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TITLE

DEVELOPMENT OF HOLOGRAPHIC QUARTERWAVE PLATE: FEASIBILITY STUDY AND PROTOTYPE FABRICATION

93-642

Development of holographic quarterwave plate: feasibility study and prototype fabrication

Final report

to

Defence Research Establishment
Department of National Defence
3701 Carling Ave.
Ottawa, Ontario
K1A 0K2
Scientific Authority: Dr Nicole Brousseau

LASIRIS INC.
3549 Ashby
St-Laurent, Québec
H4R 2K3

Contract no.: W7714-2-9668/01-ST

LASIRIS

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Executive summary

This feasibility study explored the fabrication of holographic quarterwave plates. It was found that the two most important fabrication parameters are, in order of importance, the spatial frequency and the modulation depth. It is not possible to achieve a sufficient phase retardation into photoresist with a single grating showing no rotation of the incident polarization when illuminated at normal incidence. Moreover the required phase retardation is often achieved when the grating shows some diffracted orders, which is inefficient for a quarterwave plate.

The cascade configuration shows the required phase retardation without diffracted orders and is a good candidate for the fabrication of high quality quarterwave plates. Finally, the wet etching process did not produce acceptable gratings and the Reactive Ion Etching process should be considered as a potential substitute method for producing better quality quarterwave plates with a single high index grating and no diffracted orders.

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I- Introduction

Wave plates are polarization components used in optics to introduce various phase shifts between two orthogonal field components of a wave. High quality wave plates are usually made of quartz or mica and are expensive. Moreover wave plates with large surfaces are difficult to fabricate.

It has been shown that the artificial birefringence exhibited by ultrahigh frequency gratings recorded in dielectric materials can be used to produce quarterwave plates (1). However complex processing such as x-ray lithography and reactive ion etching is needed to achieve the proper shape, depth and high spatial frequency.

It was also reported that sinusoidal holographic gratings recorded in photoresist exhibit strong phase retardation and can be used as low cost quarterwave plates (2). According to the form birefringence model (3), relief structures in photoresist behave as a negative uniaxial crystal with its optical axis parallel to the grating vector. The retardation phase produced by the grating will be dependent on its birefringence (which depends on the refractive index and the period), its relief depth and the wavelength used.

In accordance with the Statement of Work from contract # W7714-2-9668/01-ST, this report presents a feasibility study for the realization of holographic quarterwave plates in photoresist, and in particular;

1- The effect of the grating period and relief depth on the phase retardation and on the rotation of the transmitted ligth polarization state.

2- The possibility of combining two high frequency gratings in cascade to achieve the necessary phase retardation.

3- The possibility of using one high frequency photoresist grating as a mask for wet etching on appropriate substrates with high refractive index.

Finally, we will discuss the potential of this technology for the fabrication of high quality quarterwave plates.

II- Calculation of birefringence from experimental measurements

In this section we will present the experimental set-up that was used to obtain the intensity measurements needed for the calculation of the phase retardation Φ and the ratio of transmittances R. We will then establish the system of equations that is used in the calculations.

Figure 1 displays a simple measurement set-up as used for the first time by Enger and Case (4). The electric field behind the grating is given by Eq.(1)

$$E=\begin{bmatrix} T_x \\ T_y \exp(i\phi) \end{bmatrix} \exp[i(kz-wt)] \tag{1}$$

where T_x and T_y are the transmitted wave amplitudes in the direction of the x and y axis respectively. If the transmission coefficients are unequal ($T_x \neq T_y$), the direction of polarization of the transmitted wave is rotated in addition to the birefringent phase shift.

Behind the second polarizer set at an angle α with respect to the x axis, the electric field is:

$$E=\begin{bmatrix} \cos\alpha & 0 \\ 0 & \sin\alpha \end{bmatrix} \begin{bmatrix} T_x \\ T_y \exp(i\phi) \end{bmatrix} \exp[i(kz-wt)] \tag{2}$$

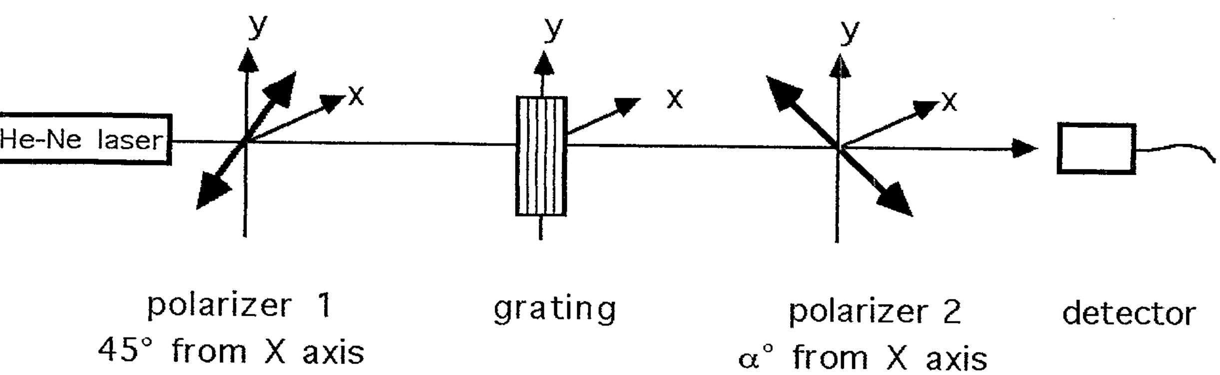


Figure 1. **Set-up for measurements of birefringence.**

Finally, the intensity measured by the detector is:

$$I_\alpha = (T_x)^2 \cos^2\alpha + (T_y)^2 \sin^2\alpha + 2T_xT_y \cos\alpha \sin\alpha \cos\phi \ . \qquad (3)$$

