International Conference on Space Optics—ICSO 2018

Chania, Greece

9–12 October 2018

Edited by Zoran Sodnik, Nikos Karafolas, and Bruno Cugny

An automated system for hydroxide catalysis bonding of precision-aligned optical systems

D. I. Robertson

W. Brzozowski

E. D. Fitzsimons

C. J. Killow

et al.

International Conference on Space Optics — ICSO 2018, edited by Zoran Sodnik,
Nikos Karafolas, Bruno Cugny, Proc. of SPIE Vol. 11180, 1118050 · © 2018 ESA
and CNES · CCC code: 0277-786X/18/$18 · doi: 10.1117/12.2536099

An automated system for hydroxide catalysis bonding of precision-aligned optical systems

D. I. Robertson[a*], W. Brzozowski[b], E. D. Fitzsimons[b], C. J. Killow[a], P. Parr-Burman[b], M. Perreur-Lloyd[a], D. Pearson[b], H. Ward[a] and M. Wells[b]
[a]SUPA, School of Physics and Astronomy, University of Glasgow, Glasgow, G12 8QQ, Scotland, UK; [b]UK Astronomy Technology Centre, Royal Observatory Edinburgh, Edinburgh, EH9 3HJ, Scotland, UK

ABSTRACT

Precision-aligned, robust, ultra-stable optical assemblies are required in an increasing number of space-based applications such as fundamental science, metrology and geodesy. Hydroxide catalysis bonding is a proven, glue-free, technology for building such optical systems from materials such as ULE, Zerodur and fused silica. Hydroxide catalysis bonded optical systems have flown in missions such as GP-B and LISA Pathfinder achieving picometer path-length stability and microradian component stability over full mission lifetime.

Component alignment and bonding was previously a largely manual process that required skilled operators and significant time. We have recently automated most of the alignment and bonding steps with the goals of improving overall precision, speed and reliability. Positioning and bonding of an optical component to within 4 microns and 10 microradians of a target position and alignment can now be reliably completed within half an hour, compared to the many hours typically taken previously. The key new features of this system are an interferometer that monitors the parallelism and separation of the surfaces to be bonded and a precision multi-axis manipulator that can optimise component alignment as it brings it down to the point of bonding.

We present a description of the system and a summary of the alignment results obtained in a series of 9 test bonds. We also show how this system is being developed for integration into a precision optical manufacturing facility for assembly of large optical systems

Keywords: hydroxide catalysis bonding, precision alignment, ultra-stable space optics

1. INTRODUCTION

Precision-aligned, robust, ultra-stable optical assemblies are required in an increasing number of space-based applications in areas including fundamental physics, metrology and geodesy. Often these optical systems are constructed from low expansion materials such as Corning's Ultra Low Expansion Glass (ULE) or Schott's Extremely Low Expansion Glass Ceramic (Zerodur), and with fused silica optics. One technique for bonding any combination of these materials is hydroxide catalysis bonding. Hydroxide catalysis bonding is essentially a glueless technique that uses an extremely small volume of hydroxide solution to catalyse bonding between the materials[1] producing extremely strong, stable structures. Structures built using this technique have already been flown successfully in NASA's Gravity Probe-B[2], and in the European Space Agency's LISA Pathfinder mission[3,4,5] and are planned for the European Space Agency's planned LISA mission[6] to observe low frequency gravitational waves.

2. ALIGNMENT AND BONDING

Our system of aligning and bonding is described in detail in a separate papers[7,8], but it is useful to summarise briefly the alignment requirements and technologies used.

Figure 1 shows a component to be bonded and the axes used to describe its location.

