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Fabrication Techniques for Very Fast Diffractive Lenses

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Abstract

Aspheric lenses with arbitrary phase functions can be fabricated on thin light weight substrates via the binary optics fabrication technique. However, it is difficult and costly to fabricate a fast lens (f/number < 1) for use at the shorter wavelengths. The pitch of the masks and the alignment accuracy must be very fine. For a large lens, the space-bandwidth product of the element can also become impractically large. In this paper, two alternate approaches for the fabrication of fast aspheric diffractive lenses are described. The first approach fabricates the diffractive lens interferometrically, utilizing a spherical wavefront to provide the optical power of the lens and a computer generated hologram to create the aspheric components. The second approach fabricates the aspheric diffractive lens in the form of a higher order kinoform which trades groove profile fidelity for coarser feature size. The design and implementation issues for these two fabrication techniques are discussed.

1.0 Introduction

The advantages offered by diffractive lenses are well known. A lens with an arbitrary aspheric phase function can be easily implemented on a thin and light weight substrate. However, if the lens is very fast (f/number <1) and the operating wavelength is short, the groove spacing at the edge of the lens becomes very narrow. For example, with a f/1 lens designed for 0.5µm operation, the zone or groove spacing at the edge is only 1.1µm. Fabricating the lens via the binary optics technique [1], the pitch of the binary masks for a 4-level lens will be about 0.25µm. In addition, the masks must be aligned with an accuracy much better than 0.25µm. If the size of the lens is also large (>25mm diameter), a substantial amount writing time with an electron beam machine will be required. Making the matter worse is the need to lower the beam intensity in order to achieve the fine pitch which further lengthen the writing time. Therefore, the fabrication of a large and fast diffractive lens with the binary optics technique is a very expensive proposition.

2.0 Computer-Originated-Hologram

To reduce the demand on the writer, optical interferometric recording can be combined with computer generated holography. Instead of generating the aspheric lens function directly as a computer generated diffractive optical element, the lens is fabricated

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by interfering a spherical wavefront produced by a refractive lens (e.g. a microscope objective) with the aspheric wavefront produced by a computer generated hologram [2] as illustrated in Figure 1. Let the desired phase function of an aspheric lens with focal length f be $\theta_H(x,y)$, and

$$\theta_S(x,y) = \frac{2\pi}{\lambda}\left[f\sqrt{1+\frac{(x^2+y^2)}{f^2}}\right]$$

be the spherical phase function that matches the optical power of the aspheric lens. A holographic lens with the desired phase function is obtained by interfering the spherical wavefront with an aspheric wavefront having a phase function of $\theta_A(x,y)$ where $\theta_A(x,y) = \theta_S(x,y) - \theta_H(x,y)$.

To achieve high diffraction efficiency, the hologram has to be recorded in the form of an off-axis volume Bragg hologram [3]. Special design considerations must be taken to produce an on-axis lens with uniformly high diffraction efficiency across the entire lens.

An on-axis lens can be created by bonding two off-axis holographic lenses together which share a common reference beam as shown in Figure 2. The desired phase function of the lens is once again decomposed into spherical and aspherical components. The spherical component, $\theta_S(x,y)$, is recorded on the first hologram using a diverging spherical object wavefront and the aspheric component, $\theta_A(x,y) = \theta_H(x,y) - \theta_S(x,y)$, is recorded on the second hologram with an aspheric wavefront produced by a computer generated hologram.

In the example, the spherical phase function is placed in the first hologram and the aspherical phase function is put in the second. It does not have to be the case. The choice of the recording wavefronts is dependent on the operating geometry for which the lens is designed. To assure diffraction efficiencies that are uniformly high across the entire lens, the rays in the object wavefronts used to record the two holograms must match as closely as possible the ray directions of the input and output fields in the playback geometry. A wide angle diffractive lens had been fabricated using this approach [4]. The f/0.7 lens was designed to detect and determine the angle of arrival of 850nm laser radiation. The rms spot size and the diffraction efficiency of the diffractive lens were both uniform to within 10% over a field of view of 45° x 45°.

Using a microscope objective to provide the optical power, the slope of the remaining aspheric term will not be very steep. The computer generated hologram can be fabricated by a variety of writing machines, including the laser writer described in the following section.

