MRO Delay Line

Lens Choice for the Beam Expander

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The Cambridge Delay Line Team

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Change Record

Revision	Date	Authors	Changes
0.1	2010-02-16	ADR	Initial version
0.2	2010-02-24	ADR	Included consequences of further errors.
0.21	2010-08-23	ADR	Small updates / reworking of results.
0.3	2010-11-15	CAH	Rework of final text.

Objective

To explain the process used to choose the lenses for the MROI delay line beam expanders.

Scope of this document

This document describes the procedure used to select the lenses chosen for the MROI delay line beam expanders (Thor part numbers ACN254-050-A1 and AC508-200-A1). The analysis presented takes into account inaccuracies associated with mounting the lenses within the beam expander mechanics, and quotes the accuracy with which the resulting beam expander as a whole must be positioned for it to operate successfully. The basis for the latter is explored more fully in the memo entitled "Positional Requirements of the Delay Line Metrology Beam Expander".

1 Introduction

The MROI delay line system uses 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-size) beam diameters typical of COTS metrology laser heads. For such long metrology paths, a large diameter beam is required to limit beam divergence — and hence signal loss — due to diffraction. The derived requirement on the MROI metrology beam diameter is that that it be no less than 21.6mm in diameter[1]. This is considerably larger than the 6mm diameter beam that the metrology system optics have been designed for, and so there is a need to expand the metrology laser beam prior to propagation to the cats-eye and subsequently to compress it upon its return.

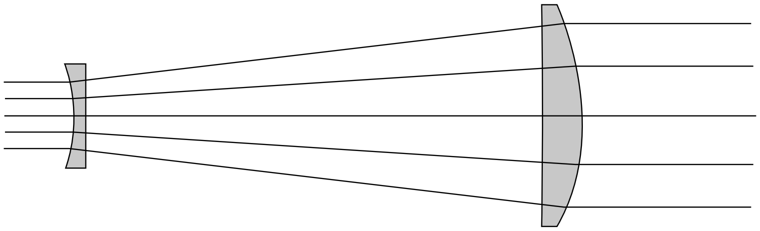

Figure 1: A simple beam expander made up of a pair of singlet lenses. The beam enters from the left and exits to right. Note that for each lens, the surface with maximum curvature faces the beam with the flattest wavefront.

Such a beam expander/compressor can be most easily realised using a pair of lenses in a reversed telescopic configuration, i.e. with the beam entering a small diameter short focal length lens "objective" lens and exiting through a larger diameter longer focal length "image" lens. Two such configurations are possible: the Keplerian design, which uses a pair of convex lenses, and the Galilean design, in which the smaller diameter lens is concave. Figure 1 shows the simplest possible example of a Galilean beam expander constructed from a pair of singlet lenses.

Most low power COTS beam expanders are of the Galilean design for the following three reasons:

- It has a shorter physical size than the equivalent Keplerian design;
- It does not produce a focal spot within the expander, which for high power laser applications can lead to undesirable local thermal instabilities;
- For a given level of lens complexity it generally introduces a lower level of aberration than the Keplerian design.

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[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.

The last of these is of most relevance to the MROI delay line implementation, and so as a result only Galilean design solutions were examined during our lens selection exercise.

2 Requirements

The key design requirements for the MROI metrology system beam expanders were established during the “Risk Reduction Experiments” phase of the MROI delay lines design activity and the subsequent production of the “Derived Requirements” document. They can be summarised as follows:

1. That the expanders be designed to operate at a wavelength of 632.8 nm (He-Ne);
2. That the expander optics be coated so as to limit the amount of light reflected off them;
3. That a magnification factor of at least $\times 3.6$ be realised, with a goal for the output beam diameter of no less than 21.6mm;
4. That the beam expanders accommodate an input beam diameter of 6mm;
5. That the expanders introduce no more than 0.05λ of RMS wavefront error to an initially perfectly collimated beam;
6. That the design of the expanders allow for the direction of their output beam to be adjusted to match the desired beam trajectory via adjustment of the tilt and shear of the incident unexpanded beam.

