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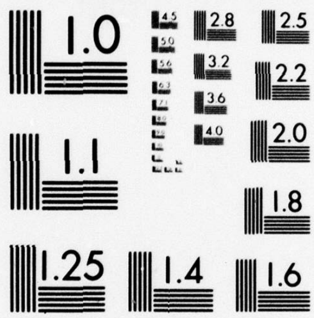

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TECHNICAL REPORT T-79-12

HOLOGRAPHIC OPTICS FOR MISSILE GUIDANCE SYSTEMS

B. D. Guenther and C. D. Leonard
Research Directorate
Technology Laboratory

20 December 1978

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U.S. ARMY MISSILE RESEARCH AND DEVELOPMENT COMMAND

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1. REPORT NUMBER T-79-12	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (*and Subtitle*) 6 HOLOGRAPHIC OPTICS FOR MISSILE GUIDANCE SYSTEMS.		5. TYPE OF REPORT & PERIOD COVERED 9 Technical Report. 6. PERFORMING ORG. REPORT NUMBER T-79-12
7. AUTHOR(s) 10 B. D./Guenther ~~and~~ C. D./Leonard		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Commander US Army Missile Research and Development Command Attn: DRDMI-TRO Redstone Arsenal, Alabama 35809		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Commander US Army Missile Research and Development Command Attn: DRDMI-TI Redstone Arsenal, Alabama 35809		12. REPORT DATE 11 20 Dec[redacted]978 13. NUMBER OF PAGES 27
14. MONITORING AGENCY NAME & ADDRESS(*if different from Controlling Office*) 12 29p.		15. SECURITY CLASS. (*of this report*) UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (*of this Report*)

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14 DRDMI-T-79-12

17. DISTRIBUTION STATEMENT (*of the abstract entered in Block 20, if different from Report*)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (*Continue on reverse side if necessary and identify by block number*)

Holographic optics
Refractive components
Reflective components
Diffractive components
Holography
Hololens

20. ABSTRACT (*Continue on reverse side if necessary and identify by block number*)

This report briefly compares holographic optics to more conventional optics and points out some of the advantages of using holographic optics in missile guidance systems. It describes the construction of two optical systems used to demonstrate some of the advantages of holographic optics.

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CONTENTS

I. INTRODUCTION

In this report we will briefly compare holographic optics to more conventional optics and point out some of the advantages of using holographic optics in missile guidance systems. We will then describe the construction of two optical systems that will be used to demonstrate some of the advantages of holographic optics.

A. Optical Components

Optical components may be classified into the following three groups according to the mechanism by which they operate:

1) Refractive Components - This type of component uses the fact that the direction of a light ray will change according to Snell's Law when the ray encounters a change in index of refraction (i.e., a change in the speed of light). Conventional lenses and prisms are examples of this type of device. The operation of the device depends upon the curvature of the surface and the index of refraction of the material.

2) Reflective Components - This type of component uses the fact that light is reflected from a metal surface (or a surface where the index of refraction changes) at an angle equal to the angle of incidence. Astronomical telescopes and shaving mirrors are examples of this type of device. The operation of the device depends upon the shape of the surface and the optical properties of the surface material used.

3) Diffractive Components - This type of component uses the fact that light exhibits wave properties and, thus, interferes with itself. Gratings and holograms are examples of diffractive components.

Diffractive components and in particular holograms differ from other types of optical components in the following ways:

1) The index of refraction of the material is not an important factor in component design. Phase holograms produce the diffraction gratings by modulating the index of refraction but here only the change in the index (the depth of modulation) is important.

2) The shape of the surface is not a first-order factor in component design. This allows conformal optics.

3) There is a large amount of dispersion - independent of component material which restricts simple designs to a narrow wavelength range.

4) Multiple functions can be combined in one element. For example, wavelength filtering and focusing elements can be produced in the same hologram.

5) Fabrication of a large number of copies is easier. In refractive or reflective components, replication techniques are restricted to only a few materials such as the plastics. Holographic elements can be replicated by contact printing or embossing which reduces their cost.

6) Computer generation of holographic elements is possible allowing the generation of components that cannot be constructed using reflective or refractive components.

