Holographic Spectrograph for Space Telescope

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ABSTRACT

A spectrograph is described which is made with dual Holographic Optical Elements (HOEs) which are identical and parallel to each other. Both optics are collimating transmission HOEs with focal points that are at equal and opposite distances from each other. The identical HOEs are formed by the interference of a plane wave parallel to the grating plane with an off-axis spherical wave originating in the near-field. In playback, a spectrum can be formed from a point source radiator placed at the position of the recording spherical wave. If played back at an arbitrary wavelength other than the recording wavelength, the image exhibits coma. This spectrograph is intended for an unusual configuration where many nearly monochromatic sources of known wavelengths are separately positioned relative to the first HOE. The special application is in a space telescope capable of resolving spectra from habitable planets within 10 pc. HOEs of this type could be fabricated on membrane substrates with a low areal mass and stowable on rolls for insertion into the second Lagrange point. The intended application is for a 50 x 10 meter class primary objective holographic space telescope with 50 x 10 m HOEs in the spectrograph. We present a computer model of the spectrograph.. Experimental results are compared with predictions from theory. A single HOE is shown to perform over a wider bandwidth and is demonstrated.

Keywords: Habitable Planet, exoplanet, membrane, HOE, spectrograph, holography

1. INTRODUCTION

The echelle spectrograph has been the most widely adopted astronomical spectrograph for resolving the highest resolution [1] and might be called a “gold standard" in performance. It uses a method of cross dispersion that disambiguates overlapping high-order spectra and displays an array of sub-spectra that are far broader in aggregate than the free spectral range of any one order alone. Resolving powers above 100,000 have been achieved by this method.

We are investigating a novel double dispersion configuration that might possibly achieve performance levels of the echelle. It does not employ high-order plane grating diffraction to magnify the dispersed radiation as an echelle does. Instead it uses holograms which operate in the first-order. This type of disperser has a broad free spectral range and can accommodate dispersion over a wide spectrum.

1.1 Motivation for this research

There are ample reasons to develop new spectrographs not only in astronomy but throughout the many disciplines that rely on spectrographic analysis. We were in need of a high resolution spectrograph as a key component of a new species of telescope that use primary objective gratings and holographic optical elements as the primary collector.[2] In this type of telescope the secondary must disambiguate a plurality of overlapping spectra that are found in the combined spectra of sources sharing a common collector. In the case of our new type of dispersive primary objective, a secondary spectrograph serves much as a secondary lens did in the original telescope.

We needed a high resolution spectrograph and may use an echelle type, but it is reasonable to investigate high frequency gratings for dispersion. Echelle gratings have been ruled on the mechanical engines available since Rowland in the 19th century. Only recently has holography provided an alternative means of grating production which is better suited to groove pitch dimensions in the visible wavelengths. This type of grating, called a Diffractive Optical Element (DOE) when it is a plane grating and a Holographic Optical Element (HOE) when it focuses, are difficult or impossible to manufacture on ruling engines and open up new possibilities in fabrication through the use of holography. In terms of our telescope concept, we were looking for a gossamer membrane HOE that could be used in space deployment. A 25 cm plane grating or even a 2.5 m plane grating can be contemplated as an dispersing element in contemporary optics, but a 50 m HOE is seemingly out of science fiction. Yet, because it is a membrane with distinct advantages in space deployment, fabrication of large HOEs by printing is being actively pursued by others.[3]

2. HOE FABRICATION AND BENCH MOUNT

2.1 Zemax model

We began our study by modeling a HOE that when combined with an identical HOE primary objective would resolve wavelengths at 0.0001 nm.[4] A Zemax model of the HOE is shown in Figure 1. The 300 µm fiber tip projects a very narrow spectrum that in the operation of the exoplanet finder combines the images of exoplanets with one system at unique and distinct wavelengths proportional to their angular separation from themselves and their parent star. The spectrum originating at the fiber is fed to the spectrograph HOEs. The spacing in the model from distal fiber tip to the first HOE is 700 meters. This is a very large device designed to form an image on an image focal plane that is 2 cm wide. It is shown in this model that the HOEs are resolving 0.0001 nm over 1.8 cm. This translates to 300 mas total separation, the presumed region of habitable planets on G class stars within 10 pc, the design objective of the telescope. The angular resolving power of the telescope is better than 10 mas.

