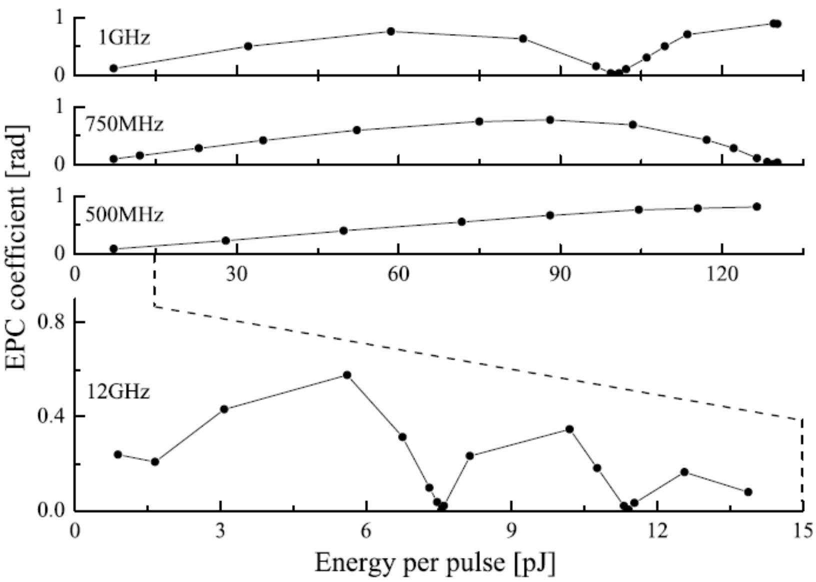

Figure 15. Energy per pulse to microwave phase conversion coefficient for a Discovery Semiconductors HLPD photodiode for a selection of carrier frequencies. Only the absolute value of the coefficient is plotted. Data obtained at OBSPARIS and published in W. Zhang *et al*., Appl. Phys. B 106, 301–308 (2012).

This opens up the possibility of operating at an optical power where the EPC coefficient is close to zero, minimising the impact of AM-PM conversion in low-noise microwave generation from optically referenced femtosecond combs, as long as the null points are sufficiently stable over time and insensitive to the exact operating conditions such as the mode-locked state of the femtosecond laser. Experiments performed at OBSPARIS indicate that this is indeed the case for pigtailed detectors using fibre that is single-mode at 1550 nm. However the exact values of the pulse energy at which the EPC coefficient vanishes are different for every photodiode, even those with the same model number, and so it is necessary to characterise each detector individually. Based on the OBSPARIS measurements, it appears reasonable to expect that a purely passive system tuned to operate at a pulse energy where the EPC coefficient is close to zero could maintain an EPC coefficient below 0.03 rad per relative energy change over long periods of time. This would ensure that the excess phase noise due to amplitude-to-phase noise conversion was 33 dB lower than the relative intensity noise of the femtosecond laser. To achieve a suppression factor greater than this, a more complicated active control system could be used.

Balanced optical-microwave detection

An alternative approach to circumventing amplitude-to-phase noise conversion in the photodetectors is to carry out the phase detection directly in the optical domain using a balanced optical-microwave phase detector (BOM-PD). In this technique, which was originally developed at MIT, a detection scheme based on a Sagnac loop interferometer is used to lock a voltage-controlled oscillator (VCO) to a harmonic of the femtosecond comb repetition rate. This scheme has been shown to be capable of generating 8 GHz signals with very low residual phase noise (–133 dBc/Hz at 1 Hz offset frequency and –154 dBc/Hz at 5 kHz offset frequency) as well as excellent long-term stability. However what had not been shown prior to the work carried out within this project was that the BOM-PD could suppress AM-PM conversion efficiently, with measured AM-PM conversion coefficients being very similar to those for photodiodes. Within the project a modified BOM-PD design was developed with a significantly improved AM-PM conversion coefficient of 0.001 rad, compared to between 0.06 and 0.3 rad (depending on the offset frequency) for previous designs.

In order to achieve high AM-PM suppression, the fibre-based BOM-PD setup developed at NPL incorporated two key changes to previously employed designs. Firstly, variable optical attenuators (VOAs) were introduced at each output of the Sagnac interferometer. These compensate for the loss in the optical circulator and ensure that the intensity on the two detectors is balanced, which is crucial for effective suppression of AM-PM conversion. Secondly, a DC voltage was added to the error signal to compensate for unwanted offsets in the loop filter electronics. Since only fairly coarse adjustments could be made using our VOAs, this DC voltage was also used to fine tune the balanced condition.

With this new design, an AM-PM suppression of up to 60 dB (Figure 16) was achieved. This level was maintained for 28 hours without any degradation and even after 3.5 days the suppression level was still 52 dB. This was achieved without any retuning or active stabilization of the system. For a microwave signal at 8 GHz, this enabled us to achieve residual phase noise levels of –131 dBc/Hz at 1 Hz offset frequency and –148 dBc/Hz at 1 kHz offset frequency. Even though these experiments used a commercial Er-fibre frequency comb with a relatively high residual intensity noise (RIN) this performance was only slightly worse (by 2 dB at 1 Hz offset frequency and 6 dB at 5 kHz offset frequency) than the best results reported to date from a BOM-PD, which were achieved using a specially designed Er-fibre laser with RIN approximately 17 dB lower. With this level of AM-PM suppression achieved in this project, the residual intensity noise (RIN) contribution to the phase noise of microwave signals extracted from optically referenced frequency combs with optimized RIN would become negligible compared to other major noise contributions.

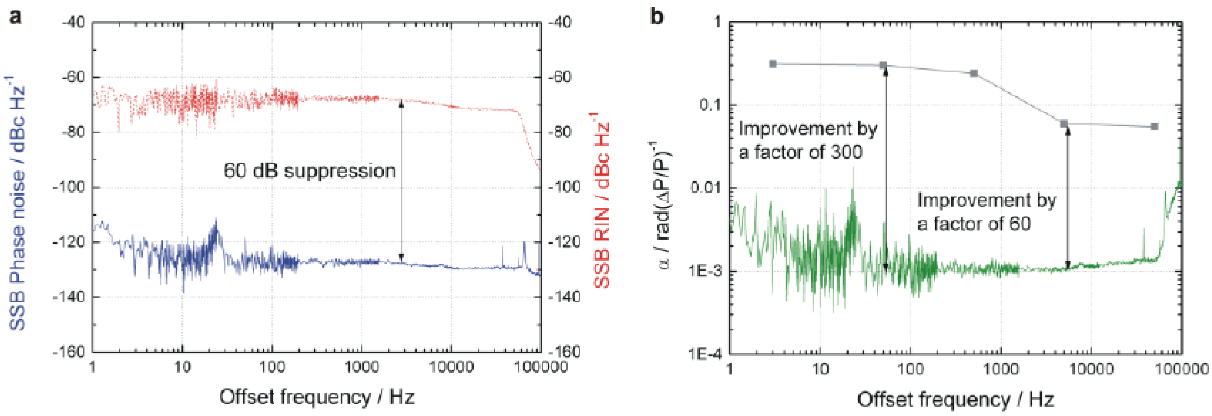

Figure 16: (a) AM-PM suppression results for the BOM-PD developed at NPL, published in M. Lessing et al, Opt. Express 21, 27057–27062 (2013). Dashed red: RIN of modulated laser signal; solid blue: measured phase noise. (b) AM-PM conversion coefficient. Solid green: calculated AM-PM conversion coefficient for our set up; grey squares: previous result from K. Jung and J. Kim, pp. 1 – 4 in Proceedings of 2012 IEEE Frequency Control Symposium.

3.3.3 Optical frequency comb locking

In order to transfer the stability of the optical local oscillator to the microwave domain, the frequency comb needs to be referenced to the optical carrier. One approach is to phase lock the comb as tightly as possible to the optical reference, but an alternative is to use the frequency comb as a “transfer oscillator”, tracking and compensating in real time for the phase fluctuations of the comb.

