Development of an ultra-stable laser in the 1.5 μm band for optical frequency transfer over optical fibre

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INTRODUCTION

Comparison of microwave frequency standards by satellite techniques is currently limited in instability at the 10^{-15} level at one day [1]. However, the best optical frequency standards have already demonstrated an instability of ~ 5×10^{-17} at 2000 s and an estimated uncertainty of 9×10^{-18} [2]. The predicted improvement in optical frequency standards motivates the need for a new transfer method capable of performing below these predicted levels of instability. The transmission of cw optical frequencies through optical fibre networks is the most promising alternative to satellite methods when it comes to comparing remote optical frequency standards. Intra-lab comparison of optical frequency standards can already be carried out with the use of femtosecond optical frequency combs, which can easily bridge the frequency gap between the different standards under test. However, a particularly more challenging task is to compare different standards at remote European laboratories. The comparison of remote standards, particularly like-for-like systems (such as the Yb^+ clocks at NPL and PTB), will be important in determining the relative uncertainty and reproducibility of these clocks. For this remote comparison method to operate below the instability level of the optical standards, a highly stable phase-coherent local oscillator is needed so as not to degrade the stability of the atomic reference being compared.

We present the development of a cavity-stabilised laser at 1543 nm that has been designed to have a coherence length sufficient for cw optical frequency transfer through many hundreds of kilometres of optical fibre. This will then allow us to carry out long-haul transmission experiments on a UK dark fibre network dedicated to photonics research (JANET Aurora, fig. 1). One access point to this network is currently available at

University College London, 20 km from NPL. Therefore, our ultra-stable optical cavity has not only been designed for vibration insensitivity but has also been designed to be transportable and have a robust cavity support architecture, along with a flexible mounting arrangement to provide protection against shocks during transportation.

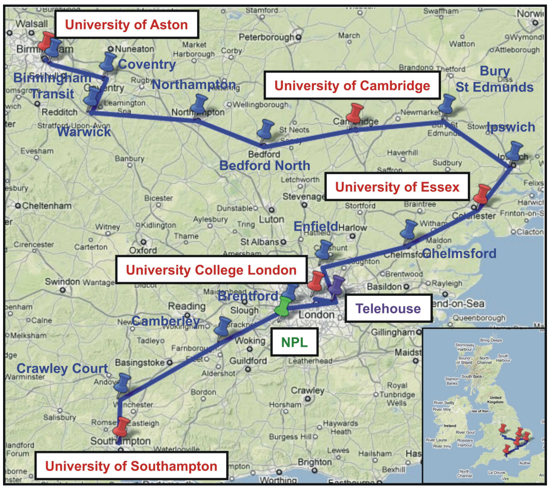

Fig. 1. The JANET Aurora dark fibre network.

This network has a total one-way length of around 800 km, meaning that experiments can be performed to test the feasibility of comparing remote optical frequency standards between distant European National Measurement Institutes (NMIs). The network connects five of the leading UK universities' photonics and optical networks research groups, but also goes via Telehouse, a major fibre network hub that could provide the point of access to fibre links to continental Europe.

CAVITY DESIGN

Both horizontally [3, 4] and vertically [5] orientated vibration-insensitive optical cavities have for some time been crucial elements in ultra-stable laser design, with the best reported stabilities now limited only by the thermal noise of the mirror substrates and coatings [6]. Tapered vertical cavities in particular have been shown to have significantly reduced sensitivity to vibrations compared to horizontal cylindrical designs. Vertical cavity designs that have appeared in the literature [7-12] are supported by a central 'collar', which is monolithic to the main spacer and which is positioned at or near the cavity midplane. This geometry offers the opportunity for the cavity to be supported in a manner that does not require a conventional V or U-block infrastructure (for example, by Teflon rods inserted into counter-bored holes in the collar [7]). We present simulation results for a 10 cm long, tapered, vertical ULE cavity that is supported by three points around the circumference of a central collar, in a plane offset from the cavity midplane by 10 mm.

A key aspect in the design of an ultra-stable optical cavity is its immunity to deformation along the optical axis under acceleration due to low frequency vibrations, particularly those below 50 Hz. The sensitivity to acceleration can be quantified as the fractional length change $\Delta L/L$ per unit acceleration. This acceleration is defined in the modelling as a body load of $-\rho g$, where ρ is the density of the ULE spacer (2210 kg m^{-3}) and g is 9.81 m s^{-2}.