The optical systems constructed for this report demonstrate some of the properties previously listed. Lenses were produced on a flat surface. Wavelength selective mirrors were produced that focus different wavelengths at different spatial locations. Finally, multiple copies of holographic lenses were produced by contact printing from a set of master plates.

B. Holographic Optical Elements

Holography is a method of recording a field and later reconstructing that field. There are no restrictions on the field other than it exhibit wave behavior. Thus, acoustic, optical, and radio frequency holograms have been produced. The radio frequency (RF) holograms are better known as synthetic aperture radar images. Figure 1 schematically shows the recording process for light. During the construction of a hologram, the interference between a source and reference wave are recorded by a photosensitive material. In regular photography, only the source wave (the image produced by a lens) would be present and the intensity variations of that source wave would be recorded. In holography, the addition of the reference wave allows us to record the direction as well as the intensity of the source wave. We can also eliminate any image producing lens that would be required in normal photography. After any required processing, the resulting hologram is illuminated by a reconstruction wave and a diffracted wave is produced by the hologram. The diffracted wave approximates the source wave; differences between the diffracted wave and the original source wave are due to nonlinearities in the photosensitive material and differences between the reconstruction wave and the original reference wave.

To make a hologram that performs the role of a simple lens, proceed as shown in Figure 2a. A converging spherical wave is produced by the lens and interferes with a plane wave at the photosensitive plate. After developing the plate, the spherical wave can be obtained by illuminating the plate with a plane wave at the same angle as used during the hologram construction.

Note that this simple holographic element does not have rotational symmetry, i.e., the illuminating beam must approach at an angle with respect to the plate's normal. This off-axis behavior can be an advantage in some systems' design; but, where it is a disadvantage, the addition of a holographic grating (Figure 2b) can produce an on-line optical system (Figure 2c).

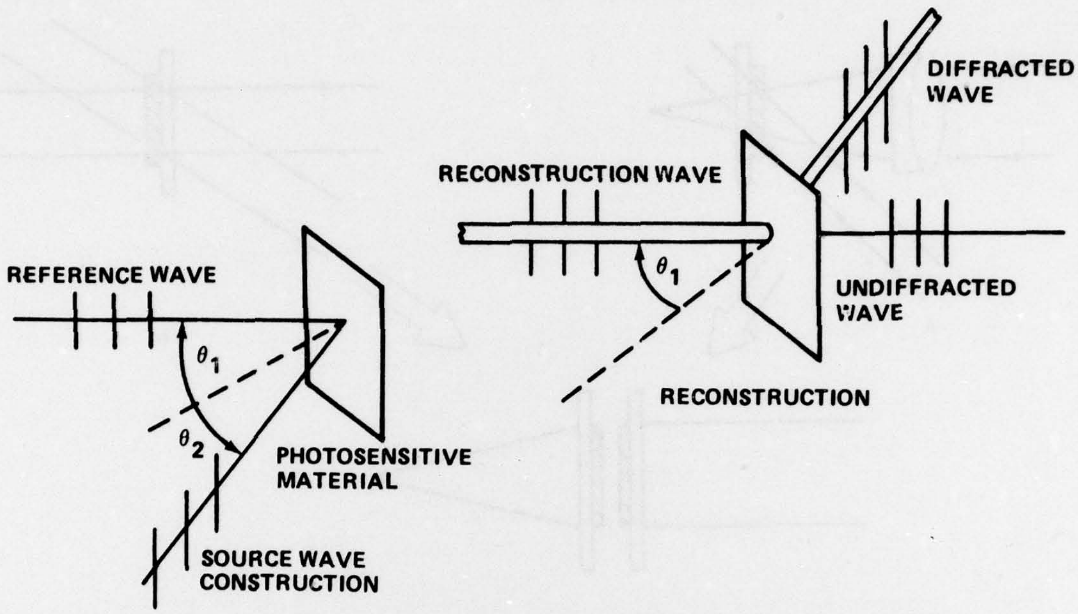

Figure 1. Holography.

Figure 2c also demonstrates that complex optical systems can be constructed by combining simple holographic elements in much the same manner as in conventional optical systems.