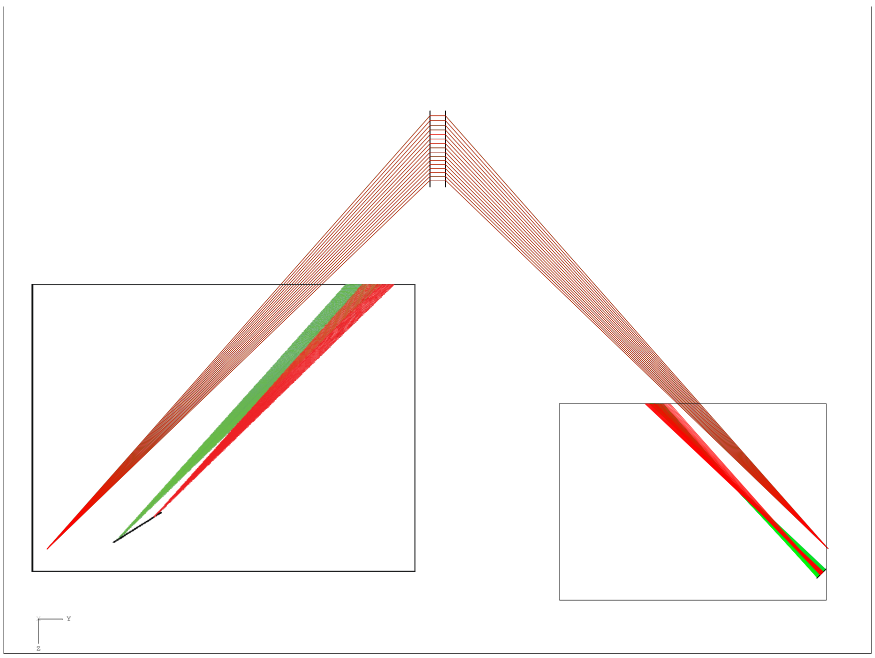


Fig. 1 Spectrograph made from dual identical HOEs. The pair of collimating HOEs focus a fiber-fed source to an image plane shown with inserts.

A HOE modeled in Zemax in Figure 1 was physically made on a holographic bench to test the concept. The HOE was scaled to a focal length of 500 mm and its Zemax computer model of the physical HOE is shown in Figure 2. The recording wavelength selected was the HeNe line of 632.8 nm. In the Zemax model all spatial filters are ideal point sources and do not have pinhole diameters. The reference beam is a plane wave at 0° (directly above the plate) and the object beam is set at 45° relative to the plane of the plate by placing the object point source at 353.553 mm on the construction y and z axes. When played back near to the recording wavelength, the predicted performance over a 2 nm spectrum is shown in Figure 2. The focal plane is slanted as with the telescope model of Figure 1. Zemax predicts a 7 mm separation on the focal plane between the two playback wavelengths.

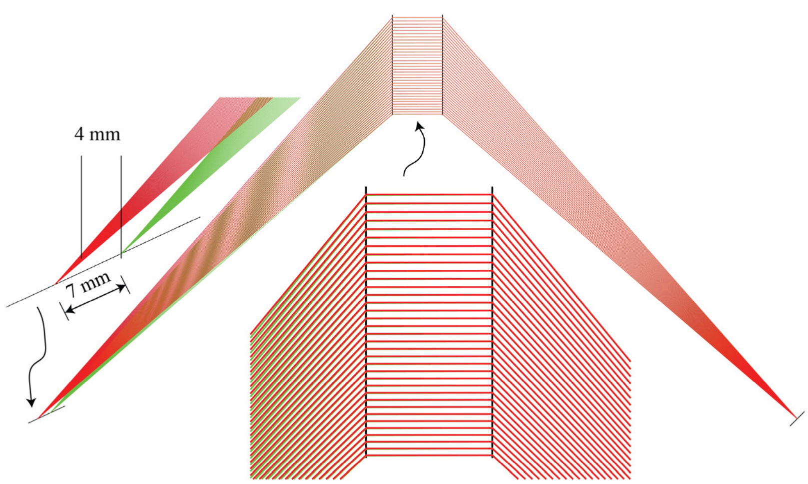


Fig. 2 Zemax model of physical HOE. Inserts show focal plane for 2 nm separation between spectral lines and the divergence of the two wavelengths.