When $T_x = T_y$, Eq. (3) has a maximum at $\alpha = \pi/4$ and a minimum at $\alpha = -\pi/4$ and Φ can be evaluated by (4):

$$\phi = \cos^{-1}\left(\frac{1 - I_m/I_M}{1 + I_m/I_M}\right) \qquad (4)$$

where I_M = maximum intensity and I_m = minimum intensity.

When $T_x \neq T_y$, more measurements are needed to obtain the phase. The measurements of I_M, I_m and $I_{\alpha=-\pi/4}$ are chosen arbitrarily and the following parameters are introduced to calculate the phase retardation Φ and the ratio R of the two transmittances:

$$M1 = I_{-\pi/4} \,/\, (I_M + I_m),$$

$$M2 = (I_M - I_m) \,/\, (I_M + I_m) \qquad (5)$$

Hence, the only information needed from the grating is its maximum and minimum transmitted intensity along with the transmitted intensity at $-\pi/4$, when the illumination beam is linearly polarized at $\pi/4$, as shown in Figure 1.

Substituting Eq.(3) in Eq.(5) the following system of equation is obtained:

$$M_1 = \frac{1}{2} - \left(\frac{R}{R^2 + 1}\right)\cos\phi$$

$$M_2 = \frac{(1 - R^2)^2 + 4\,R^2\cos\phi}{(R^2 + 1)^2} \qquad (6)$$

with $R = T_y / T_x$. This system is then solved numerically (with a computer program called MathCad (5)) to obtain Φ and R.

The birefringence Δn of the grating can also be evaluated with the following equation:

$$\Phi = (2\pi / \lambda)\ \Delta n\ t \qquad (7)$$

When the value of the relief depth t is known.

It is worth noting here that our system of equations (6) is different from the one used by Cescato et al. (2) for the same purpose. We carefully verified our equations and cannot offer any explanations as to why their equations are different . In fact, the equations proposed by Cescato et al. show a singularity at R=1, and become useless for numerical calculation.

III- Fabrication of gratings and measurements

The holographic gratings were recorded onto Shipley photoresist layers of 5 μm thick, coated on glass substrates. The gratings were recorded in a stabilized holographic set-up at $\lambda = .442$ μm, shown in figure 2. The laser beam is split in two parts, each passing through a 40 X microscope objective and a spatial filter. The two expanded beams interfere over the photosensitive plate attached in the plate holder. The incident angles of the two interfering beams were varied from 19,3° to 28,3° to adjust the gratings spatial frequency. An integrating radiometer was able to calculate the exact exposure energy and a shutter was used to control the exact exposure time. The gratings were developed using the developper solutions AZ303A for a linear development and AZ351 for a binary development. To obtain several relief depths the exposure energies were varied. The gratings were then measured in their center region with a He-Ne laser ($\lambda = .6328$ μm) at normal incidence, for I_M, I_m and $I_{\alpha=-\pi/4}$, as described in section 1. These measurements were then used to calculate the parameters Φ and R of the gratings.

Results of the measurements are shown in figures 3 to 6. First, gratings of 1500 l/mm (0.666 μm period) were recorded with different exposure energies and processed with a linear development, they were then measured for I_M, I_m and $I_{\alpha=-\pi/4}$, and finally R and Φ were calculated from the resolution of system of equations (6). From the measurement of their diffraction efficiencies (DE), it was apparent that the relief depth of the gratings had a maximum at around 20 mJ/cm^2 of exposure, since the DE would not increase for higher exposures. In figure 3, the curves of R and Φ versus exposure energy show the same behavior: an inflexion point can be seen around 20 mJ/cm^2 of exposure. We then decided to use a binary development, and the same procedure was applied to fabricate and measure gratings of the same period. Results are displayed in figure 4. It can be seen that R decreases from 20 to 52 mJ/cm^2 of

