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Infrared Information Symposia (IRIS)

Passive Sensors

J. S. Accetta
M. J. Cantella
Chairs/Editors

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Proceedings
Infrared Information Symposia (IRIS)

Passive Sensors
(Selected Papers 1990–1992)

The papers published herein have been approved for unlimited distribution and represent recent selections from the Proceedings of the Infrared Information Symposia (IRIS), an official sponsored activity of the Defense Technical Information Center. IRIS consists of a number of specialty groups representing major technology thrusts in military infrared and electro-optics technology including Targets, Backgrounds, and Discrimination; Passive Sensors; Active Systems, Materials, and Detectors; and various related subspecialties. IRIS is administrated by the Infrared Information Analysis Center (IRIA), Environmental Research Institute of Michigan (ERIM).

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CONTENTS

The Use of Diffractive Optical Element in 3-5 Micrometer Optical System

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Hughes Aircraft Company

Abstract

The use of diffractive optical elements (DOE) in most refractive reimaging infrared optical systems significantly simplifies the optical design form and improves the image quality. The basic theory of chromatic aberration correction using DOE is analyzed. A 3 to 5 um design is shown comparing the optical design form and image quality of the conventional design and the DOE improved design. The DOE improves performance while lowering cost and weight by reducing the number of lens elements and desensitizing the design to misalignments. MTF, MRT, and NEDT tests of the hardware empirically demonstrate the superior performance of the DOE design.

I. Introduction

Diffractive optical element has been applied to many imaging optical systems for more than twenty years. However, the applications so far are mainly limited to optical systems, such as head-up display (HUD), helmet-mounted display (HMD), etc., with very narrow spectral bandwidth. The use of diffractive optical element to correct the axial chromatic aberration of a silicon lens was first proposed by G. J. Swanson and W. B. Veldkamp in 1987 (reference 1). To obtain a very high diffraction efficiency for the diffractive optical element, Swanson and Veldkamp proposed a multi-step-level kinoform-like Fresnel phase zone plate to replace the continuous kinoform Fresnel zone plate (reference 3). The authors name this new class of optical element as "binary optics" because its fabrication method is basically similar to that of digital electronic parts.

A new class of optical element consisting of an aspheric and a diffractive optical element has also been proposed by Chungte W. Chen (reference 2) to significantly simplify many optical system and at the same time obtain a much better image quality. The aspheric surface and lens shape factor of this new optical element are used to eliminate spherical aberration and coma simultaneously. The diffractive optical surface is used to correct axial chromatic aberration and spherochromatism. This new class of optical element is particularly effective to simplify a low f-number optical system.

This paper describes the application of a diffractive optical element for the mid-infrared (Mid-IR) optical systems. An f/1.4, 18.0 degrees field of view, 0.608 inch effective focal length (EFL) imager is used to demonstrate the advantages of using diffraction optical element for the mid-IR optical system. Section II describes the design principles of an imager consisting of a diffractive optical element. Then, the differences between the conventional imager and the improved design are compared. Section III discusses the fabrication of this improved imager, including the diffractive optical element. Section IV compares the image quality of the both imagers, including the modulation transfer function (MTF) and noise equivalent differential temperature (NEDT).

II. Design Principles

An infrared re-imaging optical system generally consists of two modules: the objective group in front of the intermediate image plane and the relay group following the intermediate image. Figure 1.a is a typical IR re-imaging imager. It has unique properties when compared to a non-re-imaging type such as better off-axis radiation rejection, 100% cold shielding with the cold stop next to detector module, an accessible entrance pupil, smaller optical elements, ease of packaging, and limited pupil wander.

To obtain good image quality in a re-imaging optical system, the axial color of both groups has to be individually well corrected. Although , in principle, the front group axial color can be removed by the rear group, the required additional negative power of the "flint glass" in the rear group upsets the third order aberration balances. In addition, it generates additional higher order aberrations. The spherical aberration and coma of both front and rear groups has to be also partially corrected within each group. If the spherical aberration and coma of both groups are not partially corrected, the " stop shift (non-zero chief height) " induced astigmatism can not be balanced out.

The improved imager consisting of refractive and diffractive optical elements is showed in Figure 1.b. The system retains all the properties of the conventional design shown in Figure 1.a, yet the optical form is much simpler and the image quality is improved. A 40% of reduction in the number of elements has been realized. In addition, the weight and cost of the system are significantly reduced. The design principles of a re-imaging optical system consisting of refractive and diffractive optical elements are summarized as following:

1) The primary lateral color, secondary lateral color, and coma are self-corrected through the "symmetry principle", where the front group and rear group are "symmetric" with respect to the intermediate image plane.