2.2 Holographic recording

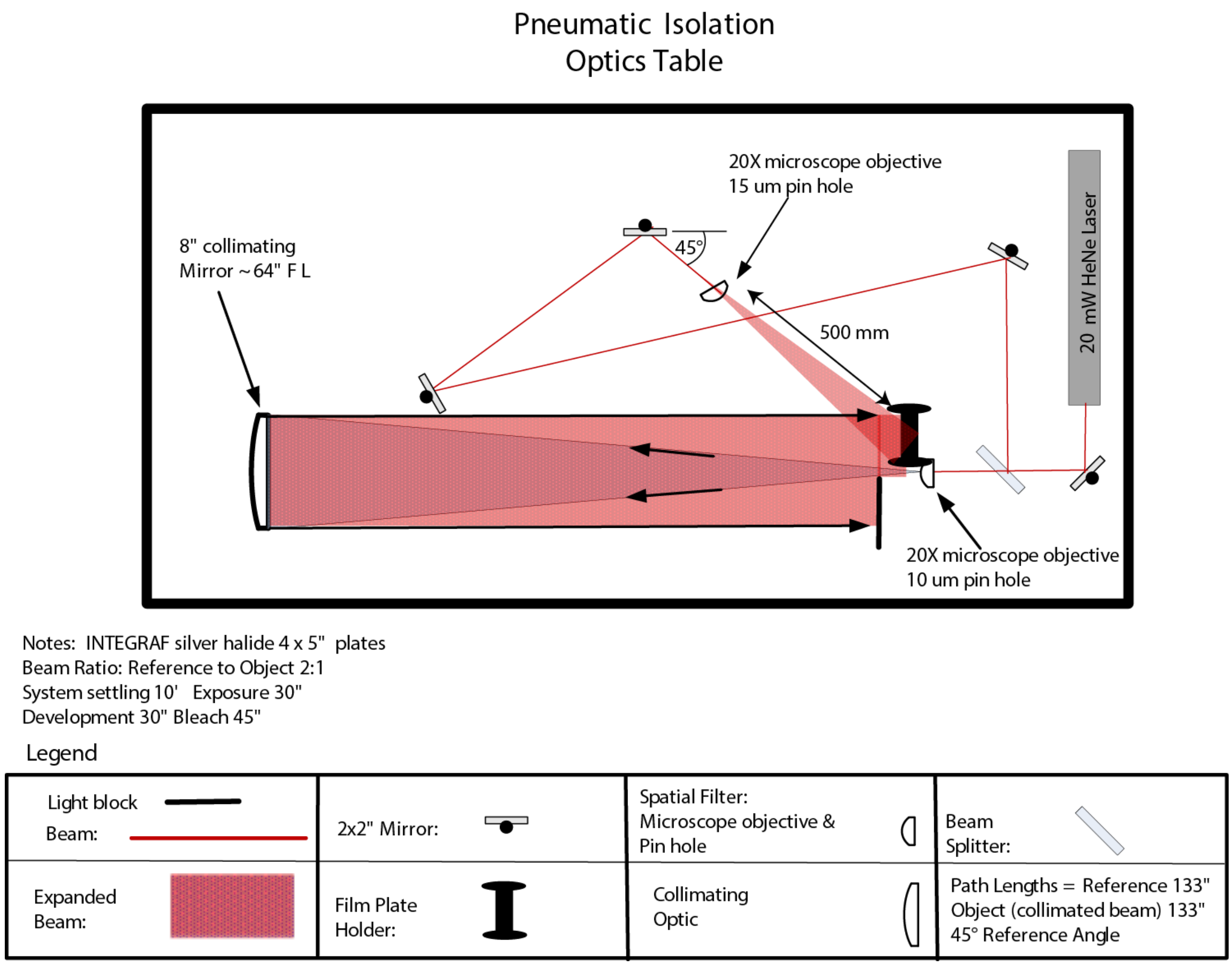


Fig. 3 HOE bench setup from above. The 8 inch mirror does not completely fill the 5 inch side of the plate.