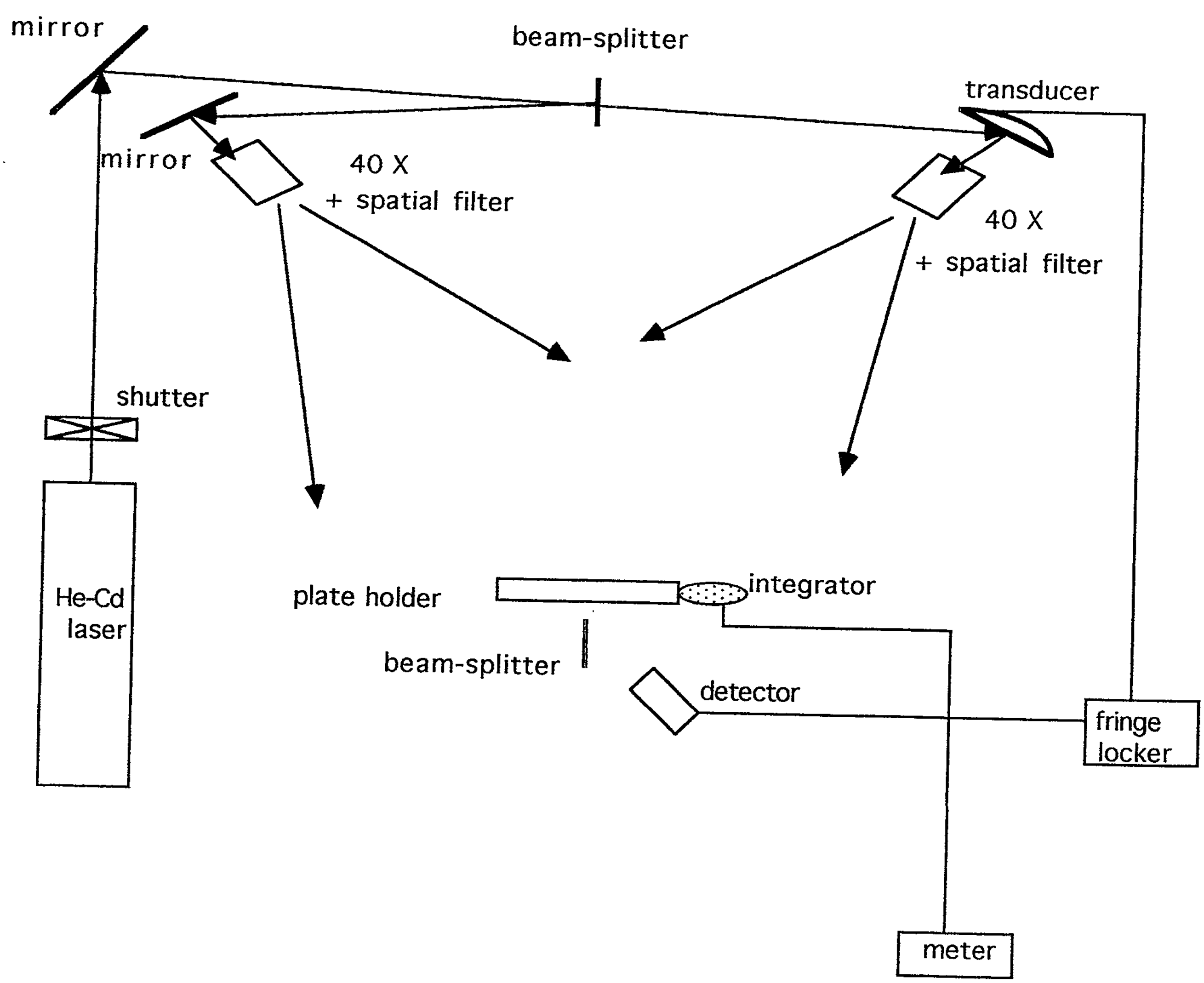
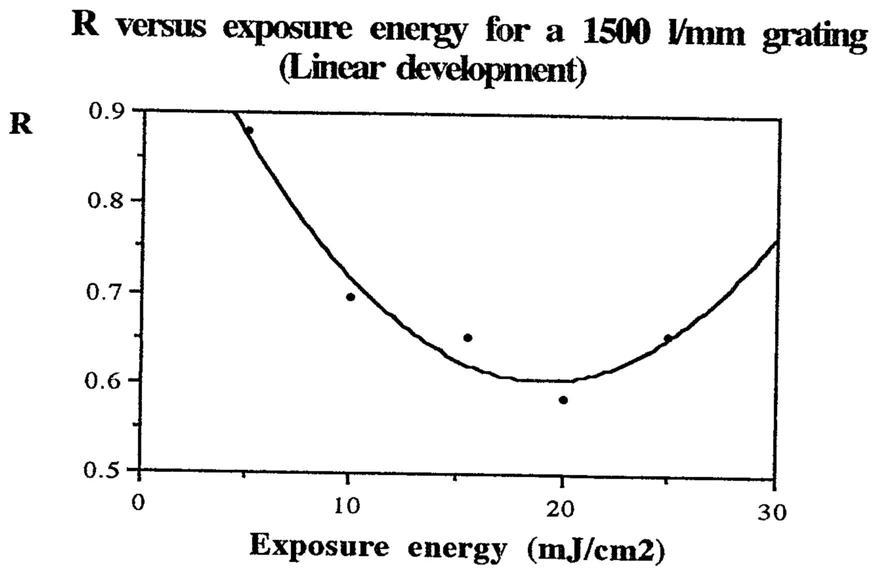