2) The axial color of the whole system is corrected by a diffractive optical element in the second group. This diffractive optical element can also be used to correct high order chromatic aberrations such as spherochromatism and chromatic coma. Since the optical power of this diffractive element is positive, it contributes a portion of the overall system power, contrary to a classical flint glass. As a result of employing the diffractive

optical element for chromatic aberration correction, the intrinsic aberrations of each element in the optical system are significantly reduced. Thus the aberration correction of the whole system is greatly simplified.

3) The spherical aberration and coma of both groups are corrected by either employing aspherical surfaces , bending the lenses, or the combination of both.

4) The astigmatism is corrected by disposing lens elements in the proper positions with adequate optical power distribution.

5) The field curvature is significantly reduced, as compared to the conventional equivalent system, as a result of employing diffractive optical element and judicious glass selection.

The H-TanU curves of both systems are shown in Figures 2 and 3, respectively. The top, middle and bottom curves in each figure are the H-TanU curves corresponding to the full field, 70% field and on-axis, respectively. The design constructed according to the above principles shows much better chromatic as well as high order aberration correction.

III. Fabrication Methods

A refractive continuous phase profile can be reduced into discrete 2 pi increments located along a common plane (Figure 4). A diffractive Fresnel zone plate type of phase profiles is formed in this manner (Figure 4b). This analog type of surface relief profile is commonly known as a kinoform and is capable of achieving 100 % diffraction efficiency at its functional wavelength. A digitized approximation to the kinoform is known as a binary optic and can be constructed as shown in Figure 4c. However, this 2-level approximation suffers from low diffraction efficiency. Therefore it is necessary to create a multilevel profile which more exactly approximates the analog profile (Figure 4d). Efficiencies of 99 % or better are achieved by surface profiles containing 16 or more digitized levels. Surface relief binary structures can be fabricated into a conventional refractive lens (Figure 4e).

Digital type binary surfaces are generally fabricated on conventional refractive element substrates via photo-lithography. A 16 level binary profile, for example, requires 4 photo-mask and etching operations. Kinoform analog surface relief profiles can be formed by single-point precision diamond machining methods. Hughes Aircraft Company possesses the capability to fabricate both digital and analog surface relief profiles (Figure 5).

On 1990 IR&D, Hughes built and tested the diffractive imager shown in Figure 1b. To maximize the diffraction efficiency, single-point precision diamond machining was used to create a kinoform surface relief on the germanium lens element. This kinoform element required 14 2-pi zones (Figure 6a). Figure 6b shows these zones as fabricated on the lens. The lighting used to capture the picture of the kinoform was arranged to highlight its diffractive nature. The success of achieving the required analog pattern is exhibited in the profilemetric trace of the surface (Figure 6c).

IV. Hardware Demonstration

To evaluate the diffractive imager, its performance characteristics were compared to an existing imager designed and fabricated via conventional methods. Both imagers are F/1.4 in speed with a .608 inch effective focal length, operate between 3.4 - 4.2 micrometer, and are mechanically interchangeable (Figure 7). Comparison of conventional v.s. binary imager optical assemblies was made on the basis of modulation transfer function (MTF), minimum resolvable temperature (MRT), noise equivalent differential temperature (NEDT), and optical transmittance. In all cases, the diffractive imager performance was superior.

The MTF measurements were conducted on a Diversified EO 1300 Optical System. In this test, a knife edge traces through the optical blur to evaluate the MTF. Unlike a simple wavefront test, all of the energy in the image including wavefront, scatter and diffraction efficiency is accounted for in the resultant MTF. Table 1 lists the MTF results. Note that the diffractive imager dramatically out performs the conventional imager.

The transmittance data was determine analytically. The reflectance and transmittance values for conventional optical elements were based on witness sample data from optical coating runs. For the diffractive imager, the transmittance must also account for the diffraction efficiency of the kinoform. The diffraction efficiency as a function of wavelength is shown in Figure 8. The imager was designed to operate from 3.4 - 4.2 micrometer and therefore has a theoretical diffraction efficiency of 98%.

The MRT and NEDT measurements were conducted in a Hughes sensor test station. The results are listed in Table 2. Note that the conventional imager results have all been normalized to 1.0. The diffractive imager again results in enhanced performance. The improvement in MRT can be attributed to the superior resolution of the diffractive imager. The NEDT result is most likely due to the higher transmittance made possible by the simplified diffractive imager.

