Introduction

The Aspheric Laser Beam Reshaper, or reshaper for short, is a pair of plano-convex aspheric lenses which perform a deterministic geometrical transformation of the optical laser beam which is directed into it. This transformation takes the form of a radially dependent magnification, which has the effect of redistributing the input laser beam power as a function of radius in the reshaper’s output aperture. Although the mathematics of the transformation are very general, and allow many possible combinations of input and output beam profiles, the current system has been designed for a Gaussian profile and specific beam waist at the input, which maps to a “flat top” power distribution at the output. This transformation is shown in Figure 1, and described in detail in Reference 1. The purpose of these application notes is to explain the nature of this transformation and to guide the user of a reshaper in setting one up and getting optimum performance from it.

Figure 1: Theoretical mapping of a cross-section of the input Gaussian laser beam to a flat-top intensity profile. The total power in the beams is the same. The peak intensity of the output profile has been reduced by the shift of power from the center of the beam to the outside.
### Technical Specifications and optical prescription

The reshaper is comprised of two fused silica plano-convex aspheric lenses, arranged with the convex surfaces facing each other. The general form is that of a Keplerian telescope, with a radially varying magnification. The design wavelength is 532 nm, although as will be seen, this prescription is usable over a wide wavelength range. The design separation of the two aspheres is 150 mm at a wavelength of 532 nm. A scale drawing of the reshaper is shown in Figure 2.

**Figure 2**: A scale drawing of the aspheric laser beam reshaping optics. The Gaussian profile laser beam is incident from the left, and the modified “top-hat” beam exits to the right. The separation is 150 mm, and the input aperture of the optics is 8.11 mm.

The Keplerian design produces an intermediate focus, as is evident in Figure 2. Evaluating the diffraction integral in the Fresnel approximation for $\lambda = 532 \text{ nm}$, one finds that the peak intensity in the region between the lenses is approximately 13,000 times greater than the intensity on axis of the incident Gaussian beam. For applications with high power beams, the effects of this intensity concentration, e.g. air breakdown, must be considered.

The current version of the laser beam reshaper is designed to process an input laser beam which has an accurate Gaussian beam profile whose $1/e^2$ beam radius is 2.366 mm. The optics are designed to accept $1 - e^{-6}$ of the incident optical power, which means that 99.7% of the input beam is transferred to the output of the device. No significant optical power is truncated by apertures, which minimizes diffraction effects in the subsequent beam. The lenses are made from high quality fused silica (Corning 7980), with the result that the optics transmit light with little loss from the deep UV (<250 nm) to the deep IR (>1.5 microns). A more detailed plot of the calculated intensity profile at the output aperture is shown in Figure 3.
A consequence of using a low dispersion material such as silica is that a single prescription for the output and input lenses is usable over a broad range of wavelengths. Figure 4 shows the spacing of the lenses as a function of wavelength which produces a collimated output beam. The relationship between the lens spacing at the design wavelength, \( d_0 = 150 \text{ mm} \), and the spacing required to collimate the beam at any other wavelength, \( \lambda \), is given in terms of the index of refraction of the lens material \( n(\lambda) \) as:

\[
d(\lambda) = d_0 \frac{n_0 - 1}{n(\lambda) - 1}
\]

where \( n_0 \) is the index of refraction at the design wavelength 532 nm.

The change in OPD as a function of wavelength for a reshaper used at its design spacing of 150 mm is shown in Figure 5. It can be seen that the OPD changes by up to +/- 4
waves from 450 nm to 650 nm. Methods for achromatizing the laser beam reshaper will be discussed in a separate application note.

**Figure 4:** A plot of the required spacing of the two aspheric lenses as a function of wavelength required to produce a collimated output beam.

![Wavelength/Spacing Relationship for Silica Reshaper](image)

**Figure 5:** The calculated OPD fan plot for an aspheric laser beam reshaper for several wavelengths in the visible region. The design wavelength was 532 nm, for which the maximum OPD is only 0.01 waves. The reshaper is adjusted for the design lens spacing of 150 mm, and has been fabricated from fused silica.

The intensity profile of the output beam varies only slightly as a function of wavelength, as can be seen in Figure 6:
Figure 6: The intensity profile of a reshaped Gaussian laser beam at three wavelengths. In each case, the spacing of the two aspheric lenses has been adjusted to collimate the output beam. The primary effect of wavelength changes is to slightly modify the effective diameter of the output “top-hat” beam.

For a perfectly constructed pair of aspheric lenses, the wavefront quality of the output beam is excellent. Theoretical calculations and Zemax ray tracing predict that the P-V wavefront error in a perfect lens pair is of the order of 0.01 waves at the design wavelength of 532 nm, rising to circa 0.1 waves at 257 nm.

Use with pulsed lasers

The main issues which arise with pulsed lasers are the typically large peak intensity, and the dispersion of the optics over the frequency bandwidth of the pulse. The lenses themselves are fused silica with AR coatings and will have the same power limitations as other fused silica lenses of the same size. In the region between the lenses, there is an intermediate focus in which the peak intensity is about 13,000 times the intensity on axis for the incident Gaussian beam (at 532 nm). If this intensity enhancement is sufficient to lead to air breakdown, then strategies such as an evacuated lens mount must be considered.

