MRO Delay Line

Performance of Beam Compressor for Agilent Laser Head

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The Cambridge Delay Line Team

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Change Record

Revision	Date	Authors	Changes
0.1	2010-03-16	ADR	Initial version
0.2	2010-03-26	ADR	Clarification on RMS errors
0.25	2010-08-11	ADR	Incremental Errors
0.3	2011-02-20	CAH	Rework of final text
0.4	2011-02-26	CAH/ADR	Rework with revised numbers
0.45	2011-04-01	ADR	Incorporated suggestions from JSY

Objective

To report the RMS wavefront error of the delay line system metrology beam that is expected to be induced by the beam compressor used to reduce the diameter of the Agilent laser beam from 9mm to 6mm.

Scope of this document

This document explains and quantifies the wavefront error that we expect to be introduced into the Agilent metrology laser beam through the use of a beam compressor located immediately after its output port. This beam compressor has no internal adjustments, and after initial alignment of the output beam from the laser head, will be located on the metrology optical table by dead reckoning. The wavefront error contributions arising from an incorrect location of the unit, from errors in its mechanical fabrication, and from the manufacturing errors of the lenses themselves are analysed and presented. The impact of these on the overall performance of the metrology system is considered.

1 Introduction

The MROI delay line system will use a COTS laser metrology system to measure the position of the cats-eye on the delay line trolley. Although such systems are commonplace, the long stroke of the MROI delay lines is not compatible with the small (i.e. mm-sized) beam diameters typical of COTS metrology laser heads. For such long metrology paths, a large diameter beam (>10 mm) is required to limit beam divergence — and hence signal loss — due to diffraction.

In order to meet this derived requirement on the MROI metrology beam diameter, a solution has been adopted in which the beam from the Agilent laser head will be initially compressed but then re-expanded to a final diameter of 24 mm for propagation to and from the delay line carriage. The initial compression is needed to allow the metrology implementation to utilise COTS optics components, e.g. mirrors, beam splitters, and retro-reflectors, that can only accommodate a beam diameter of approximately 6 mm [1].

The initial beam compression — reducing the diameter of the laser beam from 9 mm to 6 mm — will utilise a Galilean compressor comprising two achromatic doublets (see Fig. 1). These will be mounted in a custom housing with a fixed lens spacing that will be set optimally during manufacture on the basis of optical tests of the output beam. Thereafter no internal adjustment of the expander will be possible without disassembly of the unit. The unit will be located in front of the Agilent laser head on the basis of mechanical measurements, and will be held in a fixed position thereafter. There will not be any scope for routinely adjusting the position and orientation of the compressor once it has been installed.

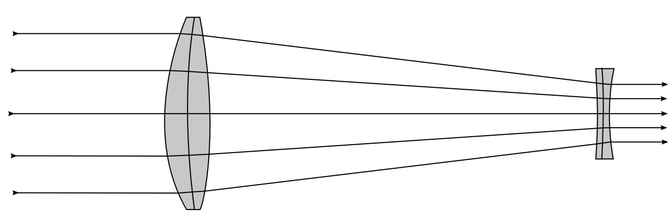

Figure 1: A schematic diagram of the beam compressor to be used immediately in front of the Agilent laser head. The collimated beam from the head enters from left and is compressed before exiting the system, still collimated, to the right.

In this note we quantify the wavefront errors that the compressor is expected to introduce into the metrology laser beam and assess the impact of these on the overall performance of the metrology system. Our conclusion is that the predicted wavefront degradation is small enough not to pose a significant risk to the operation of the metrology system.

[1] We define the beam diameter here as twice the distance from the centre of the beam to the radius where the amplitude drops to $\frac{1}{e}$ of the value at the centre of the beam.

2 Sources of Error

The lack of adjustment intrinsic to the design and mounting of the laser beam compressor means that there are several ways that the optical quality of the compressed beam might be compromised. In this note we have considered the three effects which we believe are likely to be the most important for the MROI's implementation:

1. That the lenses used in the compressor have deviations from their "design" performance due to errors during manufacture. For example, the mechanical axis of a lens may not be coaligned with its optical axis;
2. That machining errors in the compressor lens mountings lead to the lenses being incorrectly located relative to each other;
3. That the optical axis of the compressor be misaligned relative to the incident laser beam, either due to errors in the machining the external surfaces of the compressor or errors in the positioning the unit as a whole relative to the incident laser beam.

We discuss the expected magnitude of each of these imperfections in turn in the following subsections.