Tight phase locking with increased comb bandwidth

This approach to low phase noise microwave generation with optical frequency combs was explored at OBSPARIS and relies on the capability of the comb to copy the spectral purity of the cw reference to which it is phase locked over a large range of Fourier frequencies. For fibre-based femtosecond combs, the frequency noise typically extends to Fourier frequencies of more than 100 kHz. To achieve tight phase-locking of such a frequency comb to an ultrastable optical oscillator therefore requires

1. Well-designed control electronics to minimize frequency-dependent dephasing and thus achieve a servo control loop with maximal bandwidth.
2. A high-bandwidth actuator to act on the optical path length of the laser cavity in order to control the repetition rate of the comb.

The purely electronic part of the problem was solved at OBSPARIS by the combination of several standard techniques based on advanced knowledge of control theory. Tackling the second part of the problem requires access to a fast actuator that can act with low Fourier-frequency-dependent dephasing on the repetition rate of the comb over a large range of Fourier frequencies. The final approach adopted at OBSPARIS, in collaboration with an industrial partner, was to add an extra-fast actuator to the laser – an electro-optic modulator (EOM).

A complete dynamical study was performed of the effect of the EOM actuation on the free parameters of the frequency comb, *i.e*. the repetition rate f_{rep}, the carrier-envelope offset frequency f_0 and the amplitude A of the output electromagnetic field. For each of these three free parameters, the transfer function from the three actuators (piezo-mounted mirror, pump power and EOM voltage) was measured. Although different transfer functions were obtained for different mode-locked states of the laser, it proved possible to identify unequivocally the characteristics that allowed a large bandwidth to be obtained for the phase locked loop. In particular, it was found that the coupling of the EOM actuator to the f_0 beat frequency should be as small as possible, which in turn requires the crystal eigen axis of the EOM to be aligned well to the linear polarization axis of the electromagnetic field within the laser cavity. With this condition satisfied, feedback bandwidths of up to 1.4 MHz were achieved.

With this technology, the white noise floor of the microwave signal that can be generated by photodetection of the train of femtosecond pulses is no longer limited by the bandwidth of the phase-lock loop, but by the signal-to-noise ratio of the generated microwave signal. White phase noise floors as low as –150 dBc/Hz for Fourier frequencies higher than 1 kHz from a 12 GHz carrier can thus be obtained (the contribution from residual in-loop phase noise being negligible compared to this measured phase noise).

Due to interactions within the project, this EOM actuator technology is now commercially available from the industrial collaborator as an add-on option to their commercial erbium-doped-fibre optical frequency combs.

Transfer oscillator scheme

The need for fast servo loops can, alternatively, be circumvented by applying the transfer oscillator concept. Here the frequency comb is only weakly locked, and the residual fluctuations of the comb are cancelled in real time by appropriate electronic processing of the beat signals. This approach to low noise microwave generation was investigated during the project by PTB, and the transfer oscillator module developed is shown in Figure. This was used to lock a 9.6 GHz DRO to an ultrastable laser at 344 THz and was characterized by comparing the locked DRO with a second system composed of a second independent femtosecond comb and the same optical standard. The measured residual phase noise and the modified Allan deviation are shown in Figure 17.

Figure 17: Transfer oscillator module developed at PTB. This module consists of the DRO controller, tracking oscillators, mixers and narrow-band filters, and is combined in a 19 inch rack unit.

The phase noise is expected to be limited by the white noise of the photodetection due to shot noise and thermal noise at high frequencies. This level is relatively high, because the comb repetition rate is 100 MHz, while a high harmonic at 9.6 GHz is detected. This has lower amplitude than the lower harmonics, but contains the full shot noise from the average photocurrent. The drop in phase noise at frequencies above 30 kHz is due to the bandwidth of the measurement system and is not present in the microwave signal. The increased phase noise at low frequencies could be due to AM-PM conversion, but is still sufficiently low for many applications. The system shows an instability of 3×10^{-15} at 1 s averaging time.

Since the transfer oscillator method does not require a large bandwidth for locking the repetition rate, it can be applied for smaller and simpler femtosecond combs that do not easily allow additional fast servo elements to be integrated. The possible drawback is due to the limited bandwidth and differences in the delay in the different signal-processing paths that finally determine the corrected microwave frequency. These asymmetries limit the possible suppression of the phase noise, especially at high frequencies. However, at present, these limitations do not significantly contribute to the phase noise in a well-designed system, where sufficient bandwidths (> 1 MHz) are maintained in the different signal paths.

An additional advantage of the transfer oscillator method lies in its flexibility. The various dividers and the fractional multiplication factors in direct digital synthesizers can be set by software and easily adapted to different input and output frequencies that are required by potential users.

As the transfer oscillator method is ultimately limited by noise in the f_{rep} photodetection process, a combination of the BOM-PD with the transfer oscillator method has the potential to produce a simple, high performance system based on compact bulk femtosecond combs. Within the project, schemes for interfacing the two were therefore devised in collaboration between PTB and NPL.

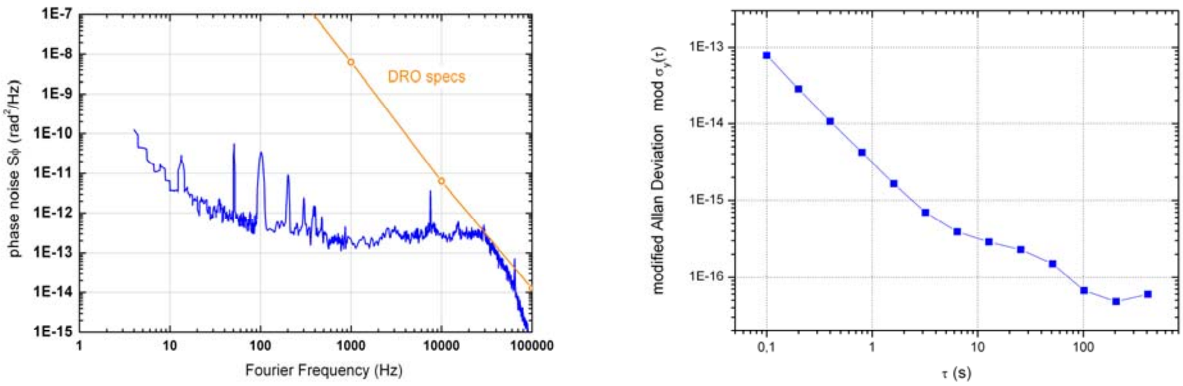

Figure 18: Phase noise of the optically generated microwave signal at 9.6 GHz (left hand graph). The open circles show the phase noise specifications of the free running DRO for comparison. The right hand graph shows the modified Allan deviation of the generated microwave signal, calculated from frequency data measured with a Pi-type counter with 100 ms gate time.

3.3.4 Reduction of high frequency phase noise

As mentioned previously, the white phase noise level achievable for microwave signals generated from optically referenced femtosecond combs is limited by the finite signal to noise ratio of the microwave signal. The main limit comes from thermal noise arising from the thermal agitation of carriers within the photodetector, and leads to an additive phase noise of –177/[10.log(P_{nfrep})] dBc/Hz, where 10.log(P_{nfrep}) is the power of the microwave power of the relevant harmonics of the repetition rate expressed in logarithmic units (dBm). To decrease this excess phase noise, it is therefore necessary to produce the largest possible microwave power at the relevant harmonics of the repetition rate from photodetection of the train of pulses.

The use of high linearity photodetectors with higher saturation levels is a first step in this direction, because they allow higher microwave powers to be generated when sufficient optical power is available. However the limited repetition rate of the femtosecond lasers used (typically < 1 GHz) results in the energy of the photoelectrons being distributed between many harmonics of the repetition rate, whereas usually only one of these harmonics is used for microwave generation, with the others being filtered out using narrow microwave bandpass filters.

Within the project this problem has been addressed by increasing the repetition rate of the pulse train externally to the femtosecond laser. At OBSPARIS, a scheme for repetition rate multiplication was developed based on cascaded Mach-Zehnder topology pulse interleavers (Figure 19). Using this system to multiply the repetition rate of a 250 MHz comb by a factor of 8, suppression of unwanted harmonics was observed to be greater than 30 dB, and the overall gain in the power of an extracted 12 GHz harmonic was 17 dB (Figure 20).

