Adaptive optics development in the EU OTTER programme

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Introduction

The Central Laser Facility (CLF) at the Rutherford Appleton Laboratory has had a programme of developing adaptive mirrors for spatial control of laser beams for nearly ten years. We chose to use a bimorph-type construction for these because it appeared to match our requirement to scale the mirrors to the size of our laser beams (~100 mm diameter). Membrane mirrors and liquid-crystal devices were too small, and pusher-type mirrors were felt to be too large and slow for this purpose.

In contrast to many other developers of bimorph mirrors, our approach has always been to use relatively low voltages (typically ±64 V) to drive the device, rather than a few hundred volts. This reduces the size, cost and power requirements of the driver electronics, and provides some safety benefits. However, it also forces us to use very thin slices of piezoceramic material (Lead zirconate-titanate, PZT) in order to obtain the voltage gradient necessary to generate the curvature of the mirror. Our bimorph mirrors all use 200 micron thick slices of PZT, which is available from the suppliers in pieces up to around 70 mm square. A prototype mirror using a single piece of this material worked very successfully, so an attempt was made to scale it up to 150 mm diameter by tiling four quadrants. This resulted in a pyramidal shape, due to the variation in stiffness of the assembly along the lines between the quadrants (Figure 1).

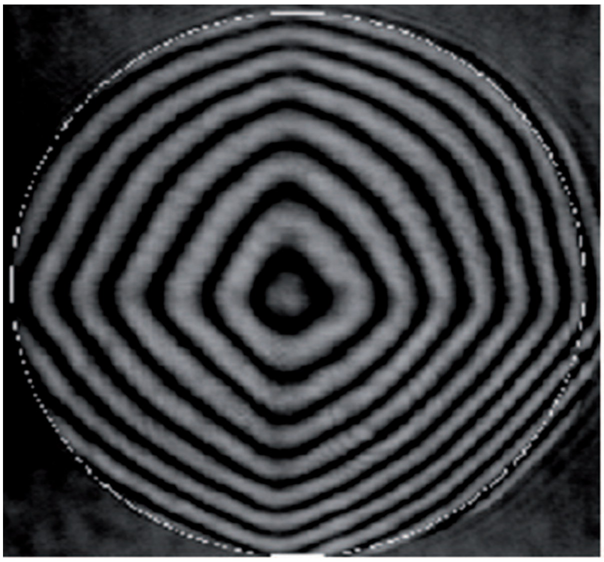

Figure 1. Interferogram of tiled-quadrant bimorph mirror, showing pyramidal shape.

This mirror was thermally annealed at 80 degrees C for several hours, and then repolished flat, after which the pyramid shape had disappeared. In later use, however, the pyramid gradually reappeared. Clearly, the tiled construction was not suitable for these devices, and an alternative was needed to achieve large apertures.

Monolithic construction technique for large bimorphs

PZT discs are made by a hot-sintering process in a large press, and are made by at least one manufacturer in diameters up to 220 mm. The thickness of the discs produced in this way is several millimetres. A layer of silver is sintered onto each face of the disc to allow the material to be poled. The manufacturer was unwilling to grind large discs to the thickness we required for our mirrors, as the resulting wafer would be extremely fragile. The technique we developed is to bond an as-made disc of appropriate size to a substrate, using UV-curing adhesive, and only then to grind the PZT to the required thickness of 200 microns. The glass substrate acts as a support for the PZT during the grinding process, so the resulting thin wafer does not