2.1 Intrinsic Lens Errors

The lenses chosen for the beam expander are COTS components from Edmund Optics. Our design utilises two achromatic doublets: an NT47-643 (25mm diameter, +150mm focal length) lens to accept the Agilent laser beam and an NT62-494 (25mm diameter, -100mm focal length) lens to project it outwards Fig. 1 shows a schematic diagram of this arrangement.

Most lens suppliers provide only limited information on the manufacturing errors of their off-the-shelf components, and for the lenses we intend to use, the tolerances supplied by the manufacturer only comment on a centration error[2] and the accuracy of the distance to the focal point. These data are consistent with a range of possible intrinsic manufacturing errors, in particular, choices for the concentricity and tilt of the lens surfaces, for which it is possible to analyse their impact on optical performance. These two types of lens errors are shown schematically in Fig. 2, and a range of possible values for these (consistent with the manufacturer data for our two lenses) is presented in table 1.

In the absence of any other information, we have chosen to characterise the intrinsic optical manufacturing errors of the compressor lenses by allocating them roughly

[2] The centration error is the half angle subtended by the circle the focal spot of a lens transcribes as the lens is rotated about its mechanical axis. The mechanical axis is defined by the centre of this spot.

Lens	Concentricity	Tilt
NT47-634	0.2mm	0.0°
(+150 mm	0.0mm	3.2°
focal length)	0.13mm	1.8°
NT62-494	0.09mm	0.0°
(−100 mm	0.0mm	1.8°
focal length)	0.05mm	1.0°

Table 1: Sets of possible lens surface errors that are consistent with the manufacturer's supplied tolerances on centration and focal length. For each lens, the final breakdown, into roughly equal contributions from concentricity and tilt errors has been used for our analysis.

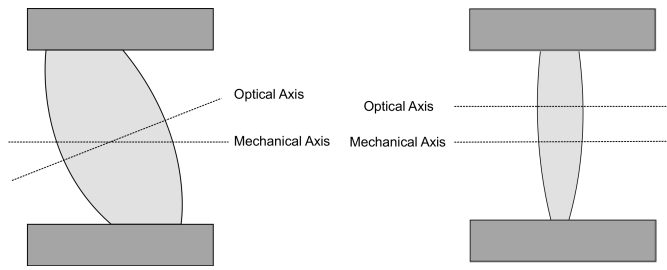

Figure 2: Lenses suffering from errors in tilt (left) and centration (right). The former is characterised by the angle between the mechanical and optical axes. The centration error is quantified by the distance between the two axes perpendicular to the direction of beam propagation.

equally between imperfections in concentricity and tilt of the lens surfaces. This corresponds to the third row of errors for each lens in table 1.

The reader should note that the method we will use to mount each lens will utilise the front and rear surfaces of each. That is, we will not center each lens using the machined surface of its edge (see Fig. 3 for an explanation of this). We expect that this mounting scheme will mitigate in large part the lens errors we have outlined above, but we have retained these errors at the magnitude presented in table 1 during our optical analysis so as to determine a very conservative worst-case performance assessment.

2.2 Mounting Errors

We have assessed that the maximum possible magnitude for the lens positioning errors resulting from inaccuracies in machining the lens mounts will be around 0.14mm in concentricity and 0.07° in tilt. These figures will apply to each lens separately, and will apply even if the lenses themselves are manufactured perfectly. The values for these errors have been derived from an analysis done for the similar mounting of a 25 mm diameter lens in another component of the delay line metrology system and so we believe that these numbers will be representative of the mounting errors expected in this optical assembly.

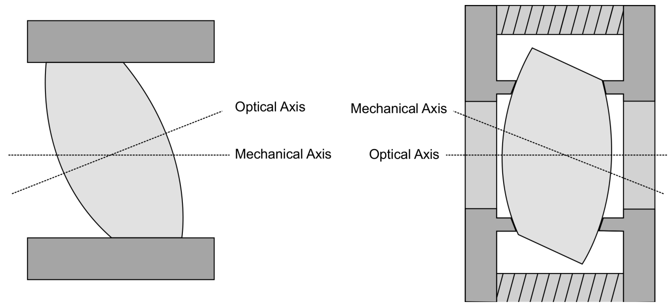

Figure 3: An illustration of the benefits of using surface mounting (right) over edge mounting (left). If a lens is mounted using its edge as a reference surface, while the mechanical axis of the lens will be aligned with that of the tube, the optical axis of the lens will not, and it is this axis which is relevant to the optical performance. When surface mounting is used, we expect the optical axis will be correctly aligned to first-order. We have adopted surface mounting for the lenses in the laser beam compressor.

