Adhesive Bonding for Optical Metrology Systems in Space Applications

Martin Gohlke¹, Thilo Schuldt¹,², Klaus Döringshoff⁵, Achim Peters⁵, Ulrich Johann³, Dennis Weise³, Claus Braxmaier¹,⁴

¹ German Aerospace Center (DLR), Robert Hooke Straße 7, 28359 Bremen, Germany
² Hochschule für Technik, Wirtschaft & Gestaltung, Braunebergerstr. 55, 78462 Konstanz, Germany
³ Airbus DS, Claude-Dornier-Straße, 88039 Friedrichshafen, Germany
⁴ Center of Applied Space Technology and Microgravity (ZARM), University Bremen, Am Faltturm 1, 28359 Bremen, Germany
⁵ Humboldt University Berlin, Newtonstrasse 15, 12489 Berlin, Germany

E-mail: martin.gohlke@dlr.de

Abstract. Laser based metrology systems become more and more attractive for space applications and are the core elements of planned missions such as LISA (NGO, eLISA) or NGGM where laser interferometry is used for distance measurements between satellites. The GRACE-FO mission will for the first time demonstrate a Laser Ranging Instrument (LRI) in space, starting 2017. Laser based metrology also includes optical clocks/references, either as ultra-stable light source for high sensitivity interferometry or as scientific payload e.g. proposed in fundamental physics missions such as mSTAR (mini SpaceTime Asymmetry Research), a mission dedicated to perform a Kennedy-Thorndike experiment on a satellite in a low-Earth orbit. To enable the use of existing optical laboratory setups, optimization with respect to power consumption, weight and dimensions is necessary. At the same time the thermal and structural stability must be increased. Over the last few years we investigated adhesive bonding of optical components to thermally highly stable glass ceramics as an easy-to-handle assembly integration technology. Several setups were implemented and tested for potential later use in space applications. We realized a heterodyne LISA related interferometer with demonstrated noise levels in the pm-range for translation measurement and nano-radian-range for tilt measurements and two iodine frequency references on Elegant Breadboard (EBB) and Engineering Model (EM) level with frequency stabilities in the $10^{-15}$ range for longer integration times. The EM setup was thermally cycled and vibration tested.

Adhesive bonding of optical components is a well-known technique. The advantages w.r.t. standard opto-mechanical setups are the mechanical and thermal stability; a disadvantage is that components once bonded can not be adjusted anymore. However, there are many application where a later adjustment is not needed or required. Beside adhesive bonding, hydroxide-catalysis (HC [1]) bonding and optical contacting are well-known methods to attach optical components. The obtained long-term thermal and mechanical stabilities are impressive. However, the techniques have higher requirements on the components (surface properties) and a cleanroom environment during integration is needed. The presented technique of adhesive bonding works with a very liquid adhesive to achieve thin layer thicknesses. It can be carried out with less effort than HC bonding. For many optical setups adhesive bonding might be a simple alternative to HC bonding and optical contacting.
1. Assembly Integration Technology

In a first activity, different adhesives were tested. The space-qualified Hysol 9313 two-component epoxy is very liquid, has a strong adhesive strength (28.9 MPa) and is thus well suited for the application described here. In tests, layer thicknesses of a few µm were demonstrated (compared to HC bonding layer thicknesses in the range of several dozen nm [2]). A thin adhesive layer is important for the later instrument performance: the thinner the film thickness, the smaller the film thickness differences, which potentially lead to errors and tilts of the bonded component. A second effect is the smaller influence of thermal expansion of the adhesive.

After these preliminary tests a simple test board was designed, cf. figure 2, left. Here, the integration steps for positioning the optical components were tested. Six mirrors (20 × 15 × 7 mm$^3$) were attached to a 10 × 10 × 4 cm$^3$ base-plate made of Zerodur. The surface of the base was specified with λ/10, this is similar to the requirements of HC bonding and guarantees the parallelism of the laser beam w.r.t. the surface of the base-plate. A pitch of the optical component cannot be adjusted by tilting. Therefore, the mirrors have specific requirements where the angle between the base and the optical surface has be within 90° ± 2 arcseconds. Two of the six mirrors were HC bonded to the base-plate, they act as reference mirrors for the later performance tests. The other four mirrors were attached using adhesive bonding. Therefore, a specifically designed jig was used in order to bring the substrate in the right position and fix them for 24 hours during the curing process of the adhesive [3]. The surfaces of the base of the mirrors were polished for the HC bonding and matt-grinded for the adhesive bonding.