3 Potential Lens Choices

In order to select lenses for the MROI beam expanders, we first restricted attention to Galilean designs. Within that context we then followed a rather simple procedure which involved selecting, without further assessment, a pair of lenses from the same vendor appropriate to one of three possible optical designs. The three designs investigated implied the following lens choices:

1. A pair of singlet lenses - e.g. Comar 250PQ50 (diameter 50mm, focal length 250mm) and 63NQ25 (diameter 25mm, focal length -63mm). These give an overall magnification of 3.6, which is clearly consistent with the expansion factor required.
2. A singlet and doublet combination - e.g. Melles Griot 01LUK0028 (diameter 25mm, focal length -50mm) and 01LA0628 (diameter 50mm, focal length 200mm). These

lenses give an overall magnification of 4.0, again consistent with the expansion factor needed. For this configuration, an initial ray-trace confirmed that better optical performance would be obtained by making the larger lens the achromat, and so we chose that configuration to investigate further.

3. A pair of doublet achromatic lenses e.g. Thor Labs ACN254-050-A1 (diameter 25.4mm, focal length -50mm) and AC508-200-A1 (diameter 50.8mm, focal length 200mm). These lenses give an overall magnification of 4, again consistent with the expansion factor required.

For each of these three cases, we then proceeded to explore via ZEMAX modelling how such a beam expander might be expected to perform when typical manufacturing, mounting and alignment errors were introduced. We expected that *a priori* the performance of the expander would improve as the lens elements were progressively achromatised. not only because of better balancing of aberrations in the individual lenses, but also because achromatic doublets are generally manufactured to a higher specification than singlet lenses[2].

4 Evaluation

For each of a lens pairings outlined above, a ZEMAX model of the beam expander was prepared assuming a plane monochromatic beam of wavelength 633nm with a diameter (as defined in footnote 1) of 6mm. The lenses were assumed to have been manufactured according to their theoretical prescriptions, but subsequently mounted such that each element was displaced and tilted with respect to its correct orientation due to imperfections in the machining of its mount. We assumed very conservative machining tolerances (see table 1) and expect that any mounting errors will in practice be much smaller than these.

The beam expander using singlet lenses manufactured by Comar produced an expanded beam with unsatisfactory wavefront quality. Even without mounting errors, its output beam exhibited an RMS wavefront error of 0.068λ and so no further consideration of this design was given.

The singlet-doublet pair from Melles Griot performed significantly better. When perfectly aligned, its lens elements introduced a wavefront error of 0.032λ. Although a limited range of mechanical misalignments of the lens elements allowed for an output beam that met the wavefront quality requirement, this could not be guaranteed when the misalignments were included in the worst possible arrangements and with their maximum possible values. In particular, for the worse case, the wavefront error at 0.074λ easily exceeded the allowed budget for a beam which when expanded travelled along the desired direction.

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[2] By way of example, the centration error for the Comar 250PQ50 singlet lens is $8.5'$, whereas the equivalent error is only $3'$ for the Thor Labs AC208-200-A1 achromatic doublet.

	Concentricity	Tilt
Objective lens	0.14mm	0.07°
Image lens	0.09mm	0.03°

Table 1: Mounting accuracy of the lenses in the beam expander due to machining tolerances of the lens mounts. These figures are the largest possible inaccuracies; it is likely the actual alignment errors will be smaller than these figures. The terms "Objective" and "Image" refer to the smaller concave and larger convex lenses in the expander respectively. The errors are larger for the smaller lens as its mounting allows it to be slid along the barrel to adjust the despace between the lenses.

The best optical performance was obtained with the pair of achromats from Thor Labs. When perfectly mounted, these introduced a wavefront error of 0.015λ, with this increasing to only 0.018λ when mechanical mounting errors were included. If we included an additional despace error (corresponding to an error in the separation of the lenses of 20μm) the resulting wavefront error remained smaller than the requirement at 0.032λ. In view of this, the achromatic doublet solution was selected for further analysis.

4.1 Further analyses

As part of the further analysis of the achromatic doublet design for the beam expanders, three additional likely sources of increased wavefront error in the expanded beam were assessed. It is likely that all three will be present at some level or another when the metrology expanders are assembled and installed at the MROI. However, we do not believe that there is a high risk that they will lead to an overall wavefront error greater than the 0.050λ limit specified in the requirements. All the figures quoted here are from the memorandum "Note on Metrology Table Installation Tolerances", which should be consulted for any details not presented here.

4.1.1 Impact of External Misalignments

When the beam expanders are installed, our mechanical tolerancing indicates that the whole beam expander assembly will likely be inserted in place with some small error with respect to its nominal location. This is expected to lead to a misalignment of the first (i.e. concave) element of the beam expander by up to ±0.3mm in height, ±0.2mm in lateral location, ±0.064° in pitch and ±0.016° in yaw. If these perturbations are introduced to the ZEMAX model of our prefered achromatic doublet design, then the revised value for the exit wavefront error increases to 0.037λ. This is still within budget and so not a major concern.

