Self Pumped Phase Conjugation

By
Neil Smith
(Advisor: Dr. Jan Yarrison-Rice, Miami University)

Abstract

We have mapped the evolution of a beam fan in the photorefractive crystal of Barium Titanate, and have determined how long it takes from when a laser beam initially propagates through the sample until the time a beam fan is created and reaches its final steady state intensity. Beam fanning is initiated through the photorefractive effect and two beam coupling between the incident radiation and the light that scatters from impurities near the input plane of the crystal. Through the use of a diffusing plate, we not only increased the amount of light diverted into the beam fan, but also decreased they time it takes to reach steady state condition. Setting the crystal at an angle to the incoming beam produces self-pumped phase conjugation, so that the beam fans into the corner of the crystal. A four wave mixing process occurs when the reflected beam intersects with the incoming beam, and produces a phase conjugate beam. This beam will simultaneously read any spatial information that the incoming beam wrote into the four-wave mixing gratings. We described the image resolution produced by normal self pumped phase conjugation as compared to that produced by a diffuser placed in front of the crystal. We also report on the speed at which the SPPC is produced without the loss of information, and produced the basis for a real time holographic optical data storage system based on photorefractive crystals.

Introduction

Beam fanning is a phenomenon caused by self induced scattering in the crystal through the photorefractive effect. In order to control the evolution of a beam fan in a photorefractive crystal, measurements have been made of the temporal evolution of a beam fan in Barium Titanate with and without the use of a diffuser at the sample's input plane of the crystal. Beam fanning is initiated through photorefraction and subsequent two beam coupling between the incident radiation and the light which scatters from impurities formed near the input plane of the crystal [5]. Figure 1 shows an example of the fan of light that is produced when a beam is introduced into Barium Titanate.

Figure 1. Beam Fan through Barium Titanate and hologram formation [1]

Note that light is shifted away from the through beam and into a fan of light that spreads to one side of the through beam. We enhanced this beam fan by placing a diffuser at the entrance face of the sample. In addition, we quantify the amount of light in and the time it takes to produce the beam fan.

Through the use of a CCD camera, we were able to image the fan's growth on a computer. Imaging software allows us to analyze the total intensity of the beam fan as it develops. The time that it takes to reach steady state can be determined with accuracy of 33 ms. We have determined that beam fanning efficiency is enhanced with the use of a diffuser and that certain diffusing elements are not conducive to better fans.

Beam fanning has a number of possible applications including detectors that will be more sensitive, and goggles that will help with the protection of people's eyes. The beam fan will be able to disperse the light before the light can do any damage to people's eyes. The beam fan is also an essential part of the self-pumping phase conjugate. Through the use of the phase conjugate, information can be stored permanently in the crystals and then read out. This could be used to create a type of permanent optical hard drive.

Photorefraction

The photorefractive effect is a nonlinear optical effect in which an index of refraction grating is formed inside a photorefractive crystal, such as Barium Titanate. This index grating is like a hologram only it is created in 3 dimensions inside the sample rather than on a flat optical plate. Light enters the sample and scatters off impurities near the entrance face. An index of refraction grating is formed between input beam and the scattered beams in the +c-axis direction due to the electro-optic effect. As the index grating grows in strength, more light is diverted into the scattered beams' direction. The result is a beam fan that is collected by a CCD camera that records the build up as a function of time. A diffusion plate placed at the entrance face of Barium Titanate increases the scattering of the incident beam. This allows more energy to be diverted from the propagating beam into the scattered beams and thus into the beam fan.

When two coherent light beams are superimposed in a photorefractive crystal, an interference pattern results, i.e., a spatial distribution of areas with high and low light intensity inside the crystal (figure 2).

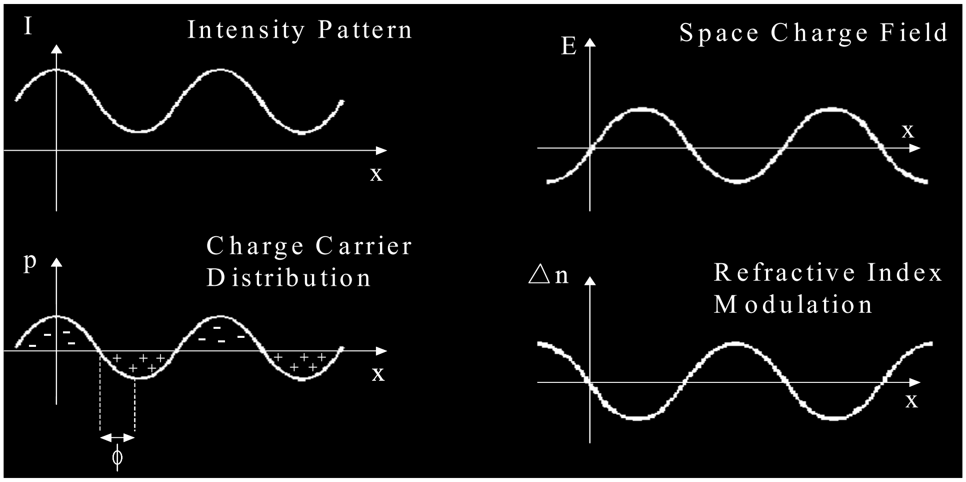


Figure 2, Photorefractive Effect

In the areas of higher light intensity, charge carriers (electrons) are excited. The gradient in the charge carrier density causes diffusion and thus the carriers migrate through the crystal. Eventually, they are recombined preferentially at donator or acceptor sites in the crystal. If this occurs in a dark region, the electrons stay trapped. The result is a charge carrier distribution. The local charge distribution evokes an electric space charge field due to Gauss's law. According to the spatial derivative in Gauss's law, the space charge field is shifted by a quarter of a grating period (equivalent to a phase of π/2) with respect to the intensity pattern. The electro optic effect then creates a refractive index distribution proportional to the electric field given by,

$$\Delta n = n_o^3 r_{eff}^2 E^3 \, . \tag{1}$$

This refractive index pattern is a phase volume hologram. This index grating reflects the input beam away from its original position and starts a repetitive process by which photorefraction strengthens the index grating and more light is diverted. This scattering, grating building, and diversion of more light continues until the system reaches a steady state – all the available charges have been moved into the dark regions and the index of refraction grating can grow no more. The diverted light produces a fan of light, which was shown in Figure 1.