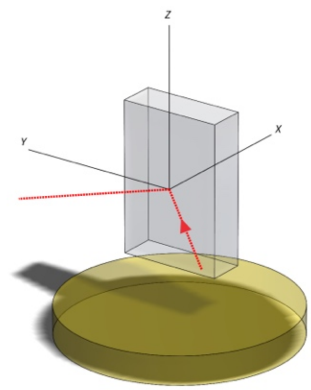


Figure 1. Alignment axes for a cuboidal optical component. The red line is an optical beam that reflects at a desired position and angle from the component's optical surface which is in the YZ plane,. Angle α is about the Z axis and describes the in-plane angle of the component. Angles β (about X) and γ (about Y) control relative alignment between the surfaces to be bonded.

2.1 Component preparation and manipulation

The surfaces to be bonded must be conformal. Typically this mean that both are polished flat to λ/10 (λ =633nm) over the bond area. The bond is thin and uniform (of order 100nm) so the final alignment of the optical surface in γ (about Y axis) is determined by the manufacture of the component and baseplate. Typically for a high-quality component a perpendicularity between optical surface and bonding surface of 5 μradians (1 arc second) can be achieved. Cleaning of the surfaces prior to bonding is also critical to successful bonding.

The component is mounted from a 6 degree of freedom hexapod actuator (Physik Instrument H824). This allows control of the position and angle of the component to better than 0.1μm and 0.3μradians, which are well within our alignment goals.

2.2 Metrology

In order for the component to bond in the desired position, they should be brought together parallel, i.e. aligned in angles β and γ so that there is minimal slippage as the bonding process takes place. The overall automation of the process also requires continuous readout of the component-to-baseplate separation. These measurements are made by the bonding surface interferometer. A frequency modulated laser beam is directed through the component along the Z axis and an interference signal results from the overlap of the reflections from the base of the component and the baseplate. The interference pattern is spatially analysed to derive angle information while the observed depth of modulation allows calibration of the separation readout. An angular accuracy of around 1μradian and displacement accuracy – once calibrated by using known steps of the Hexapod actuator – is better than 30μm, both well within our requirements.

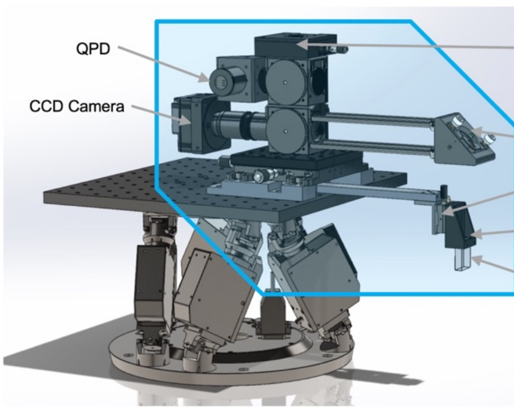
In our tests to demonstrate our automated system we define a target position, X, and angle, α, of the optical surface. To monitor the alignment we reflect a positionally stable, amplitude modulated, laser beam from the optical surface and measure the position of the reflected beam on two quadrant diodes located at different distances from the reflection point[9].

2.3 Automation

The metrology and component manipulation are controlled from a computer running a LabVIEW program. This allows automatic sequencing of many of the operations to both simplify and speed the bonding operation.

3. PROTOTYPE SYSTEM

Our prototype system, developed to refine the bonding procedure and to produce a series of test bonds, is shown in Figure 2.



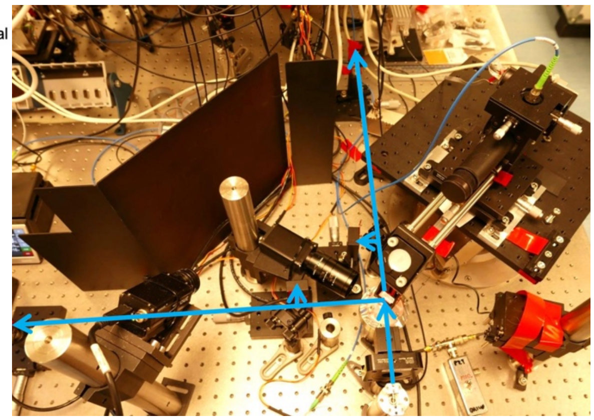


Figure 2. Prototype bonding system as used for the test bonds. (Left) The optical component and the assembly housing the vertical interferometer (outlined), both mounted on the hexapod positioner. (Right) An overhead view of the prototype system with the beam used to monitor the X and α alignment of the optical surface highlighted in blue.

