Alignment of an Offner Triplet Radial Group Delay Compensator

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Abstract

In broadband lasers with short femtosecond pulses, radial group delay (RGD) is introduced when a laser pulse passes through traditional lens systems. With RGD, the center of the beam travels behind the edge of the beam. RGD can decrease the intensity at focus by orders of magnitude. An optical system made of an Offner triplet and a pair of negative lenses can compensate for the RGD. For cost effectiveness, the primary mirror of the Offner triplet is split into two smaller spherical mirrors. Using a ray tracing model, it was shown that these mirrors must be cophased within 4 mm. The spherical mirrors were co-phased by using a 100-nm bandwidth superluminescent laser diode with a coherence length of 4 μm. The alignment was near optimum when the light was temporally coherent and interference fringes appeared. By measuring the visibility of the fringes, it was found that the co-phasing error can be reduced to less than 3 μm, which is well within acceptable tolerances.

Introduction

Radial group delay (RGD) is a phenomenon that occurs in optical systems that use convex lenses and pulses on the order of femtoseconds (1 fs = 10^{-15} s). RGD is illustrated in Figure 1, where a pulse of light passes through two lenses. The outer edges of the pulse travel through less material than the center of the pulse. The center of the pulse takes more time to pass through each lens, causing it to lag behind, resulting in the curved pulse shape seen in Figure 1 [1]. This time difference is small (on the order of femtoseconds), so in most optical systems, RGD is negligible. However, RGD is important when the pulse length is on the order of femtoseconds, and the effect becomes more noticeable with shorter pulses. RGD causes the outside of the pulse to arrive on the target before the inside, reducing the intensity by orders of magnitude in some cases [2].

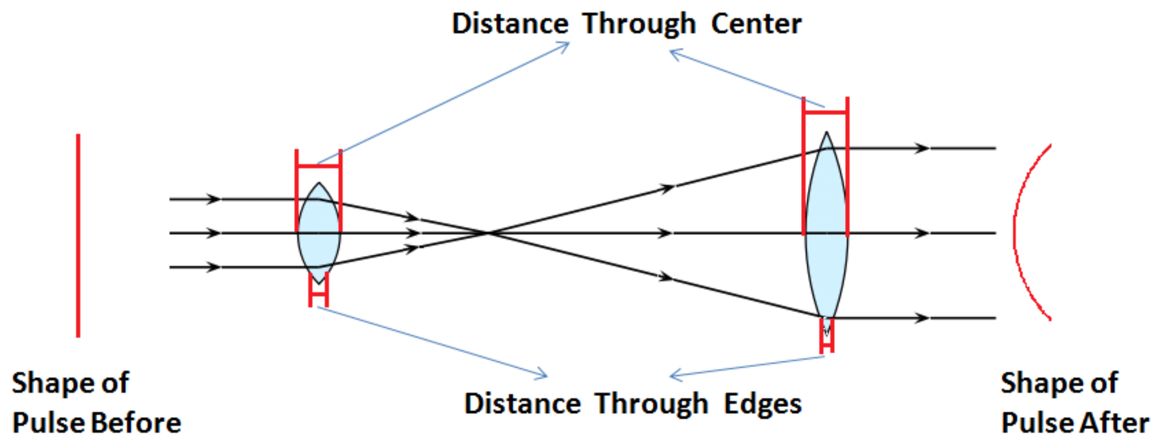
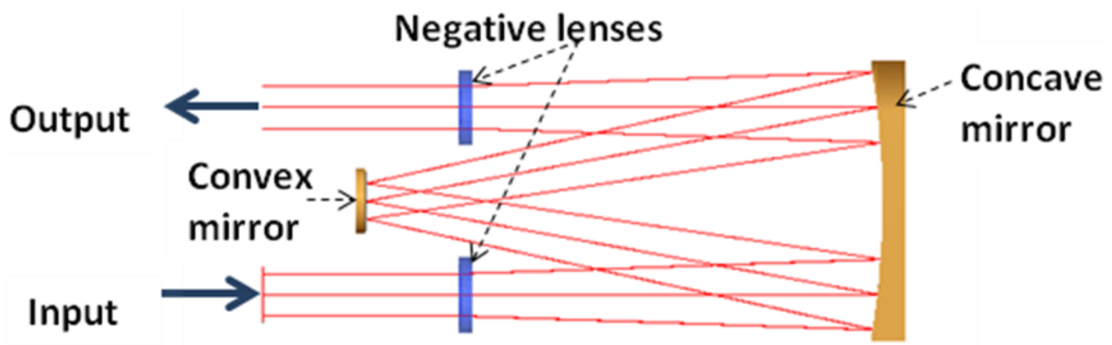


Figure 1: A pulse travelling through a system of convex lenses. When the light passes through more material, it takes a longer period of time, causing the outer edges of the pulse to escape the lens first.