Theoretical modeling of beam fanning by Segev, et al [2] and Brown and Valley [3] predict that a beam fan can be strengthened by seeding with a small-diffracted beam. They also expect the intensity distribution of the beam fan will be shifted away from the through beam with increased diffusion of the input beam.

Currently, experimental methods of increasing beam fanning include the use of a thin sample, so that multiple reflections of the input beam from front and back faces will seed the fan and speed up the fanning process [4]. Other groups such as the University of California-San Diego, have investigated the beam fanning process, but they have done it in different polymers. They have been looking at the polymers to see if the beam fan process can be enhanced through the use of different polymer materials. They are not putting gratings or diffuser plates in front of the materials to try to speed up the beam fanning process. [5] Mu, et al have shown that they can lower the threshold of phase conjugate (hologram) production by putting the photorefractive sample in a cavity, thus producing the necessary seed beams externally with multiple reflections from the mirror. [7] Our plan differs from this as the enhancement will be made with diffusing plates with no external cavity needed for feedback. The work reported here is a modification to an earlier experiment where a video camera was utilized to capture the fan. In addition, we utilized a CCD camera and video capture capabilities to record our data.

Self Pumped Phase Conjugation

The incoming beam is scattered and sets up index of refraction gratings just as before and a beam fan is produced. By carefully setting the crystal at an angle to the incoming beam, around 45° to the c-axis, the fan can be sent toward the far corner of the crystal. A small portion of the beam fan will strike the corner at the correct angle to undergo total internal reflection and will return toward the incoming beam. If you magnify the interaction region, you will see three beams interfering with one another- two writing beams and one read beam (figure 3).

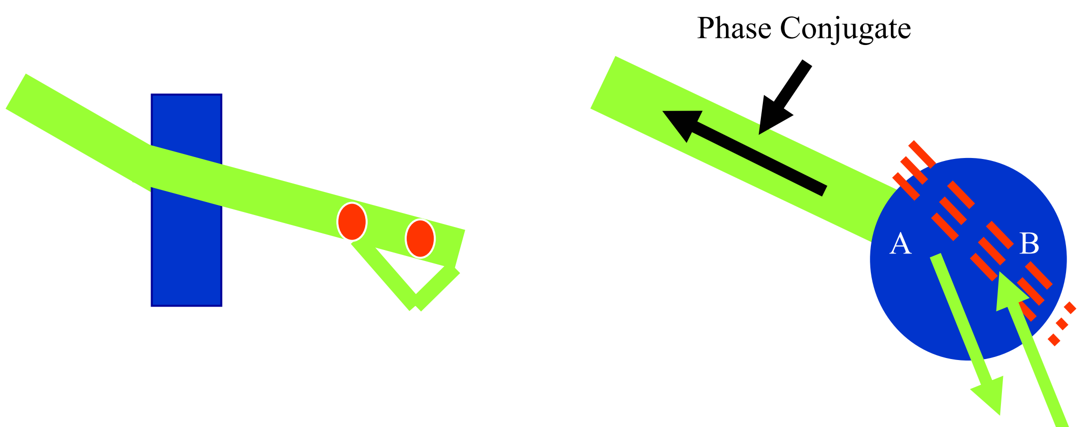


Figure 3 Four-Wave Mixing Process

In either region A or B, you see the incoming beam crossed by two counter propagating beams (figure 3). These counter propagating beams come from light traveling in both directions around the loops. A four wave mixing process occurs in the region A and B, where three beams produces a fourth phase conjugate beam. One can think of it as the incoming beam writing a grating with one other beam which is read by the third beam producing a fourth beam which is perfectly reversed in direction and phase from the incoming beam thus, it is called the phase conjugate. The phase conjugate also carries any information that was written in the grating by the incoming beam, for example the spatial information from a mask.

Experimental Set Up & Method:

Our experiment utilized an air force resolution chart as an image with spatial content, which was written in the barium Titanate and then read as a "real time" hologram. We investigated the speed and resolution of this process.