The effect of dispersion for a lens pair with the nominal 150 mm separation is shown in Figure 5, above. For transform limited pulses longer than about 1 picosecond the effect of dispersion is small. In addition, dispersion causes the different frequency components of a pulse to have different transit times through the optics, which leads to pulse broadening. These lenses have a total center thickness of approximately 1 centimeter, which is expected to produce significant pulse broadening when the pulses (assumed transform limited) are less than a few hundred femtoseconds long.
Optical prescription of the beam reshaper and modeling

The prescription of the laser beam reshaper is derived by direct solution of a set of differential equations, as detailed in Reference 1. The output from the calculation is a set of sags for the two aspheric surfaces as a function of radius. These sags are then used by the optician in order to fabricate the lenses. It is difficult to analyze many of the interesting optical effects which the reshaper can produce by direct computation with the programs which generate the sag tables. The use of a good optical design program, such as Zemax (Focus Software Inc, San Diego, Ca) is very helpful for modeling exactly how the reshaper will behave in different situations. Most of the data to be described below was obtained with the aid of Zemax, although in principle, any other similar program will prove useful.

There are a variety of methods for inputting the sag tables into an optical design program. One of the most useful is to fit the sag tables to high order polynomials and to then use the resulting analytical functions as a description of the lenses. This approach can produce results accurate to about 1/20 wave at 532, as the shape of the aspheres is reasonably well described to this level by a 16th order even-asphere. In the case of the Zemax program, the conic coefficient and curvature are ignored (k = 0, radius = infinity), and the eight coefficients of the 16th order asphere are simply entered, using a Surface Type of “Even Asphere.”

Since the laser beam reshaper will most likely find application in demanding and sophisticated applications, in the interests of providing the most germane information, the optical prescription for the optics in a form suitable for use as described above, is reproduced below, along with the specific details of the Zemax setup necessary to use it correctly. The reader is reminded that this prescription is patented (U.S. Patent 6,295,168).

1. The Zemax aperture type is “Entrance Pupil Diameter”, and is set to 8.1125 mm.
2. The Apodization Type is set to “Gaussian,” and the Apodization factor is set to 2.939.
3. The Wavelength is set to 0.532 microns.
4. The Glass type is Corning 7980 (fused Silica).
5. The Object distance is set to “Infinity”, and the stop is placed 10 mm before the face of the first lens.
6. For analysis of the effects of tilt and de-center, a “Coordinate Break Surface” is placed just prior to, and following, the input and output lenses. The Decenter and Tilt data fields of the second Coordinate Break should be Pick-ups of the corresponding data fields of the first Coordinate Break, with scale factors of -1.
7. The entrance and exit faces of the two plano-aspheric lenses have “Standard” surface types and a radius of “Infinity” (plano). The aspheric surfaces face each other, and their design separation at the design wavelength of 532 nm is 150mm.
8. A paraxial lens is placed after the reshaper, 100 mm from the image plane, with a focal length of 100 mm.
9. To study the beam profile, use the Illumination XY Scan Analysis tool. Set the sampling to 128x128, and use a minimum of 2000K rays. Make the Detector equal to 10 mm, do not use much smoothing (4 or less), and set the Surface to either the surface containing the paraxial lens or else the output aperture.

The coefficients of the “Even Asphere” are tabulated in Table 1.

Table 1: Coefficients for the "Even Asphere" Surface type for the reshaper

<table>
<thead>
<tr>
<th>Term</th>
<th>First Asphere Coefficient</th>
<th>Second Asphere Coefficient</th>
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<tr>
<td>$R^2$</td>
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<td>$1.094181E-02$</td>
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<tr>
<td>$R^4$</td>
<td>$6.354780E-04$</td>
<td>$3.380964E-05$</td>
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<td>$-2.658736E-05$</td>
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<td>$R^{16}$</td>
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</tr>
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</tr>
<tr>
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</tr>
</tbody>
</table>

**Metrology of a non-Gaussian beam profile**

The accurate measurement and metrology of a non-Gaussian laser beam is unexpectedly difficult. This is due to several things. Perhaps foremost is the difficulty of obtaining a detector with good spatial and intensity resolution with an area large enough to encompass the entire beam. Detectors such as CCD arrays can provide excellent metrology, but they are extremely sensitive, requiring attenuation of the beam (a non trivial task if accurate intensity profiles are to be preserved), and for many beams, the available array size is too small. Scanning slit profilometers, although excellent for Gaussian beams, often cannot correctly measure the profile of a flat-top beam. In any case, a scan through the beam only provides information about what is happening along that scan axis, and this is often not enough information.

Another difficulty which arises in making profile measurements of laser beams comes from the fact that the beams are coherent: they can create interference fringes and large amounts of speckle. These can seriously degrade a measurement.

**Alignment of the laser beam reshaper**

**Mounting the reshaper and general layout considerations**
In order to use the reshaper most efficiently, it must be mounted and aligned carefully. The reshaper requires 4 degrees of freedom to align it concentrically with the input laser beam. These degrees of freedom are 2 linear axes transverse to the beam propagation direction, and two angular adjustments to align the pitch and yaw of the reshaper relative to the input laser beam. These 4 adjustments are just those required to align a cylinder along an arbitrary line in space.