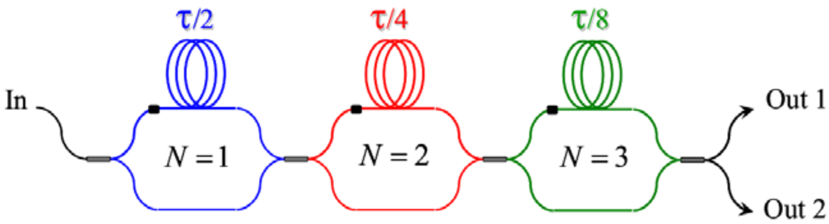

Figure 19: Pulse interleaver based on a Mach-Zehnder topology. This three-stage system allows external multiplication of the repetition rate by a factor 8. In each stage, the pulse train in one arm is delayed by half its period before recombination with the pulse train in the other arm, which leads to a doubling of the repetition rate at each stage.

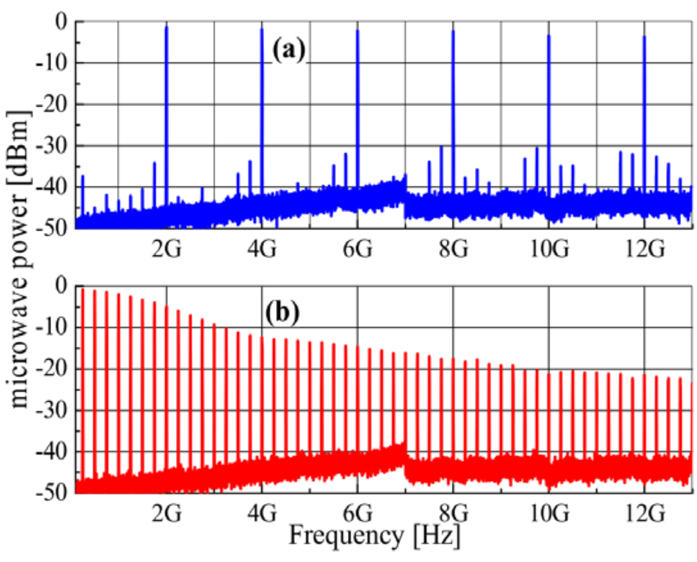

Figure 20. Photodetector (HLPD from Discovery Semiconductor) output spectrum driven with 10 mW total optical power. (a) after repetition rate multiplication of a 250 MHz pulsed laser by a factor of 8, realized with the 3-stage interleaver illustrated in figure 16; (b) photodiode driven by the un-multiplied output of the pulsed laser.

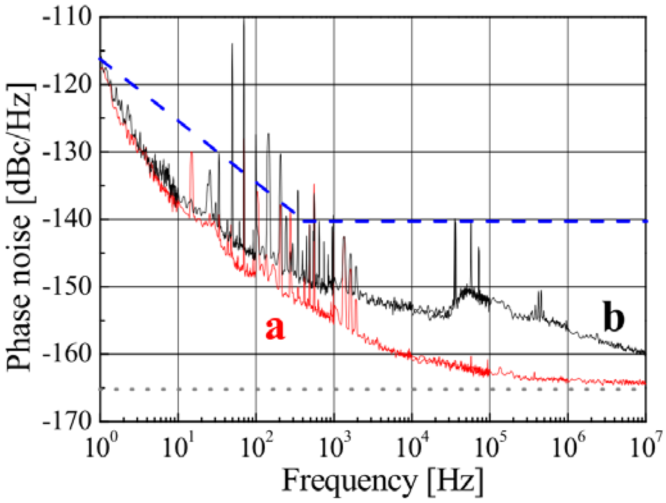

Figure 21: (a) Residual phase noise for the microwave extraction process (1 cw laser, 1 comb, 2 three-stage pulse interleavers, 2 photodetectors). (b) Residual phase noise for a complete optical-to-microwave transfer system (1 cw laser, 2 frequency combs, 2 three-stage pulse interleavers and 2 photodetectors). The dashed line represents the typical phase noise level that would be achievable without the pulse interleavers. [Published in A. Haboucha et al, Opt. Lett. 36, 3654 (2011)]

With this device, the residual phase noise demonstrated for the microwave extraction process (using one optically referenced comb but two independent Mach-Zehnder multipliers) was as low as −165 dBc/Hz at 10 MHz from a 12 GHz carrier (Figure). For the residual microwave generation process, using one common-mode optical reference but two combs and two Mach-Zehnder multipliers, a small amount of excess phase noise was observed. However at 10 MHz from the carrier, the phase noise is below −160 dBc/Hz and it remains below −150 dBc/Hz for Fourier frequencies above 1 kHz.

Finally, it has been shown at OBSPARIS that the Mach-Zehnder pulse repetition rate multipliers can be combined very effectively with photodetectors operating at pulse energies where their AM-PM coefficients are minimized. The Mach-Zehnder multiplier has two equivalent outputs, only one of which was used in the experiments described so far. By using a photodetector on both outputs and recombining the microwave signals obtained from these detectors coherently, a doubling of the signal amplitude is achieved, which can lead to a 6 dB increase in signal-to-noise ratio in the ultra-short optical pulse regime where the shot noise is negligible compared to the Johnson-Nyquist noise. By adjusting independently the bias voltage of the two photodetectors, it is possible to obtain, for a given optical power, operation of both in the regime where the AM-PM coefficient passes through zero, but with one detector exhibiting a positive slope of the AM-PM conversion coefficient versus pulse energy, and the other exhibiting a negative slope. In this way it is possible to adjust the complete microwave generation system to have a very low AM-PM conversion coefficient over a large range of incident pulse energies.

Compact high repetition rate laser sources for femtosecond combs

An alternative route to improving the white phase noise level at high Fourier frequencies is to generate a higher repetition rate pulse train directly from the mode-locked femtosecond laser. This requires a change in laser technology away from mode-locked fibre lasers to compact solid-state mode-locked lasers. This laser development was the focus of the Researcher Excellence Grant (REG) linked to the JRP, and was undertaken at the University of St Andrews (USTAN).

The laser sources investigated within the REG were based on Yb-doped tungstate materials operating around 1040 nm, that offer excellent efficiency, partly due to their direct pumping via laser diodes. The final high repetition rate laser system developed was a Yb:KGW laser pumped by a single mode laser diode. This gave good laser stability due to the small spot size achievable in the Yb:KGW crystal. Stable and self-starting mode-locking was achieved at a repetition rate of 1.02 GHz using a commercially available saturable absorber mirror. This modified laser system produced near-transform limited pulses of 185 fs duration at 1043 nm centre wavelength with a bandwidth of 7.1 nm, implying a time-bandwidth product of 0.36 (figure

22). With a 2.5% output coupler an optical-to-optical efficiency of 43% was achieved during mode-locked operation. With only 3 W of pump power, 1.36 W average power could be extracted from the laser, corresponding to a peak pulse power of 6.65 kW.

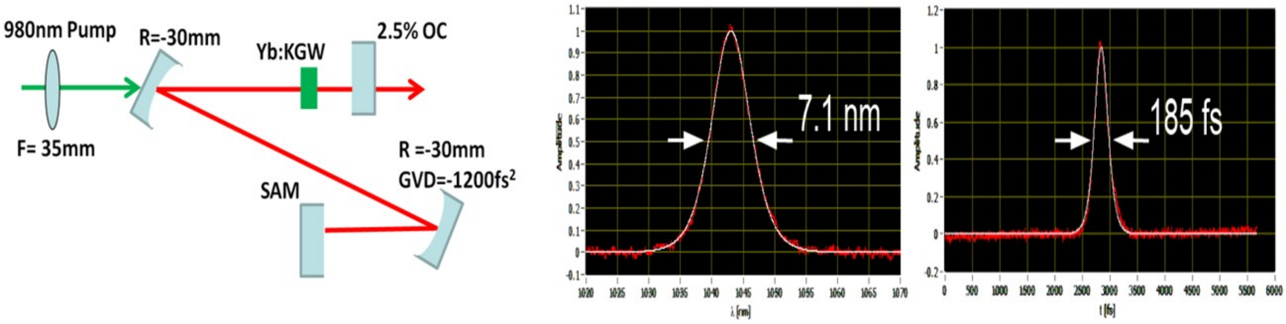

Figure 22: GHz mode-locked YB:KGW laser schematic, OC output coupler, SAM saturable absorber mirror, showing 7.1 nm bandwidth and 185 fs pulse width at 1043 nm.