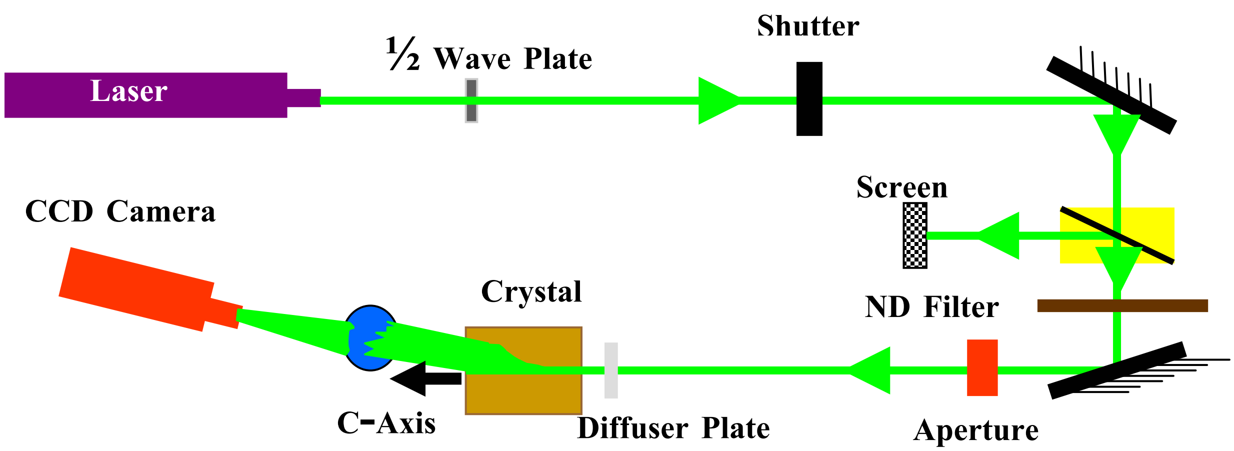


Figure 4 Experimental Set up of Beam Fanning

Figure 4 shows the experimental set up for the beam fanning experiment. A CCD camera was used to image the beam fan from the crystal to a computer where the images were analyzed. An Argon laser was used to create the input beams. Through the use of several neutral density filters, the power of the laser was reduced to below 20 mW to prevent the damaging of the Barium Titanate crystal. A shutter was then used to expose the sample to the input beam at the same time that the CCD camera and video capture software are triggered to start recording. A half wave plate is needed to rotate the polarization at the laser before it reaches the crystal. The light entering the crystal must be polarized horizontally to maximize the photorefractive effect. The beam will enter the crystal at an angle that is close to zero degrees. An aperture was used to block any stray light from the reflections that are caused by bouncing the beam off of mirrors, and any reflections that are caused by the beam splitter. Through the use of a holographic diffuser plate of 10^0 (solid angle), we were able to spread the light right before the beam enters the crystal. Lenses are then used to decrease the size of the beam fan, so that that the camera can image the fan. The image of the fan is then sent to a computer that performed the analysis of the intensity and time of the growth.

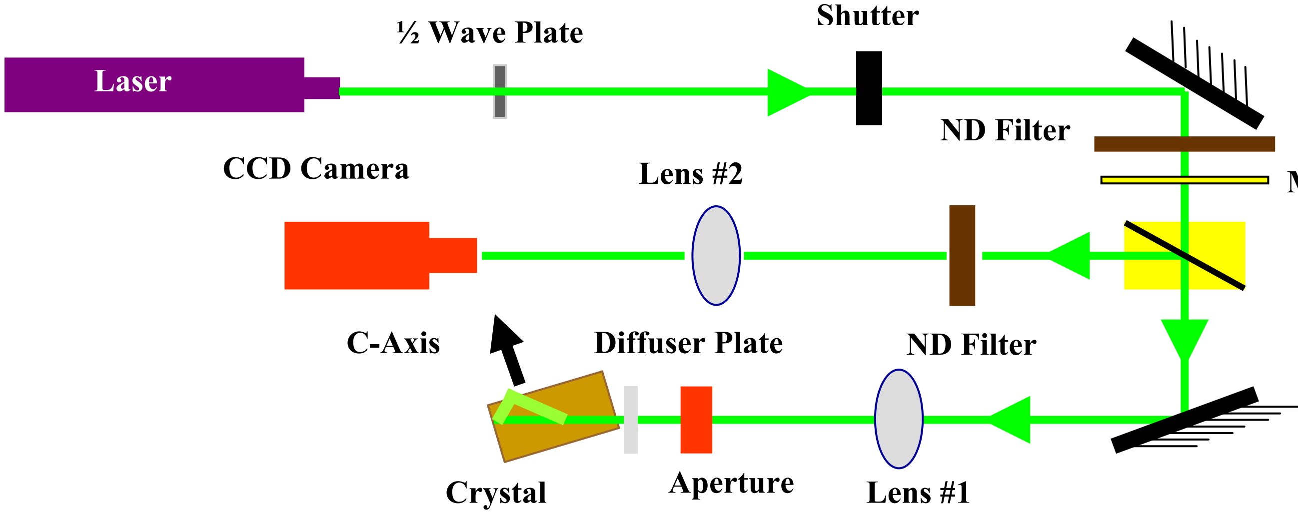
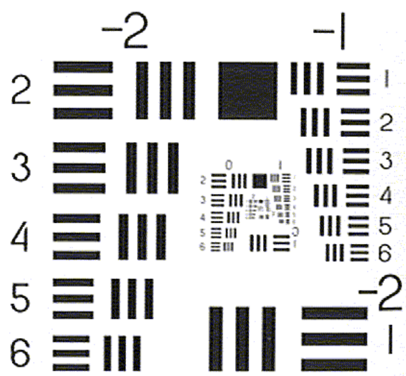


Figure 5 Experimental Set up of Phase Conjugation

Figure 5 shows the experimental set up for the phase conjugation experiment. A CCD camera was used to image the phase conjugate from the crystal to a computer where the images were analyzed. Again, an Argon laser was used as the input laser beam. Through the use of several neutral density filters, the power of the laser was reduced to prevent the damaging of the Barium Titanate crystal. The light entering the crystal must be polarized horizontally to maximize the photorefractive effect. The beam will either enter the crystal at an angle of about 45^0 to gain access to the maximum electro optic coefficients from the crystal. A beam splitter is needed to send the hologram, phase conjugate, to the CCD camera. An aperture was used to block any of the reflections that are caused by bouncing the beam off of mirrors, any reflections that are caused by the beam splitter, and was used to isolate the phase conjugate from the other beams that came from the beam splitter. Through the use of a holographic diffuser plate of 10^0 (solid angle), we were able to spread the light right before the beam enters the crystal. Lens #1 (F_1 = 100mm) in figure 5 was used to image the mask onto the crystal in a one to one ratio. This was done by placing the lens at a length of 2f from both the mask and the crystal. Lens #2 (F_2 = 100mm) was then used to magnify the image from the crystal onto the CCD camera by a 10x magnification (figure 5). An USAF resolution test pattern was used as the mask to measure the amount of resolution that can be stored inside the crystal (figure 6).