C. Why Holographic Optics for Missile Guidance Systems?

More and more missile guidance systems are using narrow wavelength band radiation in the visible and infrared (IR) region of the spectrum. Holographic optical components operate best when limited to a narrow wavelength band and offer the following important advantages over conventional optical systems:

1) Very complex optical systems can be reduced to one or two holographic lenses. This can provide a weight advantage as well as increased ruggedness.

2) Computer-generated holograms can produce optical systems we do not know how to construct using conventional optics. Manufacturing and engineering costs can also be reduced through the use of computer-generated holograms.

3) Holographic optical elements can be replicated easily and for a low cost. The manufacturing costs are reduced because the materials are inexpensive and the fabrication costs are low, but more importantly,

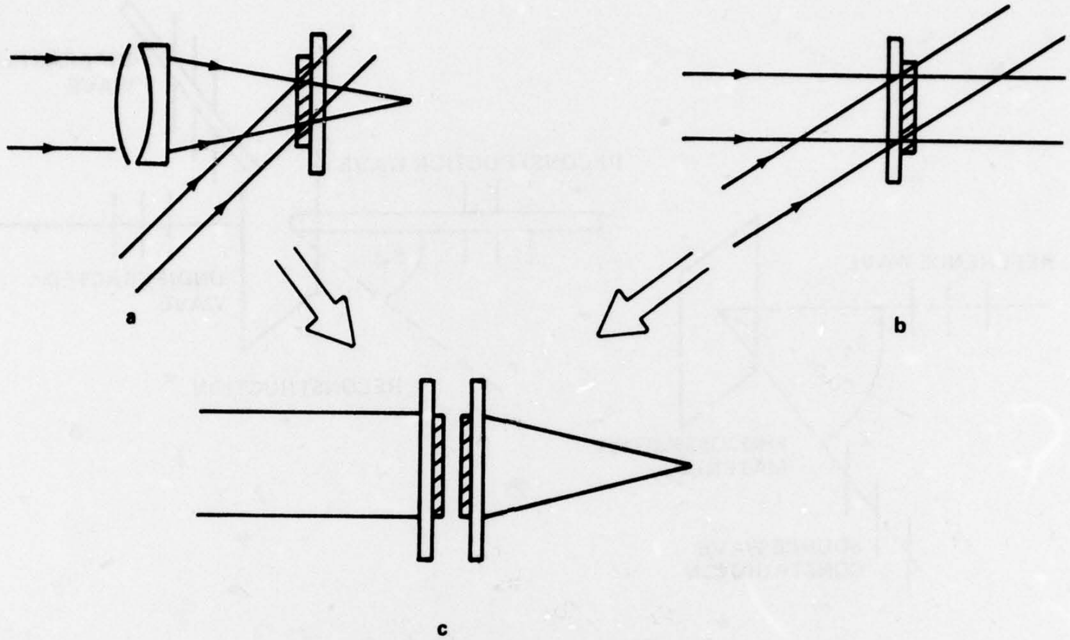

Figure 2. Hololens.

the production personnel do not require extensive training.

4) Either reflection or transmission optics can be constructed, reducing the dependence on available optical materials.

5) The optical systems can be made to conform to the shape of the enclosure. For example, optical elements can be constructed on a sensor window which conforms to the shape of the missile.

D. Applications

Several immediate applications to current missile systems are apparent:

1) A simple stepwise zoom lens can be configured to perform a beamrider-type mission. With only two components, zoom ratios of almost any value can be constructed. Because the zoom lens can be constructed to work in reflection, the operational wavelength is uncoupled from the holographic materials used.

2) A set of wavelength filters that also perform optical functions can be constructed. The bandwidth of the filters can be controlled as

can their center frequency. These filters would be of use in missile systems that used wavelength as a discriminant.

3) In present laser designator systems, the aerodynamic performance of the missile is reduced to have a sensor window with minimum optical aberrations (Figure 3). It should be possible to construct a holographic corrector plate that would correct the optical aberrations of a sensor window that had good aerodynamic characteristics.