Figure 2. Set-up used to record the photoresist gratings



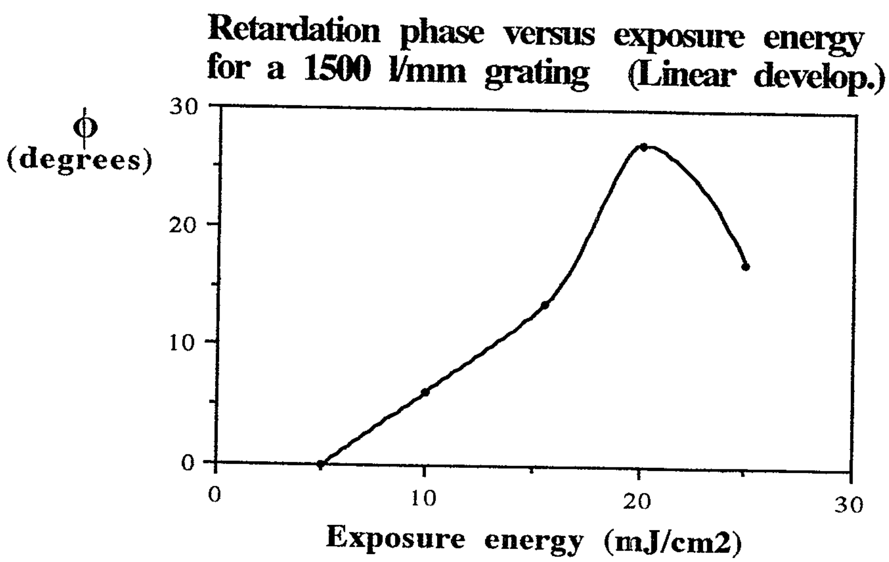
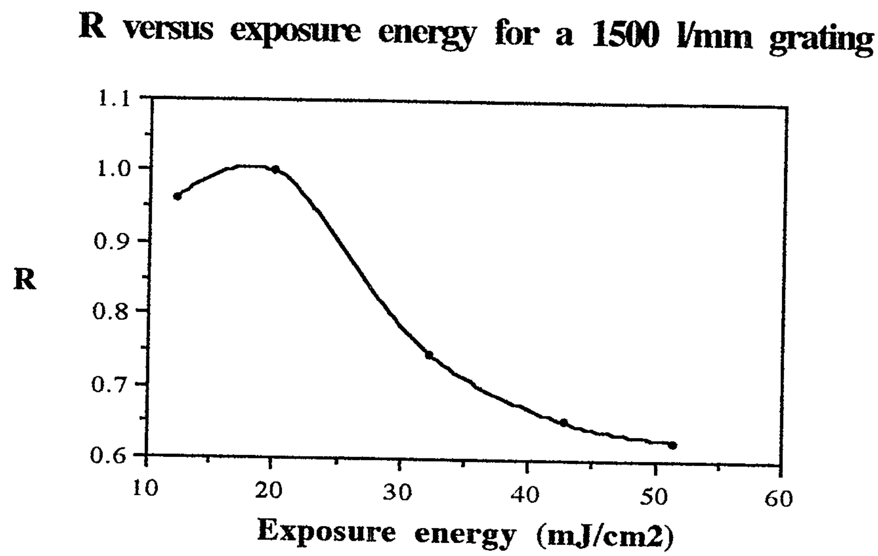


Figure 3. Ratio R and phase retardation Φ versus exposure energy for gratings of 1500 l/mm (linear development)



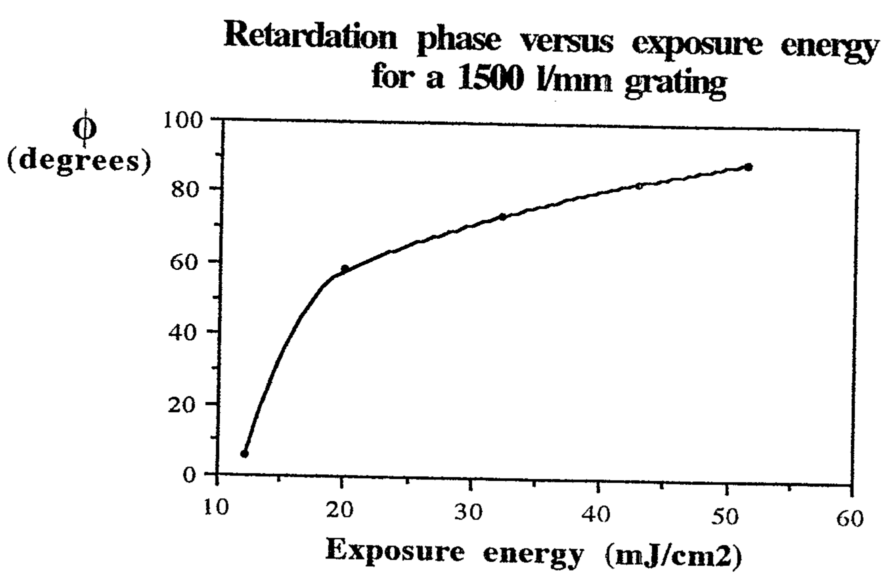
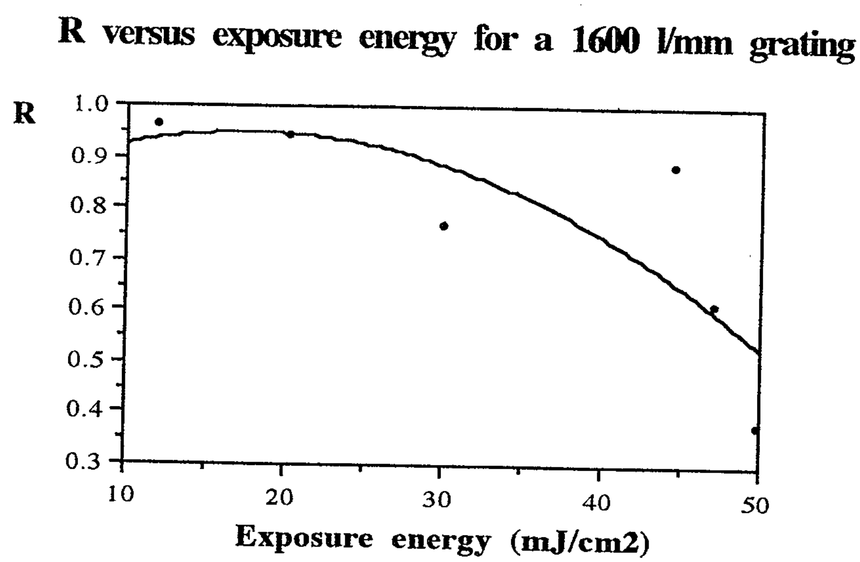