Resolution in Line Pairs / mm

		Group	
Elements	**4**	**5**	**6**
1	16	32	64
2	17.9	35.9	71.8
3	20.1	40.3	80.6
4	22.6	45.3	90.5
5	25.4	50.8	101
6	28.5	57	114

Figure 6, USAF Resolution Test Pattern

When the phase conjugate enters the diffuser plate, before the light enters the crystal, the light is gains a phase difference of $e^{i\Phi}$. When the phase conjugate exits the crystal, the image once again goes through the diffraction grating. Because the phase conjugate is in the opposite direction with an opposite phase angle, the image will be effected by $e^{-i\Phi}$. The two phase components will add to have a no net effect on the image,

$$E_{out}^{(-z)} = E_{in}^{(-z)} e^{i\Phi} e^{-i\Phi} = E_{in}(-z) \quad . \qquad (2)$$

This means that the image with and without the diffraction grating should look exactly the same.

Results

A: Beam Fanning

As light enters the crystal, the light reflects off of impurities in the crystal. Through the photorefractive effect, more and more of the light is reflected into the beam fan. Through the use of a diffraction grating, more of the light is reflected into the beam right from the start and thus the fan will grow more quickly.

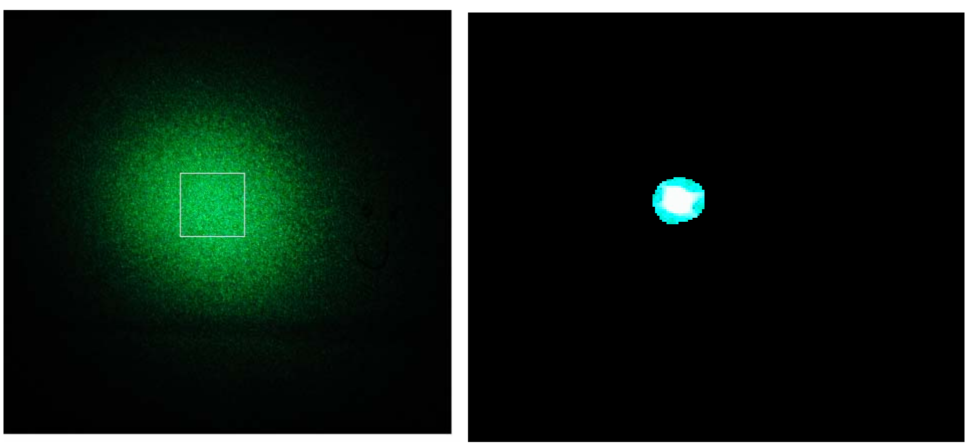


Figure 7, Beam Through Diffuser Plate (left), Beam (right)

If the diffraction grating is too strong, light will be diffused too much, and then the photorefractive effect will not occur because there is insufficient intensity of light directed correctly into the crystal (figure 7).

Next the growth of the beam fan was measured. As seen in the pictures in figure 8, the beam fan grows in time. Time 1 is 1 second, time 2 is 5 seconds, time 3 is 10 seconds and time 4 is after 15 seconds.

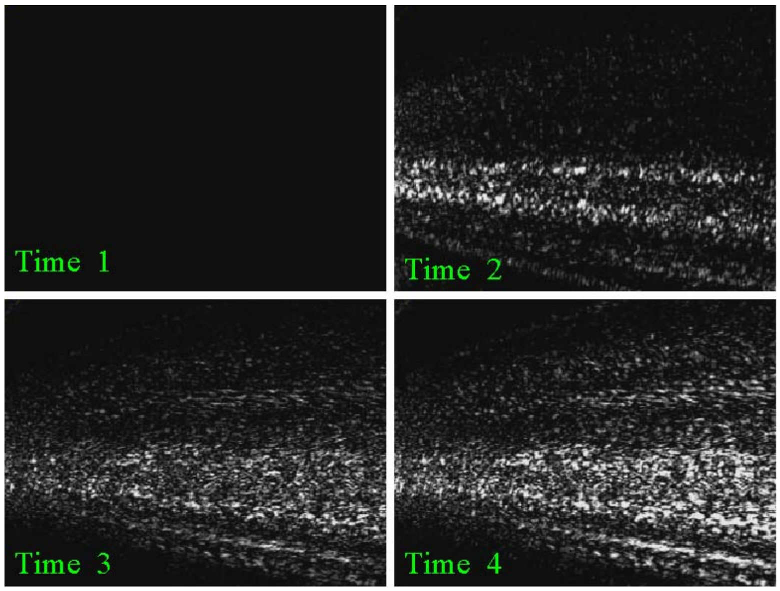


Figure 8, a. Beam Fan Without Diffraction Grating

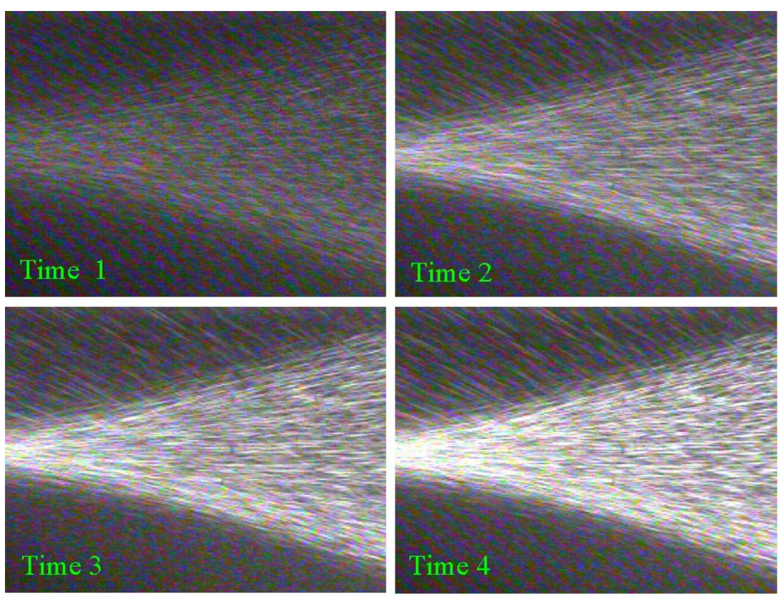


Figure 8, b. Beam Fan With Diffraction Grating

The time in which the fan grows depends both on the power that the incoming beam has, and the use of a diffraction grating. In the picture of the fan without the diffraction grating, figure 8 a, the area around the fan is dark, and has little light outside the fan at time 1. The picture with the diffraction grating, figure 8 b, you can see that more light is being diverted around the crystal at time 1. Even with the loss power from the scattering of the incoming beam, the beam fan grows faster from the head start.