2.0 Higher Order Kinoform

Kinoform [5] and Fresnel lens are both collapsed versions of a refractive lens. With a Fresnel lens, the optical path differences (OPDs) at the transitions between zones are many wavelength. The OPDs between zones can vary slightly and they are not exactly integer number of wavelengths. In other words, the zones of a Fresnel lens are not phased to produce diffraction limited performance. The optical path difference at the transitions between the zones of a kinoform, on the other hand, is exactly one wavelength. The angle of the first order diffraction of a kinoform matches the refraction angle of the wedge shape groove and a diffraction efficiency near 100% can be obtained.

A higher order kinoform resides between a Fresnel lens and a conventional, or first order, kinoform. The optical path difference between zones of an nth order kinoform is exactly equal to n wavelengths where n is an integer number greater than one. The zone spacing of an nth order kinoform is n times wider than its 1st order counterpart as illustrated in Figure 3. With a higher order kinoform, the angle of the nth order diffraction matches the refraction angle and a diffraction efficiency near 100% can also be achieved.

Higher order kinoforms are attractive because they can be fabricated very efficiently with a laser writer. A laser writer uses a focussed laser beam to expose a photo-sensitive recording material such as photographic film or photoresist. The scanning of the laser spot over the recording material can be accomplished by moving the recording material under the beam using a translator or a rotating drum, or by scanning the beam with a polygon, holographic or acousto-optics scanner. The spot size of a laser writer is typically >1μm which is much larger than available with e-beam writing machines. However, a laser writer is capable of postioning resolutions that are much finer than the spot size. In addition, they can provide gray scale writing capability with up to 8-bit of dynamic range.

To achieve high diffraction efficiency, the profile of the zones of a kinoform lens must be produced with high fidelity. It can be accomplished only if the spot size of the writing beam is smaller than the zone spacing. A 1st order kinoform with a zone spacing of 1μm, for example, cannot be fabricated with a laser writer whose spot size equals to or larger than 1μm. The laser writer, however, can be used to fabricate a higher order kinoform of the same lens function as illustrated in Figure 4. The laser writer cannot produce the sharp transition between zones but its effect on diffraction efficiency becomes less and less significant as n becomes larger. We should emphasize, however, that the fabrication of higher order kinoform does not reduce the resolution requirement in the positioning of the writing beam.

While using a larger n will place less demand on the spot size, it will also require a larger dynamic range, more linear recording and better control of the coating thickness. The rms phase error introduced should be < 1/8 of a wave to provide diffraction limited performance. As the zone becomes larger and higher, it will be increasingly more difficult to achieve the required profile fidelity.

In Figure 5, we show the normalized film thickness of a linear photoresist coating after processing as a function of exposure energy. The recording can be linearized by using a lookup table to adjust the exposure energy accordingly. Figure 6 shows the profilometer trace of linear grooves fabricated on a 5μm coating. They correspond to zones of a 5th order kinoform designed for 500nm operation. The rms phase error was less than 1/8th of a wave.

4.0 Concluding Remarks

It is difficult and expensive to fabricate a fast diffractive lens of appreciable size using the binary optics fabrication technique. We have described two alternate approaches that can be used to fabricate very fast diffractive lenses with arbitrary aspheric phase functions at much lower cost. The computer-originated hologram combines the strengths of optical holographic recording and computer generated hologram. The higher order kinoform trades profile fidelity for coarser feature size. Both approaches can be implemented using a laser writer with a spot size > 1μm. The use of laser writer is attractive for the following reasons. 1) Laser writers are much less expensive to acquire and operate than e-beam writing machines. 2) The spot size is independent of the laser power which allows very high writing speed by using a high power laser. 3) With gray scale writing capability and beam positioning resolution much finer than the spot size, a computer generated hologram can be written directly from its phase description without special coding or formatting. 4) By writing first onto a photographic film to form a gray scale mask, copies can be made on linear photoresist or other materials by simple contact printing.