The MTW-OPAL laser, under construction at LLE, will use ultra-broadband pulses of lengths of only 15 fs, so RGD would impact it greatly. To compensate for RGD, a system could be constructed using an Offner triplet and two concave lenses, shown in Figure 2a. Just as convex lenses in conventional image relays cause the center of a pulse to lag behind, concave lenses, with more material near the edges, will cause the outer areas of the pulse to pass through slower, forcing the pulse back into its initial shape. However, once the collimated beam passes through a concave lens, it begins to diverge. To account for this divergence, an Offner triplet, composed of a large concave mirror and a small convex mirror, can be used to form a perfect image on another concave lens which recollimates the beam [3]. Due to the large beam size of the MTW-OPAL laser, if an Offner triplet were to be constructed, it would require a very large spherical mirror, both expensive and difficult to manufacture. Instead, two smaller spherical mirrors could be used in its place, as shown in Figure 2b. To do this requires cophasing the two concave mirrors as if they were on the surface of the same sphere. It was assumed that the cophasing would need to be very precise to keep aberrations to a tolerable level. It was necessary to discover how much precision was required through modeling the Offner triplet and then to actually cophase the mirrors to learn how much precision could be reasonably obtained.

(a)



(b)

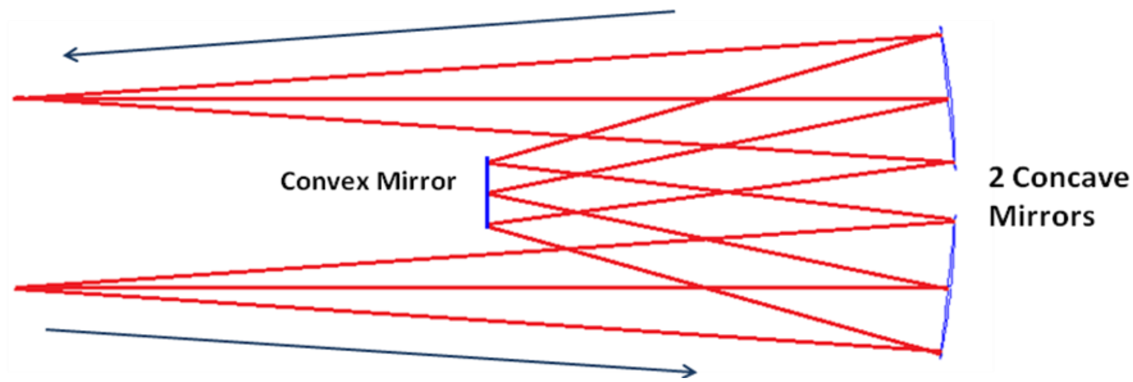


Figure 2a: A setup of two concave negative lenses and an Offner triplet to compensate for RGD without aberrations.

Figure 2b: Similar to Figure 2a, but with two separated concave mirrors as part of the Offner triplet. This prevents issues due to cost and manufacturing of a large mirror, but requires cophasing the two smaller mirrors. For simplicity, the negative lenses aren't shown, but the beams are diverging as if they had already passed through them.

Set-up for Cophasing Concave Mirrors

The setup used in testing the precision of cophasing can be seen in Figure 3. In order for the two concave mirrors to be cophased properly, they must be cophased correctly in three dimensions: tip, tilt and translation, all of which can be adjusted for each mirror individually. The first two relate to the angle at which the mirror is directed while translation is simply forward or back. It is also important for the two mirrors to be at the same height; setting the height of two such mirrors is very simple. While aligning the mirrors for tip and tilt, the camera is hooked up to a monitor that displays the relative locations of the part of the beam that has been reflected off each mirror. Because of this, the mirrors can be aligned by hand for tip and tilt simply by adjusting the mirrors until the dots from each mirror overlap.