Figure 4. Ratio R and phase retardation Φ versus exposure energy for gratings of 1500 l/mm (binary development)



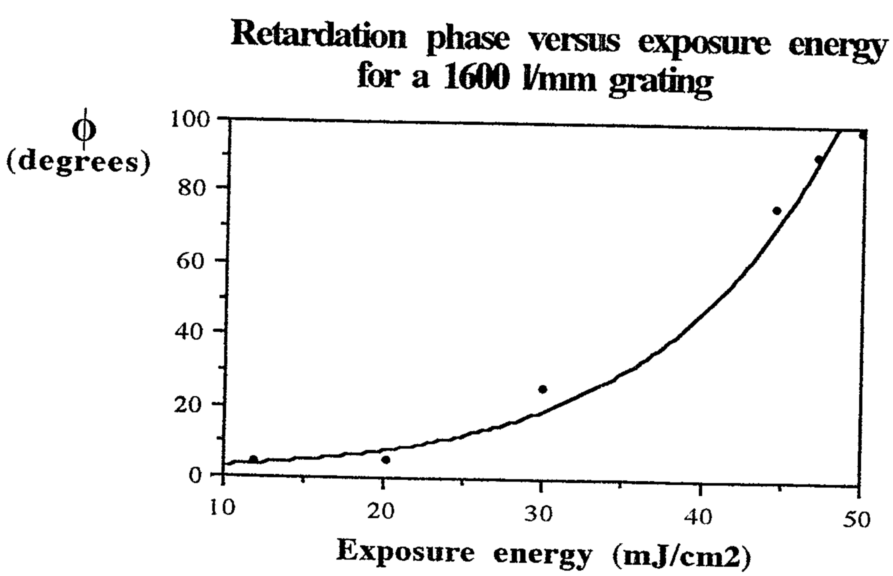
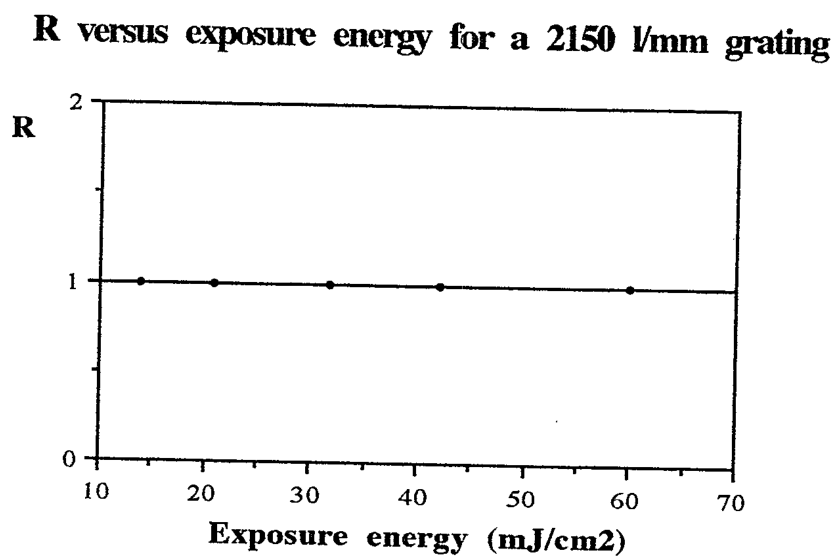


Figure 5. Ratio R and phase retardation Φ versus exposure energy for gratings of 1600 l/mm (binary development)



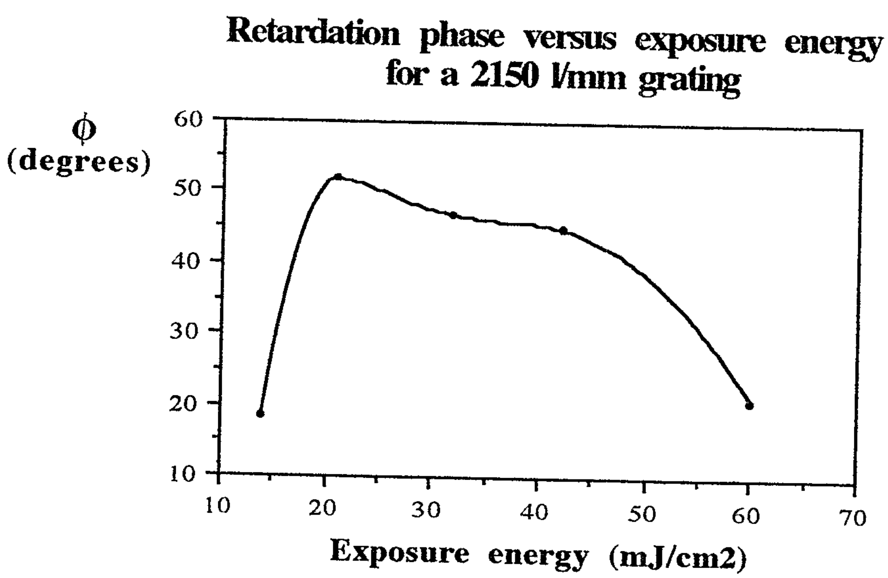


Figure 6. Ratio R and phase retardation Φ versus exposure energy for gratings of 2150 l/mm (binary development)

