fabricated.

A great deal of work has been reported recently on binary optics.[3,4] These elements can be made with high diffraction efficiency, by approximating the blazed profile of a kinoform with a staircase structure. We wondered how well we could produce axi-symmetric kinoforms by diamond machining.[5]

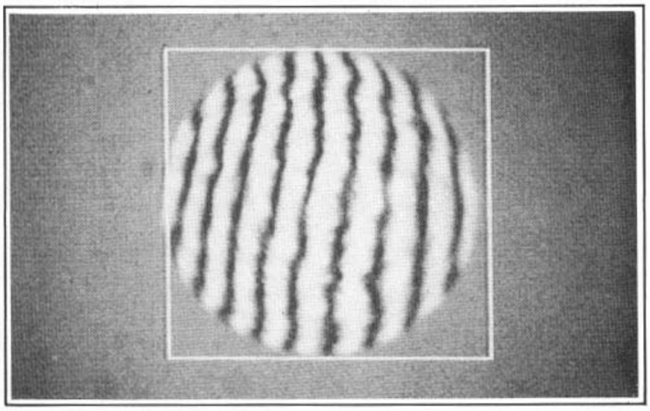
We attempted to produce a simple kinoform by single-point diamond machining a flat disk of polymethylmethacrylate (PMMA), a commonly used optical plastic. The kinoform was designed to focus collimated HeNe light with the diffracting surface toward the finite conjugate. Our intent was to determine the capability of the technique, so the specifications were ambitious: wavelength = 633 nm, clear aperture = 12.5 mm, EFL = 25 mm (f/2.0). This required 1215 annual facets. The width of the smallest facet was 0.0026 mm, and the step height was 0.0012 mm.

The fabrication challenge was significant! To maintain efficiency, the vertical steps in the sawtooth-like pattern of facets had to be kept steep, with sharp corners. This required careful selection of a diamond tool with a fine cutting point. A variety of cutting geometries and rates were explored.

We verified the phase continuity of the kinoforms. The wavefront error of the first diffracted order was recorded with a Fizeau interferometer (see figure). The fringes were continuous over the entire aperture, with 0.089 waves RMS wavefront error. The residual error was due largely to the quality of the substrate, not the kinoform itself.

We measured efficiency of the first and zeroth diffracted orders by measuring the transmission of an unexpanded HeNe laser as the beam was translated across the lens. The best results maintained >70% efficiency over most of the f/2 aperture. Energy in the unwanted zero order was less than 2%.

Our expectation was that efficiency would decrease with increasing aperture because the errors of the machining process would become more significant as the kinoform facets become smaller. We attribute the axial losses mostly to scattering from the fine turning marks that occur when such a pointed tool is used.



Kinoform wavefront error

While the capability to produce non-symmetric aspheres or lens arrays is not as complete as with the computer-generated mask techniques, useful kinoforms can be produced by diamond machining. This method can easily be extended to spherical or even aspheric base curves.

This work was done with our colleagues D. Combs, J. Mader, and W. Plummer.

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Hybrid diffractive-refractive telescope

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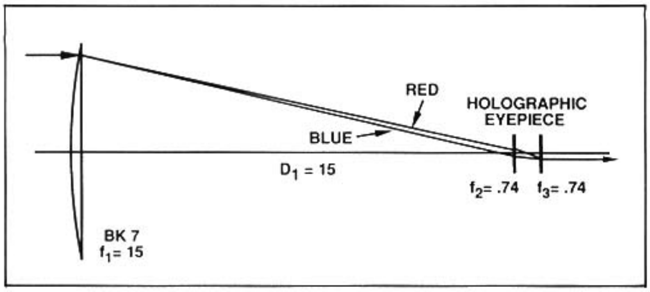
Many optical design advantages including smaller lens curvatures and larger aperture elements may be obtained from mixing diffractive and refractive elements to form hybrid lenses.[1,2] These advantages are also found in hybridizing conventional optical systems. Hybrid diffractive-refractive optical systems are particularly interesting due to recent advances in highly efficient, low scatter, broadband fabrication techniques such as bleached silver halide, dichromated gelatin, photopolymer recording materials, and blazed surface-relief techniques.[3–5] This optical benefit from mixing diffractive and refractive components in systems can be illustrated by our design for the hybrid telescope, in which the compound achromat objective is replaced by a much simpler singlet or low-curvature doublet when followed by a diffractive eyepiece. In contrast to the design shown, earlier workers have considered combinations of achromatic groups, e.g., see the Galilean telescope with an achromatic objective followed by an achromatic holographic doublet eyepiece.[6]