Repetition rate stabilisation

A repetition rate stabilization system was implemented for the 1 GHz Yb:KGW laser system. The pulse repetition rate is detected using a fast photodiode and compared with a reference 1 GHz oscillator using a double-balanced mixer. The error signal from the mixer is then used to control the repetition rate of the laser via feedback to the piezo-electric transducer on which the output coupler is mounted. The loop filter used in the stabilization circuit was provided by NPL, together with advice to the REG researcher on control loop optimisation. Although the control bandwidth achieved was not particularly high, being limited by resonance frequencies of the piezo-electric transducer, this should not be an issue for low-noise microwave synthesis as long as the transfer-oscillator scheme discussed above is employed.

Supercontinuum generation for carrier-envelope offset frequency stabilization

For stabilization of the carrier-envelope offset frequency of the comb produced by the mode-locked Yb:KGW laser using the *f*:2*f* self-referencing scheme, it is first necessary to generate a coherent octave-spanning spectrum. Theoretical calculations and simulations showed that the pulses produced from the laser are insufficiently short to generate such a supercontinuum directly. It is therefore necessary first to spectrally broaden and then to compress the pulses in order to achieve a shorter pulse duration for coupling into the nonlinear fibre used for supercontinuum generation, using a combination of three different fibre types, one for each of the three processes needed. Initial tests of the theoretical model were performed using a 70 MHz repetition rate Yb:KYW laser and good agreement between experiment and theory was achieved in this case. Unfortunately, however, the experimental results achieved with the 1 GHz Yb:KGW laser did not match the theoretical simulations, and it was not possible to achieve a coherent octave-spanning spectrum using this laser configuration. Hence it was not possible to stabilize the carrier-envelope offset frequency of the comb. Possible ways in which this limitation could be overcome in future work include increasing the power of the pump laser, reducing the laser repetition rate to 500 MHz, or a novel method for carrier-envelope stabilisation without the use of a supercontinuum.

3.3.5 Summary and conclusions

In summary, within the project developed a new toolbox of components for low-noise microwave synthesis from optically-referenced femtosecond combs has been developed, which can be configured to provide systems with performance levels appropriate to particular applications (Figure 22). For example, for less demanding applications, simple photodetection may be sufficient, perhaps combined with the transfer oscillator module to bypass the need for tight phase locking of the optical frequency comb. For applications where lower phase noise levels are required, other schemes should be considered, such as the BOM-PD, or photodetectors operated at their minimum AM-PM point, combined with repetition rate multiplication techniques.

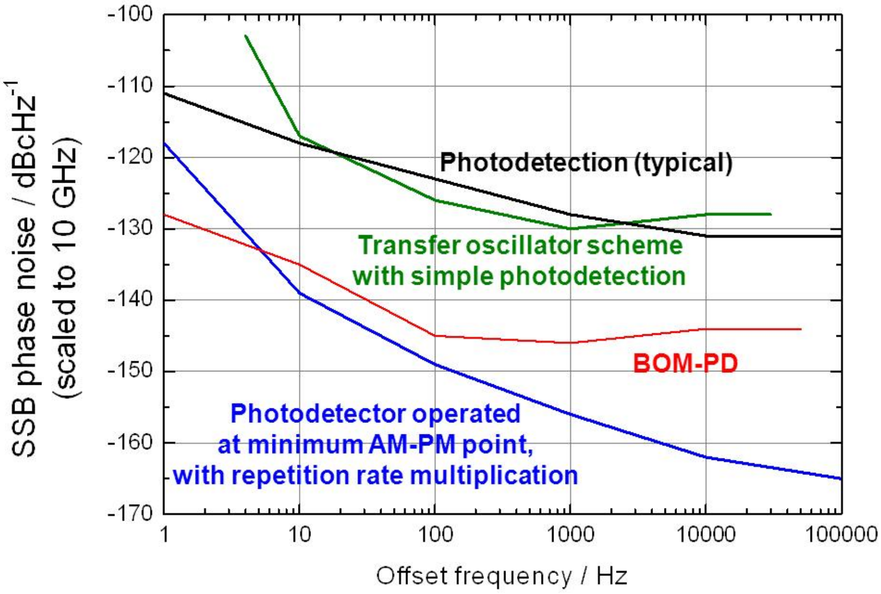

Figure 23. Comparison of the residual phase noise achieved using different microwave generation schemes (scaled to 10 GHz).

Research within this project objective included activities in OBSPARIS, NPL and PTB, which covered a range of techniques for generating very low phase noise microwaves from optical local oscillators reported in the previous objective, all of which demonstrated results going beyond the state of the art. These incuded:

- AM-to-PM noise conversion-free detection at specific pulse energies at the detector at OBSPARIS
- NPL demonstration of AM-to-PM phase noise suppression in the optical domain achieving 60 dB suppression improvement over previous measurements.
- Tight phase locking of the frequency comb to optical carrier of an ultrastable optical oscillator at OBSPARIS, reaching -150 dBc/Hz above 1 kHz for a 12 GHz carrier
- Licensing of this tight phase locking technique to Menlo Systems GmbH
- PTB demonstration of transfer oscillator scheme achieving 3 x 10^{-15} instability at 1 second averaging, thereby not significantly increasing the optical local oscillator stability following the optical-to-microwave conversion
- Efficient frequency comb repetition rate multiplication from 250 MHz to 2 GHz by OBSPARIS using multiple Mach-Zrender fibre interferometers to suppress unwanted phase noise from unused rep rate frequencies

3.4 Microwave frequency standards

Many middle-range-accuracy time and frequency standard applications involving time synchronisation between remote antennae (e.g. telescope arrays for very long baseline interferometry) or synchronisation of remote data systems, employ high performance quartz oscillators or commercial rubidium atomic clocks, which are referenced to an external signal such as GPS. However, for industrial autonomy the frequency standard should ideally provide an accurate and stable reference independent of the external reference signal over extended periods. These medium capability clocks and timing systems that are synchronised to higher accuracy remote timing systems such as GPS are fine whilst they have the GPS access. However, loss of access to the GPS signal, due to intentional jamming or difficulties in achieving direct line of sight to the satellites eg in high-rise urban areas, requires that the local clocks have sufficient accuracy and stability to maintain timing synchronisation during these GPS-denied periods. Currently quartz oscillators only give good short-term stability and do not provide an accurate reference over extended periods. There are industrial stand-alone rubidium and caesium atomic clocks available, the caesium systems providing the better accuracy, but these tend to be expensive rack-mounted systems, whereas there is a need for low-SWaP (size, weight and power) portable atomic clocks for use in mobile communications in defence, aerospace and telecoms.

3.4.1 Caesium-filled hollow core fibres

The viability of gas-filled hollow core fibres as optical frequency standards in the mid infra-red for application as references in optical communications and sensing has been discussed earlier in this report. The development of sealed HCF cells filled with acetylene has been demonstrated both in this project and with methane and carbon dioxide elsewhere in the literature. Given the reasonably inert nature of these molecular gases, the successful filling and sealing techniques developed have led to good progress in achieving stand-alone HCF cells providing narrow optical references against which to stabilise mid infra-red lasers. The project has also pursued the possibility of filling HCF with alkali vapours such as caesium with a view to providing simple atomic references for microwave frequency standards. In particular, the project hasinvestigated the viability of a Cs-filled HCF to provide a 9.2 GHz clock system with a low-SWaP (size, weight and power) that could be used in the field in a variety of mobile applications in defence, security and communications, thereby allowing, in particular, clock resilience and hold-over at the medium performance level in mobile situations where access to GNSS satellite signals is unavailable or denied.