It is common practice in laser labs to adjust a laser beam to be coaxial with a lens system by using the 4 degrees of freedom of a Z-fold mirror system for alignment. Although it is technically possible to accomplish the alignment of the reshaper this way, it is not the best method. The reshaper exhibits quite different optical effects for transverse translation adjustment and angular adjustment, and having these axes decoupled cleanly greatly facilitates making the required alignment.

When used with a perfectly prepared input laser beam, which is to say one with the ideal waist size and profile, no excess divergence, and a very flat wavefront, the reshaper exhibits two primary signatures when it is misaligned. For translational misalignments, the beam profile will deviate from the desired profile, although the Optical Path Difference (OPD) can be quite small even for substantial misalignment. For angular misalignment, the primary aberrations are wavefront tilt and coma. Although the OPD contributed by the wavefront tilt can be large, it is the coma which causes the most difficulty. Even small angular misalignments can have a substantial effect. Successful operation of the reshaper requires that the angular misalignment be less than about 140 microradians with respect to the input beam, and translationally centered on the input beam to less than 25 microns. Although these tolerances are not large, they are well within the capabilities of normal translational and rotational stages commonly employed in a laser laboratory. For example, Newport 425 series linear stages and Model 36 tilt/rotation stages easily allow the required precision. It is very useful for the reshaper to be mounted in a long V-block, as close to the axes of rotation as possible. This allows the reshaper to be removed from the optical system and replaced without affecting the alignment, and also minimizes translation due to lever arm effects of the rotational degrees of freedom.

Because the reshaper requires careful alignment to the laser beam, thought should be given to the general optical layout of the laser system in the vicinity of the reshaper. Generally, the required optical components are either a single mode optical fiber and collimator or a spatial filter to prepare the input beam to have a clean Gaussian profile, some sort of adjustable magnification telescope to allow resizing of the Gaussian waist, and the reshaper. Since the optical alignment of the laser source (fiber or spatial filter), the variable magnification telescope, and the reshaper is critical, it makes sense for these components to be mounted on a separate optical breadboard, so that they may be kept in good rough alignment at all times, and only fine adjustment will be necessary if the overall optical setup must be moved or reconfigured. Having a pair of mirrors in a Z-fold configuration at the input of the reshaper optics section, and the means of knowing when they have been adjusted properly, can allow substantial optical realignment upstream of the reshaper optical assembly to be performed, and then compensated for without having
to constantly adjust the reshaper optical alignment. The use of the Newport Active Beam Alignment System can decouple upstream laser system realignments from the reshaper automatically, and in a critical application where uptime is of great concern, it is highly recommended.

Cautions and concerns

It must be emphasized that the laser beam reshaper provides a fixed geometrical radial remapping of the optical power entering the input aperture to the output aperture. This is not a magic bullet for curing a bad laser beam. It is, instead, very much a “Garbage-In, Garbage-Out” sort of situation. If the input laser beam has a poor profile, which is to say, is non-Gaussian, and/or the wrong waist size and divergence, then these deficiencies will be echoed in the output beam profile. A Gaussian profile which has a waist which is too big will transfer excess power to the edges of the aperture, and have a “cat’s ears” profile. This may be useful in its own right, but represents a typical error due to poor beam preparation. Conversely, if the input beam is too small, the output beam will have too much power near the center, and exhibit a “humped” or rounded profile.

Other issues which must be considered are the effects of dirt, dust, and etalon fringes. Any dust or dirt on the optics can introduce diffraction rings downstream. These can modulate the intensity in their vicinity by many percent. The severity of these effects depends on which optical surfaces they occur on. Generally, flat-top optical beams get much more scrutiny than generic laser beams, which makes these effects both noticed and onerous. Another annoying effect is etalon fringes between plano and other plano or spherical surfaces in the optical train. It may seem intuitively correct to align optics in a laser system so that all surfaces are centered and perpendicular to the beam. These, however, are exactly the conditions which can create wavelength dependent etalon fringes, which manifest themselves as linear or circular (bull’s-eye) fringe patterns in and around the laser beam. Although often unnoticed in generic applications, in precision illumination applications, these effects can add many percent RMS noise to the laser beam profile. Tilting optical surfaces to “walk-off” the spots, and deliberately de-centering lenses by small amounts is often enough to minimize these effects to practically useful levels.

Another annoying artifact which can impact the use of the laser beam reshaper and its metrology is laser beam speckle. This grainy modulation of the light intensity on a surface is caused by interference between light scattered from different parts of a rough surface. Highly polished and exceedingly well anti-reflection coated surfaces can aid immensely in reducing speckle from lens surfaces and mirrors, as can being sure that all optical surfaces are very clean. It is crucial to clean mirror and other optical surfaces carefully, as microscopic scratches caused by dragging bits of dust entrained in the optics cleaning paper can cause unacceptable levels of scattered light downstream. It is a good practice to pre-clean the surface with pinpoint blasts of sub-micron filtered high pressure dry nitrogen (NEVER Freon-type “lens dusters”!!) before using lens tissue and a solvent. The use of a small diameter plastic tube on the gas delivery nozzle will avoid untimely scratches on the optic…
The message is that the reshaper will expose many deficiencies in an optical setup. It demands a clean, well prepared and characterized input beam, careful although practical alignment and it will generate an output beam in which the lack of attention to the foregoing details will be obvious.