The beam fan did increase in speed with the diffuser plate. The total increase in speed was about five times faster with the diffuser plate than with out the diffuser plate.

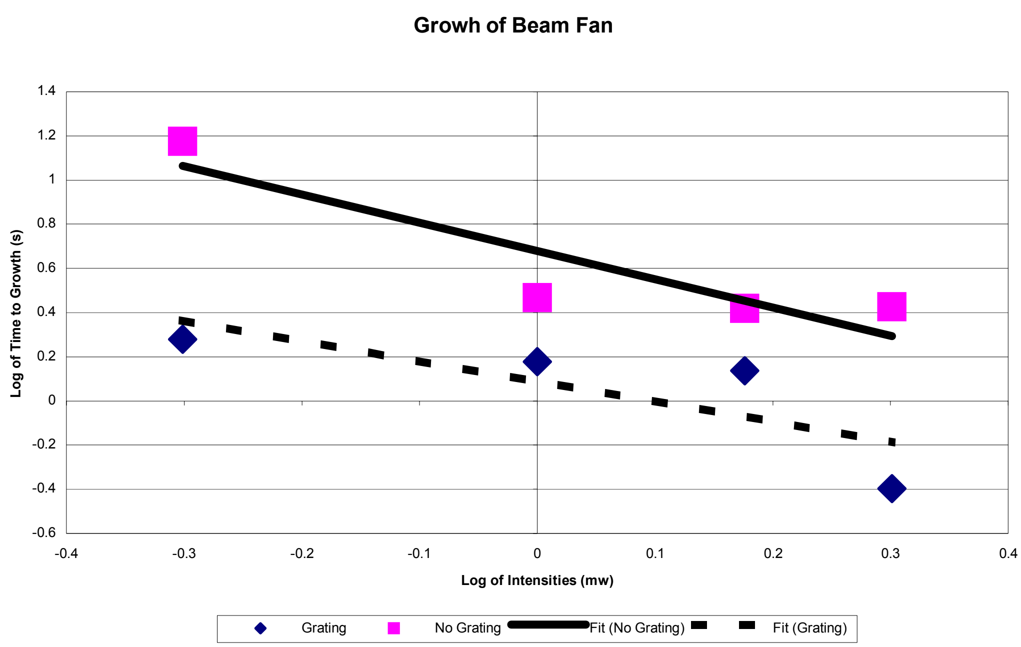


Figure 9 Beam Fan With and Without Diffuser Plate

The best-fit lines are running parallel with each other when plotted on a log-log scale. This is because theory predicts that the growth of the beam fan will increase as the exponential of an exponential when the power is increased. The data above represents the average of 4 trial runs at powers of 2 mW, 1.5 mW, 1 mW and 0.5 mW.

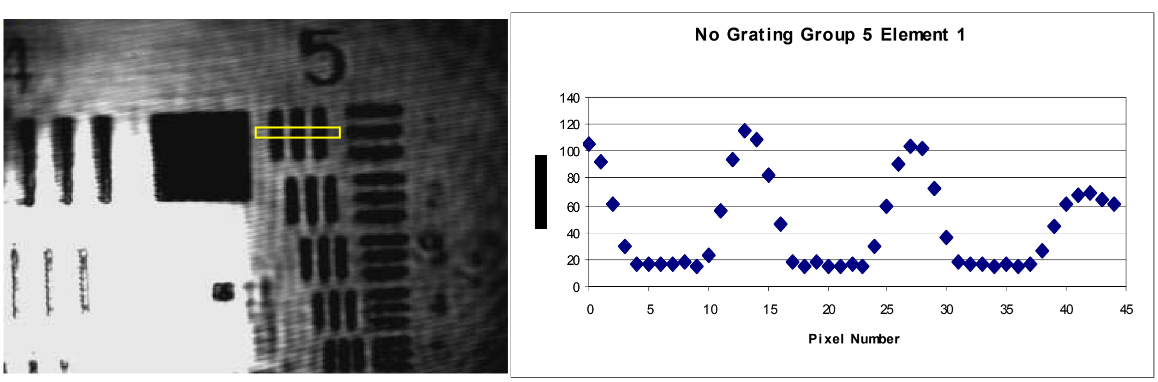
Analyzing the beam fan was a multi part process. First, a real time movie was taken of the beam fan. This gave an "avi" file used that was recorded at 30 frames per second. A real time image of the growth of the fan, as well as the time for each frame was recorded. The video started to record when a shutter was open that let the beam enter the crystal. This allowed for consistent measurements, which produced very similar results over the four trial runs. After the movie was recorded, it was then saved as an "avi" file that was easily broken down into individual frames. This movie was then broken down into frames. Each frame contained a still picture of the growth of the beam fan as in figure 8. Then a sample was taken every 20ms. The picture was then placed into *Image J*, which is an analyzing program. In *Image J*, the pictures were then analyzed using a plot profile of the image. This means that the intensities across the whole image were added together to give a single number of the average integrated intensity. This process was repeated 4 times for each power with and without the diffraction grating.

Total integrated intensities were graphed as functions of time and times to reach $(1-\frac{1}{e^2})I_{ss}$ were determined and designated as rise times. As you can see from figures figure 9, the addition of the diffraction grating caused the rise time to decrease with the addition of a diffraction grating. It was surprising that the addition of the diffuser plate decreased the risen time by a factor of 5x. One negative side effect of using the diffuser is that the diffraction grating also caused a great amount of scatter of the original beam. The scatter from the diffuser was then subtracted as back ground noise from the measurements.