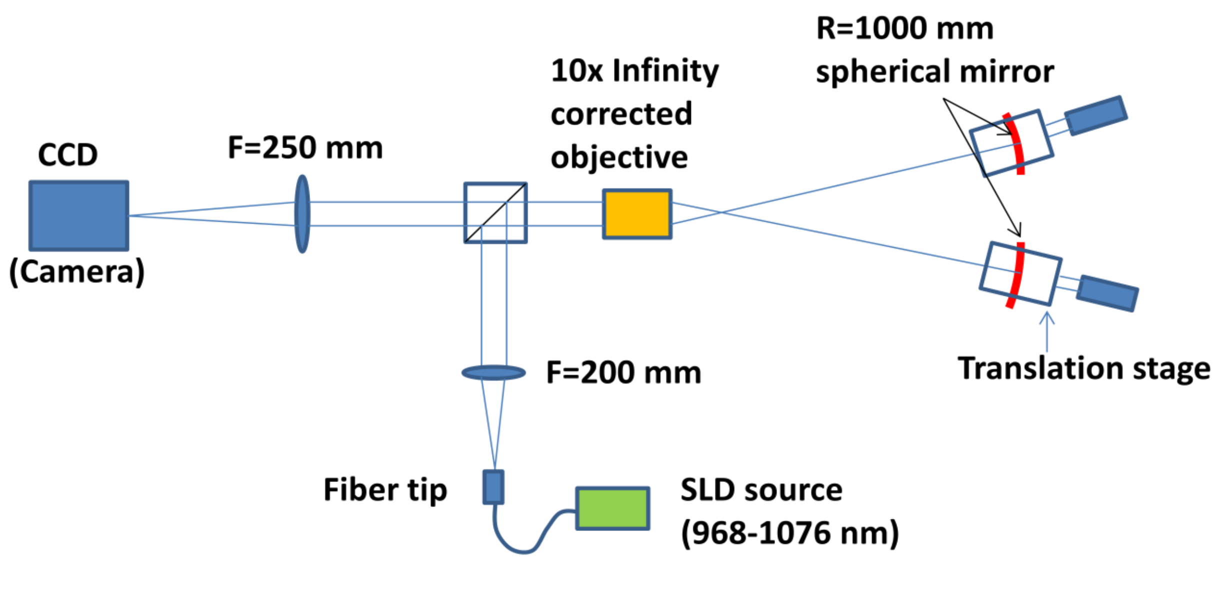


Figure 3: The optical setup used to cophase the two spherical mirrors seen on the right. A broadband super-luminescent diode (SLD) of wavelengths 968-1076 nm is used as the source, which is then collimated by a lens. The beam then passes through an infinity corrected objective to be spread across the two mirrors before being reflected back through the objective, focused by another lens, then observed by a camera that can detect the IR light.

Aligning the translation of the mirrors, however, is more difficult. It was assumed that the mirrors would have to be very precisely cophased. To achieve such precision, the beam source has a very short coherence length of only 4 µm. This means that the beam is only able to interfere with itself if the path difference between the beam reflected off one mirror and the beam reflected off the other is within only a few times the coherence length, with the most interference seen in only a 4 µm window centered around the mirrors being perfectly cophased. Therefore, the translation stages the mirrors are mounted on are adjustable to an accuracy close to a micron.

Simulation of the Offner Triplet

Using a ray tracing program in MATLAB, a model of the Offner triplet was constructed as seen in Figure 4. Because tip, tilt and height can be fairly easily adjusted for, the main goal of the simulation was to discover how far one mirror can be translated relative to the other without a significant aberration appearing in the beam. To do this, one mirror was moved out of perfect alignment a little at a time while the wavefront error was examined until the resulting wavefront error from max to min was about 0.1 waves, the acceptable tolerance. This acceptable translation of one concave mirror was found to be up to 4 mm away from perfect cophasing. The wavefront error from a perfectly aligned Offner triplet can be seen in Figure 5a, while the error in a triplet with a 4 mm translation in one concave mirror is shown in Figure 5b.