**Collimating the reshaped beam**

The laser beam reshaper acts, in many ways, like a Keplerian telescope with roughly unity magnification and a length of 150 mm. As the spacing between the lenses is changed, the collimation of the output light will also change. This effect can be used to adjust the collimation for a flat OPD at any given wavelength as shown is Figure 4. In setting up a reshaper from scratch, the alignment and the collimation must both be set. Although they are completely separate, these adjustments often must be iterated, as aligning the system is impossible if the reshaper is not roughly collimated, and collimation cannot be performed if the system is not reasonably aligned.

One starts by setting the housing length to the length appropriate for that intended wavelength using a pair of calipers and the table supplied with the reshaper. This should roughly collimate the beam during initial alignment. After the reshaper has been roughly aligned in the input beam so that light is emerging from the output aperture with little obvious signs of coma, the diameter of the emerging beam can be observed in the near and far fields. If power levels are low enough, a card in the beam may be sufficient. The collimation is set by rotating the output lens carrier adjustment so that the diameter is the same over a meter or two of optical path from the output aperture. This should bring the OPD down to the point that fine adjustment of the reshaper alignment can continue. When the output profile in both the near and far (greater than 500 mm) fields is reasonably close to the ideal profile, the collimation can be fine tuned using a shearing plate interferometer, a Blue Sky Collimeter™, or a Shack-Hartmann sensor (or other wavefront sensing device) in the usual way to achieve the specified OPD. When the collimation is optimized, the final alignment of the reshaper can be performed.

**Effects of poor beam quality**

*Non-Gaussian Input Beam*

The primary symptom of an input laser beam with a Non-Gaussian input profile is a systematic departure from the ideal output profile. This often takes the form of humps or dips, sometimes asymmetrical, in the profile.

*Bad $M^2$ of input beam*

The input beam can have a bad $M^2$ for many reasons. Experience has shown that an $M^2$ of less than 1.10 can give acceptable output profile flatness. If the poor $M^2$ is due to ellipticity, the resulting output profile will also be elliptic, with a flat-top profile only along the axis whose beam waist is equal to the design reshaper beam waist. The other axis will exhibit either peaking towards the edges of the beam or else humping in the middle, depending on the size of the input beam relative to the nominally correct value.
**Input Beam with poor wavefront quality**

The laser beam reshaper has demonstrated diffraction limited output wave quality, which is to say, less than $\lambda/4$ Peak-valley OPD. The potential output wavefront quality is limited by the precision of the reshaper fabrication (which is fixed for a particular device) and by the wavefront quality of the input beam. Clearly the reshaper, being similar to a Keplerian telescope with magnification of -1 cannot improve the wavefront quality of a bad input laser beam. This is why a spatial filter or good single mode optical fiber is recommended. Either of these devices can potentially produce a wavefront into the reshaper with $\lambda/10$ P-V OPD.

**Use of an optical fiber to improve beam quality**

A single mode optical fiber produces, in the far field, an optical profile which is very nearly Gaussian. When used with a high quality collimation optic, a fiber is capable of generating a optical profile from the reshaper which is indistinguishable from the design profile. For operation in the visible, a 3 -3.5 micron fiber is a good choice. The collimation and beam waist adjustment can be combined in a single optical device by using two high quality achromats separated by an adjustable spacing to realize the collimation optic. The spacing between the lenses adjusts the effective focal length of the pair, while the spacing of the pair from the fiber adjusts the collimation. Iteratively adjusting the two spacings can yield a near perfect Gaussian beam with exact waist and collimation required for the reshaper. The drawback of a fiber input system is, of course, the optical power which can be delivered. Experience has shown that several hundred milliwatts can be safely delivered through such a system.

**Use of a spatial filter to improve beam quality**

Another strategy for cleaning up an input beam with poor optical quality is the use of a spatial filter. It is important that the parameters of the filter (input focal length, pinhole size) be chosen astutely for best power transfer and beam quality. For an input beam which is reasonable to begin with, choosing the pinhole diameter to correspond with the zero of the first Airy ring in the focal plane of the input lens will yield a high quality optical profile. It is, of course, important that the collimating optic be of sufficiently high quality so as to not degrade the wavefront of the transmitted beam. The use of a pair of achromats, as described for the case of an optical fiber, above, can allow both the collimation and variable input waist functions to be combined in a single location. Consult the Newport catalog for advice on choosing appropriate optical components.