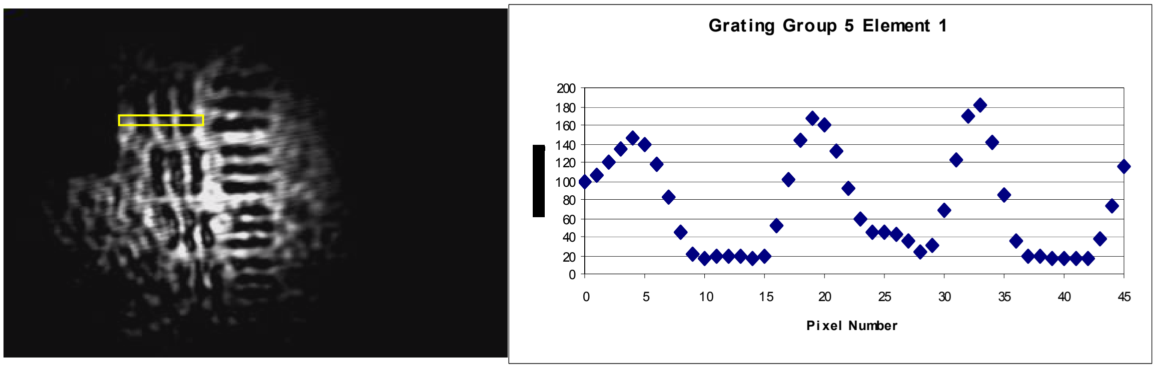
B: Self Pumped Phase Conjugation

B.1. Image Resolution of Self Pumped Phase Conjugate

A phase conjugate of the input mask is produced within 60 seconds via self pumped phase conjugation. The image of the mask would appear 10 cm from the beam splitter. By placing lens #2 11 cm from this image, a magnified image of the mask's phase conjugate is created (figure 5). The air force resolution chart contains a series of vertical and horizontal lines of decreasing separation nested inside each other (figure 6). Magnification allows us to determine the best resolution which is possible for data storage in a photorefractive crystal. For example, group 5 element 1 corresponds to 32 line pairs per mm or a spacing of 0.0312mm, and group 5 element 6 corresponds to 57 lines per mm or a spacing of 0.0197mm, while group 6 element 1 corresponds to 64 lines per mm and a spacing of 0.0175mm (figure 6).

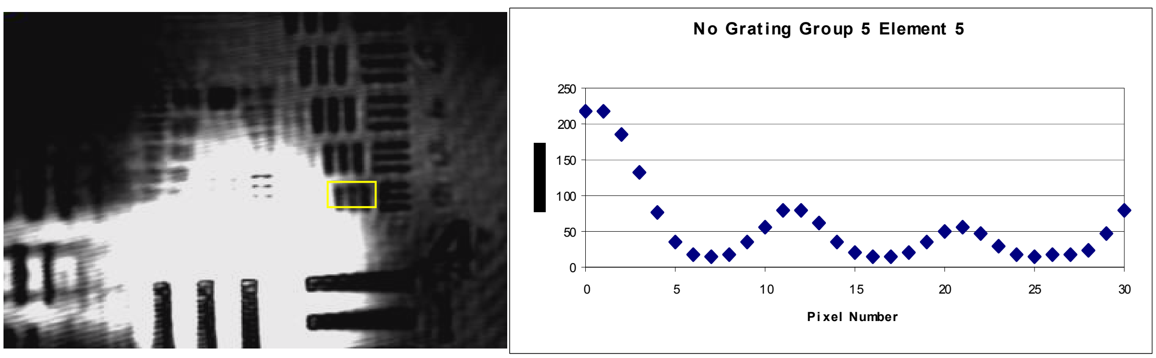


a. without diffuser plate

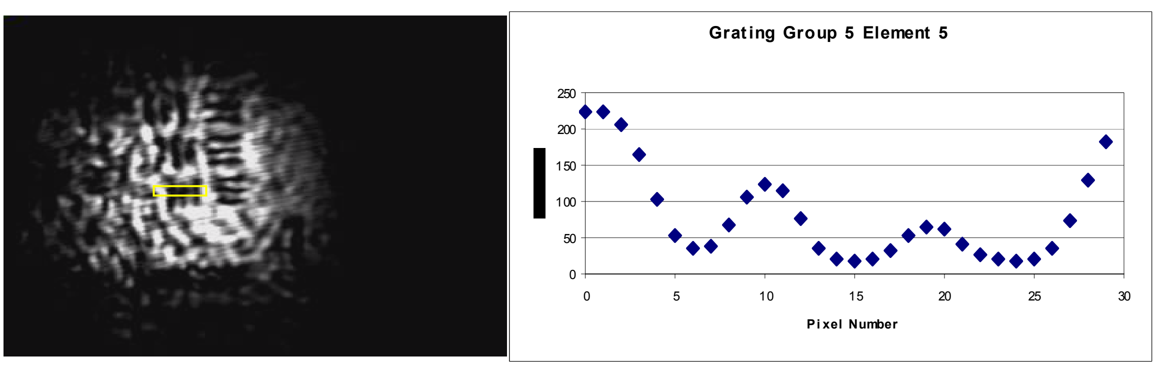


b. with diffuser plate

Figure 10 Image of Phase Conjugate of Group 5 Element 1



a. without diffuser plate



b. with diffuser plate

Figure 11 Image of Phase Conjugate of Group 5 Element 6

As you can see in figure 10 and 11, phase conjugate images of the mask, which were produced with and without the diffuser, are able to provide good resolution, however the image without the diffuser plate is much clearer and has higher contrast.

A plot profile, using Image J, was created using the slices indicated by the box on the images in figure 10 and figure 11. The plot profile will tell how defined the edges of the lines are, and how dark and light the areas are between the lines. The higher the values on the graph, the whiter the image is, which happens between the lines. Similarly, the darker the image is, the lower the values on the graph, which lines corresponds to the black stripes on the images.