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References

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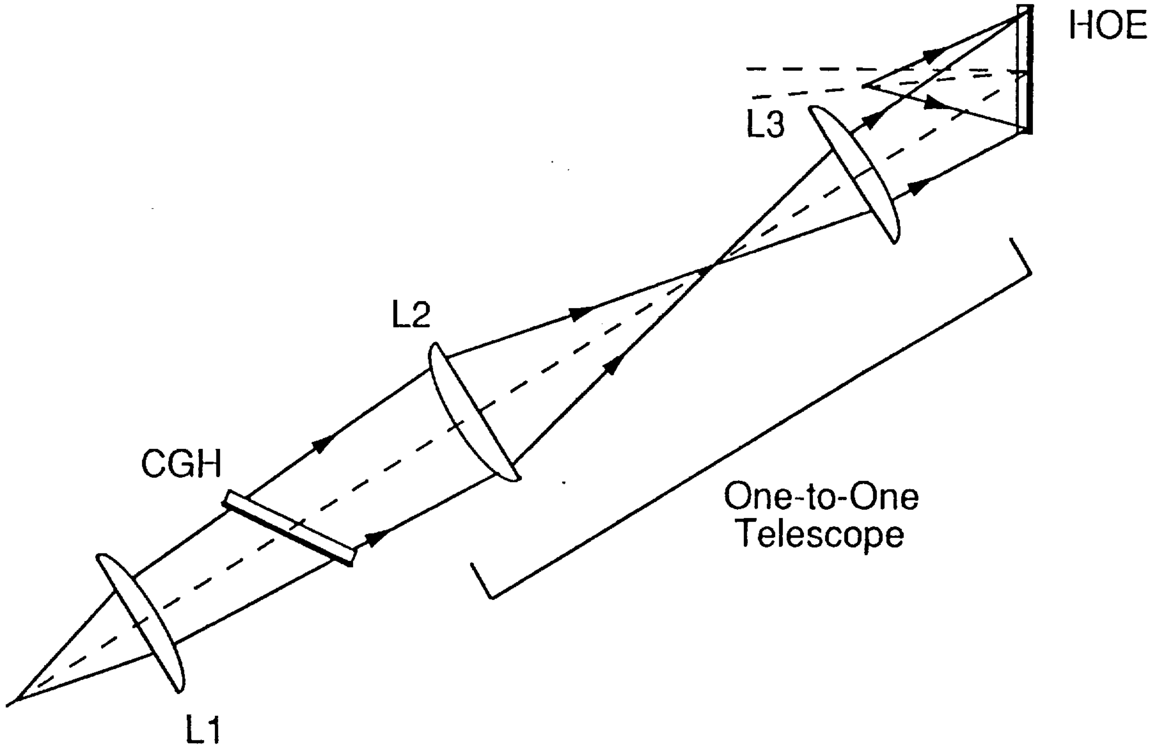
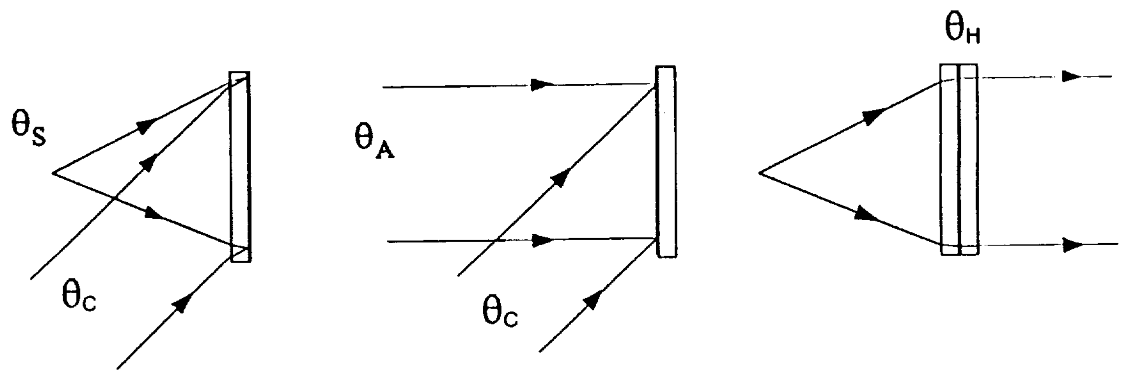


Figure 1. Fabrication of a computer-originated hologram.