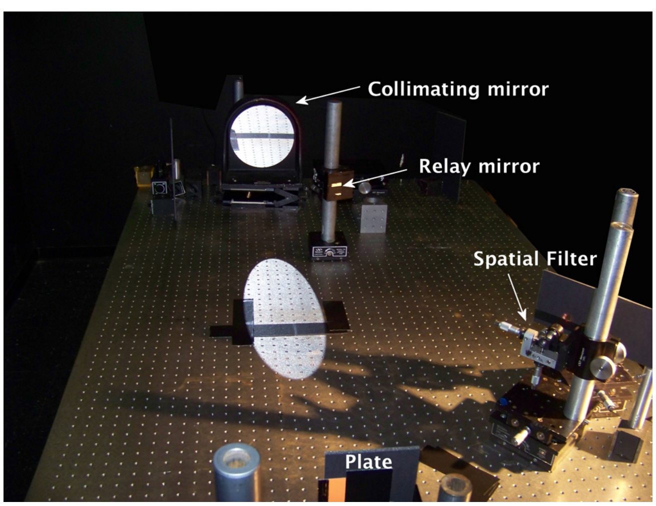


Fig. 4 The optical table. The plate is shown from backside. The oval is a reflection of the camera flash off the mirror.

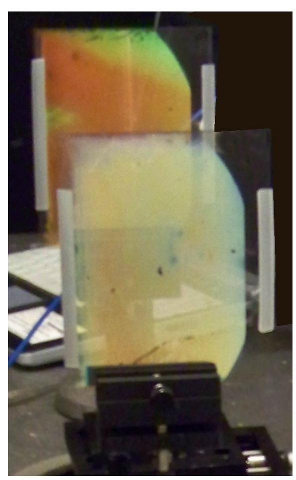


Fig. 5 Pair of the resulting HOEs as mounted in an experimental spectrograph.

HOEs were created on 4 x 5 in. silver halide glass plates. Figure 3 shows a schematic of the setup. Figure 4 is a photograph of this bench. The transmission HOE was mastered in quadruplicate with a pair of plates for each of the two participating laboratories. Figure 5 shows a HOE pair in service on a spectrograph bench. The 8 in collimating mirror did not fill the plate completely leaving corner areas unexposed. Blemishes did not noticeably affect tests.

2.3 Spectrograph test benches

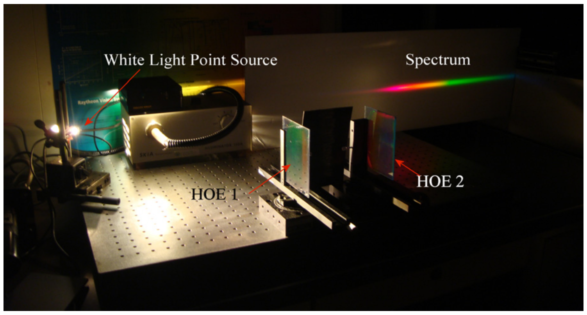


Fig. 6 Breadboard on optical bench RUM, Puerto Rico

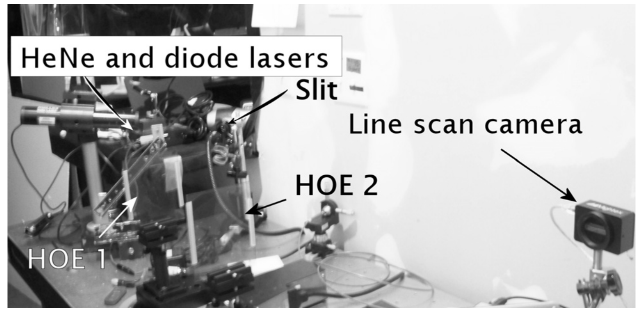


Fig 7 Dual HOE optical Bench at 3DeWitt lab, Cairo, NY

Figure 6 shows the bench at the Holography Lab at Recinto Universitario de Mayagüez (RUM) where the HOEs were fabricated. The playback from a white light point source was made at the same angle and distance as the spatial filter that was the object beam of the hologram. The spectrum from the second HOE projected onto a diffusing screen and spanned nearly a meter. A bench with equivalent optics was set up at the 3DeWitt laboratory to corroborate results, Figure 7.