Following the concept further, a holographic element could be used to improve the optical performance of any optical train used in a missile guidance system. The use of a holographic corrector could reduce the total cost of an optical system by relaxing the tolerances on the conventional optical components.

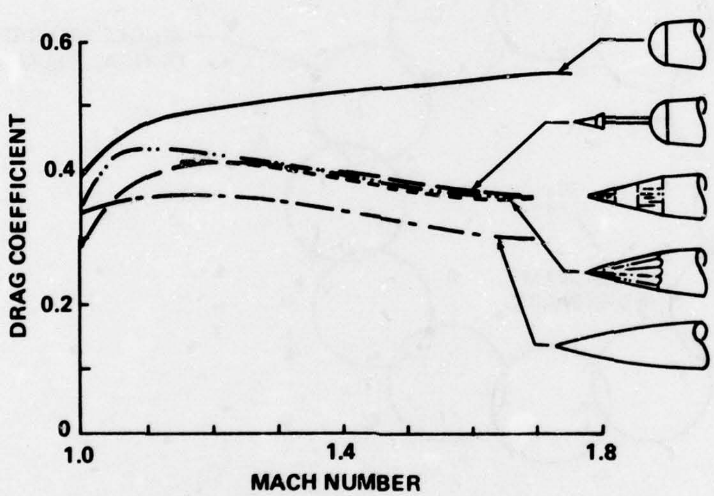

Figure 3. Aerodynamic performance of several bodies [Ref. NASA TM-X-64 and NACA (1951)].

The two demonstration systems discussed in this report were selected to verify the feasibility of the first two applications. The last application discussed will be the subject of a later report. Because the devices constructed during this work were simple demonstration components, no ray tracing calculations were made to optimize the design of the components. Codes are available to optimize holographic optical systems [1, 2] and should be used when constructing an operational system.

II. ZOOM LENS DEMONSTRATOR

A. System Design

To generate a zoom lens that utilizes the economy provided by low cost replication requires that a master copy of the lens elements be produced. An operational zoom lens would then be constructed by making contact prints of each element from the master copy.

The design selected for a demonstrator involved a set of 12 discrete elements (Figure 4).

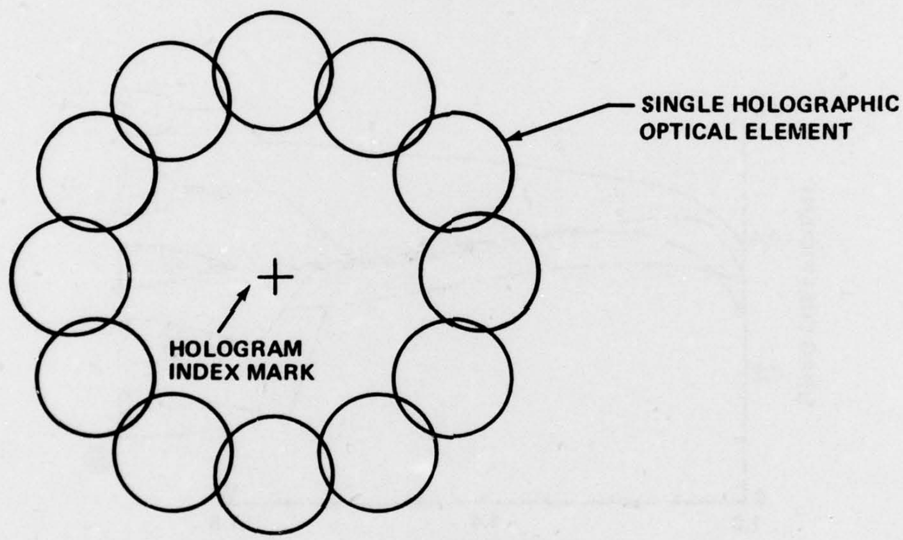

Figure 4. Design selected for demonstrator (12 discrete elements).