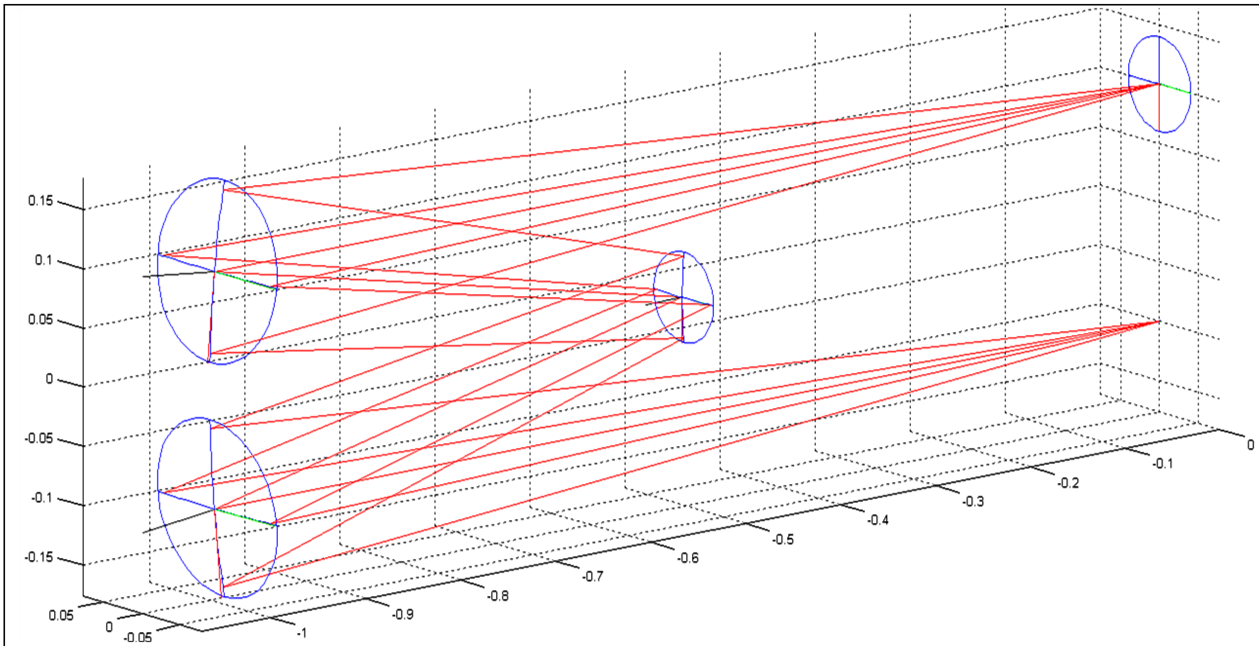


Figure 4: The model of an Offner triplet using a ray tracing program. The Offner triplet is comprised of the two concave mirrors on the left, which are initially perfectly cophased, and the center convex mirror. The detector plane is in the upper right, where the wavefront error is analyzed.

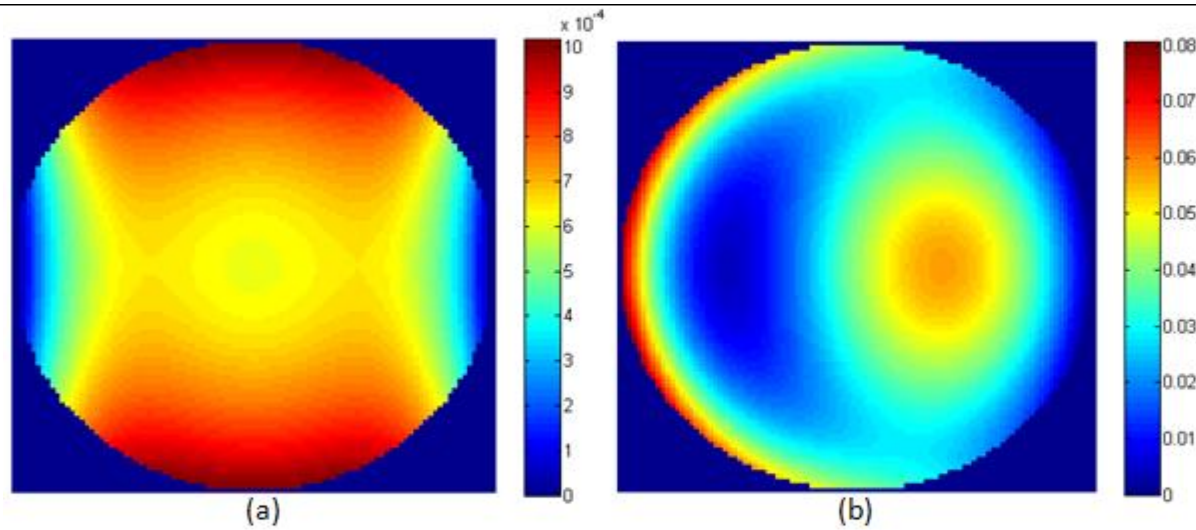


Figure 5a: The miniscule wavefront error when the concave mirrors are perfectly cophased. Note that the scale is x10^{-4} and is measured in waves.