The optimum lens despace, i.e. separation, will be determined optically when the beam compressor is assembled, and will utilise plastic spacers with appropriately matched CTE's to ensure that thermal effects after room-temperature optimisation will not be significant. For our compressor design, a despace of 170 μm will lead to a beam diameter change (due to defocus) of approximately 1 mm after a 10 m propagation path. We expect to be able to measure the beam diameter to half a millimetre, and so we have assumed a total defocus despace error after assembly and optimisation of 100 μm[3].

2.3 Overall Positioning Error

Once assembled, the beam compressor unit will be attached to the baseplate on which the Agilent metrology laser head will be mounted. The laser head will first have been adjusted in location and pointing direction using optical targets on the metrology table, and so any errors in the final positioning of the compressor will result from a combination of the errors in this laser adjustment and any mechanical imperfections in the assembled compressor unit and mount. Our assessment of the quadrature sum of these suggests that the location of the compressor will be accurate to better than 250 microns in each axis perpendicular to the beam travel direction and that any angular misalignment between the mechanical axis of the compressor and the axis defined by the input laser beam will be no greater than 6 minutes of arc in each axis. A summary of these worst-case errors is given in table 2.

[3]The expected thermal expansion for the compressor for a $\pm 10^\circ$ C temperature change is $\pm 20\mu$m, i.e. only a very small contributor to the total error we have allocated.

Error	Magnitude
x, y displacement	0.25 mm
Tilt about x or y	0.1°

Table 2: Maximum possible errors associated with the positioning of the beam expander with respect to the Agilent laser beam direction. These values apply to each axis separately. The metrology laser beam propagation direction is along the z axis.

3 Analysis

We have used ZEMAX to model the beam compressor optics, including all of the sources of error outlined in Section 2, and interrogate the quality of the compressed output beam. Any wavefront error contributions corresponding to tip and tilt of the output beam will be removed using pairs of actuated relay mirrors that the laser beam will hit prior to propagation out to the delay line trolleys, and so only defocus and higher order wavefront errors are a concern. As a result, the results presented below have had the contributions associated with tip and tilt of the compressed beam removed.

In the worst possible combination of all of the above errors, the RMS wavefront error introduced into the compressed laser beam was found to be 0.053λ at 633 nm. A breakdown of the relative contributions to this total arising from the different sources outlined in Section 2 is shown in table 3. This clearly identifies despace, i.e. errors in the inter-lens separation leading to defocus of the output beam, as the largest contributor to the overall wavefront error, closely followed by the manufacturing errors on the lenses themselves. We remind the reader, though, that the surface mounting technique we intend to use for the lenses will likely mitigate this latter source of error significantly.

Error	RMS Wavefront Error / λ	
	Worst case	Median
Baseline optical design	0.00042	n/a
Manufacturing errors	0.029	0.007
Mounting errors	0.032	0.007
Alignment errors	0.037	0.007
Despace	0.053	0.024

Table 3: Cumulative "worst-case" and "median" wavefront errors for the metrology laser beam after propagation through the metrology beam compressor. Entries in successive rows include all the error contributions arising from the preceding rows. The median performance on the last line has been computed assuming the despace is fixed at 100 μm. If this too is allowed to vary between $\pm$100 μm, then the median performance reduces to 0.014 λ.

As well as a "worst-case" RMS wavefront error figure , table 3 also includes estimates for a "median" expected wavefront error. These values were determined by drawing independent values for each of the three primary error contributors from uniform distributions with a range equal to $\pm$ the expected error, and evaluating the median wavefront error from one thousand of these randomly generated scenarios. In this case, we found a characteristic overall wavefront error of roughly 0.024λ at 633 nm, with once again the despace contribution being dominant.

4 Conclusions

The wavefront error in the MROI delay line metrology beam due to propagation through its custom beam compressor is expected to be relatively small — only 0.053λ in the worst case assuming realistic manufacturing, assembly and alignment errors. This corresponds to a figure of 33 nm RMS. A more realistic estimate, that does not assume that all the error contributions add in the worst possible way and so is a "median" figure, is some two times lower at 15 nm RMS.

The optical error budget associated with the delay line metrology system allows for a total RMS wavefront error of 136 nm, of which 100 nm is contingency. The budget currently (see INT-406-VEN-0107 r1.0, 31 January 2008) has no allocation for a laser beam compressor, and so it will be necessary to utilise some of the contingency to accommodate the impact of the use of such a device. The residual contingency will thus be 94 nm in the worst case, or 99 nm for a "median" case (where we have subtracted the applicable values in quadrature), and hence not be significantly affected by the compressor we have designed.