3. PERFORMANCE

3.1 Experiments

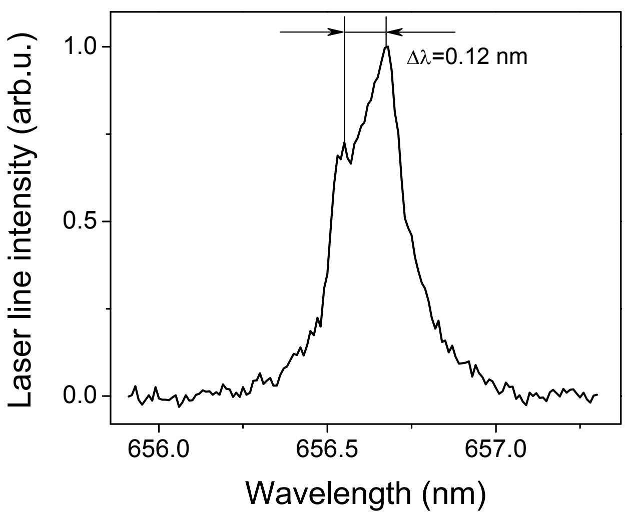


Fig. 8 DSSP mode lines as recorded Triax 320 Horiba Spectrometer

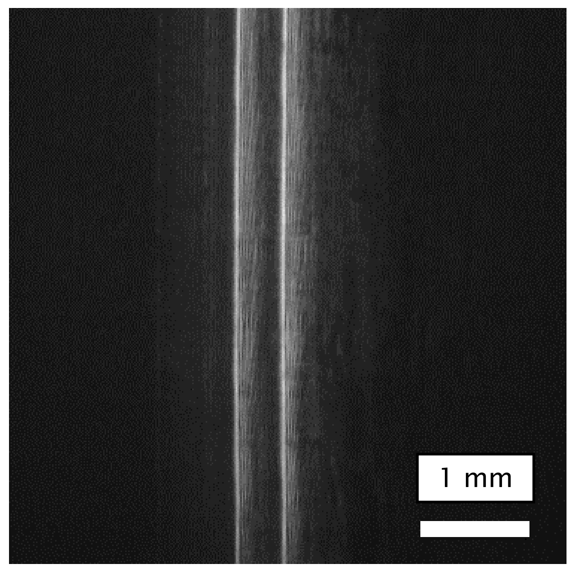


Fig. 9 DSSP mode lines as seen through dual HOEs

In the RUM experiment, to obtain holographic spectrometer dispersion, a DPSS laser was used which generates two narrowly spaced laser lines (two laser modes) of similar intensity at ~ 656.7 nm. Spectral separation between these laser modes was measured by calibrated Triax 320 Horiba Spectrometer. This is a scientific-grade single grating spectrometer with a plane diffraction grating of 1200 lines/mm. It proved extremely challenging to separate laser modes with this spectrometer when set up at the limit of its resolution using a 10 µm slit width. The acquired spectrum of the DPSS laser is shown in Figure 8. The two laser lines are spectrally separated by 1.2 Å. The same two laser modes were imaged through the dual HOE spectrograph and recorded by a CCD camera. The resulting image is shown in Figure 9. The scale bar is 1 mm. Separation between laser lines in Fig.2 is 0.43 mm. The lines are clearly resolved and fit within a single-pixel line of the image. Therefore in this particular case, the resolution is limited by resolution of CCD matrix. Resolution of the holographic spectrometer in present geometry is estimated to be higher than 0.004 nm. Coma appears between the lines tapering off to one side This was ignored to make the resolution calculation.

In a separate experiment in the 3DeWitt laboratory, a test was conducted on the bench of Figure 7 above by comparing two lasers. The experimental result is shown in Figure 10. A laser diode exhibiting 2 modes was measured at a center frequency between modes of 631 nm with an Ocean Optics USB-4000 spectrometer, Figure 11. The USB-4000 could not resolve the two modes. The diode is referenced to a HeNe laser with a known emission of 632.8 nm. The displacements were imaged on a Mightex SSE-1304-UWE line scanner which is without a glass cover and intended for use to image coherent radiation. Speckle artifacts are evident from the diffusing surface (paper). The output of the USB 4000 in is shown with pixel and wavelengths in the abscissa. The dual HOE spectrograph scan covers 600 pixels on center while the USB-4000 spans 35 pixels. Pixel width is 8 μm for the line sensors in both spectrometers.