exposure while the phase retardation Φ increases. The phase retardations obtained are more important with the binary development, and we achieved a grating with Φ = 89°, which can be considered a quarterwave plate with 1.1% accuracy. However, the use of this grating as a quarterwave plate would require compensation of the incident polarization direction, since the value of R is .64, which means that the grating will rotate the incident polarization. Moreover, gratings of 1500 l/mm used at normal incidence with He-Ne light, will show two diffracted orders at ± 88°.

Gratings of 1600 l/mm (.625 μm period) were fabricated, processed with the binary development and measured as described above. At such a spatial frequency, the gratings no longer diffract He-Ne light at normal incidence. Results are shown on figure 5. It still can be seen that R tends to decrease, while Φ increases with the exposure energy. It was possible to achieve a grating with Φ = 90.9°, and a rotation of the incident light (R = .62).

Finally, gratings of 2150 l/mm (.465 μm period) were produced and figure 6 presents the results. R remains equal to unity whatever the exposure energy but Φ, after an abrupt increase, decreases as the exposure energy is increased. In this case, since Φ is always smaller than 90°, a quarterwave plate could only be realized with the addition of two gratings in cascade, with the advantage that the resulting plate will not rotate the incident polarization. It is worth noting here that we have achieved gratings with DE > 99% when illuminated at Bragg incidence. As far as we know, these results have never been published before. Figure 7 displays the behavior of DE versus exposure energy for 2150 l/mm gratings recorded in photoresist.

In conclusion, our results indicate that for gratings with periods smaller or equal to the incident wavelength, R tends to decrease with the exposure energy (which is related to the relief depth), while Φ increases and can reach 90°. Those gratings can be used as quarterwave plates if one can tolerate a slight rotation of the incident polarization. On the other hand, gratings with periods greater than the incident wavelength no longer rotate the incident polarization (R = 1) but show

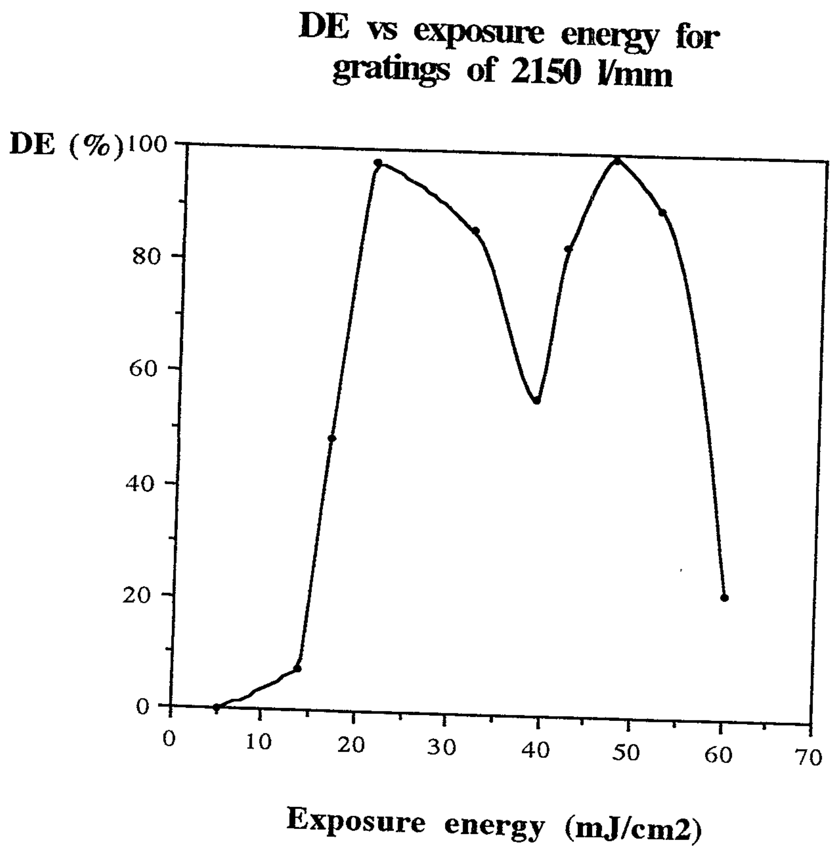


Figure 7. Diffraction efficiency versus exposure energy for gratings of 2150 l/mm

phase retardations smaller than 90°. There is an inverse relationship between the effect of the spatial frequency of the grating and the maximum achievable phase retardation. For maximum phase retardation, it is desirable to use the smallest possible spatial frequency.