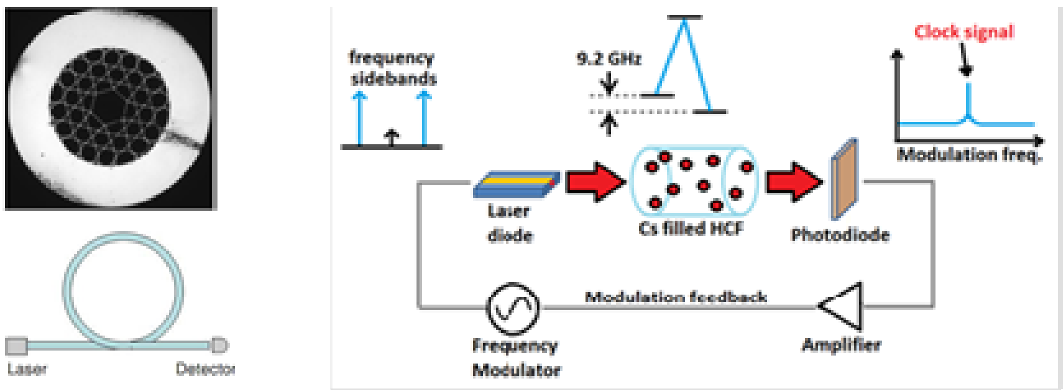

Figure 24: Hollow core fibre clock schematic showing a) cross-section of typical HCF Kagome fibre, b) simplified HCF clock architecture and c) HCF system concept

The hollow core fibre clock concept is based on the principle of coherent population trapping (CPT). The Cs-filled HCF is probed by a semiconductor laser operating close to one of the Cs resonance D lines such as at 852 nm. Tuneable microwave modulation at a 4.6 GHz frequency close to half of the 9.2 GHz ground state hyperfine clock frequency is applied to the laser diode drive. With a strong enough microwave modulation intensity, the optical carrier frequency is suppressed, providing two optical frequency sidebands on the carrier separated by a tuneable 9.2 GHz frequency. When this frequency is resonant with the Cs hyperfine separation, the atomic population becomes trapped in a superposition of ground states, with result that the 852 nm laser light is not absorbed by the atoms. This results in a small increase in detected laser light, thereby providing optical detection of the microwave resonance. This clock signal is then extracted and provides an error signal against which to electronically servo the microwave oscillator to the Cs resonance. This technique avoids the need for generation and delivery of relatively large microwave waveguide equipment of ~ 3 cm cross-sectional dimension (corresponding to the Cs 9.2 GHz wavelength), relying instead on the focussing and manipulation of the 852 nm wavelength, thereby offering a much more compact microwave clock based on modulated light.

An example of a micro-structure HCF is shown in figure 24. The microstructure has the effect of achieving tight confinement in the hollow fibre core, thereby providing guiding of the probe light. The microstructure can be of two generic types, photonic band gap PBG or anti-resonant (Kagome). In general, the PBG HCF provides for smaller core diameters in the region of 5 μm – 20 μm diameter, whereas the AR HCF has core diameters in the range 20 μm – 100 μm. Whilst the former allows better single mode guiding, the latter provides larger absorption volumes and reduced Cs wall relaxation rates, at the expense of multi-mode guiding with reduced guiding efficiency. The typical lengths of fibre used here varied form 20 cm - 50 cm.

Figure 25 shows a schematic and photo of the HCF vacuum system. The HCF is connected to the vacuum apparatus by means of two fibre feedthroughs at each end of the fibre. The feedthroughs are fixed to two small chambers evacuable by means of turbo pump or sputter ion pump. The chambers contain Cs-impregnated ribbon dispensers, activated by means of current through the ribbon. The full length of the fibre could be heated to several tens of degree ^{0}C in order to vary vapour pressure post-dispensing. Each chamber could be sealed from the pump system independently, with pumping through the fibre via the other chamber as necessary. The absorption of 852 nm laser light by Cs in the fibre could be monitored by passing the 852 nm through the fibre and detecting the transmitted light by means of a detector positioned facing the fibre end through a vacuum window. In this arrangement it was necessary to take account of the contributing absorption in the short length of chamber between the fibre tip and window. In order to calculate this absorption, a separate probe beam could be sent orthogonally through the chamber to a second detector to determine the chamber absorption across its full width and allow scaling to that in the tip-to-window length. One of the major issues in filling the fibre was the potential for uneven Cs condensation in the fibre leading to aggregation of material in specific points along the fibre. Careful attention to the filling procedure avoided this, but at the expense of slow fill times over extended periods of a few weeks. This extended filling time resulted in a slower rate of progress than originally expected, with result that the later anticipated deliverables were not fully achieved in the way originally anticipated.

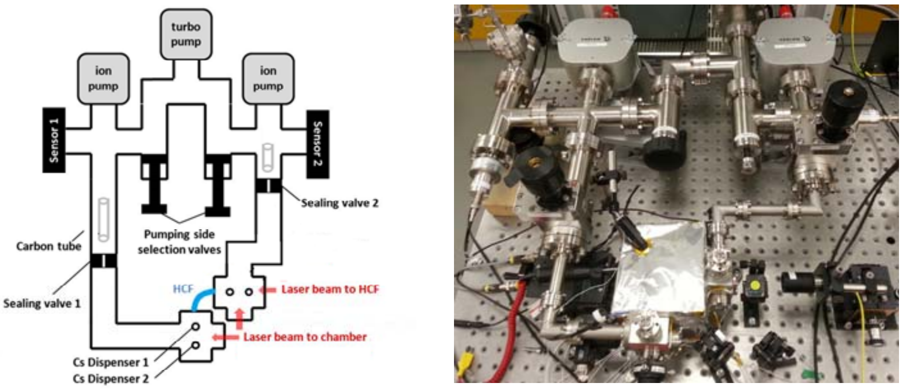

Figure 25: Schematic and photo of the HCF caesium filling apparatus

3.4.2 Spectroscopic investigations of Cs-filled HCF

In order to monitor the extent of the Cs absorption in the HCF, a Cs optical reference arrangement was set up (Figure 26). This involved the use of an extended cavity diode laser (ECDL) operating at 852 nm. The single mode 852 nm laser output was circularised by means of an anamorphic prism pair and transmitted through an optical isolator before being split into three. One of these was sent a wavemeter to record and set the wavelength to the 852 nm region. The second output was transmitted and retro-reflected through a bulk 20 cm long Cs cell arranged to detect Doppler-free Cs 852 nm D2 saturated absorptions in order to provide high resolution frequency reference marker spectra as the laser was tuned through the linear Doppler-limited Cs absorption. The remaining beam was split into two, with one part transmitted by fibre to a focussing lens and launched into the HCF fibre through an input window and transmitted through the HCF to a detector / CCD at the far end, and the other part used as the chamber reference beam

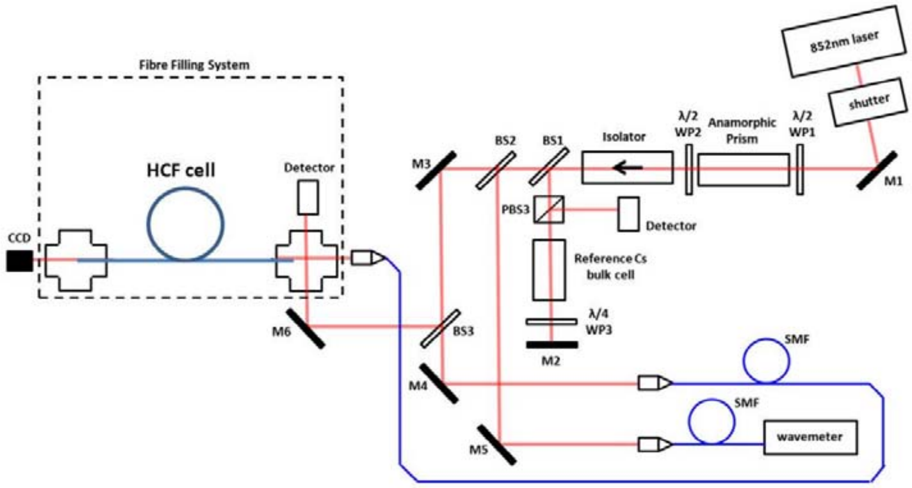

Figure 27: Optical reference system for monitoring Cs absorption at 852 nm in HCF and chamber

In order to compare the efficiency of the Cs filling of the hollow core fibre, a saturated absorption arrangement was set up through a 20 cm length of HCF. The results are shown in comparison with the saturated spectra observed in the reference cell, and given below in Figure 27. It is clearly shown that the Doppler limited absorption profile from the HCF mirrors that obtained in the reference cell. Further, the saturated spectra observed in the HCF are stronger than in the reference cell, showing greater contrast and equivalent Doppler-free linewidths for equal linear absorption signals. This confirms the effectiveness of the filling process as well as the suitability of the HCF architecture to provide narrow linewidth spectroscopic signals.