**Effects of wrong input beam waist size**

If a Gaussian beam of the wrong waist size enters the reshaper, the output beam profile will systematically depart from the design profile. If the waist is too big, the profile will be peaked at the edges (cat’s ears profile). If the waist is too small, the center region of the output beam will be rounded, or “humped”. Both of these beam profiles have certain
interesting potential applications, and it may be that deliberately mismatching the input waist can have some practical utility. Generally, it is very important to have the ability to easily adjust the input beam waist to the nominal specification of 2.366 mm at the $1/e^2$ points. The obvious way to do this is to use a zoom beam expander with sufficient range to accommodate the transformation from the incident laser beam to the desired waist. Adjusting this waist size empirically is quite possible, but if the zoom expander is of poor quality, this approach can be very frustrating. One disease which many expanders suffer from is a change of pointing angle or centration of the transmitted beam as the waist size is varied. This, of course, will affect the alignment of the reshaper, with the result that for each magnification change the entire reshaper will have to be readjusted carefully. When one adds the fact that the zoom expander collimation often changes with the expansion ratio, this can be a very tedious process. It is much easier to adjust the waist size with a beam profile measuring device such as a Beam Scan™ (Photon, Inc) or a CCD based system, re-collimating between adjustments. This approach usually converges quickly to the correct values.

For those without such metrology, the procedure is as follows:

1. Adjust the output beam waist size at the output of the variable telescope for an approximate visible diameter of 8.11 mm. This is the total optical input aperture of the reshaper at the $1/e^6$ intensity points of the Gaussian beam. Assuming that the power levels are safe, viewing the output of the expander through a card or piece of paper at the output lens of the expander and measuring the diameter with a pair of calipers can work.

2. Collimate the expanded beam in the far field either with a shearing plate interferometer or other optical collimation tester, or else measure the diameter of the entire visible beam at a point a meter or so downstream while adjusting the collimation control (NOT the expansion control!).

3. Check the visible diameter at the output again, and then the collimation. Over a meter, there should be very little change in the 8.11 mm diameter disc.

4. Input the beam into the reshaper, and adjust the centration, angular alignment, and collimation of the reshaper to give a propagating beam with no obvious coma or intensity asymmetries. At this point, having a CCD camera to monitor the actual beam profile is essential. This measurement must be performed at the microwatt level typically, as CCD cameras are very sensitive. A good way to attenuate the beam adequately to observe it on a CCD camera without degrading either the wavefront quality or the intensity profile is to use a high quality highly reflecting mirror with an anti-reflecting polished back surface as an attenuator. The Newport BD.1 coating (for the visible) will transmit only a few tenths of a percent of the incident light. This is often ideal for illuminating the CCD camera. The reflected beam, with most of the optical power, can be directed to a beam dump.

5. The output profile is observed on the CCD camera, and compared to the desired profile. If there is too much power on the edge of the beam, the input beam is too big, and the expander telescope must be set for lower magnification. Conversely, if the power is concentrated in the center, the expansion magnification must be increased. If these adjustments to the magnification are done in small increments,
the output collimation of the reshaper can be restored by using the collimation adjustment of the expander telescope NOT the reshaper (which has been adjusted for collimation already). Small tweaks of the magnification, followed by collimation adjustments will usually yield a satisfactory output profile in short order.

**Deliberate mismatching of the waist to achieve a desired profile**

The output profile of the reshaper has several interesting shapes when the input laser beam waist is different from the design $1/e^2$ radius of 2.366 mm. If the applied waist is too small, the power concentrates more in the center, and the profile is “humped”. If the input waist is too big, the power shifts to the outside of the aperture and the beam has a “cats ear” profile, with hot edges and low intensity in the center. Both of these profiles may be of some interest in certain applications. A plot of the various profiles as a function of the input waist size is shown in Figure 7 and also in Figure 8.

![Output Beam Profiles for Different Input Waists](image)

**Figure 7:** A plot of three calculated output profiles for three different input laser beam waists. The ratio is in terms of the design input waist diameter of $W_0=2.366$ mm. In the case of the “cat’s ears” profile, the overfilling of the aperture will lead to diffraction rings in the far field.
Figure 8: A plot of the various shapes which the output profile can achieve, depending on the input beam waist. The ripples in the intensity profile are due to sampling artifacts in the optical analysis program. Overfilling the input aperture will lead to diffraction rings in the far field. The curves are labeled by the ratio of the applied waist radius to the design radius $W_0=2.366$ mm.

It should be emphasized that the results plotted in Figure 8, above, were obtained by ray-tracing. As the input beam waist is made larger than the design value, the input laser beam begins to overfill the input aperture, and some optical power will be truncated by a hard edge. This will cause diffraction rings in the far field which will become more severe as the “cats-eye” shape becomes more pronounced. The effect will be relatively small at the output aperture, however, and the resulting laser beam can still be used in the far field by means of relay or imaging optics, as described below.

Aligning the reshaper

Assuming that the laser beam reshaper has been properly mounted in a long V-block on a set of stages with the required 4 degrees of freedom, and that a Gaussian laser beam with suitable waist size is available, the procedure for aligning the system is described below. It is assumed that the laser beam is in the visible, and that the power levels are sufficiently low that the beam profile can be viewed on a card in the beam without danger. If these conditions are impossible to meet, the user must adapt the procedure described so as to perform the operations in a safe manner.
1. Roughly align the reshaper optical axis to be collinear with the input laser beam. In order to avoid an endless round of adjustments, it is most desirable that the input beam be well characterized, having a $1/e^2$ waist of 2.366 mm, a good Gaussian profile, and is well collimated. As an aid to adjusting the co-linearity, a cylinder with diameter equal to the reshaper housing diameter and ends accurately perpendicular to the axis of the cylinder may be fabricated. On one end of the cylinder, an accurately centered variable iris, such as the Newport ID-0.5 is placed. On the other face of the cylinder is mounted a flat mirror with a highly reflecting face, with the face oriented towards the iris. The cylinder is placed in the V-block and the centration of the input beam is observed on the iris while the translational controls are manipulated. The reflected beam from the mirror is used to align the angular orientation of the V-block by observing the back reflection of the input beam at a location upstream of the reshaper. Using an iris located some distance upstream of the input beam zoom telescope can be very helpful. Sliding the cylinder along the V-block while watching the centration is also a good test.