Telescopes, binoculars, and similar systems traditionally require achromats for objective elements, since the longitudinal chromatic aberration from a singlet objective is so large that eyepieces cannot readily correct it. However, such achromats can limit large-aperture systems because



First-order design for a novel hybrid telescope consisting of a single glass (BK-7) objective with a two-element diffractive eyepiece. In one design, this holographic eyepiece consists of two positive elements of focal length $f_2 = f_3 = 0.74$, separated by their focal length.

the curvatures required of their components are much stronger than the curvatures of singlets with the same net optical power. Also, much larger quantities of optical materials are required, which is of particular concern in the infrared and in systems where weight is a factor. For example, in the visible spectrum, an achromat is classically formed by starting with a low-dispersion (crown) element containing 2.5 times more optical power than required in the final objective (and hence with much stronger surface curvatures). Then a negative lens made from high dispersion (flint) glass is cemented to the positive element, thereby eliminating the excess power and achromatizing the objective. The artificially enhanced curvatures in the crown element limit the maximum aperture and aggravate aberrations in resultant achromats. However, a hybrid diffractive/refractive telescope can eliminate the need for such bulky objectives, since a diffractive eyepiece is capable of correcting the large longitudinal and transverse chromatic aberrations of singlet refractive objectives. The separation between the red and blue foci for both diffractive and refractive lenses is roughly the focal length divided by the V-number. For glass elements, the V-number is 20–80, while for a diffractive lens in the visible it is close to −3.5. Setting these contributions equal and opposite corrects the chromatic aberration and constrains the ratio of focal lengths—hence the magnification—to be the ratio of V-numbers, e.g., in the range of 6–23 for visible-band materials. By splitting the holographic eyepiece into two elements, lateral color (variation of magnification with wavelength) may also be corrected.

A first-order hybrid telescope layout is illustrated in the figure. The simple singlet objective has a focal length of 15 in green light, matching the separation between the objective and the first diffractive eyepiece element. Axial green rays pass through the center of the first eyepiece lens and are re-collimated by the second lens of the eyepiece.

As shown in the figure, red and blue axial rays receive too little and too much optical power from the singlet objective, respectively, but are brought to a common height and collimated by the diffractive eyepiece, thus eliminating both longitudinal and lateral chromatic aberrations.

Many variations on this first-order hybrid telescope are possible including using "hybrid singlets"[1] either in the objective or in the eyepiece. These hybrid lenses exhibit nearly arbitrary V-numbers, and would thus allow simplified telescopes with a broader range in magnification. Similarly, forming the diffractive elements on curved substrates offers an additional degree of freedom in the higher order optical design. Finally, we note that these diffractive components may be volume holographic elements, surface relief, binary, computer generated elements, etc., depending on the best design approach for the desired efficiency, bandwidth, and spectral region.

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Wide field diffractive lenses for imaging, scanning, and Fourier transformation

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Diffractive optical elements offer the potential to reduce significantly the weight, size, and cost of a variety of optical systems that currently use refractive and/or reflective components. Unfortunately, the utility of conventional holographic lenses has been plagued by uncorrected field aberrations, particularly coma and astigmatism. However, recent advances in surface-relief diffractive lenses provide the optical designer with enough degrees of freedom to eliminate third-order coma, astigmatism, and field curvature.

We have developed a set of design equations[1,2] for the third-order (Seidel) aberrations that include the effects of the location of the diffracting zones, the placement of the aperture stop, and the bending of the diffractive lens substrate. We find that with a single, planar diffractive element, one can completely eliminate third-order coma,