V. Summary

The use of diffractive optics is a powerful design tool. We have shown analytically and empirically that the application of a DOE to a 3 - 5 micrometer imager significantly simplifies the optical design form and improves the optical performance.

VI. Acknowledgements

We wish to thank and acknowledge the contributions of Albert Efkeman and Donald Morrison of Hughes Leitz Optical Technologies. Mr. Efkeman originated the concept of precision diamond machining Kinoform surface reliefs; his crucial support and enthusiasm made the project a success. Mr. Morrison developed the tooling methodology that made possible the Kinoform fabrication.

Reference 1:

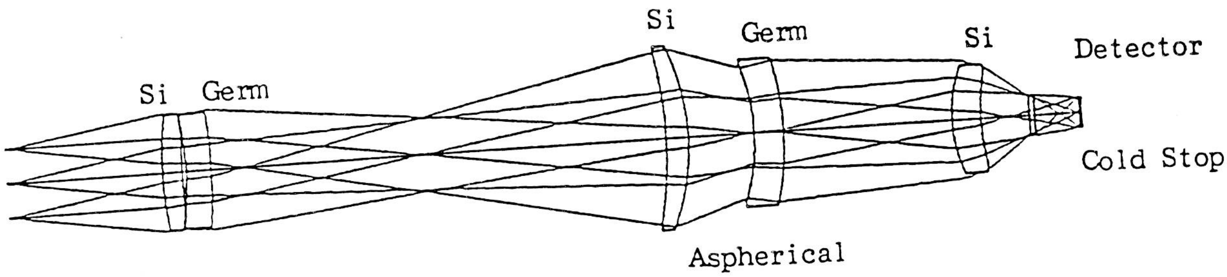
"Infrared Applications of Diffractive Optical Elements", Gary J. Swanson and Wilfrid B. Veldkamp, SPIE Proceedings, Vol.885,paper #22,1988.

Reference 2:

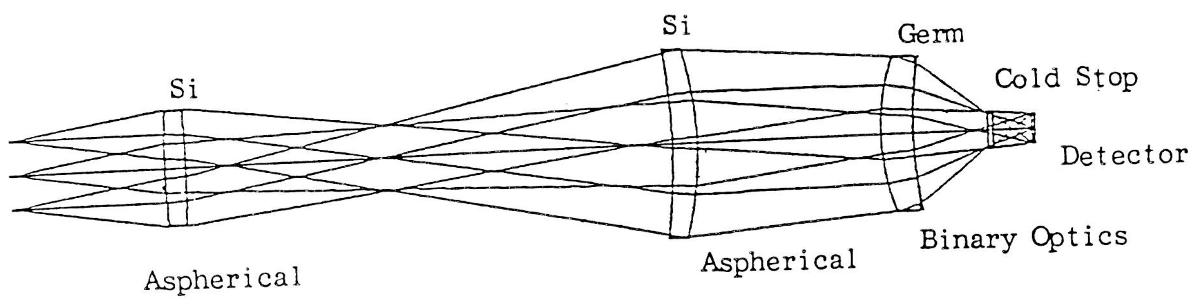
"Optical Element Employing Aspherical and Binary Grating Optical Surfaces". Chungte W. Chen, US patent, 5,044,706.

Reference 3:

"The Kinoform: a New Wavefront Reconstruction Device", L. B. Lesem, P. M. Hirsch, and J. A. Jordan,Jr., IBM J. Res. Dev.13, 150-155 (1969).



(a) Conventional Design



(b) Binary Design

Figure 1 The sketches of a conventional imager and its corresponding binary imager are shown in (a) and (b), rspectively.