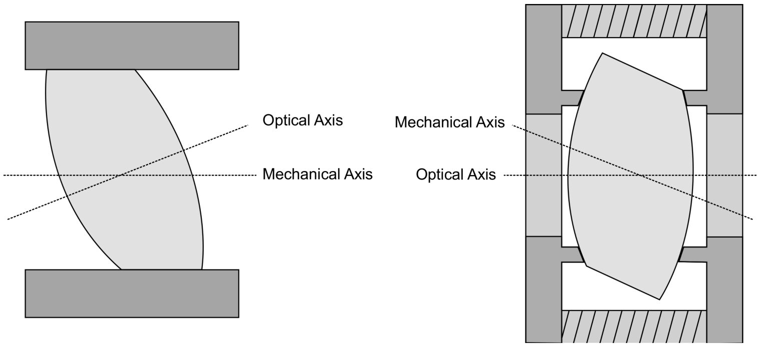

Figure 2: An illustration of the benefits of using surface mounting (right) over edge mounting (left) of a lens in a cell. If the edges of a lens are used to register the element, then this can lead to the lens vertex not being mounted centrally and the optical axis of the lens not being parallel to the optical tube assembly. If "surface mounting" (right hand panel) is used, this helps mitigate against these problems. This is the type of lens mounting that has been adopted for the MROI beam expanders.

4.1.2 Impact of Lens Manufacturing Errors

As for all COTS components, it is expected that there will be errors in the manufacturing of the expander lenses that may compromise their optical performance. The two most common defects, which vendors can provide some information on, are misalignment of the optical axis of a lens from its mechanical center, and failure of its optical axis to be parallel to the axis defined by the mechanical barrel of the lens (see the first panel of figure 2 for a cartoon describing these two faults). The mounting scheme we have designed for the beam expander lenses uses the surface of the lenses to register them in the optical tube assembly and we expect this to mitigate to a large extent the lens fabrication errors we have described above (see right hand panel of figure 2).

We have, however, quantified the impact of the full contributions of lens manufacturing errors on the Thor achromats used in our favoured design. In the global worst case, where the maximum lens manufacturing errors are combined with all the other contributions to misalignment in the most unfavourable manner, the final RMS wavefront error in the expanded beam will be 0.054λ, i.e. slightly over the allowed budget. However, a more realistic assessment of the impact of the cumulative effects of all sources of misalignment was obtained by examining the distribution of RMS wavefront errors obtained by drawing randomly from uniform distributions of all the expected perturbations. In this case the median RMS wavefront error for a very large number of independent realisations of the errors was only 0.019λ, well within the wavefront quality requirement.

4.1.3 Impact of Seasonal Despace

A final source of optical degradation considered in our investigation was the seasonal defocus associated with thermal expansion and contraction of the stainless steel optical tube assembly of the expander. This is expected to have a magnitude no larger than $\pm 40\mu$m over the course of a year (which corresponds to assuming a $\pm 10^\circ$ C range in temperature within the inner BCA[3]). When included at its maximum value as a static contribution to misalignment, this led to an eventual median RMS wavefront error (again quantified via Monte Carlo exploration of uniformly distributed populations of contributing misalignments) of 0.047λ, i.e. just within budget.

5 Conclusion

Of the three classes of lens pairs investigated, only a pair of achromatic doublet lenses was able to meet the requirements placed on the beam expander as laid out in section 2. For a beam expander comprising two COTS Thor Labs lenses (ACN254-050-A1, diameter 25.4mm, and focal length -50mm and AC508-200-A1, diameter 50.8mm and focal length +200mm), the optical performance was found to be satisfactory, meeting the requirements even when misalignments of the beam expander had been assumed and other possible sources of error were included, e.g. lens manufacturing errors, lens mounting errors, and seasonal temperature variations in the optical laboratory.

Because only one pair of COTS lenses was investigated in detail, we cannot confirm that an alternative combination of lenses does not perform better. However, since the chosen lenses appear to meet all the requirements for the MROI beam expanders [4], we have accepted these as a reasonable choice.

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[3] We expect the fluctuation of the temperature to be much smaller than the value assumed here, but no specification has yet been made. The figure used here is extremely pessimistic.

[4] The Thor Lab lenses are available with a "visible" anti-reflection coating with a reflectivity of approximately 0.3 % at 633 nm. This coating has been specified for the final expander procurement.