2. With the input beam centered on the reshaper optical axis, and the V-block aligned parallel to the input beam, place the reshaper in the V-block. Light should emerge from the output. View the output profile on a white card placed in the near field (near the housing) and the far field (500 mm to 2 meters from the housing). The reshaped profile will often vary considerably between the two viewing locations. In the near field, the profile shows effects due to translation of the reshaper perpendicular to the optical axis. In the far field, the profile is degraded by coma and other aberrations due to angular misalignment. If the translational and angular (pitch and yaw) controls are varied systematically while observing the near and far fields, the reshaper may be aligned in a straightforward manner.

3. First, observe the reshaped beam in the near field and adjust the transverse position of the reshaper to give a beam which is circularly symmetric. Having a dim beam is helpful to avoid visual overload.

4. Now observe the output profile in the far field and adjust the pitch and yaw to make the profile as symmetric and circular as possible.

5. At this point, the beam may be converging or diverging. Roughly adjust the collimation, as previously described, and reiterate the near field-far field adjustments to get the profile as circular, symmetric, and as collimated as possible while viewed on a card.

6. Having run out of missiles, it is now time to switch to guns. Before viewing the profile on a CCD detector or other beam profiling device, collimate the output beam with a shearing plate interferometer or other such device. Having adjusted the intensity for the dynamic range of the beam profiler, observe the profile. If the laser input beam waist is not the correct diameter, or is not collimated, the output profile will exhibit either excess power on the edge of the beam (cat’s ears) or if the waist is too small, humping near the middle. If this is the case, the waist size will have to be readjusted and collimated, and the proceeding alignment repeated.

7. When the beam in the near field appears similar to the theoretical output profile, the output wavefront should be measured or estimated if the metrology to do so is available. A Shack-Hartmann sensor is the ideal tool, but some idea of the beam
wavefront flatness can be obtained by observing the extinction of the beam when it is analyzed with a Blue Sky Collimeter™ or other such interferometric tool. These measurements can be used to really fine tune the angular misalignment.

It should be noted again that transverse misalignments cause errors in the output profile, although they have little effect on the wavefront, while angular misalignment produced drastic effects on the wavefront quality. The signatures and magnitudes of these effects are described below in detail, as is the effect of input beam mismatch.

**Errors due to Tilt Misalignment**

The wavefront quality for the reshaped beam can be diffraction limited when the reshaper is aligned properly, as described above. If the alignment is not optimum, the aberrations introduced by the misalignment will degrade the wavefront. The primary misalignment is angular. If the reshaper’s optical axis is not collinear with the optical axis defined by the propagation of the input Gaussian beam, the aspheric surfaces of the reshaper will contribute substantial aberrations. The tolerance for the reshaper to exhibit diffraction limited performance is rather small, being of the order of 140 microradians, or 30 arc seconds. This tolerance is, however, rather easily achieved with standard optical alignment devices.

To better understand the effects of tilt misalignment, an optical design program was used to explore the wavefront errors which arise from angular misalignment. These results are summarized in Figures 9, 10, and 11. 2D images of the transmitted beam profile for various misalignments are shown in Figure 12.

In Figure 9 is plotted the net RMS wavefront error for the reshaper as a function of angular misalignment, with piston and wavefront tilt subtracted. The dominant wavefront error for angular misalignment is wavefront tilt, although this is not generally considered an aberration, as it merely represents a new optical axis for the propagating reshaped beam.
Figure 9: The RMS wavefront error for the reshaped wavefront as a function of angular misalignment. The effects of tilt of the wavefront and piston have been subtracted.

The Peak-to-Valley wavefront error of the reshaped beam as a function of misalignment is shown in Figure 10. The large slope to this curve is due to the tilt in the output wavefront.
Figure 10: The Peak-to-Valley Wavefront error versus angular misalignment. This plot includes the effects of tilt in the wavefront, which is the predominant effect.

The largest true aberration to the reshaped beam’s wavefront is coma. The reshaper generates large amounts of coma for small angular misalignments. This coma, described by the $Z_8$ coefficient of the Standard Zernike Polynomial set, is plotted in Figure 11, along with the other three most egregious aberration coefficients, $Z_4$, $Z_6$, and $Z_{16}$. These coefficients were obtained by fitting the Standard Zernike Polynomial set to the output wavefront. The actual polynomial terms corresponding to the coefficients are shown in Table 2.