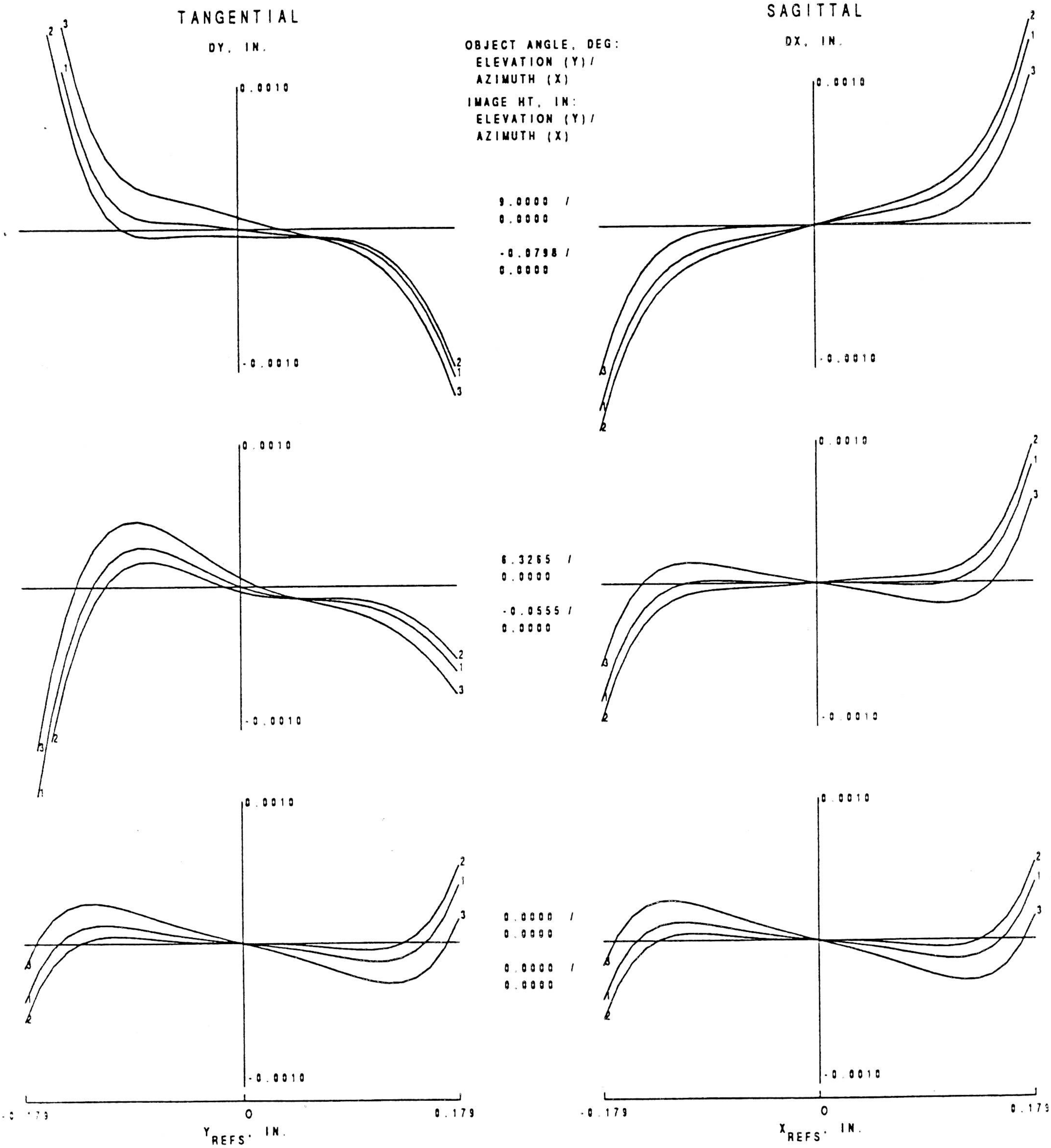


Figure 2 The H-TanU curves of the conventional imager shown in Figure 1.a

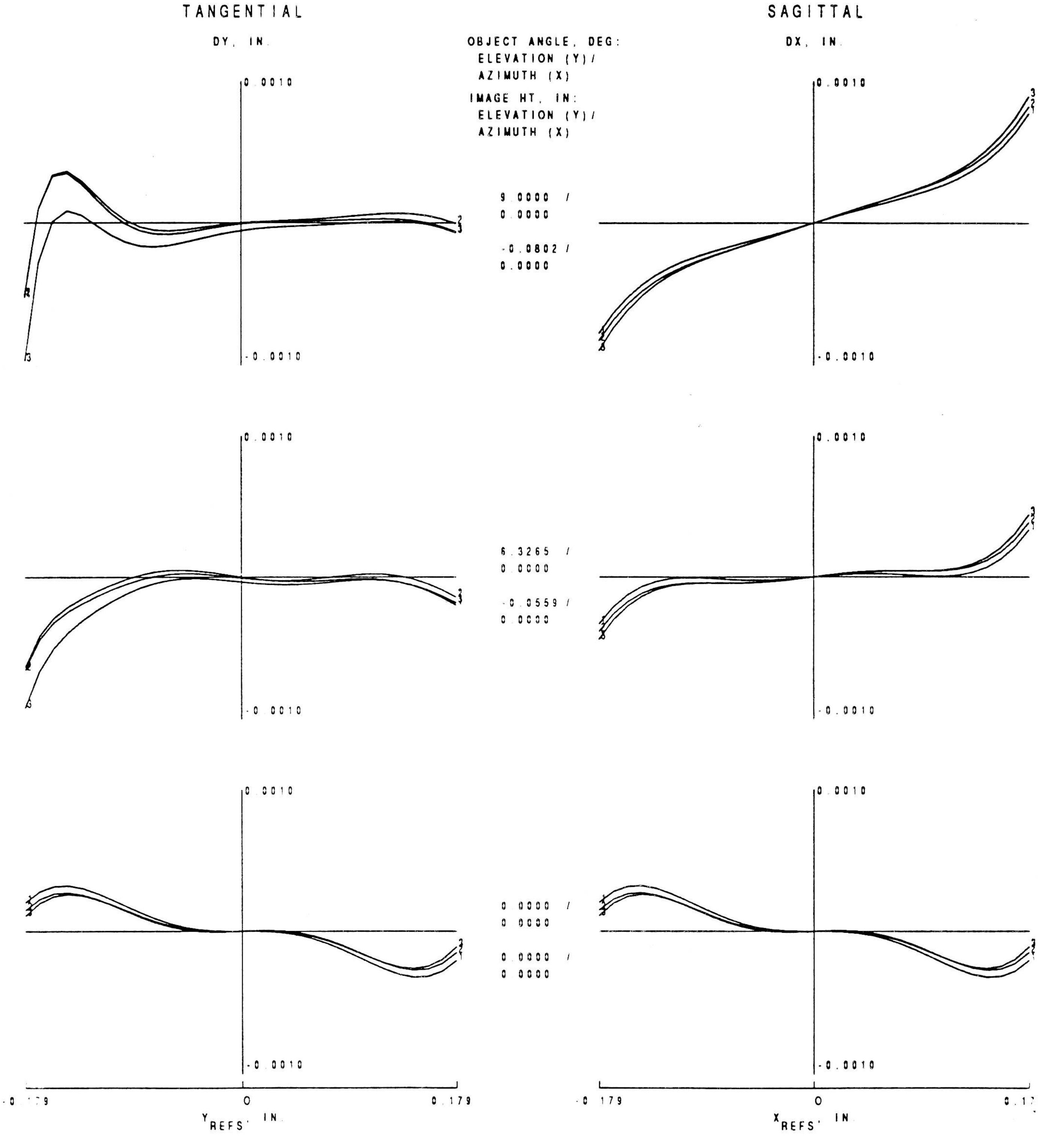


Figure 3 The H-TanU curves of the