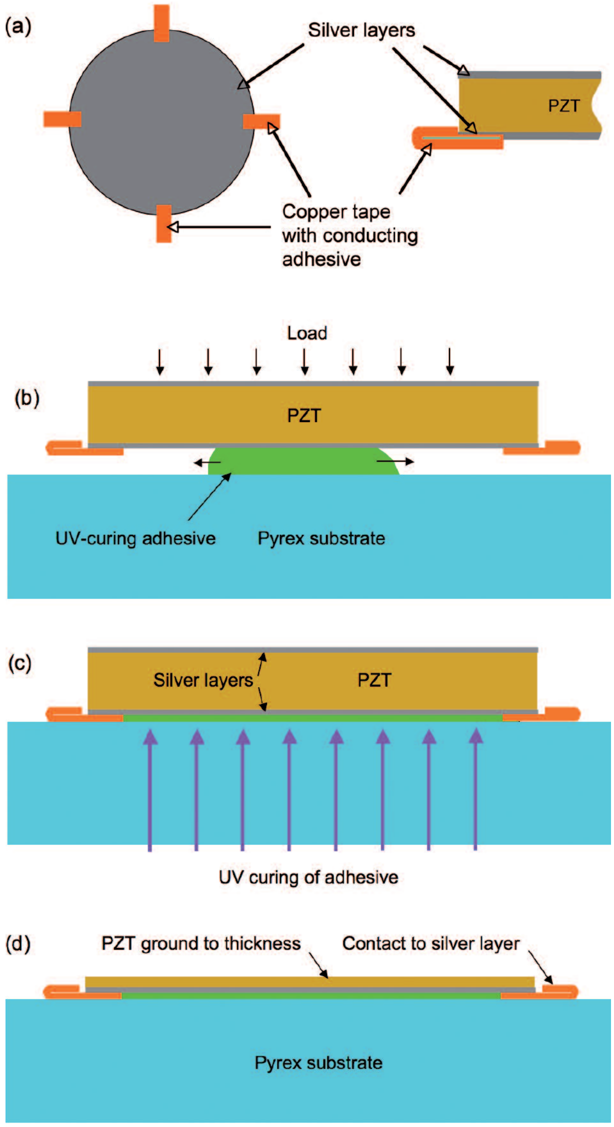

Figure 2. Assembly of monolithic bimorph mirror. (a) Layout and detail of spacers; (b) Gluing; (c) Curing the adhesive on a UV light box; (d) Completed assembly

need to be handled directly. The grinding is easily done using standard optical abrasives and techniques, and to date none of the assemblies that we have processed in this way has suffered a breakage of the PZT.

The common ground electrode required for the action of the mirror is provided by the silver layer on the bonded side, and contact with this layer is made using pieces of adhesive copper shielding tape, in which the adhesive is loaded with silver to make it conductive. The tape segments also serve as spacers to ensure the adhesive layer has a uniform thickness. Figure 2 shows the various stages in the assembly process.

The thickness of the copper foil spacers is typically 70 microns, so the amount of adhesive required can be calculated quite accurately. A small excess is used to ensure the adhesive will reach the edge of the PZT all round. It is important to ensure there are no significant bubbles in the adhesive, as when the film spreads out between the PZT and the glass, even a nearly invisible bubble will acquire a noticeable area. The spreading of the adhesive takes a long time, typically four to six hours depending on the diameter of the parts.

Clearly, since the initial thickness of the PZT disc is typically 2 to 3 mm, the great majority of the material is lost in the grinding process, but fortunately it is not expensive. Once the assembly has reached the state shown in Figure 2(d), the next step is to form the desired electrode array on the exposed surface of the PZT using photoresist masking techniques. A layer of resist is spun onto the assembly, baked, then exposed through a mask carrying the pattern of the electrodes. On development, the electrode areas are left clear of resist, with fine lines of resist separating them. The exposed edge of the substrate and the contact tabs are also covered with resist. The assembly is then sputter-coated with copper to form the metallic electrodes. Once coated, the residual resist is dissolved away in acetone, leaving only the pattern of actuators in copper on the face of the PZT. Electrical resistance between adjacent electrode areas is greater than 20 MΩ.

Using the technique described above, a 150 mm diameter mirror was constructed that is capable of handling a 100 mm diameter beam from the CLF's Vulcan laser. This mirror made it possible to operate the Vulcan Petawatt beamline at close to the diffraction limit (Figure 3).

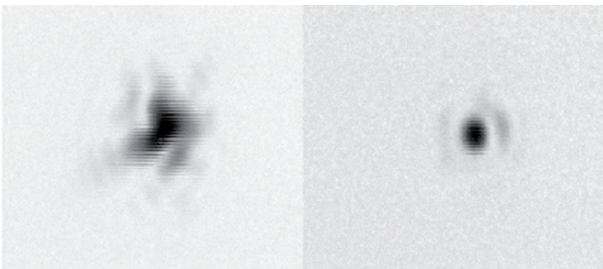

Figure 3. Left: Vulcan Petawatt beam without AO. Right: Vulcan Petawatt beam with AO running.

Large-aperture monolithic mirror

Following the success of the Vulcan adaptive mirror, we have now scaled up the process to produce a mirror of 250 mm diameter. The largest PZT disc obtainable was 220 mm diameter and 5 mm thick, and this was bonded to a 250 mm by 5 mm thick Pyrex glass substrate as described above. Figures 4 and 5 respectively show the components assembled in a dry state, and after the adhesive had been applied and begun to spread out. This particular assembly was glued with the substrate on top, sandwiched between two plate glass slabs to ensure the load was spread evenly.

After grinding, the exposed PZT showed a pattern of grey circles: these are a consequence of the fabrication process and do not affect the material's properties. The 250 mm mirror has now been patterned with its electrode array (Figure 6) and is awaiting gold coating. Once coated it will be mounted in a custom-made holder, and contact wires attached between the electrodes and connecting sockets mounted on the holder.