When the cavity is held at discrete points, accelerations (especially in directions orthogonal to the cavity axis) can lead to a bending of the spacer, which causes the mirrors to tilt through an (albeit very small) angle. By supporting at three discrete points one is able to realise the symmetric distribution of forces necessary for maximum vibration insensitivity. This tilt leads to a change in the optical axis and hence a fractional length change between the two mirrors. Additionally, due to imperfections in the cavity construction, such as mirror contacting onto the spacer, there is normally an offset between the mechanical and optical axis of the cavity. State-of-the-art vertical cavity sensitivities are $< 4 \times 10^{-12}$ $m^{-1}s^2$ in the vertical direction and $< 2 \times 10^{-11}$ $m^{-1}s^2$ in the horizontal directions [8]. Our goal for fractional length change was therefore $< 5 \times 10^{-12}$ $m^{-1}s^2$ in all directions. For a frequency of 200 THz, this corresponds to a sensitivity of 1 kHz $m^{-1}s^2$, which is roughly an order of magnitude better than for similar vertical cavities [5, 7]

SIMULATION RESULTS

Comsol finite element modelling (FEM) software was used to analyse stress-induced deformations of the optical cavity in order to evaluate how the structure would react to certain loading conditions. As the accelerating frequencies are smaller than the intrinsic eigenfrequencies of the cavity (typically in the range above 10 kHz for 10 cm long cavities), the forces coupled to the spacer accelerate it as a whole [4]. This quasi-static deformation allows us to evaluate the cavity in terms of a static analysis.

A variety of designs were modelled but in the end a volume symmetric design was chosen and optimised for vibration insensitivity (fig. 2). The following parameters were kept constant when calculating the fractional length change minimum: cavity length L, collar thickness t, cone minor radius r and support patch radius p_r. The cone major radius R was then varied to find the zero crossing point. Additionally the radial position of the support patch s and the radius of the collar c were maintained such that

$$S = R + 5 \text{ mm and } c = R + 10 \text{ mm}. \quad (1)$$

Figs. 3 and 4 show that for a vertical acceleration, a fractional length change close to zero can be obtained for a major cone radius of R = 32 mm, with the support point positioned at a further 5 mm in the y direction. The final collar radius was therefore c = 42 mm, and the taper angle θ = 21°. The support points were set as the boundary conditions and restrained to move in any direction.

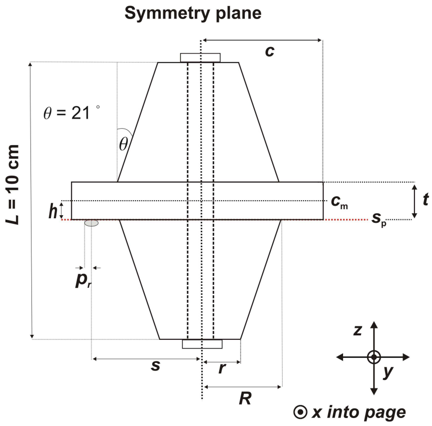

Fig. 2. Schematic of cavity parameters.

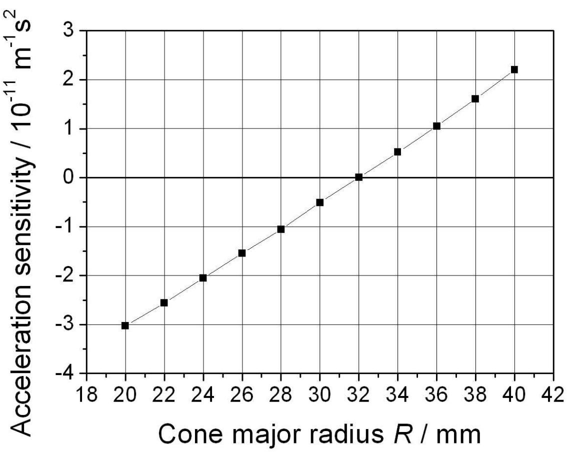

Fig. 3. Varying cone major radius.

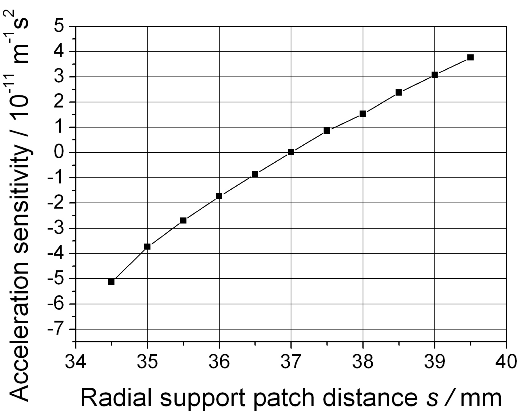

Fig. 4. Varying position of support patch from plane of symmetry.

The response of the cavity to horizontal accelerations was also calculated, along with the displacement profile laterally along the mirror surface.

Table 1. Simulation results for final cavity design.