A 25X variation in focal length, with 12 discrete elements would require a change of 1.34X in linear magnification in each step, resulting in a magnification error between steps of ±17%. This means that the mismatch in projected area between steps would be no greater than 37%. A cross sectional drawing of this zoom is shown in Figure 5. The mechanical axis of the zoom lens is denoted by AA'in Figure 5, while the optical axis is denoted by CC'. The plates may be rotated about AA' to change the magnification of the system, or individual light sources may be used to address each lens group. Each lens group consists of four individual lens elements. Element I collimates the light from a source H, 17-mm away. Element II uses the collimated light beam, now propagating at an angle with respect to CC' in Figure 5, to form an image on the CC' axis a distance X from Element II. Element III produces a collimated beam from the source at a distance (200-X) mm to its left. The collimated beam from Element III is, as was the case for Element I, propagating at an angle with respect to CC'. Element IV uses this collimated beam to form an image at a distance f.

The maximum value of f was arbitrarily selected to be 1875 mm. To obtain a zoom ratio of 25:1, the minimum value of f must be 75 mm. The other 10 values of f are obtained by requiring a change of 1.34 between each value from maximum to minimum. The other focal lengths are found by the requirement that the image size is constant. If the input image height is H, then the height of the output image, F, can be expressed as

$$F = \frac{f}{200 - x} \quad \frac{x}{17} \quad H \tag{1}$$

With f = 75 mm let x = y and with f = 1875 mm let x = 200 - y. Solving for y, we obtain y = 166.7 mm. This results in a magnification of 22X, i.e. the image height is F = 22.06 H. The required focal lengths are given in Table 1. Inspection of Table 1 reveals that Element III is a mirror image of Element II. We can use this fact to reduce the number of master plates from four to three. Other system parameters were constrained by available optical components and mechanical restrictions limiting available recording geometrics.

B. Construction of Master Plates

The experimental arrangement is shown schematically in Figure 6. The beam from the argon laser strikes a polarized beam splitter B1 which functions as a dielectric mirror with 100% reflectivity. Upon reflection the beam strikes a 50:50 dielectric beam splitter, B2. The transmitted signal beam strikes mirror M1, passes through the microscope objective and spatial filter assembly S1, and is collimated by L1 (a 5-in. diameter, 24-in. focal length lens). A second lens, L2, (a 178-mm f.l., f/1.9 Super Cinephof Special) produces a converging spherical beam which is recorded at the hologram. To produce the master of Element IV, L1 and L2 are removed. The reference beam is reflected from B2 onto mirror M2 and then reflected through the spatial filter and collimator assembly onto the hologram at an angle of 35° with respect to the signal beam. Attenuators A1 and A2 are to equalize the intensities of the two beams at the hologram. The optical distance from B2 to the hologram is the same over the signal and reference beam paths. A number of baffles and apertures were strategically placed to eliminate stray reflections and to insure that neither the reference nor signal beams were larger than 18 mm at the hologram. The baffles and apertures have been removed for clarity. A granite table and air suspension (automobile