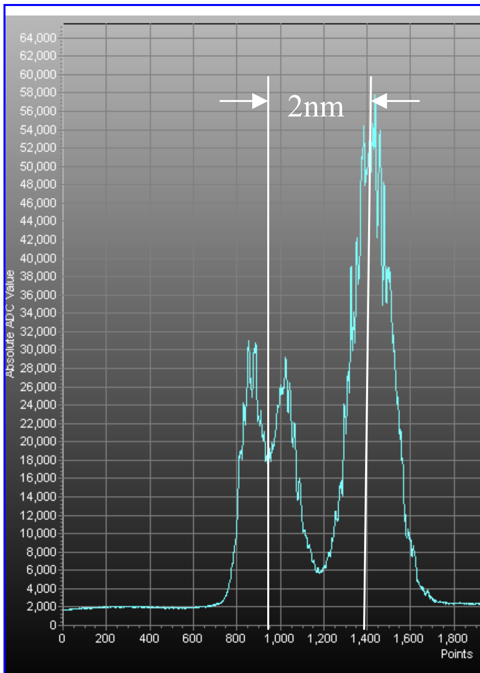


Fig. 10 Comparison of diode exhibiting two modes and HeNe laser using dual HOE and line scan camera. Compare with Fig 11.

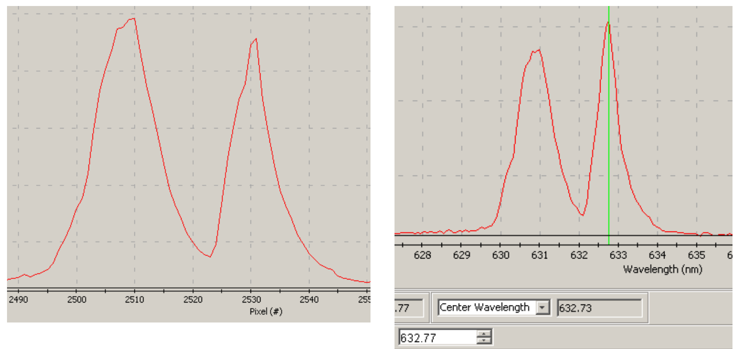


Fig. 11 Diode and HeNe lasers of Fig. 10 using miniature Ocean Optics USB-4000 spectrometer in pixels (left) and wavelength (right).

The spacing between the center of the diode's two modes and the HeNe emission line in Figure 10 measures 4.8 mm. The resolution of the dual HOE spectrograph is approximately 0.003 nm, closely matching the estimate of the corroborating RUM experiment illustrated in Figures 8 and 9.

In order to estimate the throughput of the dual HOE spectrometer a Newport 1830 picowatt optical power meter was used to take readings of the energy of the HeNe emitted after the slit and as received at the line sensor. A measured flux of 3.66 nW was emitted out of the slit, and the focused energy near the image plane after the second HOE was measured at 0.9 nW. The throughput efficiency was therefore estimated to be approximately 25%.

3.2 Analysis of the data

By definition, linear dispersion is

(1) $$D_\ell = \frac{d\lambda}{d\ell} = \left(\frac{\text{Å}}{\text{mm}}\right)$$

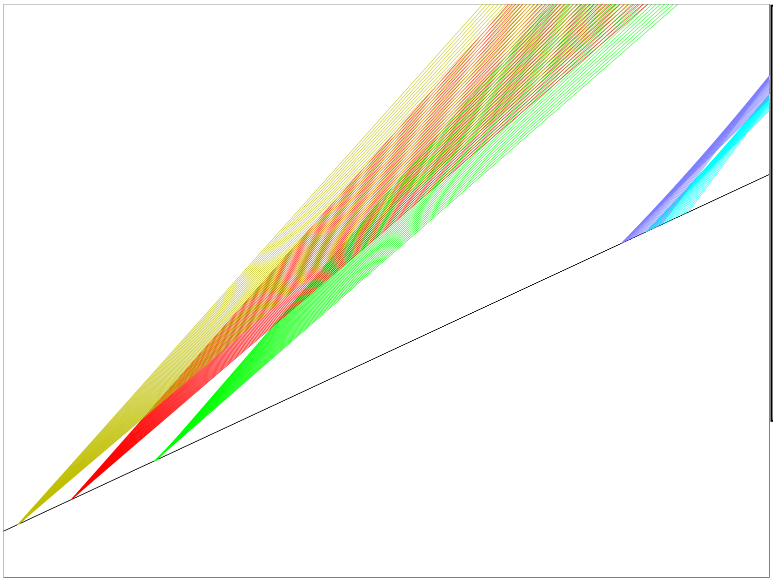
So for the spectrometer of the experiment of Figures 8 and 9

(2) $$D_\ell = \frac{d\lambda}{d\ell} = \frac{1.2}{0.43} = 2.79 \quad \left(\frac{\text{Å}}{\text{mm}}\right)$$

3.3 Comparison with Zemax models

The displacement of lines in the experiment of Figures 10 and 11 was 2.2 mm less than the Zemax prediction owing, perhaps to the angle of incidence on the line sensor which was not rotated from the grating plane normal. This may also explain why the two diode modes are not completely separated at the image plane. The linear sensor was tracked in a line parallel to the normal of the grating plane and not at the slanted focal plan predicted by Zemax.