3.1 Process

The process for a single bond is almost completely automated and follows the following sequence:

- Clean component and baseplate and mount both in the system (manual processes)
- Automatically align the surfaces to be bonded and move the component to ~200μm above the baseplate
- Align the optical surface to achieve the desired X and α
- Raise the component and apply the bonding fluid to the baseplate
- Automatically bring the component down to the point of contact with the bonding fluid, performing any minor corrections to the alignment of the optical surface
- Wait 12 minutes for the initial phase of the bonding process to take place and then release the component from its clamp

The overall process can now be reliably completed by a single operator in a timescale of around 30 minutes; previously bonds of this precision took a team of several operators around 1 day to complete.

4. ALIGNMENT RESULTS

A series of 9 test bonds were completed using the described procedure using two subtly different bonding fluids. The overall alignment results were extremely good as shown in Table 1. In all cases the reflecting optical surface is within 4μm of its nominal position and the angular errors are below 10μradians. Full details of the bonding timeline and the fluids used are given in[7].

Table 1. Alignment errors for the 9 test bonds. Bonds 1 to 4 were made with a pure sodium hydroxide solution and bonds 5 to 9 were with the sodium hydroxide solution with added sodium silicate. There are no significant differences in final alignment achieved with the two solutions. The uncertainty for the measurements is also shown.

Test number	X error (μm) (±2 μm)	α error (μrad) (±5 μrad)	β error (μrad) (±5 μrad)
1	-3	2	2
2	-1	-1	4
3	-3	6	4
4	-2	8	3
5	-3	-1	-4
6	-1	-1	-2
7	-3	-4	-2
8	-1	-1	-6
9	-2	-2	1

5. PRODUCTION FACILITY DESIGN

The work described above has demonstrated a system and procedure to achieve the precision alignment and bonding of a single component in a test setup. The next step is to design and build a full production facility for complex optical assemblies.

5.1 Target design

Our current design is driven by the need to build optical benches doer the planned LISA mission, but is relevant for any complicated optical system. As an indicator of the scale and complexity of the assembly scenario we are targeting, the preliminary design of the LISA optical bench is shown in Figure 3.