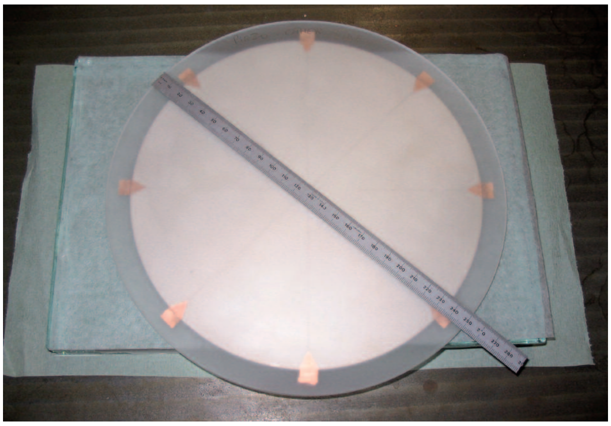

Figure 4. Dry assembly of 250 mm adaptive mirror.

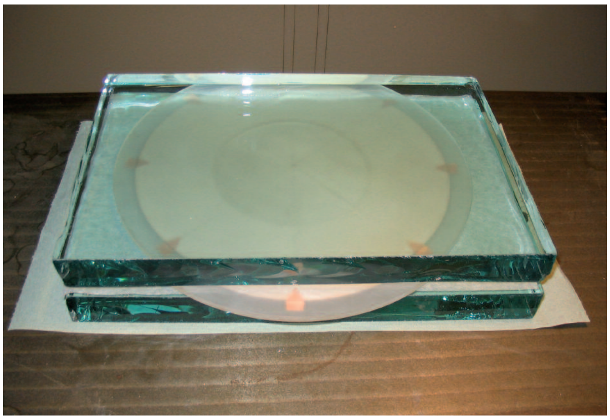

Figure 5. Gluing of 250 mm adaptive mirror in progress.

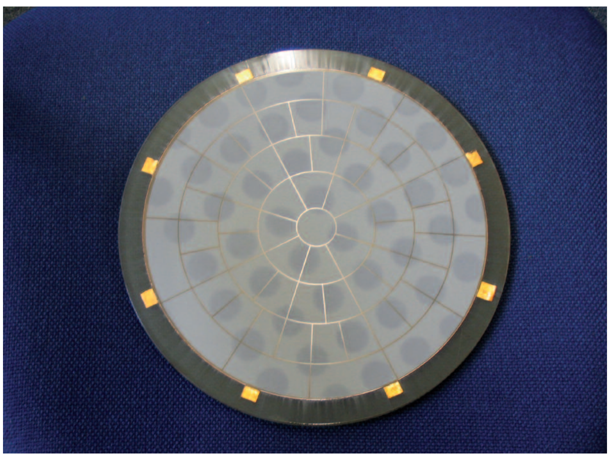

Figure 6. The 250 mm mirror with the resist mask.

Investigation of low-stress dielectric coatings

Up to the present time we have used only gold coatings for the adaptive mirrors, because the extreme aspect ratio (50:1) of the substrates means they will be severely distorted by the internal stresses in the coating if conventional dielectric multilayers are applied. A dielectric coating would be highly desirable for damage resistance; however, the highest damage thresholds are generally obtained with coatings deposited at high temperature, which are also the most highly stressed and hence cause the greatest curvature. We have therefore investigated some low-stress dielectric coatings for 1053 and 800 nm, to determine whether they offer better damage resistance than metal coatings without inducing severe curvature in the thin AO substrates.

Substrates of 76 mm diameter and 1.5 mm thickness (i.e. having the same 50:1 diameter to thickness ratio used for the adaptive mirrors) were coated with two types of dielectric multilayer. These were normal-incidence high reflectors for 760-840 nm and for 1053 nm. We also tried a different kind of metal coating, a proprietary protected silver layer from a commercial coating company. The substrates were checked interferometrically before coating, and were all within one wave of flatness.

The sputtered coatings were deposited at only 40 degrees Celsius, and the supplier was confident that the layers would show extremely low stress. However, the coated substrates were found to have significant convex curvature: on average 7.5 waves for the 760-840 nm coating and 10 waves for the 1053 nm. As the uncoated substrates were all within 1 wave of flatness, there is clearly some level of stress in the coatings despite their low-temperature deposition. Measurements of the protected silver coating showed that the substrate had become 11 fringes (5.5 waves or 3.5 microns) concave. The concave shape is in contrast with the pure dielectric low-stress coatings, which produced a convex curvature.