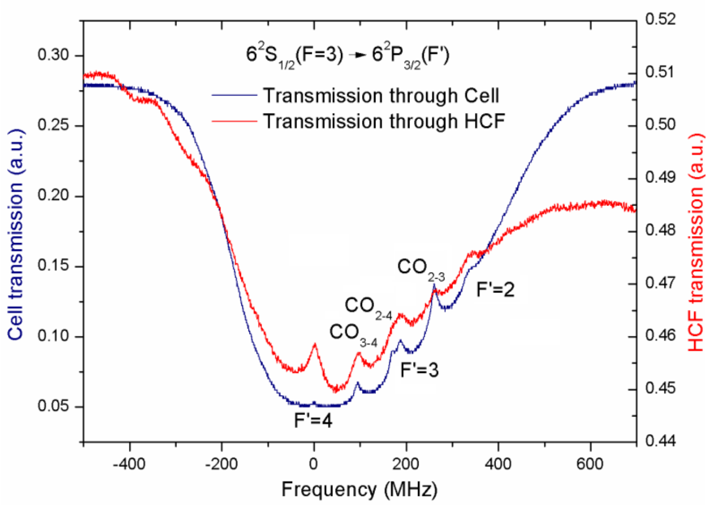

Figure 26: Cs 852 nm Doppler-free saturated absorption spectra observed via transmission through the Cs reference cell and through the hollow core fibre; CO crossover resonance

Given the extended time required to investigate and develop an effective HCF filling procedure, it was not possible to extend the spectrosocopic investigations of the multi-photon techniques within the hollow core fibre beyond the optical saturated spectra data obtained. As a result CPT microwave clock signals were only observed within the reference cell.and not the HCF. The main limitation here was the need to remove the HCF from the vacuum apparatus in order to set up the CPT detection which involved magnetic field application. Development of a robust sealing procedure of the HCF required more R&D than was available towards the end of the project.

3.4.3 Cs-filled HCF microwave clock design

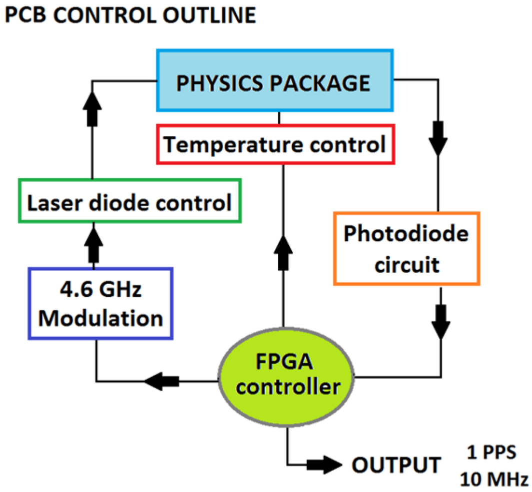

Figure 28: Control circuit design for stabilising the microwave local oscillator to detected CPT signals

A hollow core fibre-based microwave clock package was designed and is shown in figure 28. The HCF complete wth probe laser, HCF, detector, magnetic field and thermal shroud is designated in the figure as the physics package. An FPGA controller provides necssary control voltages to the physics package as well as feedback control signals to the 4.6 GHz modulation of the probe laser that result from the optically-detected CPT error signals at the photodiode. The FPGA functionality also provides for divided-down outputs to give standard clock output signals at 10 MHz and 1 pulse per scond.

3.4.4 TACC short-term stability

The microwave frequency standard investigated within the project that targeted high performance industrial clock capability involved a clock architecture based on laser-cooled magnetically trapped atoms on a chip (TACC). An existing prototype TACC set-up at project start has been taken further within the project by comparing the TACC clock frequency against a SYRTE reference maser. The reference maser, calibrated by the SYRTE fountain clocks, has a short term stability close to $1 \times 10^{-13}\ \tau^{-1/2}$. The TACC frequency drift is measured to be 5×10^{-16} per day. The measurement of the TACC stability uses Ramsey spectroscopy. The microwave LO (local oscillator) frequency is tuned to the half-height of the central fringe, which is the point of maximum slope and measure the transition probability in a cyclic fashion, while toggling between the left and right side of the fringe. Every 20 cycles the LO frequency was slightly adjusted to compensate for the clock drift and thereby remain on the steep slope. The frequency steps are added when analysing the data. The measured stability of the frequency difference f_{TACC}-f_{maser} is shown in figure 29. The first point of the Allan variance is at 16 s which is the cycle time. The Ramsey time is 5 s. This is, thanks to the new concept of interrogating trapped atoms, one order of magnitude longer than in a fountain clock. The short term behaviour of the clock frequency stability follows $5.8 \times 10^{-13}\ \tau^{-1/2}$ which is a 2 fold improvement since the beginning of this project. The TACC thereby surpasses the performance of the best commercial atomic clock (Symmetricom / Microsemi) by one order of magnitude. The stability improvement is due to an increase in the number of atoms per cycle, as well as a careful analysis of cross correlations between the clock frequency and all simultaneously-measured parameters. The dominant improvement comes from a correction by the density of the atom cloud. This information is available, because, as a novelty, TACC's detection is made via absorption imaging of the two atomic clouds on a camera. Thereby the atomic density can be determined at every cycle. Further significant improvement of the TACC short term stability is beyond this contract, since it implies important changes to the vacuum system.

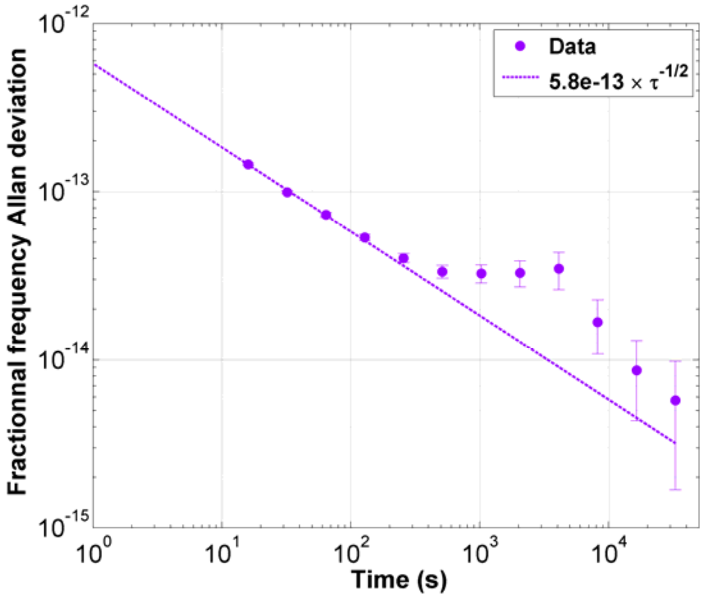

Figure 29: Data set of the LNE-OBSPARIS Trapped-Atom-Clock-on-a-Chip stability when compared to a hydrogen maser. The points show the Allan standard deviation of the fraction frequency difference f_{TACC}-f_{maser} between TACC and the maser. The maser stability is known to be near to 1 $10^{-13}\tau^{-1/2}$ with a long term drift of 5 10^{-16} per day. The measured difference of 5.8 $10^{-13}\tau^{-1/2}$ at short term meets the deliverable. The long term stability of 10^{-14} at one day, which was a deliverable is outperformed by a factor 3.