binary imager in shown Figure 1.b

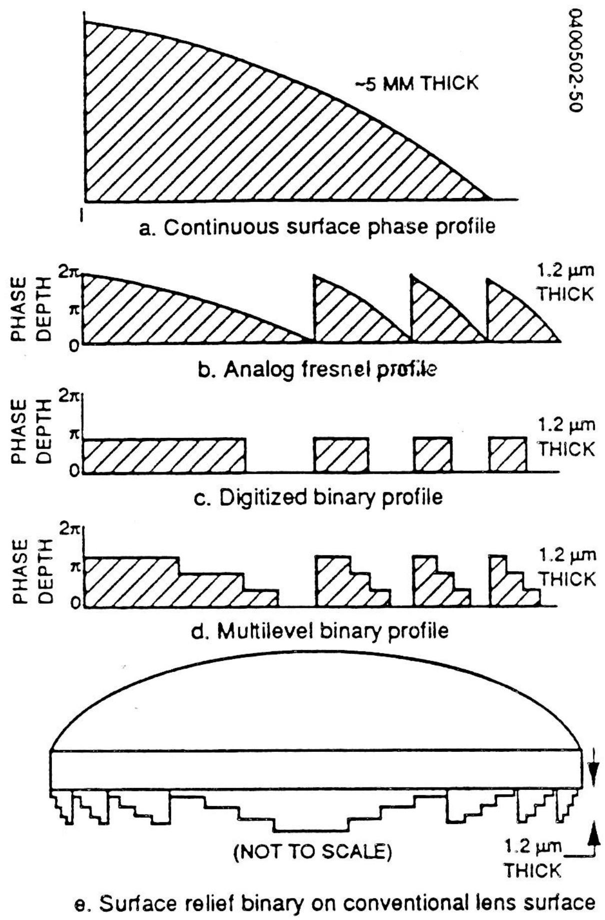


Figure 4. Binary Optics Concept. Binary optics are simple surface relief profiles with very high diffraction efficiency.