Desired phase function $\theta_H = \theta_S + \theta_A$

Figure 2. Fabrication of an on-axis lens by bonding two off-axis volume holograms

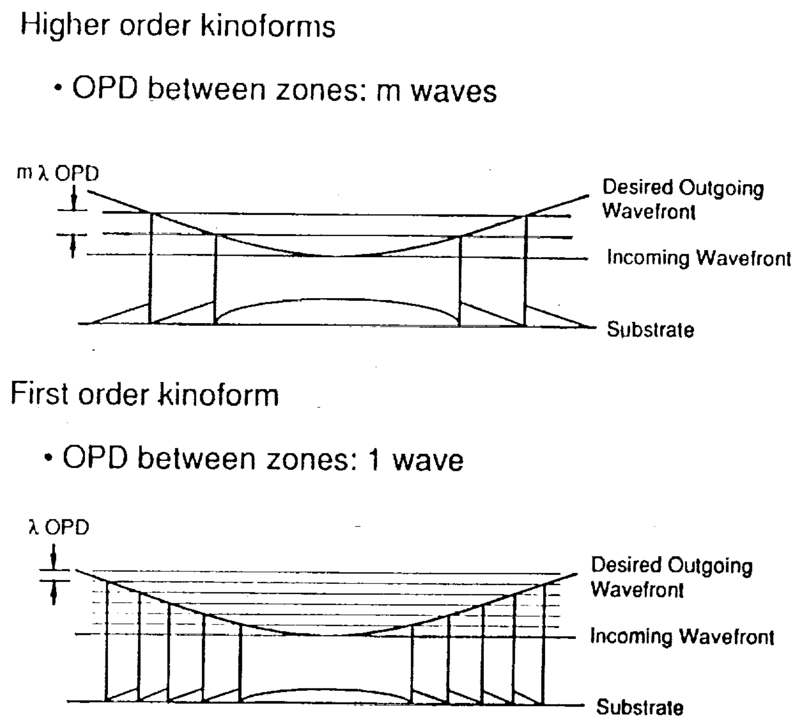


Figure 3. First order and higher order kinoforms

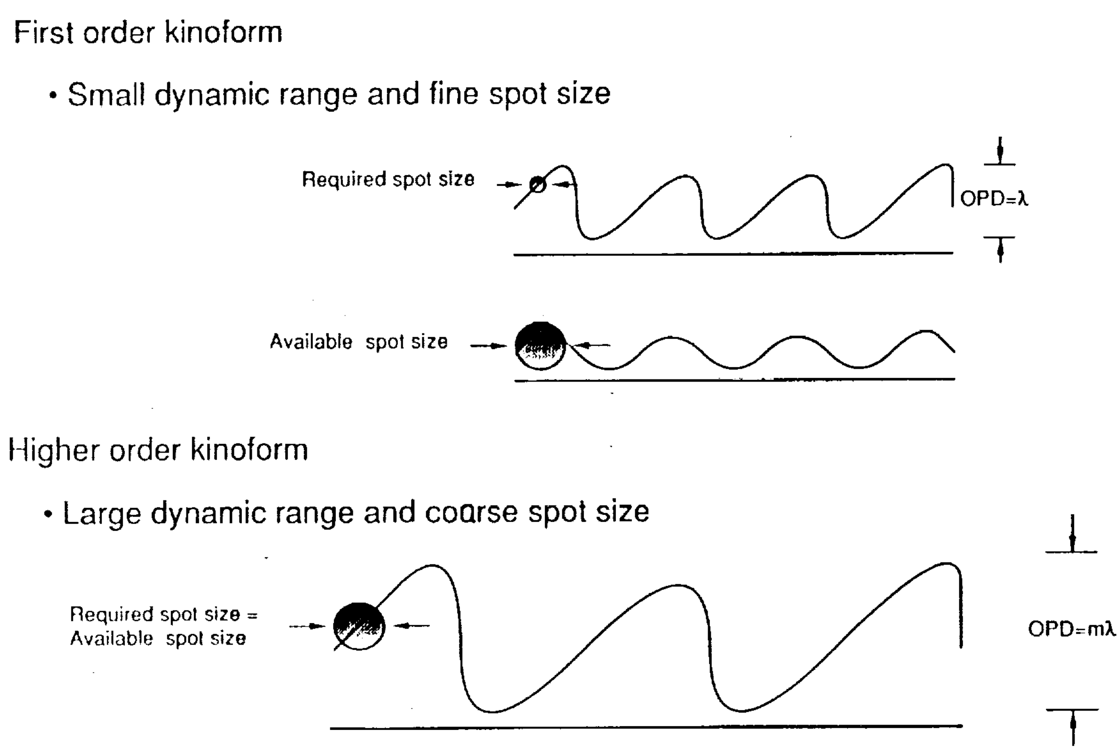


Figure 4. Fabricating kinoforms with a laser writer