3.4.5 TACC long-term stability and accuracy

TACC's long term stability was evaluated by continuing the comparison to the SYRTE's reference maser during several days. With the maser drift being negligible, all the frequency instability can be attributed to TACC. The measured difference f_{TACC}-f_{maser} shows an oscillation at 3000s which is caused by fluctuations of the laboratory temperature imposed by the air conditioning. At longer timescales the stability improves again approaching the initial 5.8 x $10^{-13}\tau^{-1/2}$ behaviour to within a factor 2. The stability reaches 6 x 10^{-15} at 30 000 s (~0.3 day). This outperforms the targeted deliverable of 10^{-14} at one day by a factor 3. For the long term stability, as for the short term stability, correction of the clock frequency by the atom density gave the dominant improvement. The analysis of cross correlations with other parameters like the magnetic field, revealed these of sufficient stability, such that the clock frequency is not affected. The results have been submitted for publication [Szmuk 2015].

The accuracy is the property of predominant interest when it comes to providing a master-clock capable of autonomous operation. Given the excellent short-term stability, the trapped atom clock is a promising approach to surpassing the performance of state-of-the-art commercial clocks. Prior to the project the absolute frequency of TACC had not been evaluated. During the project the consortium performed

- Measurements of the parameters identified as affecting the clock frequency: the magnetic field, the atom density, and the two-photon clock interrogation mechanism. Independent measurement procedures for these parameters were developed and their effect on the clock frequency calculated.
- A theory for the TACC was elaborated including the spin self-rephasing mechanism. It allows to predict the clock frequency.
- Measurements of the absolute frequency of the TACC and comparison with the theory (target accuracy in the 10^{-13} range).

The absolute frequency has been measured through comparison with the SYRTE's reference maser, which is calibrated by the SYRTE's primary standards. The frequency was measured as a function of the 4 principal experimental parameters, the Ramsey time, the magnetic field, the atom temperature and the atom number. The absolute clock frequency and the contrast of the Ramsey fringes were modelled by a Monte Carlo simulation using predetermined parameters. Good agreement was found between measurement and model (a few x10^{-13}) allowing to predict the clock frequency from the independently measured parameters.

The final error budget on the clock accuracy is dominated by the uncertainty with which the atom temperature can be determined using standard methods. This leads to a clock accuracy of 10^{-11}, falling short of the target. Future work should target more accurate temperature measurements by potentially new methods. Parts of this work have been published in [Maineult 2012]. A second publication is in preparation.

Unlike most primary standard clocks, the compact clock solutions considered in this project objective involve the use of two or more photons to perform the atom interrogation. LNE-OBSPARIS has investigated the effects of this multi-photon interrogation mechanism on the clock performance. Concerning the TACC short term stability, no degradation was observed, proving the complete equivalence to a one-photon interrogation. With respect to clock accuracy, a frequency shift, known as the light shift, was observed, due to the weak coupling of each of the two photons with the nearby intermediate atomic level, which is not a clock state. A procedure to evaluate this shift to the level of 10^{-11} has been developed and applied. Furthermore, it was shown that a particular choice of the ratio between the two single-photon Rabi frequencies eliminates the light shift. In fact the multi-photon interrogation employed in TACC, makes the evaluation of the light shift particularly easy, where in single-photon clocks complicated evaluation procedures have to be conceived.

3.4.6 Summary and conclusions

The research activity targetting this project objective was carried out by NPL and LNE-SYRTE. In order to cover a range of industrial clock applications, NPL focussed on low SWaP portable thermal atom microwave clocks with target stabilities and accuracies in the 10^{-11} – 10^{-12} range, whilst LNE-SYRTE concentrated cold atom clock systems with stabilities and accuracies in the 10^{-12} – 10^{-13} range to make advances over the current commercial rack-mounted systems. In the former case, the development of minature clocks based on Cs vapour-filled hollow core fibres represented a new activity beyond the state of the art in respect of well-controlled introduction of alkali vapour into the HCF platform, with a considerable learning curve. As a result, the R&D into Cs filling and sealing of the HCF took longer than anticipated, and thus did not allow investigations into the generation of microwave coherent population trapping signals before the end of the project. However, two-photon saturated absorption spectroscopic signals were achieved, identifying the alternative opportunities for near infra-red 852 nm frequency standards based on alkali-filled HCF. The trapped atom on a chip clock activity was able to build on a prototype device established prior to project start, enabling a successful characterisation and measurment of stability and accuracy for the device within the project. The major results going beyond the state of art comprise:

- Development of procedures for filling hollow core fibre with alkali atoms
- Observation of caesium saturated spectra with good signal to noise contrast compared to saturated signals observed in the bulk reference cell.
- Derivation of design for detection of coherent population trapping signals in Cs-filled HCF.
- CPT signals in hollow core arrangements have now been observed in a follow-on project
- Measurement of TACC frequency stability of 5.8 x10^{-13} $\tau^{-1/2}$, reaching 6 x10^{-15} at 30,000 s, and surpassing long term stability requirement by a facor of 3.
- Stability superior to that published for the best commercial clocks
- Initial accuracy measurements demonstrated fractional accuracies of 10^{-11}, falling short of targeted 10^{-13} range, and requiring further investigation.

4. Actual and potential impact

4.1 Metrology achievements

The project worked towards the transformation of NMI-based frequency standards technology, which is typically bulky, power-hungry and generally capable of operation only within a well-controlled laboratory environment, into a new generation of high performance, compact, portable, robust and turn-key instruments that are well-suited for operation in industrial environments. The industrial prototypes developed within the project address the limitations of existing industrial frequency standards across a wide range of market sectors including telecommunications, instrument manufacture, gas sensing, aerospace, defence and navigation.

To meet the frequency traceability needs of the telecommunications industry, a new generation of optical frequency standards based on lasers stabilized to gas-filled hollow-core fibres has be developed. The application of this new fibre technology eliminates problems associated with misalignment of bulk optics, enabling compact and turn-key standards to be developed. Compared to commercial systems, which do not employ molecular or atomic references, up to two orders of magnitude improvement in stability and accuracy seem feasible. Extension of the technology to wavelengths of interest to other applications such as gas sensing was also investigated. A laser setup for realizing a frequency reference at 2051 nm by locking the laser to carbon dioxide (CO_2) spectrum was built and characterized at DFM. This wavelength has importance in e.g. measurement of atmospheric carbon dioxide from satellites.

Applications in the aerospace, defence and navigation sectors, such as radar, rely principally on the short-term stability of a frequency standard, and so here the requirement is for improved local oscillators with frequency stability and phase noise superior to that of the best commercially available oscillators, but with acceptable size, complexity and power consumption. Both optical and microwave local oscillators prototypes were developed within the project. A compact and transportable optical local oscillator was developed based on a laser stabilized to an ultra-low-expansion high finesse optical cavity that is specially designed to have very low sensitivity to vibrations. An ultra-low-noise microwave local oscillator was developed by stabilizing a compact femtosecond comb to an optical local oscillator. A variety of approaches was explored in an effort to demonstrate improved phase noise at high Fourier frequencies.

Other applications in communications, aerospace, defence and security require autonomous operation, free from the need for an external reference signal, to cater for instances where the external signal is unavailable. This may arise inadvertently through eg multipath reflections in high rise city areas or solar storms affecting GNSS signals, or by design through intentional jamming. In such cases an atom-based frequency standard, rather than a local oscillator, is required in order to enable continued timing synchronisation during the signal “black-out” period. Within the project, two different technologies for atom-referenced microwave frequency standards have be investigated, targeting industrial applications with different performance requirements. For medium performance (clock stability and accuracy in the 10^{-10} – 10^{-12} range) standards based on Cs-filled hollow-core fibres were studied. This technology is well suited to the production of extremely compact standards with excellent prospects for integration into mobile technology. For applications requiring higher clock performance (clock stability and accuracy in the 10^{-12} – 10^{-13} range) a trapped atom clock on a chip was investigated.

4.2 Dissemination activities

4.2.1 Scientific publications

The project has generated 24 high impact publications in key journals and a further 2 are in preparation. These incorporate the significant scientific outputs of the projects. A list is provided in section 6.