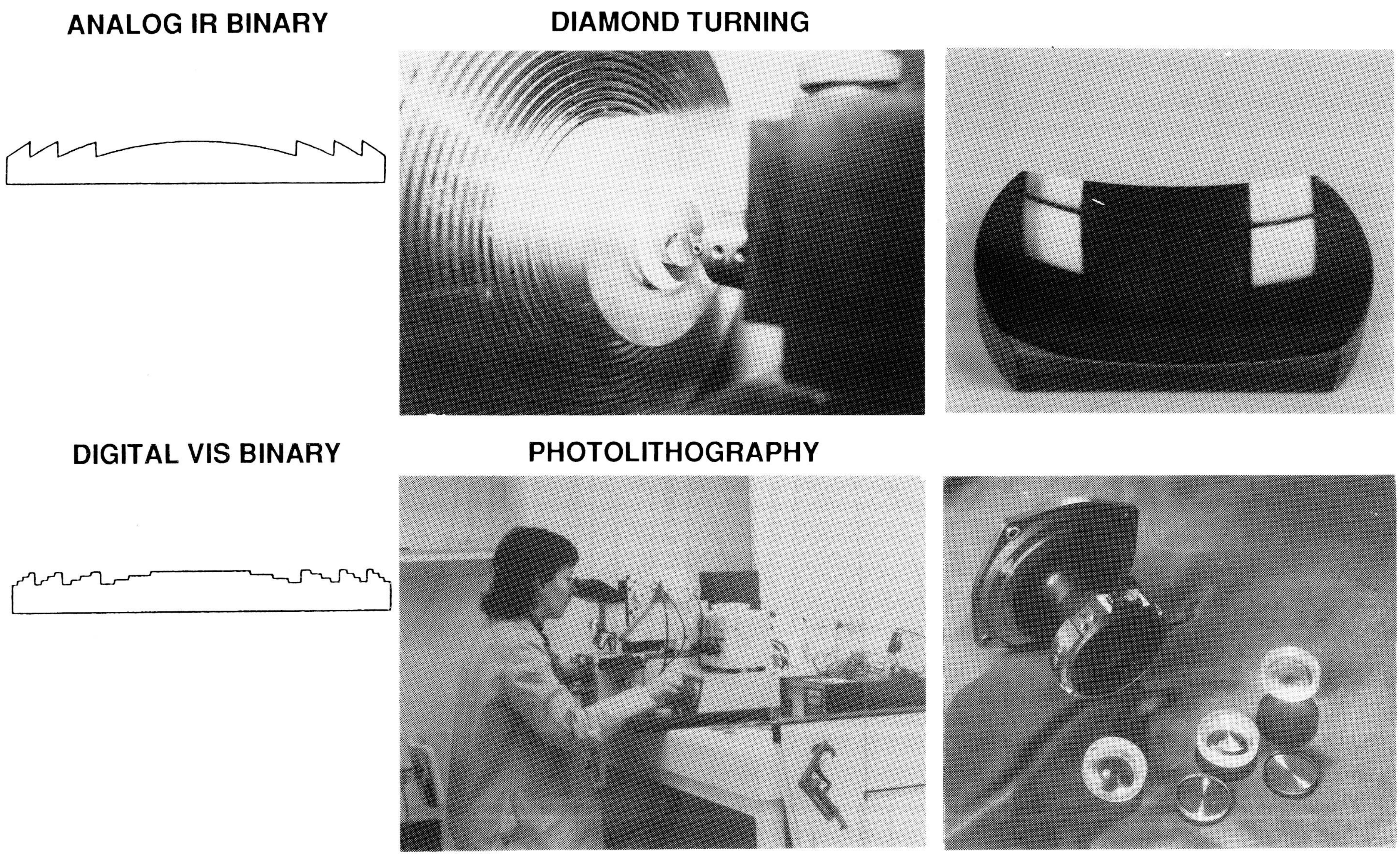


Figure 5. Hughes Diffractive Optics Fabrication Capability. Hughes can fabricate either analog or digital surface relief.