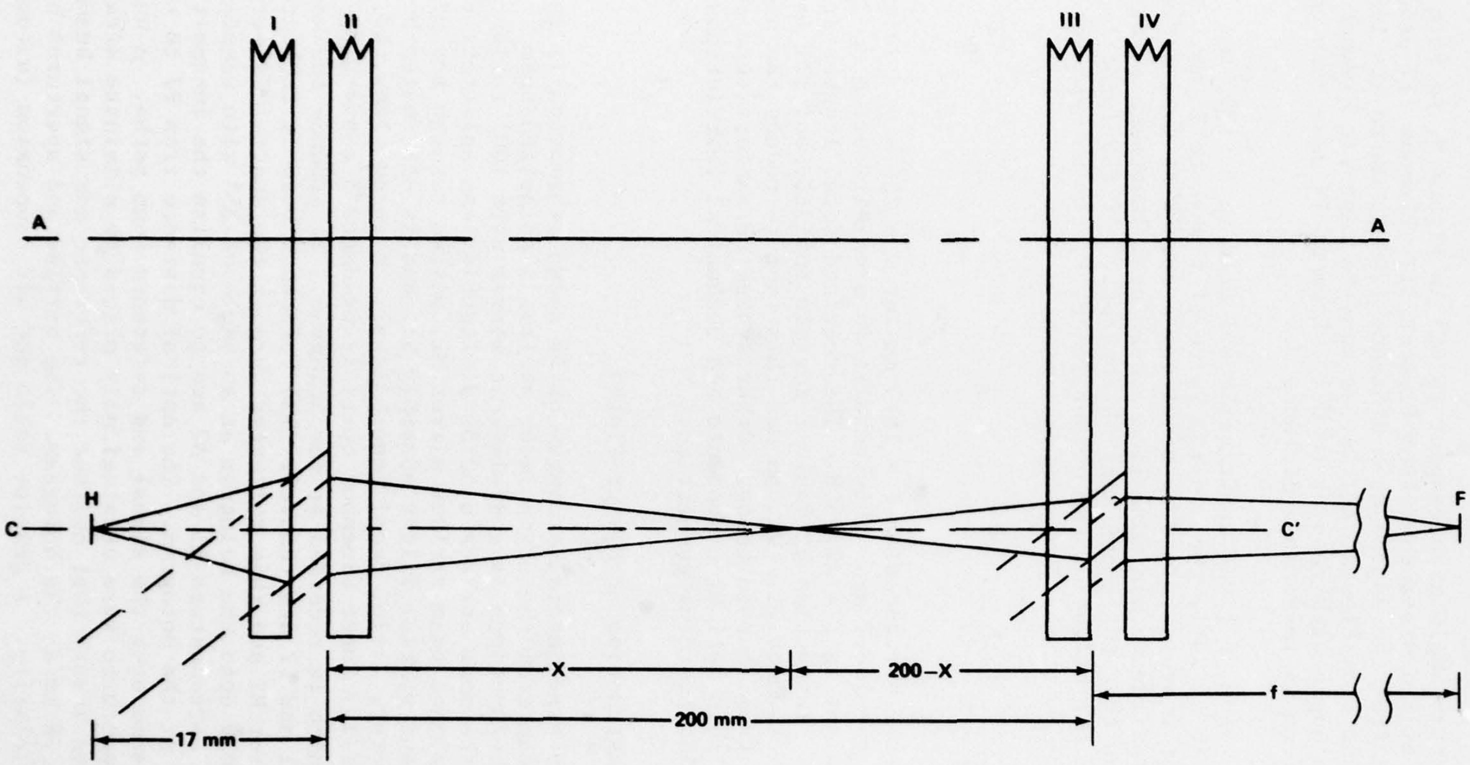

Figure 5. One lens group of the holographic zoom lens system with an input object H and an output image F. (The spacing between I and II and the spacing between II and IV are greatly exaggerated.)

TABLE 1. FOCAL LENGTHS OF THE VARIOUS ELEMENTS

Exposure No.	Element No.			
	I	II	III	IV
1	17	167	33	75
2	17	158	42	100.5
3	17	147	53	135
4	17	135	65	180.5
5	17	121.5	78.5	242
6	17	107	93	324
7	17	93	107	434
8	17	78.5	121.5	581
9	17	65	135	7709
10	17	53	147	1044
11	17	42	158	1399
12	17	33	167	1875

*Element lengths are given in millimeters.

inner tubes) were used to eliminate vibrations. In addition, heavy black currents surrounded the experiment to isolate the system from strav light and air currents.

In constructing master plates, one must keep in mind that the master will be a mirror image of the final holographic element. When microflats were used as the substrate, a glass microflat was gated with zylene over the emulsion layer to compensate for distortions arising from the beam passing through glass during operation of the copy elements. The focal lengths in Table 1 had to be corrected for this 6-mm (0.25-in.) glass plate which reduced the optical path length by 2 mm. For example, in making the 17-mm focal length element, the source was 13 mm from the emulsion (i.e., L2 was 191 mm from the emulsion). When using standard photographic glass plates with a thickness of 0.040 in. this correction was neglected. In construction of the master plates, attention must also be paid to the direction of the reference beam. For Master II and Master III the reference must intercept the emulsion before it crosses the mechanical axis (AA' in Figure 5). For Master I and Master IV the reference beam must cross the mechanical axis before it intercepts the emulsion.