Figure 5b: The wavefront error when one concave mirror is translated 4 mm relative to the other, resulting in a peak to valley wavefront error of almost 0.1 waves, the acceptable tolerance.

Testing the Precision of Cophasing

The setup seen in Figure 3 was constructed on an optical table. With the source turned on and using the display from the camera, the two spherical mirrors were cophased for tip and tilt by overlapping the two reflected dots onto the same point. From there, one mirror was slowly translated until an interference pattern was seen where the dots overlapped. Tip and tilt were adjusted whenever necessary to maintain beam overlap. After that, the mirror was translated 3 µm at a time from the point an interference pattern could be seen until it could not. 3 µm was about the smallest interval which the translation stage could move at a time while preserving significant accuracy. At each interval, ten pictures of the interference pattern were taken, a fraction of a second apart. This was because the air flow in the room caused the beams to vary slightly. Many pictures were taken so at least one would show the beams being nearly perfectly overlapped in each interval.

Another MATLAB program was used to sort out the best picture for each interval by finding which one had the smallest area with a relatively high beam intensity. The program then calculated the visibility of each of these images. The visibility, V, of an interference pattern is a quantifiable value for contrast between the fringes and can be calculated as

$$V = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}},$$

with I representing the beam intensity. Visibility is always a value between 0 and 1, with 1 being the greatest possible contrast between fringes. The min and max values were found by examining the intensity along a horizontal line passing through the center of where the beams overlapped, as seen in Figure 6.