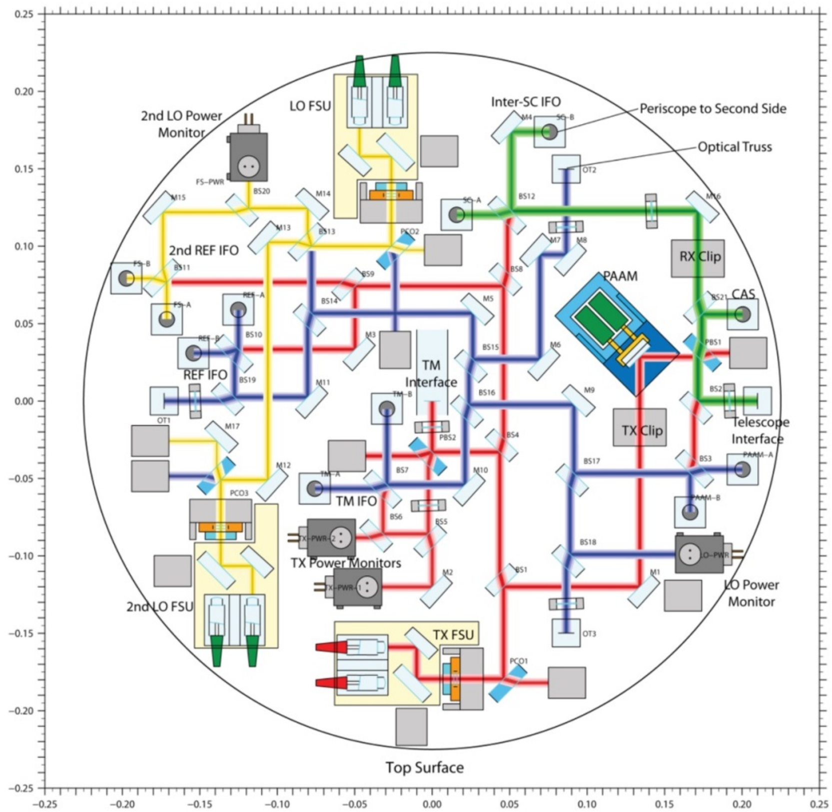


Figure 3. LISA Optical Bench concept (A-side). A representative preliminary design of the LISA optical bench. The design will evolve, but this gives a good idea of the complexity of the optical system which the facility is designed to build. The LISA optical bench is two sided; the side shown is the more complicated. Axis scales are in metres.

The design of the facility is based on a conservative LISA optical bench of diameter 540mm that can have components placed on it in any position and orientation on either of the two flat surfaces. In addition there must be space around the optical bench to mount beam measuring devices[9] and the whole volume must be accessible for measurement by a coordinate measuring machine (CMM).

Our draft facility design is shown in Figure 4 in which a compact bonding surface interferometer and hexapod are mounted on a boom from a wide range XY translation stage. The interface between the boom and hexapod is a rotation stage. The whole assembly is mounted within the measurement volume of a coordinate measuring machine.

The bonding surface interferometer and the hexapod component positioner already demonstrated are being re-engineered into a more compact form suitable for this build facility. An initial prototype of the redesigned system is shown in Figure 5 which shows the interferometer and component holder mounted under a smaller hexapod. We are currently testing a prototype interferometer using a larger hexapod and initial performance is good.

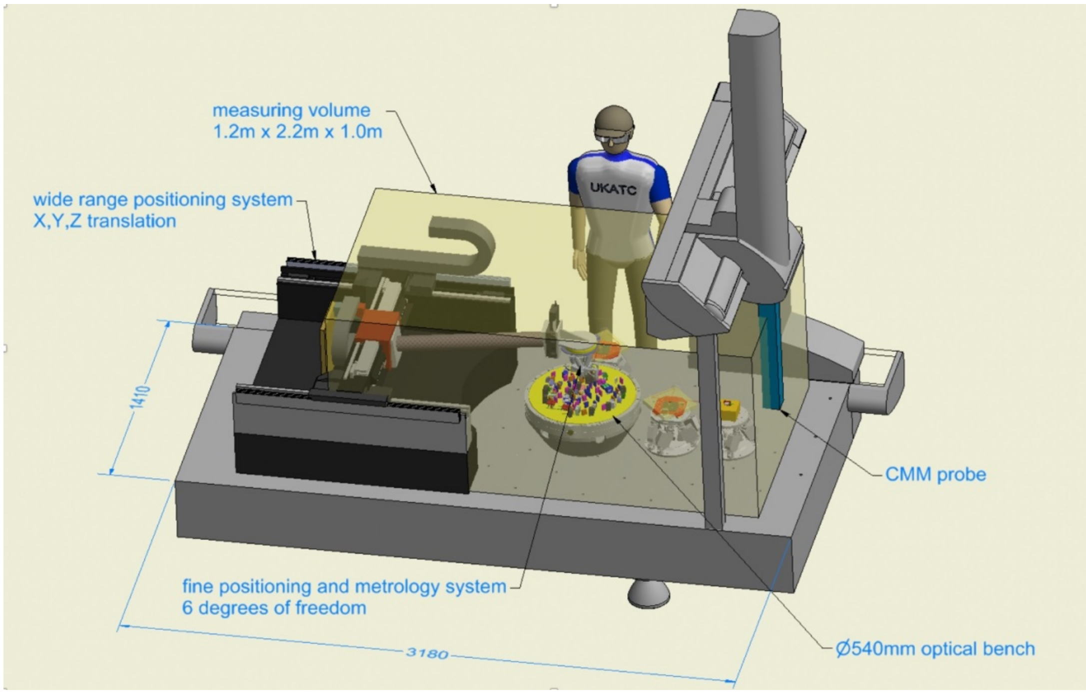


Figure 4. An implementation of the overall component positioning system.