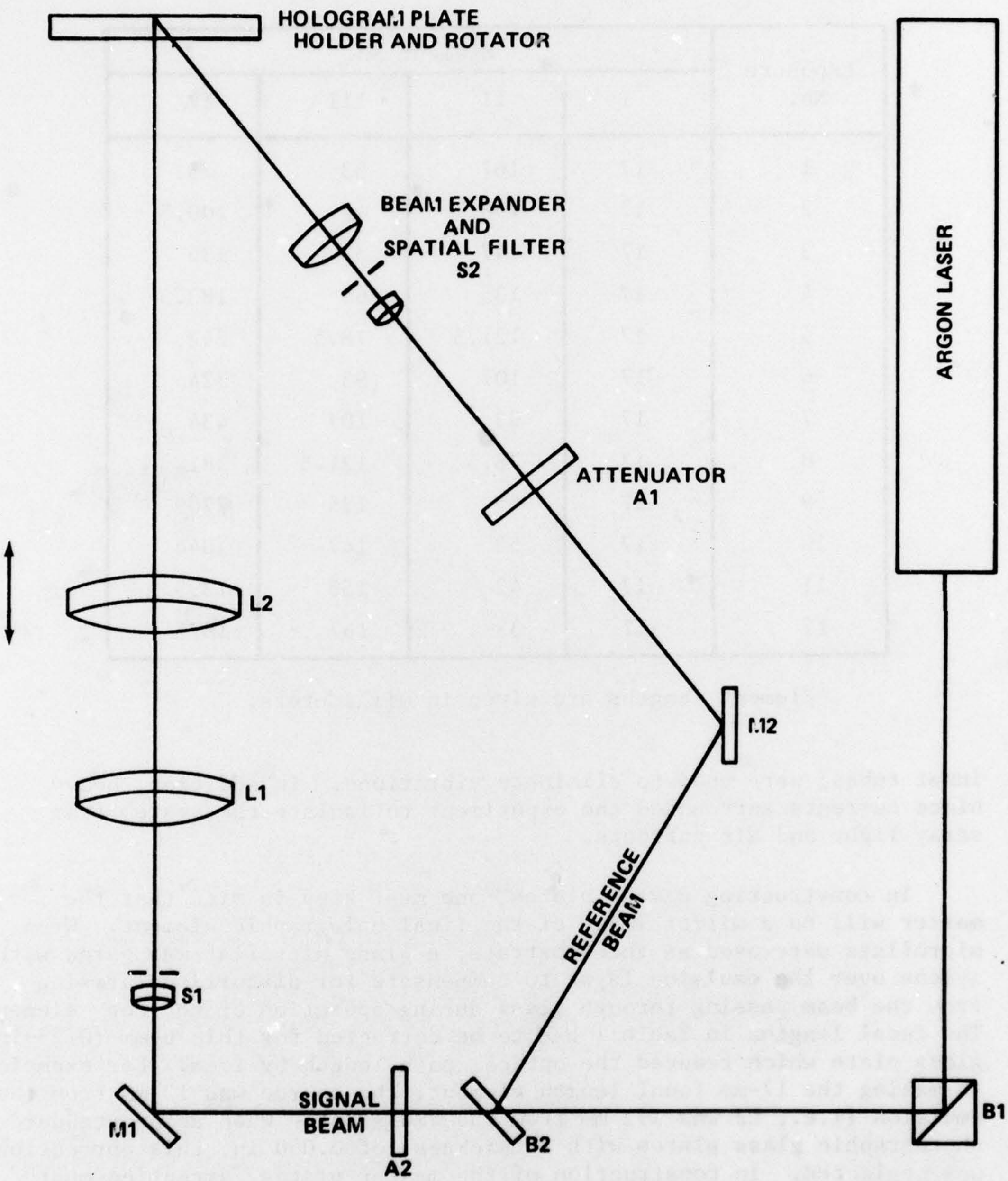

Figure 6. Schematic of setup for manufacture of holographic lenses.