2. Optical Setups

2.1. Heterodyne Interferometer

In a first application, we integrated a heterodyne interferometer, developed in the LISA context. 17 optical components (beam splitters and mirrors made of fused silica) were integrated to a 20 × 20 × 4 cm$^3$ base-plate made of Zerodur where a contrast of 90% of the superimposed beams after the recombination BS was achieved. This is an indication of the small tilting of the bonded optical component w.r.t the surface of the base-plate. The noise performance of the interferometer is in the pm range for translation measurements and in the nrad range for tilting (both in the LISA frequency band) and it was not limited by the mechanical design.
2.2. Iodine-Based Frequency References

Two setups on elegant breadboard (EBB) and engineering model (EM) level were developed, based on a state-of-the-art laboratory setup realized at the Humboldt-University Berlin [4]. The laboratory setup employs modulation transfer spectroscopy using an 80 cm long iodine cell. A frequency stability in the range of $3 \times 10^{-15}$ for integration times between 100 s and 10,000 s was demonstrated. Based on this setup, an EBB and later an EM was developed, which should be smaller and lighter than the existing setup. They should also have a better thermal and mechanical stability in order to survive environmental tests such as thermal cycling and vibrational testing, both without spoiling the reached performance [5].

With respect to its later application in space, a fiber-coupled spectroscopy setup on elegant breadboard (EBB) level was realized using adhesive bonding technology as described above. In order to reduce the size of the setup the beam path through the iodine cell was folded. In this triple pass configuration, the length of the cell can be reduced to 30 cm while the effective length is still 90 cm. The optical setup can now be integrated on a smaller $55 \times 25 \times 5$ cm$^3$ base-plate. The base-plate is made of OHARA Clearceram-Z HS, a thermally and mechanically highly stable glass ceramics with a low CTE of $2 \cdot 10^{-8}$ K$^{-1}$. All optical components which possibly influence the beam pointing stability (beamsplitter, mirrors etc.) are integrated using adhesive bonding. All other components (polarizer, wave plates, etc.) which do not influence the optical path were held in special holders made of Invar (CTE of $\sim 10^{-6}$ K$^{-1}$). Additional plates made of Invar were also attached to the sides of the base-plates, they are used for integration of detectors and cell cooling.

Based on the experience with the EBB setup, a more compact and ruggedized setup on engineering model (EM) level was designed and realized. The main issue for a compact setup is the realization of a compact multipass cell. The cell uses a $10 \times 10 \times 3$ cm$^3$ fused silica spacer with wedged windows. The cell of the EM is designed for a nine-pass configuration (corresponding to 90 cm interaction length as used before). All optical components are made of fused silica. They are integrated on a $38 \times 18 \times 10$ cm$^3$ base-plate also made of fused silica. Performance tests at the Humboldt University Berlin show similar frequency stability of about $1 \cdot 10^{-14}$ at an integration time of 1 s and below $5 \cdot 10^{-15}$ at integration times between 10 s and 100 s for the EM and EBB setups, comparable to the laboratory setup. The EM setup was also environmentally tested including thermal cycling (-20°C to +60°C) and vibrational testing (sine vibration up to 30 g; random vibration up to 25.1 g). The frequency stability was measured before and after the tests where no degradation was observed.
3. Conclusion
Adhesive bonding as discussed in this article is seen as an easy-to-handle technique for realizing space-compatible optical systems. A high sensitivity heterodyne interferometer was realized showing noise levels in the pm range for translations and nrad range for tilting. Two compact iodine-based frequency references were developed, showing a frequency stability in the $10^{-15}$ range at integration times between 100 s and 1.000 s. These iodine references are an attractive alternative to the baseline cavity-based frequency references and fulfill the requirements for LISA and NGGM. Another advantage is the absolute frequency stability of an iodine setup. The offset frequencies are in the range of only a few kHz and below which would save time in the lock acquisition between several spacecraft.

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