Considered together, these results suggest there is no method of producing a fully dielectric layer that will not induce some degree of curvature in a substrate with a 50:1 diameter-to-thickness ratio. However, a relatively small curvature can be tolerated, provided it is consistent, by figuring the opposite curvature into the substrate before coating. This will need to be tested with a complete AO assembly, i.e. one that has a PZT slice on the back, as this will almost certainly increase the stiffness.

Laser damage tests

One of each of the dielectric coating samples, the protected silver sample and a standard gold coating (for comparison) were sent to the Laser Research Centre at the University of Vilnius in Lithuania (LRCV) for laser damage testing. In discussion with LRCV, the following set of test regimes was defined:

A: N-on-1 tests at varying intensity with Nd:YAG laser at 1064 nm at 10 Hz, 4.5 ns pulse length (N=1000)

B: N-on-1 tests at varying intensity with Ti:sapphire laser at 800 nm at 10 Hz (N=1000)

C: N-on-1 tests at varying intensity with Ti:sapphire laser at 800 nm at 1 kHz (N=10,000)

All tests to be carried out at normal incidence (0 degrees)

We sent four samples to LRCV: one each of the 1064 nm and 760-840 nm low-stress dielectric samples, the protected silver sample, and a standard gold-coated optic to serve as a reference. The following set of tests was carried out (note that there is no point in testing all the samples at both wavelengths):

1053 nm coating sample:	test scheme A
760-840 nm coating sample:	test schemes B and C
Protected silver coating sample:	test schemes A, B and C
Gold coating sample:	test schemes B and C

An example of the damage curves produced in these tests is shown in Figure 7, for the 1053 nm low-stress coating.

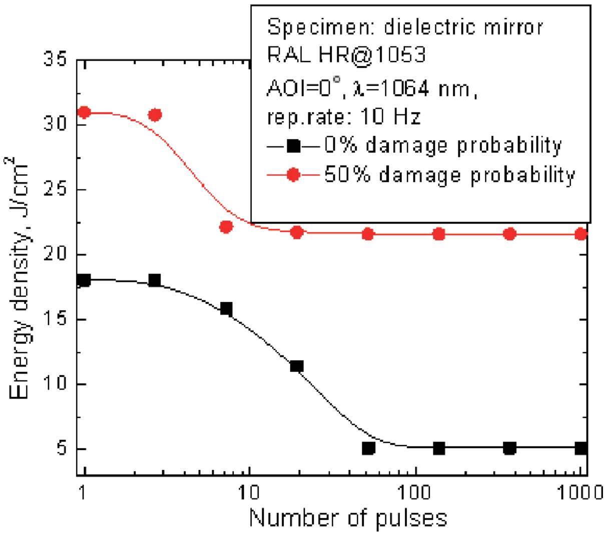

Figure 7. Damage test results for the 1053 nm dielectric coating.

The coating has an excellent damage resistance of 5.1 J cm^{-2} for 4.5 ns pulses, greatly superior to gold. The full set of results is summarised in Table 1 below: the fluence quoted in each category is that for which there is zero probability of damage after the number of shots specified at the head of the column.

Test: Coating	Nd:YAG 1053 nm 3.5 ns pulses 10 Hz (1000 shots)	TiS 800 nm 130fs pulses 10 Hz (1000 shots)	TiS 800 nm 130fs pulses 1 kHz (10000 shots)
Gold	Not tested	0.21 J cm^{-2}	0.34 J cm^{-2}
Protected silver	1.9 J cm^{-2}	0.31 J cm^{-2}	0.43 J cm^{-2}
760-840 nm low-stress dielectric	Not tested	0.15 J cm^{-2}	0.19 J cm^{-2}
1053 nm low-stress dielectric	5.1 J cm^{-2}	Not tested	Not tested

Table 1. Summary of laser damage test results for trial adaptive mirror coatings.

These data are moderately encouraging. For a 1053 nm mirror, the low-stress dielectric is an excellent solution, as the LDT of gold at this wavelength and few-nanosecond pulse durations is at most 300 - 400 mJ cm^{-2}. Provided the curvature can be precompensated by figuring the substrate prior to coating, such a mirror would have excellent characteristics.

For Ti:sapphire the position is less satisfactory. The protected silver is the best of the coatings, being 50% better than gold and twice as good as the dielectric. However, the LDT is still an order of magnitude less than the best coating for 1053 nm. The use of different materials for the low-stress dielectric may be worth investigating, as this is known to have a significant effect on damage behaviour. This, together with trials of curvature compensation for the 1053 nm coating, will be pursued in the coming year.