4.2.2 Conferences and related fora

The project consortium has given in total 59 presentations at various relevant conferences around the world. Particular invited and notable presentations included:

ICAP 2014, Washington:
Haeffner et al, PTB *Ultra-low frequency noise based on a 48-cm long ULE cavity for a Sr lattice clock*
Maineult et al, OBSPARIS *Trapped atom clock on a chip*

IEEE International Workshop on Metrology for Aerospace 2013, Benevento, Italy
Sterr, PTB *Optical clocks for applications on ground and in space*

Royal Society – dstl Quantum Landscape meeting, 2013, UK
Gill, NPL *Precision timing and clocks*

EFTF 2013: Prague, Czech Republic
Lessing et al, NPL *An optical-microwave photodetector for generation of low noise microwave signals from a frequency comb*
Falke et al, PTB Sr lattice clock with reduced BBR uncertainty
Gill, NPL (plenary) *Optical clocks – Way ahead of their time*

EFTF 2013, Goteborg, Sweden

Maineult et al, OBSPARIS *Spin pair resonances in a trapped atom clock*

4th ESA international woekshop on optical frequwncy standards and clocks 2011, Trani, Italy
Webster, NPL *Force insensitive optical cavity*

4.2.3 Stakeholder engagement and standards

Impact has been created through several stakeholder engagement activities. Prototypes and design recommendations arising from the project have resulted in follow-on interactions and informal collaboration with industry. Further, the project resulted in a number of follow-on collaborative projects that have received national or European funding. Other projects concern direct technology transfer to the industrial partners of the project and other stakeholders, which in some cases has led to new products under license.

Two electronic newsletters were produced during the project, targetting stakeholders, including those organisations who had already expressed their interest in the project via letters of support and the wider community via knowledge transfer networks, The newsletters reported recent results and forthcoming conference and workshop announcements.

Most of the project maintain strong links to academia and have students and post-doctoral fellows working in their laboratories. A number of PhD theses concerned with research that formed part of the project R&D activities were submitted during the project. In addition, a number of students and postdoctoral fellows participating in the state-of-the-art research in the metrology institutes went on to new positions in industry, other government institutions and space agency-related concerns, disseminating knowledge acquired during the project.

Particular examples of stakeholder engagement include the following activities:

- With regard to hollow core fibre optical frequency standards at 1.5 μm telecoms wavelengths, the sealing and coupling techniques for HCF-based gas cells are already of interest to industry, particularly the microstructure fibre fabricators such as NKT Photonics and Chylas, and optical telecoms equipment manufacturers such as Agilent. Contacts and interactions with such companies were carried out during the project with a view to industrialization of HCF prototypes. Regular meetings with the Collaborator NKT Photonics have been held (DFM, EJPD).
- The wavelength standards, which have been developed in this project have the potential to provide improved calibration procedures for optical spectrometers and other optical measuring instrumentation. The compact all-fibre gas cells developed in the project have been tested by one of our industry partners, Agilent, and have proved their applicability as internal wavelength standards for optical spectrometers.
- The successful demonstration of spectroscopy measurements at 2 μm using HCF-based gas cells and stabilized lasers for atmospheric CO_2 concentration measurements opens new possibilities for environmental monitoring, both with ground-based sensors and with satellite-based sensors, with active ESA interest in the development of the latter for Earth observation for global climate change studies.
- METAS (EJPD) and collaborator Diamond envisage the development of optimized gas-tight fibre optics connectors.
- The ongoing research activities have been reported to the IEC TK86 Swiss Committee (EJPD). The committee has visited METAS in November 2012.
- The prototype at MIKES was demonstrated to representatives from the Finnish Geodetic Institute, in prospective of measuring the earth gravitational potential using accurate compact frequency standards
- The development of high-stability vibration-insensitive optical reference cavities for use in laser frequency stabilisation in industrial and mobile environments is clearly identified in the take-up by manufacturing companies for high resolution spectroscopic instrumentation, Following the industry workshop at the end of the project, where the in-vacuum cubic cavity optical local oscillator was demonstrated, MenloSystems GmbH began serious discussions with the NPL and PTB partners concerned in respect of licensing possibilities to market the optical cavity arrangement. With further

discussions over the next 18 months, licensing arrangements have been agreed for the cavity system to be added to the SME product portfolio

- Further, portable optical reference cavities with capability for space qualification are already showing significant traction with ESA and national space agencies. The NPL cubic cavity design demonstrated in the project is also now under consideration in existing and new projects for space-based cavities to provide the means for high stability lasers for gravity mapping, space optical clocks and potentially a space-based gravitational wave observatory
- PTB and Menlo-Systems successfully applied within the German technology transfer programme ZIM to develop rugged, transportable reference cavities and mountings, optical couplings, laser stabilization units and temperature controls. This project has started in August 2013.
- A meeting took place at PTB with representatives from ESA, University Düsseldorf, RUAG Sweden, SP Sweden, LNE-OBSPARIS to discuss technologies for rugged optical reference cavities and microwave generation and characterization by optical frequency combs.
- With regard to microwave frequency synthesis, the project has achieved impact through follow-up projects receiving national or European funding. A number of these concern technology transfer to the industrial collaborators in the project, leading to integration into new products. An example is the OBSPARIS development of low-noise microwave generation using optical frequency combs combined with fiber spool-based interferometers for repetition rate multiplication, in collaboration with MenloSystems GmbH. The technology transfer has been awarded a Eurostars grant for the STAMIDOF project aiming at industrialization of a low-noise microwave source. .
- Miniature caesium microwave clocks based on thermal Cs atoms loaded into hollow core fibre and probed with microwave-modulated laser light have generated significant interest from the UK defence science and technology laboratory as very low SWaP devices suitable for mobile operations in the field, and UK companies interested in manufacturing such devices. A number of NPL presentations on microwave and optical micro-clocks were given at various science and industry workshops during 2012 – 2014, organised by UK Ministry of Defence, Innovate UK and UK quantum hub-related universities
- The trapped atom clock on a chip (TACC) concept using magnetically trapped cold rubidium atoms comprises a few cm^3 physics package volume, and shows leading-edge stabilities for this compact size, as outputs from the project. This is thus well positioned for integration into a small high accuracy microwave clock platform, and there has been interest from France-based multi-national companies
- Representatives of CNRS, NPL, OBSPARIS and PTB took part in the instrument definition consortium for the proposed ESA STE-QUEST mission.
- Representatives of LNE are part of the science consortium for the NASA ISS mission “Cold Atom Lab”.

4.2.4 Workshops

A dedicated workshop targeted at presenting the results to an industrial audience was held at the University of Neuchatel Switzerland on 27th June 2014. The workshop, organised in collaboration with partners from the EMRP project on Microwave clocks (IND55 MClocks) saw more than 80 participants from NMIs, academia, industry and stakeholders. The workshop featured oral presentations from 7 invited speakers, poster presentations and an enthusiastic public discussion among all participants on the results and future needs for research and development on clocks for industry. The discussion confirmed the high level of the achieved results and defined future research needs.

4.3 Examples of early impact

Two examples of early impact can be illustrated:

The first concerns the take-up of project-funded technology by SME collaborator MenloSystems GmbH. Here, OBSPARIS transferred know-how during the project on low-noise microwave generation using fibre spools and frequency combs, to the SME. Subsequently, following the industry workshop in Neuchatel described above where the in-vacuum cubic cavity optical local oscillator was demonstrated, the SME began discussions with the NPL and PTB partners concerned in respect of licensing possibilities to market the optical cavity arrangement. Following further discussions over the next 18 months, licensing arrangements have been agreed for the cavity system to be added to the SME product portfolio.

The second example concerns the interactions, outlined above, during 2012 – 2013 within the UK with academic and industrial stakeholders on miniature atomic clocks. This publicity helped play a part in the establishment of the need for low size, weight and power industrial clock technology within the emerging UK quantum technology programme. This was a major UK initiative established in late 2014, funded by government and championed by EPSRC, Innovate UK, the MOD dstl science and technology laboratory and NPL, and which resulted in the set-up of a number of academic quantum hubs with the specific goal of achieving strong technology transfer routes to industry.

5 Website address and contact details

One of the main routes of dissemination has been through the project website:

http://www.frequencystandards.eu/

This has kept stakeholders informed of what the project is about and up and coming news and events. The project website is maintained by NPL and will remain open for reference. The contact person for general questions about the project is the coordinator, Professor Patrick Gill, NPL (patrick.gill@npl.co.uk)

6 List of publications

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