<table>
<thead>
<tr>
<th>Polynomial term</th>
<th>Zernike Polynomial</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z_4$</td>
<td>$\sqrt{3}(2\rho^2 - 1)$</td>
</tr>
<tr>
<td>$Z_6$</td>
<td>$\sqrt{6}(\rho^2 \cos(2\phi))$</td>
</tr>
<tr>
<td>$Z_8$</td>
<td>$\sqrt{8}(3\rho^3 - 2\rho) \cos(\phi)$</td>
</tr>
<tr>
<td>$Z_{16}$</td>
<td>$\sqrt{12}(10\rho^5 - 12\rho^3 + 3\rho) \cos(\phi)$</td>
</tr>
</tbody>
</table>
Figure 11: The coefficients of the four most dominant Zernike Standard Polynomials from fits to the transmitted wavefront of the reshaper as a function of angular misalignment.

2D false color plots of the reshaped beam as viewed on a card are shown in Figure 12 for distances of 10 mm and 1000 mm from the output aperture. Red indicates the regions of highest intensity, with orange, yellow, green and blue respectively indicating decreased intensity. It should be noted that the effects of angular misalignment are dramatically observed in the far field, but poorly seen close to the output aperture. The effects of de-center, however are easily seen at the output aperture. As mentioned previously, the separation of the effects of de-center and angular misalignment are key tools for quickly aligning the reshaper.
**Figure 12: Tilt Alignment Aberrations**

<table>
<thead>
<tr>
<th>Tilt (deg)</th>
<th>10 mm From aperture</th>
<th>1000 mm From aperture</th>
<th>Tilt (deg)</th>
<th>10 mm From aperture</th>
<th>1000 mm from aperture</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.005</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td>0.05</td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
<tr>
<td>0.008</td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
<td>0.075</td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
</tr>
<tr>
<td>0.01</td>
<td><img src="image9.png" alt="Image" /></td>
<td><img src="image10.png" alt="Image" /></td>
<td>0.1</td>
<td><img src="image11.png" alt="Image" /></td>
<td><img src="image12.png" alt="Image" /></td>
</tr>
<tr>
<td>0.02</td>
<td><img src="image13.png" alt="Image" /></td>
<td><img src="image14.png" alt="Image" /></td>
<td>0.2</td>
<td><img src="image15.png" alt="Image" /></td>
<td><img src="image16.png" alt="Image" /></td>
</tr>
</tbody>
</table>

**Figure 12:** Computed 2-D intensity plots in the near field (10 mm from the output aperture) and far field (1000 mm from output aperture) for various angular misalignments. The reshaper was tilted in one axis. The highest intensity is red, with yellow, green and then blue indicating lower intensities.
**Effects due to centration misalignment**

Since the reshaper is an axially symmetric design which performs a fixed radially deterministic transformation of applied optical power, any de-centration of the input beam will result in a distortion of the nominally flat-top output profile. This effect is shown in Figure 13 and Figure 14. Figure 13 shows a series of plots of the output profile for de-centrations ranging from zero to 0.5 mm. The effect of the de-centration is largely to produce a slope in the flattened top of the profile along the axis which was de-centered. Interestingly, the profile of the other axis is unchanged from the theoretical shape, although the peak power is reduced. This allows for a deliberate de-center to be introduced in some applications, such as oblique illumination, to compensate for geometrical effects and thus produce a more nearly uniform illumination on a surface.

Figure 14 is a plot of the slope of the flat-top as a function of the de-center. This plot can be used to estimate the sensitivity of the profile flatness to de-center, and can be of use in either understanding centration tolerances or in designing a deliberately skewed illumination profile.

**Figure 13**: Scans across the center of the output beam profile computed with the Zemax optical design program for systematic de-centering of the input Gaussian beam from the optical axis. The slight asymmetry, rounding, and ripples in the intensity profile are artifacts due to the choice of scan parameters in the computation.
Figure 14: The slope of the output profile as a function of Gaussian input beam decenter. Multiply the slope at a given de-center by the width of the flat-top section of the output profile (approximately 6 mm) to calculate the change in intensity over the width of the beam due to decenter.

Minimizing profile errors during propagation

The reshaper’s design output profile will theoretically propagate for many meters without noticeable degradation due to diffraction. This is due to the use of the entire input beam to the $1/e^6$ intensity points, which eliminates diffraction from power truncation by hard edges, and also the soft roll-off in the optical power. This soft edge allows much better propagation than the canonical radial step function profile which is often seen in the theoretical literature.

In practice, the very small local shape errors (Intermediate Spatial Frequency or ISF errors) introduced during optical polishing, which may be on the order of a few nanometers in size, cause very small local slope errors in the optical surfaces. These ISF errors have the effect of very slightly deviating optical rays from their design directions. Since the flat optical profile results from a careful remapping of optical power from the input beam to the output beam, any deviation by a ray from it’s intended location will result in less power at that point and more power somewhere else. Thus as the beam propagates from the output aperture to the far field, there is a noticeable degradation in the optical profile from flatness. For best performance, without using any ancillary optics, the propagation distance should be kept to less than one meter.
There are several ways of sidestepping this problem, however. In spite of the small local deviations (milliradians or less) that ISF introduces, the overall divergence of the reshaped beam is of the order of 100 microradians. This means that it is easy to relay the beam from one place to another without the need for excessively large or costly optics. There are two basic systems for relaying the output beam profile: imaging optics and afocal systems.