	Fractional length change per unit acceleration ($\Delta L_z/L$) $m^{-1}s^2$		Mirror offset tolerance per unit acceleration ($\delta(\Delta L_z/L)/\delta_{x,y}$) $m^{-1}s^2$ mm^{-1} in x, y direction	
Load direction	Goal	Simulation	Goal	Simulation
z	$< 5 \times 10^{-12}$	2×10^{-13}	5×10^{-11}	x: 8×10^{-14}, y: 2×10^{-14}
y	$< 5 \times 10^{-12}$	1.5×10^{-12}	5×10^{-11}	2.6×10^{-11}
x	$< 5 \times 10^{-12}$	4×10^{-14}	5×10^{-11}	2.4×10^{-11}

Table 1 shows the results for our cavity as obtained from the FEM simulations. This suggests that our response to vertical accelerations could be < 0.1 kHz $m^{-1}s^2$ and similarly < 0.3 kHz $m^{-1}s^2$ for horizontal accelerations. From measurement of the amplitude of low frequency vibrations in the UCL lab (fig. 5), which is one point of access to the Aurora network, we predict that the inherent frequency noise of the cavity at 1 Hz should be better than 10 mHz/√Hz, and therefore the laser stability should not be limited by the vibrational environment. The displacement profile across the surface of the mirrors was also in specification, with all other tolerances falling within the machining precision specified by the manufacturer when cutting the spacer from a single piece of ULE glass (i.e. < 0.3 mm or 1.5×10^{-11} $m^{-1}s^2$ mm^{-1}).

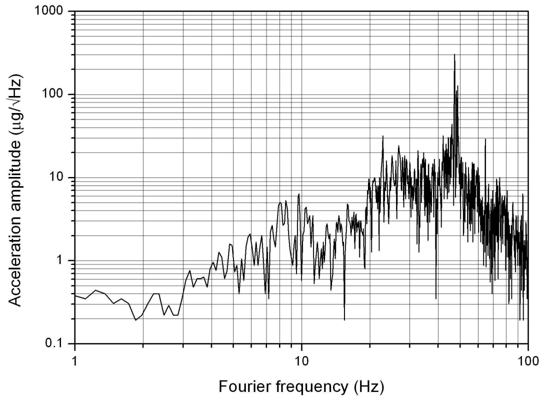

Fig. 5. Seismometer measurements of low frequency vibrations on an optical table in the UCL Optical Networks Group lab.

One final optimisation of the modelling was to vary the size of the support patch radius to assess the effect this had on the fractional length change. It is clear from Fig. 6 that there are two points where there is a minimum, when the radius is 2.5 mm and about 3.7 mm respectively. The tolerance between 2.5 mm and 4 mm was calculated to be 5×10^{-13} $m^{-1}s^2$ mm^{-1}, which means as long as the patch radius can be controlled to be between these two sizes then it will not significantly affect the overall vibration sensitivity.

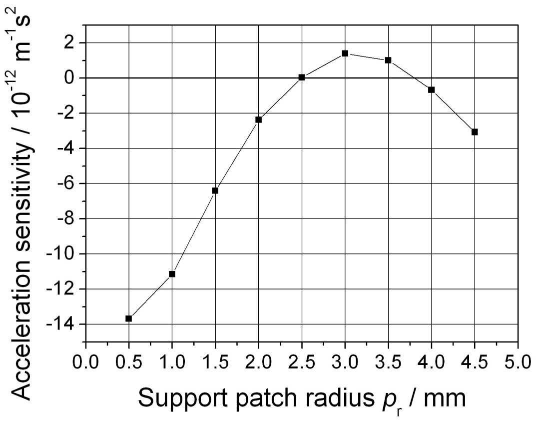

Fig. 6. Varying size of support patch radius.

CAVITY MOUNTING

The cavity support structure has a relatively simple but robust architecture, comprising three semi-rigid support points that retain the vibration sensitivity requirements as defined in the modelling. We achieve this by bonding our cavity collar to a supporting ring, made of aluminium, using vacuum-compatible room temperature vulcanizing (RTV) silicone sealant. The silicone is deposited onto the glass surface through holes in the aluminium ring, which is separated from the glass collar by a vertical distance of 1 mm. We are therefore able to form three discrete support points separated by 60° around the circumference of the collar for symmetry. This method has been tested with a dummy aluminium cavity, used primarily to verify the strength of the silicone and its adhesion qualities.

FUTURE WORK

Once the mounting is complete, our cavity will be operated under a two-stage temperature control and kept under high vacuum to reduce perturbations to the cavity length. We will then proceed to lock a commercial single-mode Koheras fibre laser, with a nominal free-running linewidth of a few kilohertz, to our ultra-stable cavity via the Pound-Drever-Hall technique.

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