In group 5, element 1, the image looks qualitatively better for the original phase conjugate, the plot profile shows less of a difference between the two phase conjugates (figure 10). This can be seen by the plot profile of a slice taken across the resolution lines, as indicated by the yellow box on the images. Even though the plots appear to be similar in the figure 10 b, there appear to be a skinner dark area than in the plot without the diffuser plate (figure 10 a). Similarly, the peaks which correspond to the white areas between the lines is wider with the plot without the diffuser plate, figure 10 a, than the plot with the diffuser plate, figure 10 b.

Not until group 5 element 6 can the differences between the two methods becomes apparent. While the contrast between the white parts of the images and the dark parts of the image is worse, not as defined, a difference can be told between the two. Notice that the dark areas of the image without the diffuser plate are still defined, and have a flat bottom between the white areas (figure 11 a). When looking at the definition of the lines, it is clear that the slope of the lines of the phase conjugate with the diffuser plate, figure 11 b, is much greater than the slope of the original phase conjugate, figure 11 a. This means that there is a greater definition of the lines in the original phase conjugate.

The best image that could be produced using the diffuser is group 5, element 6, which has a resolution of 57 line pairs per millimeter or a spacing of 0.0197mm (figure 11). The best image with out the diffraction grating is group 6, element 1, which has a resolution of 64 line pairs per millimeter or a spacing of 0.0175mm (figure 12). This means that there is a difference of 7 lines per millimeter better resolution of the original phase conjugate than a phase conjugate with the diffuser plate.

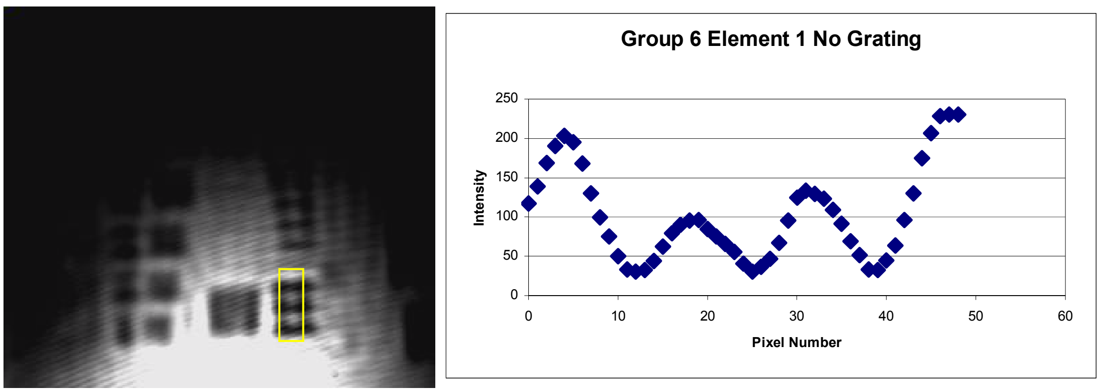


Figure 12 Group 6 Element 1 Without Diffuser Plate

The plot profile in figure 12 tells us that there high contrast outside the bar pattern, and the middle lines are starting to blur together. The next element of group 6, element 2, is indistinguishable both quantitatively by using the plot profile technique, and qualitatively.

B.2 Speed of Self Pumped Phase Conjugate

A photo detector was placed in the path of the phase conjugate 20cm from the lens #2 (figure 5). The lens was used to focus the phase conjugate onto the photo detector. Measurements were taken using a lab VIEW program, which took 250 measurements per ms. The program measured the intensity at which the phase conjugate grew in time. Just like with the CCD camera, a shutter was open to allow the light to enter the crystal. When the shutter opens, the program started to take the measurements. The average of the 4 time trials that the phase conjugate took to grow to $1\text{-}e^{-2}$ of steady state was then plotted on a log-log scale. This is because the times that it takes the phase conjugate to grow decreases as an exponential function of the power.

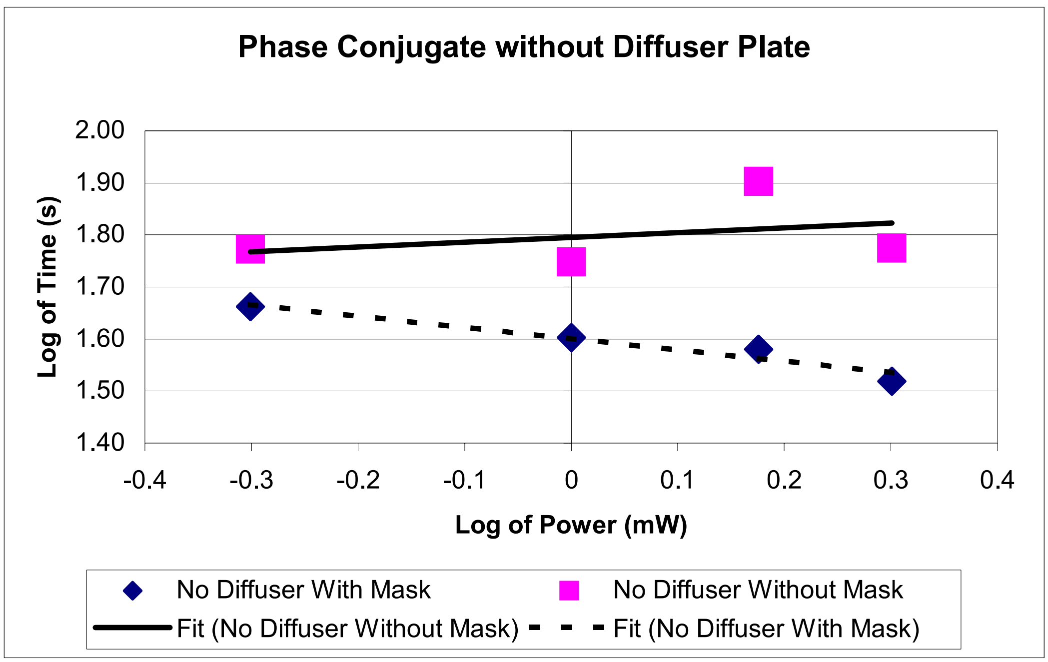


Figure 13, a. Phase Conjugate Without Diffuser Plate

If the incoming beam passed through the mask, the mask would cause the incident beam to diffract before the beam reached the crystal. When comparing the phase conjugates growth with and without the mask, figure 13 a, we see than when the incident beam runs through the mask, the times decrease as the power increases. This is caused by the mask acting like a diffraction grating, thus causing the light to scatter before it enters the crystal. This is the same way the beam fan reacted. When the incident beam did not pass through the mask, the times decreased as the power increased, but did not increase by a significant amount.