There is also a direct relationship between the spatial frequency and the rotation of polarization induced by the grating. For minimum rotation, or no rotation at all. a sufficiently high spatial frequency must be used. As the ideal waveplate should show a strong phase retardation and no rotation, a compromise must be found in terms of spatial frequency.

The effect of the modulation depth on the phase retardation is clearly very important and allows for a fine tuning of the waveplate within the operating range defined by the spatial frequency. It is clear that the dominant parameter is the spatial frequency of the grating, with the modulation depth being the second most important parameter. For example, the rotation “R” is strongly dependant on the modulation depth but can be made independant of it if the spatial frequency is high enough.

The diffraction efficiency at Bragg condition can be very close to the theoretical limit for a volume phase grating, which is a very interesting feature of these gratings. In terms of the overall quality of the grating waveplates, we note that the exposure-development process is critical and must be carefully controled to eliminate any variation of performance over the grating surface. Some cosmetic defects can be seen as a result of uneven exposure and/or development. We measured a maximum variation of phase retardation Φ of +/- 5% over a 1.5” X 1.5” area on the 1500 l/mm grating and +/- 12% for the 1600 l/mm. These results were obtained with a reasonable level of effort and we believe that the uniformity of performance can still be significantly improved.

IV- Combination of two gratings in cascade to obtain a quarterwave plate

Since high spatial frequency gratings show less retardation phase than low spatial frequency gratings (while showing no rotation of polarization), it could be worthwhile combining two such gratings in cascade to obtain a quarterwave plate. Figure 8 shows the experimental scheme to obtain circularly polarized light with two gratings, each with the same phase retardation $\Phi < 90°$. α is the angle of the incident polarization and β is the angle between the two gratings.

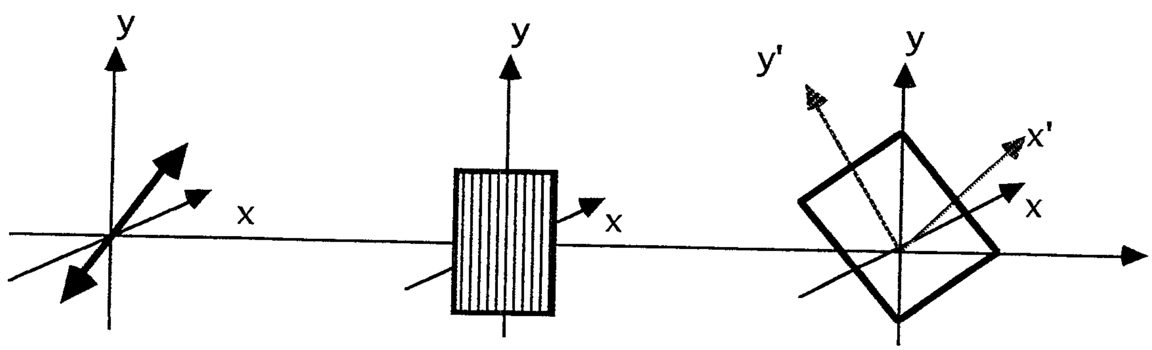


Figure 8. Experimental scheme to obtain a quarterwave plate from two gratings.

After the first grating, the transmitted electric field will be:

$$E_y = T_y \sin\alpha \cos\theta$$
$$E_x = T_x \cos\alpha \,(\cos\theta + \Phi) \qquad (8)$$

where Φ is the phase retardation induced between the two components by the grating. For the sake of simplicity let T_y and T_x be equal to unity (which holds true for high spatial frequency gratings). After the second grating the electric field must be expressed in terms of the new coordinates x' and y', and knowing that for a rotation of an angle β the new coordinates can be expressed as:

$$
\begin{aligned}
y' &= y \cos\beta - x \sin\beta \\
x' &= x \cos\beta + y \sin\beta ,
\end{aligned}
\tag{9}
$$

the final electric field will be:

$$
\begin{aligned}
E_{y'} &= \sin\alpha \cos\theta \cos\beta - \cos\alpha \, (\cos\theta + \Phi) \sin\beta \\
E_{x'} &= \sin\alpha \cos(\theta + \Phi) \sin\beta + \cos\alpha \, (\cos\theta + 2\Phi) \cos\beta
\end{aligned}
\tag{10}
$$

where the phase retardation Φ induced by the second grating has been taken into account.

For two given gratings with equal phase retardation Φ, and for an incident polarization α, the angle β between the two gratings will be ajusted so as to produce a resulting phase retardation of $\pi/2$ between $E_{y'}$ and $E_{x'}$. The combination of gratings 1 and 2 will then be equivalent to a quarterwave plate. Figure 9 shows a diagram displaying the angles α and β to obtain a quarterwave plate from two equal gratings each with a phase retardation Φ, as per our numerical calculations. By modifying slightly the system of equations (10), a graph could also be obtained for two gratings with different phase retardations Φ.

As an example, for two gratings showing identical phase retardation of Φ=50 degrees, we note that the angle between them should be β= 2.7 degrees and the incident polarization angle α= 41 degrees for the cascade grating to work as a quarterwave plate. In practice, it has proved difficult to fabricate two gratings with the exact same phase retardation and we used two gratings with different Φ and experimentally found the correct angle between them. The same type of curve as in Figure 9 could have been calculated but this was outside the scope of this work.