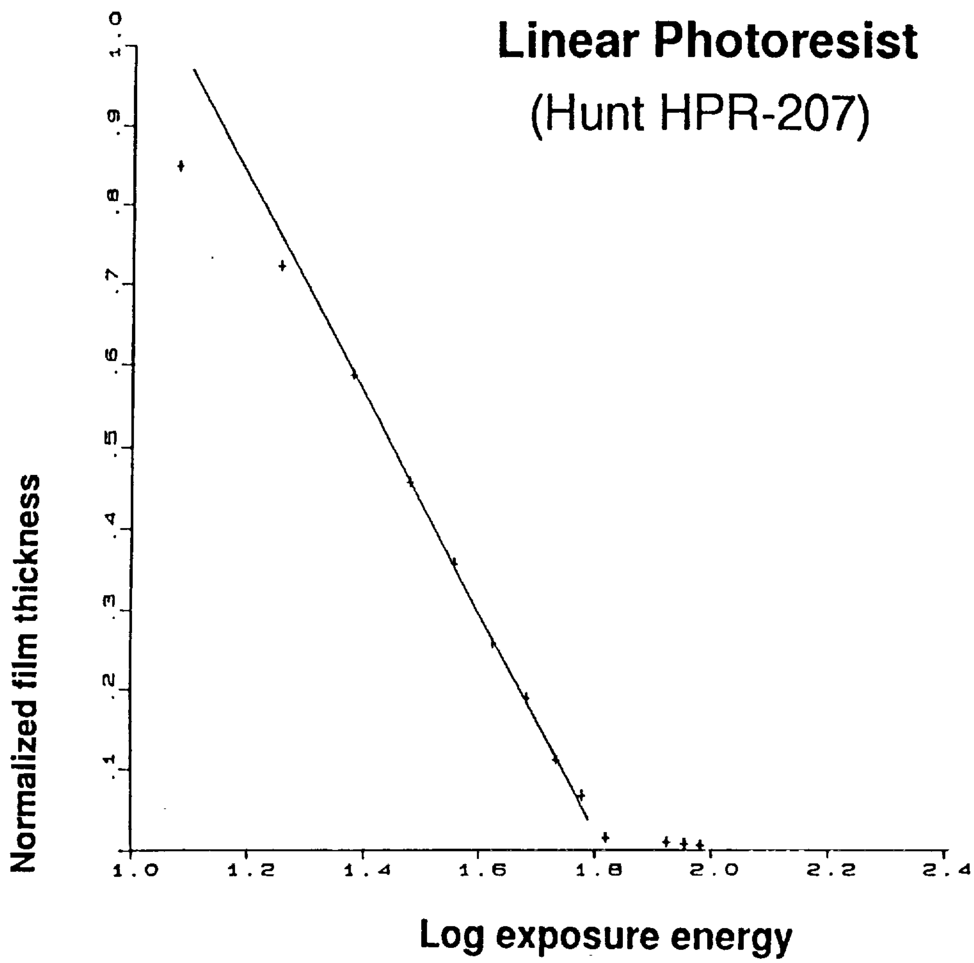


Figure 5. Normalized film thickness of photoresist after processing as a function of exposure energy

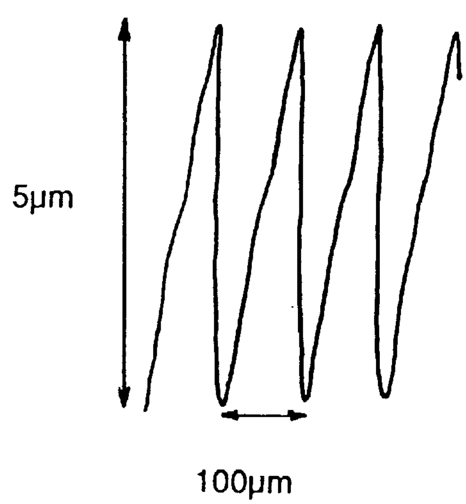


Figure 6. Profilometer trace of linear blaze fabricated on linear photoresist. (Corresponds to 5th order kinoform designed for 0.5μm operation)