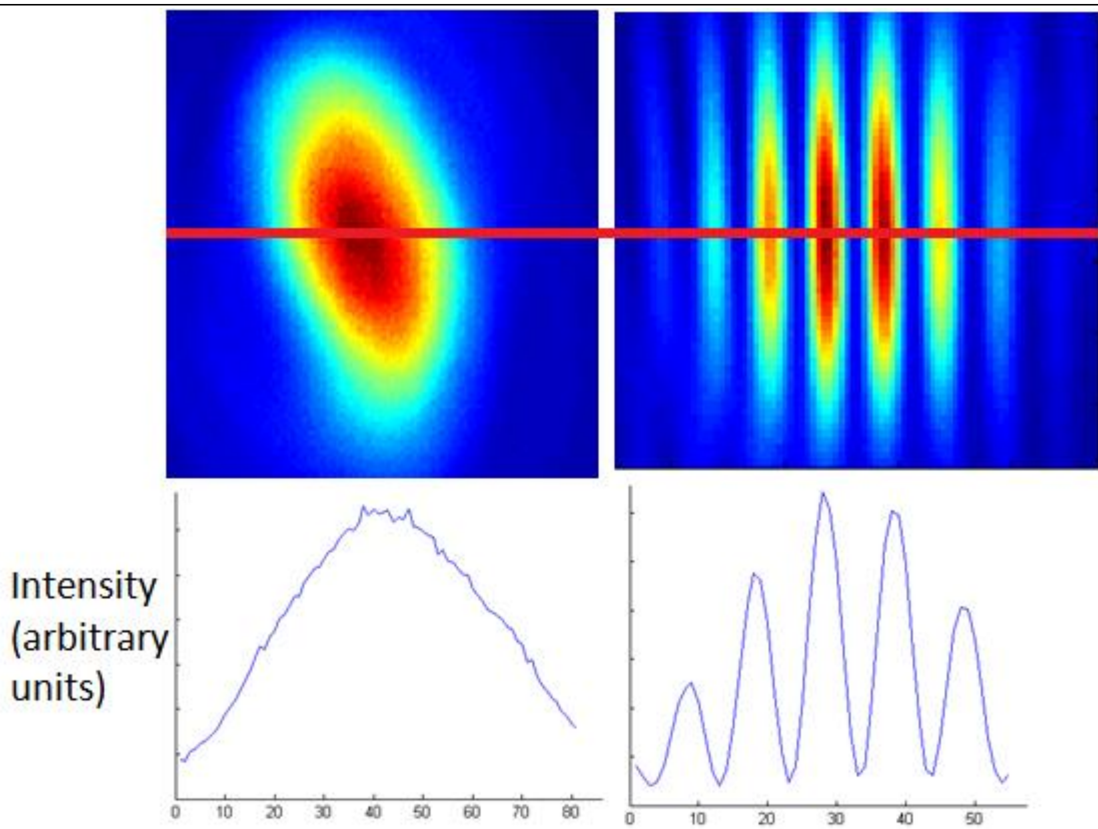


Figure 6: Images of the beam and corresponding intensity lineouts. The image and graph on the left come from a translation about 18 µm from perfect cophasing while the image and graph on the right come from a translation about 1 µm from perfect cophasing. The red line through both images passes through the center of the beam and is where the intensity was analyzed to create the graphs seen beneath. The x axis for the graphs is position. The visibility was calculated using the maximum and minimum values near the center of each graph. As such, the visibility of the image on the right is much greater than that of the image on the left, as should be expected given their translations from perfect cophasing.

The visibility for each translation was graphed, as seen in Figure 7. Due to the accuracy of the translation stages, there was a potential error of ±1 µm in the translation. It was also deemed reasonable, given the method for selecting the optimal image for each interval and the calculation of visibility, that there was a potential error of ±0.05 in visibility. From the data, it can be seen that there is a range of positions of about 3 µm in which maximum visibility is obtained. Cophasing the mirrors is then achieved within 3 µm.

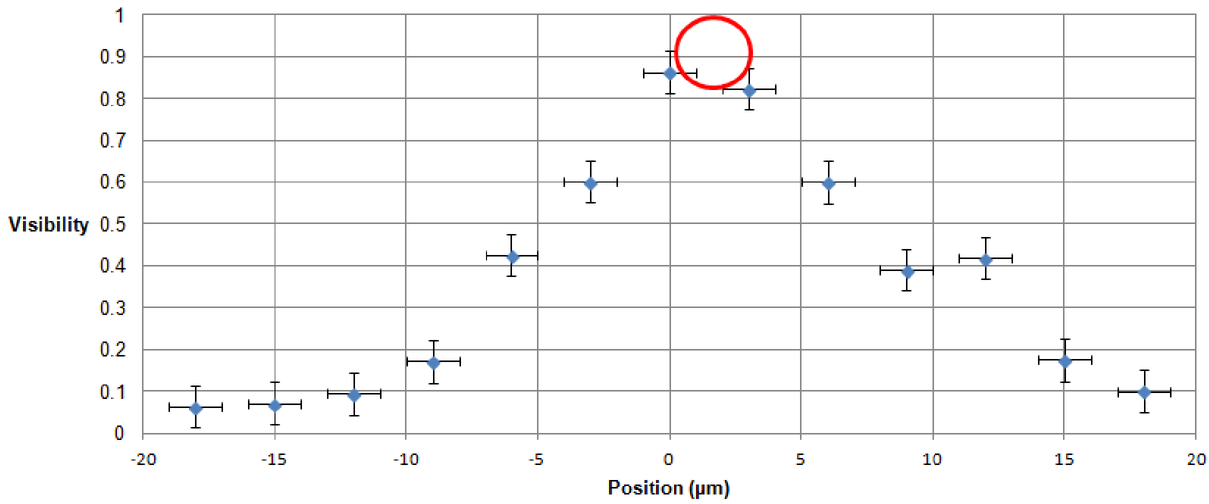


Figure 7: Graph of visibility versus position of one mirror relative to perfect cophasing. The zero of the position axis is only an estimate based on the data point with the highest visibility. It is more likely that the actual center is slightly to the right. This would be at the peak of the observed curve, likely within the red circle shown.

Conclusion

To compensate for radial group delay in the MTW-OPAL laser, a proposed solution uses concave lenses and an Offner triplet. However, to reduce the cost of manufacturing, the concave mirror of the triplet could be split into two that are cophased. It was found that the mirrors would be easy to cophase in all dimensions except for translation. A ray-tracing program was used to determine that the translation tolerance is 4 mm. An optical setup was then assembled to test the alignment of two such concave mirrors. This setup included a broadband laser with a coherence length of 4 µm and the mirrors mounted on translation stages. One mirror was translated until an interference pattern with high visibility was seen. It was found that the mirrors could be cophased to an accuracy of about 3 µm, well within the 4 mm tolerance. By demonstrating this, it was determined that the use of two smaller mirrors in the Offner triplet is feasible.

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