There is coma on one side of Figure 9 which is predicted by its Zemax model, Figure 12 which shows the anticipated foci from both benches.



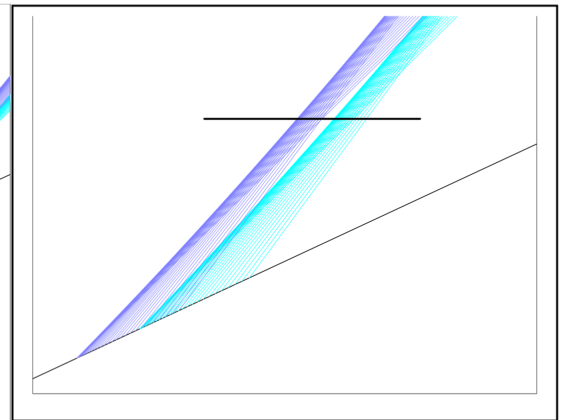
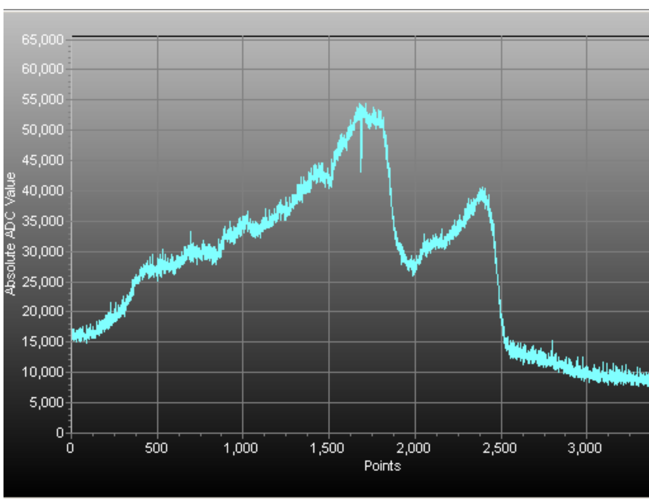


Fig. 12. Zemax model of focal plane for both experiments. Central wavelength of 632.8 nm and a diode at 631nm focus sharply, but 655 nm does not. Insert shows detail with probable location of camera array focal plane drawn in.

Similarly at shorter wavelengths, focus is not maintained. The Hg lines at 579.066 and 576.960 were modeled in Zemax and are shown in Figure 13. An image taken with a line scan is shown in Figure 14. A weak source contributed to the poor resolution, but the intrinsic soft focus does not recommend the spectrograph over a useful bandwidth.



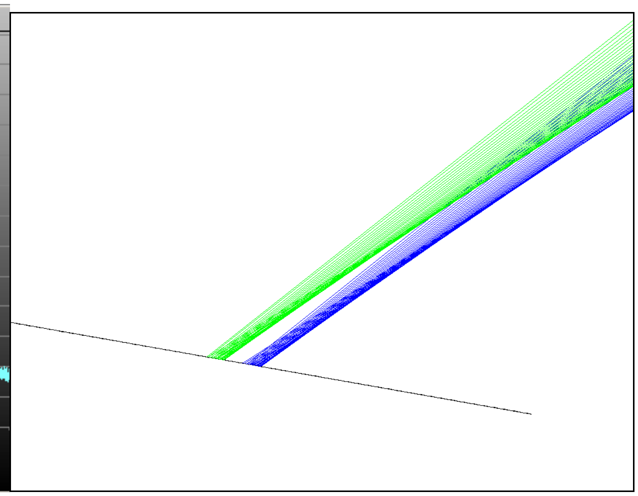


Fig. 13 Bench recording of Hg lines 2nm apart (left) and a Zemax model at image plane predicting the soft focus.

3.4 Follow-up single HOE experiment

Although it was observed during the experiment of Figures 10 and 11 that the Hg lines did not focus well after the second HOE. the lines were quite clear to the eye from the first HOE. The image was recorded with a color CMOS camera, Kodak Z812 IS, and is shown in Figure 14 with the derived intensity curve across several of the resolved lines.