**Use of telescopes to relay and change spot diameter**

Afocal systems such as telescopes can be very useful for relaying the output beam profile from one point in space to another, and also for changing the size of the flattened beam. There are two types of telescopes, Keplerian and Galilean. Of the two, the Keplerian form is best suited for relaying applications, although either type may be used to change the beam size.

The Keplerian form of a telescope has two positive optical elements and an intermediate focus inside the telescope. The advantage of this form of telescope for relaying a flattened beam profile from the output aperture of the reshaper to another location is that the Keplerian form has two external focal planes, one on each side of the telescope. All rays crossing a focal plane on the way into such a unity magnification telescope will, assuming properly designed lenses, cross the output focal plane with exactly the same ray heights and angles, although the image is inverted due to the intermediate focus. If the telescope has a magnification other than unity, the ray heights scale by the magnification, and angles scale by the inverse of the magnification.

What this means practically, is that if the flattened beam profile from the reshaper were needed at a distance of, say, 4 meters from the output aperture, a Keplerian telescope could be used to relay that image without the degradation to the profile caused by ISF errors. In this case, a unity magnification telescope composed of identical 1 meter focal length lenses, with the first lens located 1 meter from the output aperture of the reshaper will relay the profile at that aperture to a point 4 meters from the aperture with no loss of profile quality. A simple calculation shows that for the 8.11 mm aperture, with a 1 meter focal length, the lenses are working at an f/# of 123. This large f/# suggests that simple plano-convex lenses, such as the Newport KPX124, with an AR.14 coating (for the visible) would be a good choice. In this case, the plano surfaces should face towards the center of the telescope.

In some cases, a very long focal length lens might be needed. This can be very awkward to find in a catalog, but there is a simple solution. An arbitrarily long focal length lens can be built by combining plano-concave and plano-convex lenses a distance $d$ apart. If the convex and concave surfaces face each other, and the focal lengths $f_1$ and $f_2$ are chosen to be exactly the same (implying identical radii), then the equation for the effective focal length $f$ of a combination of thin lenses,

$$\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 f_2}$$
reduces to the simple form

\[ \frac{1}{f} = \frac{d}{f_i^2}. \]

Thus, the focal length of the pair of lenses of identical (but opposite) focal lengths is

\[ f = \frac{f_i^2}{d}. \]

This lens pair is shown in Figure 15.

**Figure 15:** A plano-convex and plano-concave lens pair with equal but opposite focal lengths used to make a variable focal length lens for long focal lengths.

A lens of arbitrarily long focal length may thus be made by simply setting the distance between the two lenses. If the spacing is zero, since the radii of the two lenses are the same, they form a block of glass with plano surfaces. The focal length of this combination is clearly infinity, as the formula predicts. For general use, choosing a pair of plano-convex/concave lenses with a focal length of 150 mm, such as the Newport KPX100 and KPC031 will provide focal lengths according to Table 1:

**Table 3: Focal lengths of plano-convex/concave compound lens**

<table>
<thead>
<tr>
<th>Vertex separation (mm)</th>
<th>Focal Length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Infinity</td>
</tr>
<tr>
<td>2.25</td>
<td>10,000</td>
</tr>
<tr>
<td>5.625</td>
<td>5000</td>
</tr>
<tr>
<td>4.50</td>
<td>4000</td>
</tr>
<tr>
<td>11.25</td>
<td>2000</td>
</tr>
<tr>
<td>22.5</td>
<td>1000</td>
</tr>
</tbody>
</table>
**Use of imaging optics to change spot diameter**

A question which often arises is the issue of how to change the size of the reshaped beam profile. The design is for an output aperture of 8.11 mm, with the soft-edged flat-top beam shown in Figure 2. The flat-top region extends over a diameter of roughly 6 mm. This design point may not be suitable for all users. There are several ways in which the beam diameter can be changed without resorting to making new aspheres.

As mentioned in the previous section, an afocal telescope may be used to magnify or demagnify the beam profile. This has the advantage that the output beam is collimated, but requires very large or small lenses if large magnification or demagnification is required. Another technique is to use a single lens to make an image of the output beam profile at some point in space. In laser optics, lenses are routinely used to focus the beam. The idea that they can image the beam is less commonly employed. A lens, however, will form the image of the profile of a laser beam at a point in space at another point in space just as if it were making an image of a 2 dimensional object plane. The difficulty is that the laser beam is not collimated and continues to diverge after the desired image plane. The optical setup is as shown in Figure 16, and can be found in any optics text. The location of the object and image planes are given by the lens equation and the definition of the magnification desired. If $O$ is the distance from the lens principal plane to the object, which may be taken as the output aperture of the reshaper, and $I$ is the distance from the other principal plane to the location of the desired image of the output beam profile, then

\[
\frac{1}{O} + \frac{1}{I} = \frac{1}{F}
\]

and

\[
M = \frac{I}{O},
\]

where $F$ is the focal length of the lens, and $M$ is the desired magnification. Using this technique, flat-top optical beam images as small as 100 microns diameter and as large as several meters in diameter have been created, with no apparent degradation of the profile. If desired, the image may be spatially filtered to remove high frequency noise by placing an appropriately sized pinhole at the focus of the lens.
Figure 16: The optics of imaging the laser beam profile to change its size.

References