CASCADE CONFIGURATION

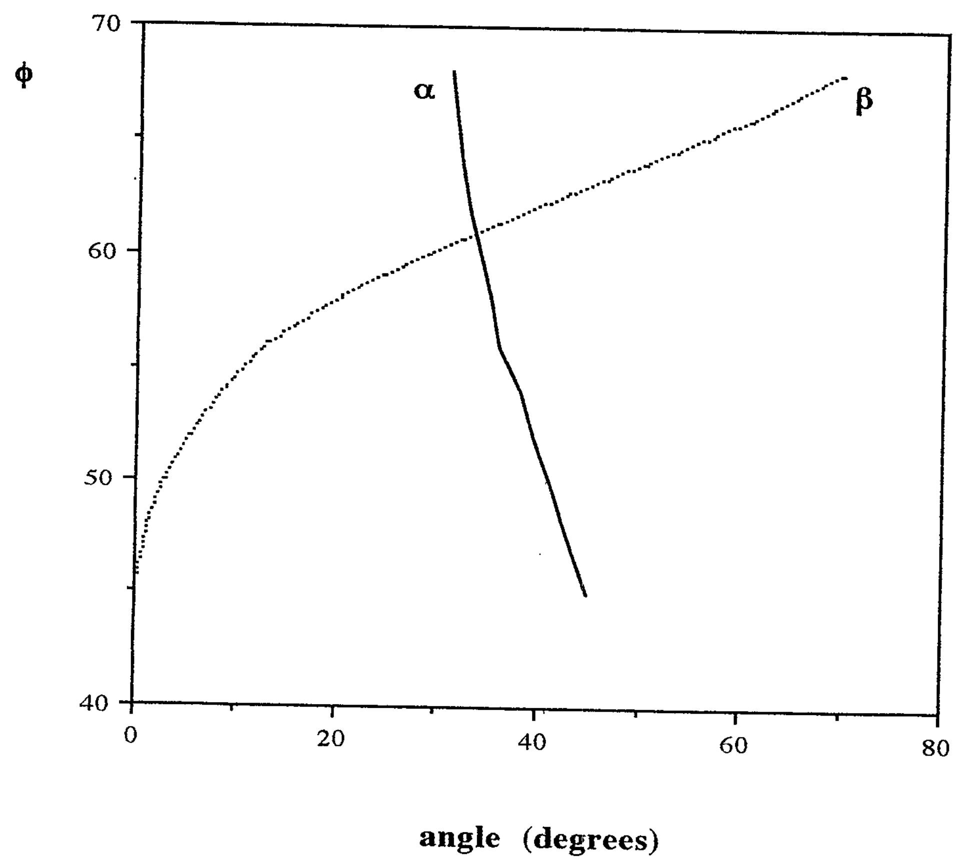


Figure 9. Angles α and β necessary to obtain a quarterwave plate from two gratings with identical phase retardation Φ.
α is the incident polarization angle and β is the angle between the two gratings.

The cascade quarterwave plate that was fabricated exhibits the required phase retardation (90 degrees) without any rotation of the incident polarization. The overall quality of the grating pair is good but more work should be done to improve the cosmetic quality and the overall uniformity. A potential problem with these grating waveplates could arise from the internal reflections, or guided diffracted orders, that can be observed upon illumination with a direct laser beam. We believe that a careful study of this phenomenon and its possible remedies should be done to improve the quality of the cascade holographic quarterwave plates.

V- Fabrication of gratings using the wet etching process

The objective here is to fabricate a grating with a suitable modulation depth onto a high refractive index substrate material. In order to establish a reliable process, we first attempted to fabricate the etched gratings onto standard glass. The wet etching process uses hydrofluoric acid as a solvent of the exposed glass.

We used a combination of chrome and photoresist on glass substrates as our starting point. Once the grating has been recorded, it is necessary to dissolve away the exposed photoresist down to the chrome layer, while still leaving the unexposed photoresist essentially untouched. This proved very difficult to achieve with our 5 microns thick emulsions.

The next step is to dissolve away the chrome using a photomask etchant solution (CR-4). This locally uncovers the glass substrate, which is then ready to be etched away using the acid. In practice, we found the whole process to require a significant level of effort before we could fabricate anything acceptable. We were not able to successfully achieve the first step of the process (a chrome grating), probably because of the initial thickness of our emulsions and the photoresist development process that was not adequate.

It would be of interest to study this fabrication process in greater detail with one possible improvement; the etching of the material should be done in a Reactive Ion Etching (RIE) system in order to produce a potentially better etched grating.

VI- Conclusions

The scope of this work was to evaluate the feasibility of holographic quarterwave plates. We successfully demonstrated the feasibility of such waveplates both in the single and cascade configurations.

The wet etching fabrication process was attempted but we could not fabricate the gratings using this technique. This process is still promising but requires a more exhaustive study.

The results obtained in the context of this feasibility study are very promising. The waveplates that were fabricated show the required phase retardation and acceptable overall performance. We believe that this technology has the potential for producing high quality large size waveplates. A better understanding of optical phenomenon involved along with a carefully designed fabrication process will allow for the production of these high quality waveplates.

We believe that the etching of gratings onto high index material should still be considered as a candidate for a single grating quarterwave plate. However, the cascade configuration, with high frequency gratings, is the most promising configuration and should be studied and developed in greater details.

VII- References

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