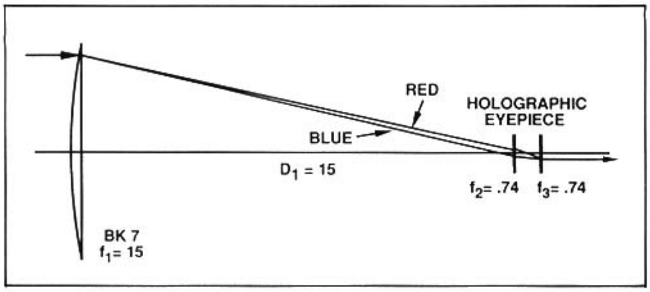

First-order design for a novel hybrid telescope consisting of a single glass (BK-7) objective with a two-element diffractive eyepiece. In one design, this holographic eyepiece consists of two positive elements of focal length $f_2 = f_3 = 0.74$, separated by their focal length.

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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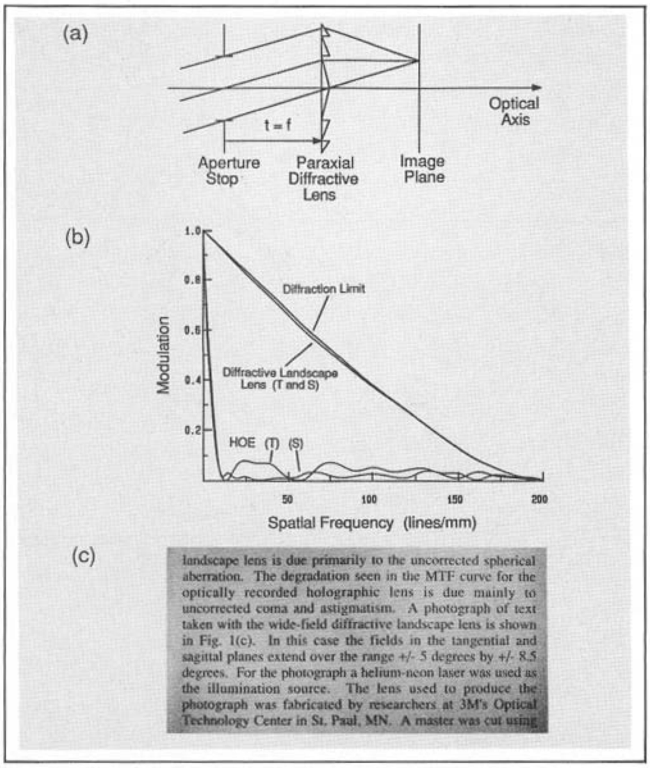
Diffractive optical elements offer the potential to reduce significantly the weight, size, and cost of a variety of optical systems that currently use refractive and/or reflective components. Unfortunately, the utility of conventional holographic lenses has been plagued by uncorrected field aberrations, 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,



landscape lens is due primarily to the uncorrected spherical aberration. The degradation seen in the MTF curve for the optically recorded holographic lens is due mainly to uncorrected coma and astigmatism. A photograph of text taken with the wide-field diffractive landscape lens is shown in Fig. 1(c). In this case the fields in the tangential and sagittal planes extend over the range +/- 5 degrees by +/- 8.5 degrees. For the photograph a helium-neon laser was used as the illumination source. The lens used to produce the photograph was fabricated by researchers at 3M's Optical Technology Center in St. Paul, MN. A master was cut using

Telecentric diffractive landscape lens. The system layout is shown in (a), with the aperture stop located in the front focal plane of the lens. The modulation transfer functions of $\lambda = 0.6328\ \mu m$ for an F/8 diffractive landscape lens and an F/8 holographic lens at 10° off-axis are shown in (b). S and T refer to the sagittal and tangential orientations of the target grating lines. A photograph taken with an F/8 diffractive landscape lens is shown in (c). The illumination was provided with a HeNe laser. The field of view is approximately 10° × 17°.

astigmatism, and field curvature by the proper choice of zone locations and aperture-stop position, and that the higher-order field aberrations are small. If required, correction of the remaining spherical aberration can be accomplished using an aspheric plate located in the aperture stop. These results allow one to achieve diffraction-limited (monochromatic) imaging over a wide field of view using a single, planar diffractive lens with remote aperture stop. The bending of the substrate can be used to provide a desired (non-zero) amount of spherical aberration or distortion. The elimination of field curvature and astigmatism provides a well corrected image that is formed on a planar, rather than curved, surface; hence, these diffractive lenses are well suited for imaging applications involving photodetector arrays.

The layout for a wide-field diffractive landscape lens is illustrated in part (a) of the figure. The diffractive structure consists of Fresnel zone-type rings. The radius of the mth zone r_m is taken to be $r_m = [2m\lambda_o f]^{1/2}$, where λ is the design wavelength and f is the focal length of the lens; this is simply the paraxial approximation to the Fresnel zone formula. In effect, by choosing the paraxial form for the zone spacings, one is building a specific amount of spherical aberration into the lens element. When the aperture stop is placed in the front focal plane of the lens, this built-in spherical aberration is used to eliminate the coma and astigmatism. In addition, field curvature is automatically zero for a diffractive lens. To obtain high diffraction efficiency, each zone is blazed—a linear blaze yields a theoretical diffraction efficiency of 99%.

The performance that can be obtained with an f/8 diffractive landscape lens (object located at infinity) is shown in part (b) of the figure. MTF curves for the diffractive landscape lens are compared to an ideal diffraction-limited lens and an optically recorded holographic lens; these curves were generated using exact ray tracing methods. Each lens has an f-number equal to f/8, and a focal length of 100 mm. The field angle for each lens is taken to be 10°. The small dip in the central portion of the curve for the diffractive landscape lens is due primarily to the uncorrected spherical aberration. The degradation seen in the MTF curve for the optically recorded holographic lens is due mainly to uncorrected coma and astigmatism. A photograph of text taken with the wide-field diffractive landscape lens is shown in part (c) of the figure. In this case, the fields in the tangential and sagittal planes extend over the range +/- 5° by +/- 8.5°. For the photograph, a helium-neon laser was used as the illumination source. The lens used to produce the photograph was fabricated by researchers at 3M's Optical Technology Center in St. Paul, Minn. A master was cut using diamond turning methods. The master was then used in a compression-molding operation to form a replica lens in PMMA.

In addition to imaging applications, wide-field diffractive singlets make excellent Fourier transform lenses[1] and laser line-scan (F-Θ) lenses.[2] The performance of the wide-field diffractive singlets has been compared to conventional refractive lens systems. With monochromatic light, it is found that the diffractive lenses provide equal or superior performance to that obtained with refractive lens systems containing several elements. The savings in weight and cost can be substantial.

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