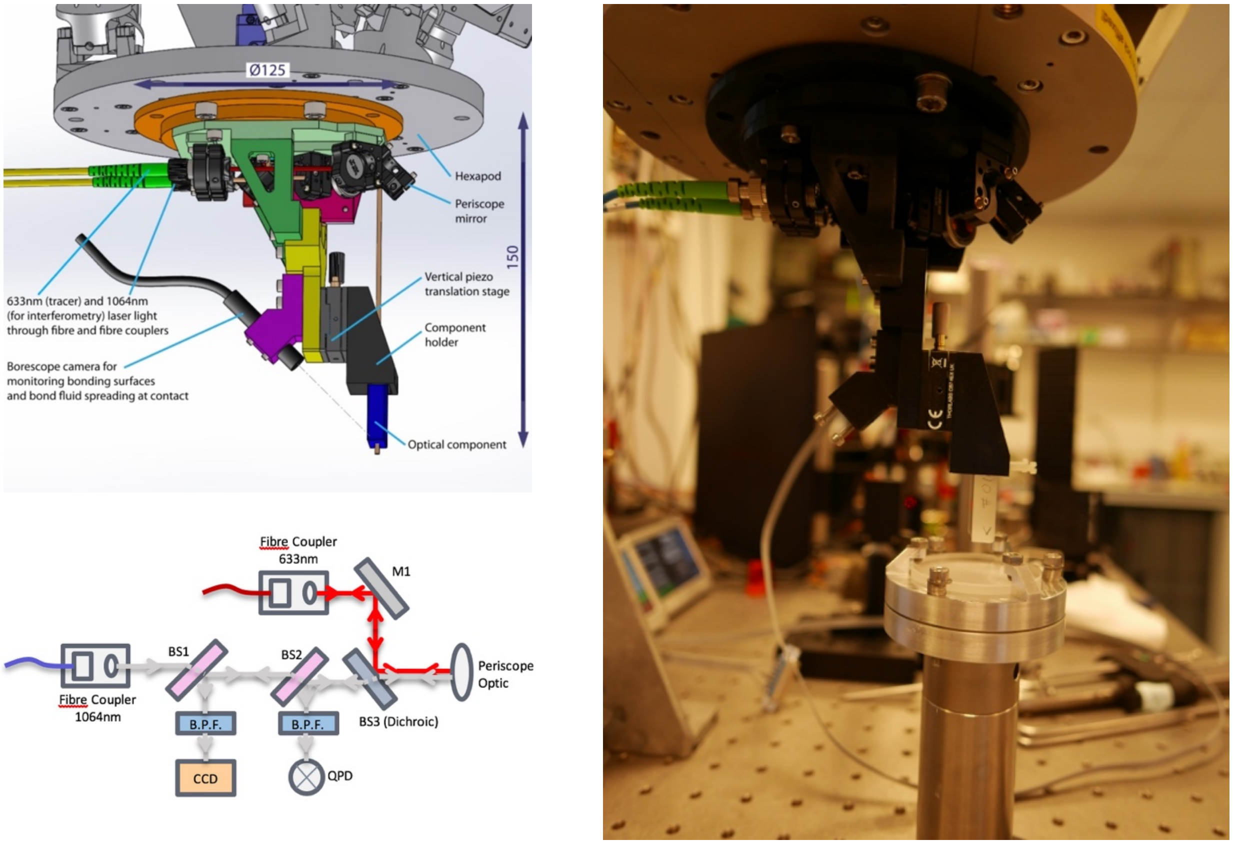


Figure 5. (Top Left) CAD assembly of the optical component holder and vertical interferometer mounted on a hexapod. All dimensions are in mm. (Bottom Left) Optical sketch, BSx are beamsplitters, BPF are bandpass filters, and QPD is a quadrant photodiode. (Right) A 3D printed assembly of a similar design mounted below a hexapod. The hexapod used here is for testing purposes, the final implementation will use a hexapod with a smaller footprint.