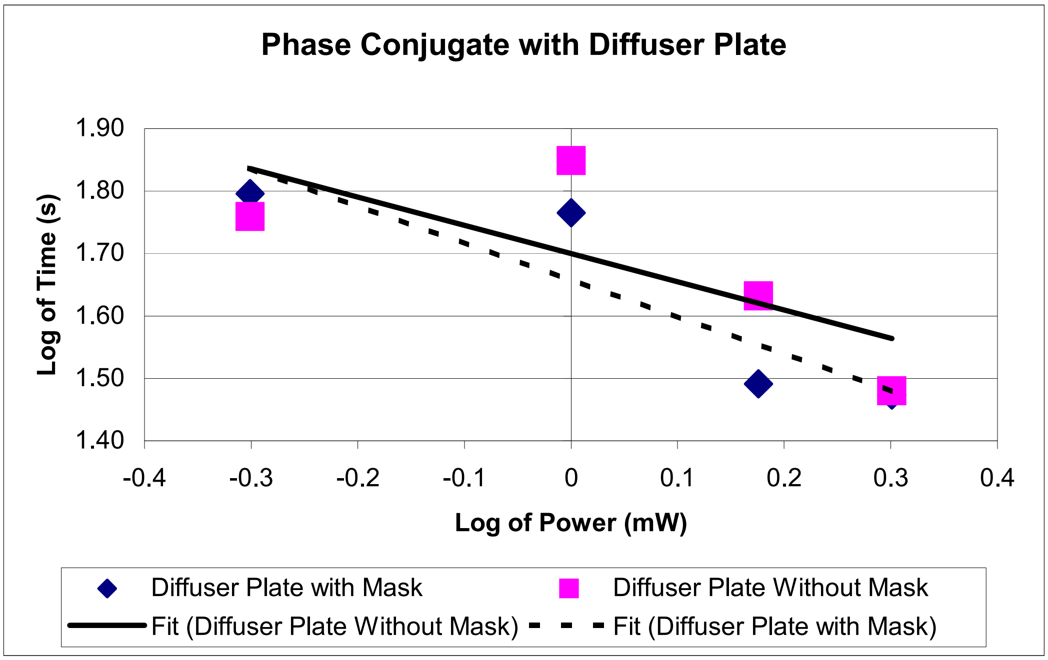


Figure 13, b. Phase Conjugate With Diffuser Plate

When using a diffuser, the slopes of the best-fit lines were very similar in fashion, figure 13 b. This suggests that the diffraction caused by the mask is not enough to over come the effects of the diffraction grating. On average the times were smaller when using the mask. This means that the extra diffraction caused by the mask is a noticeable effect, but did not affect the speed at which the phase conjugate grew by a significant amount. The mask, on average, affected the growth speed of the phase conjugate only by one or two seconds. This means that the used of the diffuser plate had a much more significant affect on the incident beam, and effectively negated the diffraction caused by the mask. Since the phase conjugate depends on the beam fanning effect, it was believed that the phase conjugate would also grow in the same fashion.

When the mask is not used, the phase conjugate grows faster at the lower powers when a diffraction grating is used, but has almost the same growth time as when a diffuser plate is not used. The growth time is faster without the diffraction grating at higher powers when a mask is not used.

Notice that the phase conjugate rise times are not significantly different with and without the diffuser plate. This affect could be explained by looking at what the diffuser plate is actually doing to the beam. When the diffuser plate is placed in the path of the incident beam, the light is spread out before the beam enters the crystal. This causes a loss of power from the spreading of the beam both away from the section of the crystal that is being used to write the grating, and also diverts the light further into the beam fan with a different angular component. While the extra angular component helps the beam fan to grow quicker, this also diverts light from the four wave mixing process. The diffraction grating also diverts light that would be used in the four wave mixing process and sends the light to opposite side of the crystal where the light is not used. Both the extra angular component and diverting the light from the plane of the crystal which the gradient is being written will cause less power going into the four wave mixing process, and causes the time in which the phase conjugate develops to decrease. While the diffuser plate helped to speed up the beam fan growth, it could be inhibiting the speed of the phase conjugate. So with two competing effects, the net result was that the phase conjugate rise times was very similar with and without a diffuser.

Conclusion

The beam fan time decreased by a factor of 5 through the use of a diffusing plate to increase the scatter of the incident beam. Thus, the growth in the phase conjugate was expected to be 5x faster using the diffusion plate, just as in the beam fan results, however, the time it took the phase conjugates to grow to steady state was not strongly effected by using the diffuser. In fact it is indeterminate whether or not using the diffusing plate is better or not. The resolution difference was not that great between the diffuser plate and without the diffuser plate.

It was found that the best resolution of the phase conjugate with the diffuser plate was 57 line pairs per millimeter. The best resolution with out the diffuser plate was 67 line pairs per millimeter. This means that the phase conjugate did not fully cancel the effects that were caused in passing through the diffuser upon entry of the crystal. The diffuser plate did increase the speed at which the beam fan grew but the phase conjugate rise time was less responsive to the diffuser. However the image quality as determined by contrast and clarity suggests that the use of a diffuser plate is comparable to not using the diffuser plate.

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