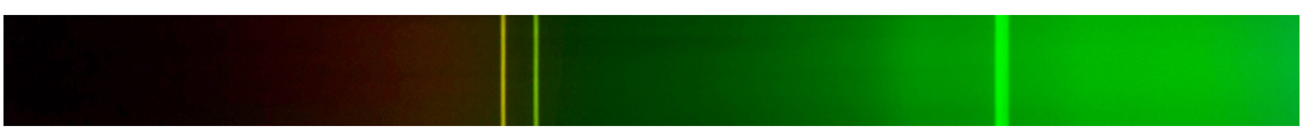
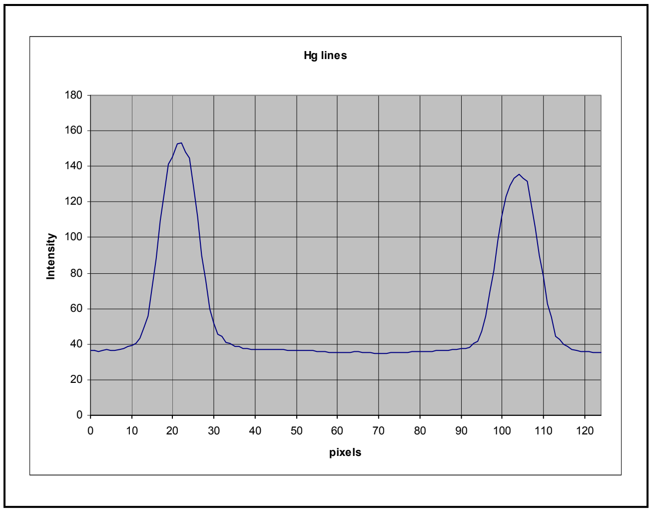


Fig. 14 Hg lines of 579.066, 576.960 and 546.074 nm as seen through HOE 1 and recorded with a simple CMOS camera

The performance of the single HOE spectrograph can be compared with the Ocean Optics USB-4000 in Figure 15.



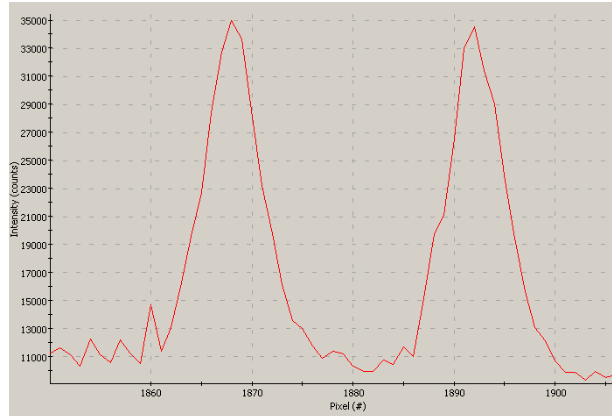


Fig. 15 The camera recorded scan of Figure 14 over lines 579.066 and 576.960 nm is graphed (left). The same lines on USB-4000 miniature spectrometer (right)

Using NIH ImageJ software to analyze the Hg lines of 579.066 and 576.960 nm, the intensity curve of Figure 14 was derived from a table. Camera pixels are 1.56 μm wide and the two wavelengths span 82 pixels over a band of 2.1 nm. The HOE is resolving approximately 0.026 nm, roughly an order of magnitude less than the double HOE but without any apparent loss of focus. This spectrograph could be realized with a larger HOE. If the HOE was 30 inches wide instead of 4 inches, the resolving power would be 0.004 nm and possibly extensible for the intended use as the secondary for the telescope being studied for exoplanet spectroscopy. We can make such a HOE in our laboratory for testing.

4. CONCLUSION

A spectrograph with two collimating HOEs has been designed, built and tested for use in an astronomical telescope as a possible substitute for a high resolution echelle spectrograph. The concept is premised on the notion that a collimating HOE when played back through itself is capable of forming focused images without refraction or reflection optics. A test HOE was made, mounted and tested. Spectral resolution from a small 4 x 5 inch silver halide plate appears to be better than 50,000 at its construction wavelength but does not focus off that central wavelength. When one of the HOE pairs is used as a collimator and spectra are recorded by a secondary camera, the bandwidth is not constrained by loss of focus. Further research with a single HOE is now anticipated.

ACKNOWLEDGEMENT

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