6. CONCLUSIONS

We have demonstrated an automatic alignment system that allows us to build optical systems with optics precision-aligned to within 4μm and 10μrad of target and bonded within these limits using the hydroxide catalysis process. The alignment technique uses interferometric sensing of the separation and relative alignment of the surfaces to be bonded, and uses these signals, along with the position and angle of a beam reflected from the optical surface, to control a 6 degree of freedom component manipulator. The overall process is reliable and reduces the time taken for a precision bond from of order 1 day, to less than 30 minutes. We are further developing the system with the aim of incorporating it into a facility for the building of complex, precision aligned, optical systems such as those required for LISA.

7. ACKNOWLEDGEMENTS

This work was funded by the UK Space Agency and by the European Space Agency. We acknowledge support by the University of Glasgow, the UK Astronomy Technology Centre, and the Scottish Universities Physics Alliance.

REFERENCES

[1] van Veggel, A.A. and Killow, C.J. "Hydroxide catalysis bonding for astronomical instruments" Advanced Optical Technologies (3) (2013).

[2] Everitt, C.W.F. DeBra, D.B. Parkinson, B.W. Turneaure, J.P. Conklin, J.W. Heifetz, M.I. Keiser, G.M. Silbergleit, A.S. Holmes, T. Kolodziejczak, J. Al-Meshari, M. Mester, J.C. Muhlfelder, B. Solomonik, V. Stahl, K. Worden, P. Bencze, W. Buchman, S. Clarke, B. Al-Jadaan, A. Al-Jibreen, H. Li, J. Lipa, J.A. Lockhart, J.M. Al-Suwaidan, B. Taber, M. and Wang, S. "Gravity Probe B: Final Results of a Space Experiment to Test General Relativity" PRL (106) 221101 (2011).

[3] Armano, M. et al, "Sub-femto-g free fall for space-based gravitational wave observatories: LISA Pathfinder results" Phys. Rev. Lett. (116), 231101 (2016).

[4] Armano, M. et al, "Beyond the Required LISA Free-Fall Performance: New LISA Pathfinder Results down to 20uHz" Phys. Rev. Lett. (120), 061101 (2018).

[5] Robertson, D.I Fitzsimons, . E.D. Killow, C.J. Perreur-Lloyd, M. Ward, H. Bryant, J. Cruise, A.M. Dixon, G. Hoyland, D. Smith, D. and Bogenstahl, J. "Construction and testing of the optical bench for LISA Pathfinder" Classical and Quantum Gravity (\bf 30), 085006 (2013).

[6] K. Danzmann, K. et al., "LISA: Unveiling a Hidden Universe" Report No. ESA/SRE2011(2011)3, 2011

[7] Robertson, D.I. Fitzsimons, E.D. Killow, C.J. Fitzsimons, E.D. Perreur-Lloyd, M. and Ward, H. "Automated precision alignment of optical components for hydroxide catalysis bonding" Submitted for publication (2018).

[8] Killow, C.J. Fitzsimons, E.D. Perreur-Lloyd, M. Robertson, D. I. and Ward, H. "Mechanisation of precision placement and catalysis bonding of optical components" International Conference on Space Optics, Proc. of SPIE Vol. 10562 (2016)

[9] Fitzsimons, E.D. Bogenstahl, J. Hough, J. Killow, C.J. Perreur-Lloyd, M. Robertson, D.I. and Ward, H. "Precision absolute positional measurement of laser beams" Applied Optics (52), 2527--2530 (2013).