The master holograph upon reconstruction, generates the reference and signal beams to create the copy hologram. For maximum diffraction efficiency in the copy, the master hologram should produce a transmitted and diffracted beam of equal intensity to develop maximum fringe contrast during copying. High quality amplitude holograms did not produce copies with high diffraction efficiency because the transmitted beam intensity was much larger than the diffracted beam intensity. To produce an amplitude hologram where the two beams had nearly equal intensity required a large amount of overexposure. The resulting high density masters would require very long copy exposure times. A large number of bleach techniques were evaluated (bromine, iodine and copper bleaches), but the scattering noise produced by bleaching (which would be copied) made this technique unacceptable for producing master plates. It was, therefore, decided to use dichromated gelatin with a 50% diffraction efficiency for the master plates.

Obtaining 12 holographic lenses, each with 50% diffraction efficiency, is much more difficult than obtaining a large number of holograms near 100% efficient. The film does not provide any limiting near the phase modulation required for 50% diffraction efficiency and small changes in modulation cause large diffraction efficiency changes. Considerable variation in diffraction efficiency was noted in our best master plates, but it was found that the copies produced were quite uniform.

Elements I and II are cemented together, emulsion-to-emulsion in the final assembly as are Elements III and IV. This means that shifts in the Bragg angle (the angle the hologram makes with the reconstruction beam for maximum diffraction efficiency) must be held to a minimum. The angle shifts are a result of index of refraction and/or emulsion thickness changes during processing. Shifts as high as 10° can occur and are a function of emulsion thickness, offset angle (angle between the signal and reference beams), and ammonium dichromate concentration used to sensitize the emulsion. The following commercial emulsions were evaluated: Kodak 649F, 131, 120, and Agfa 10E56. It was found that Kodak 131 emulsion with a 25% ammonium dichromate concentration would give a Bragg angle shift of only 1° with diffraction efficiencies approaching 100% when used at a 30° offset angle. Kodak 131 emulsion was selected for both master and copy plates. The techniques used to prepare these emulsions and to process them after exposure are found in another report [3].

From the time an emulsion is sensitized until the final copy has been assembled, the relative humidity around the emulsion must be held below 40%. Dehumidifiers held the exposure and processing areas below 40% relative humidity. Once master plates were produced, they were stored over Drierite (anhydrous $CaSO_4$). Because of the very high dichromate concentrations used in this work, greater care than normal had to be taken to control moisture contact with the emulsion between sensitization and processing. The technique used was to gate a cover plate over all sensitized emulsions using zylene as the gate material. By sealing the gate with aluminized tape (the type used in making lantern slides), the gate could be maintained for over 1 hour.

C. Copying

To produce multiple copies once the three master plates were produced, the setup shown in Figure 6 was modified by replacing B2 with a mirror and removing the attenuator A1. The master plate is gated to the sensitized copy plate, emulsion-to-emulsion with care taken to ensure that the master is clean. Smudges and fingerprints on the back of the master will be copied onto the copy plate. The very intense copy beam produced by the modification of Figure 6 is then used to make 12 short exposures for each copy of a master by positioning the master so that the copy beam is aligned for optimum reconstruction.

The only stability problems that arise during the copy process are instabilities produced by the liquid gate. Due to short exposures and a rigid mounting scheme, stability was not a problem in making copies of the zoom elements. However, in other experiments we found two modifications to the copy configuration reduced stability problems. A mirror can be used to deflect the copy beam downward allowing gravity to be used to hold the master and copy plates together. A cylindrical lens can also be inserted in the system before spatial filter S2 (Figure 6) so as to form a narrow band of light across the holographic plates parallel to the optical axis. This band of light can be moved across the plates by translating the cylindrical lens. These modifications worked very well and provided the additional benefit of allowing the exposure to vary across the plate. This exposure method would be a useful production technique.

In the production of both masters and copies, the use of a backing plate is advised to reduce scattered light and reflections from the back surface of the plate. We uniformly overexposed and developed a film plate to be used as the backing plate. The emulsion side of this plate was gated to the back of the holographic plate.

III. HOLOGRAPHIC COLOR FILTERS

As was mentioned in Section I, the performance of the holographic optical element is a strong function of wavelength. This fact can be used to obtain an optical element that is wavelength selective.

To demonstrate the utilization of a holographic optical element as a wavelength filter, the optical element shown schematically in Figure 7 was constructed. The element is to perform as a mirror for

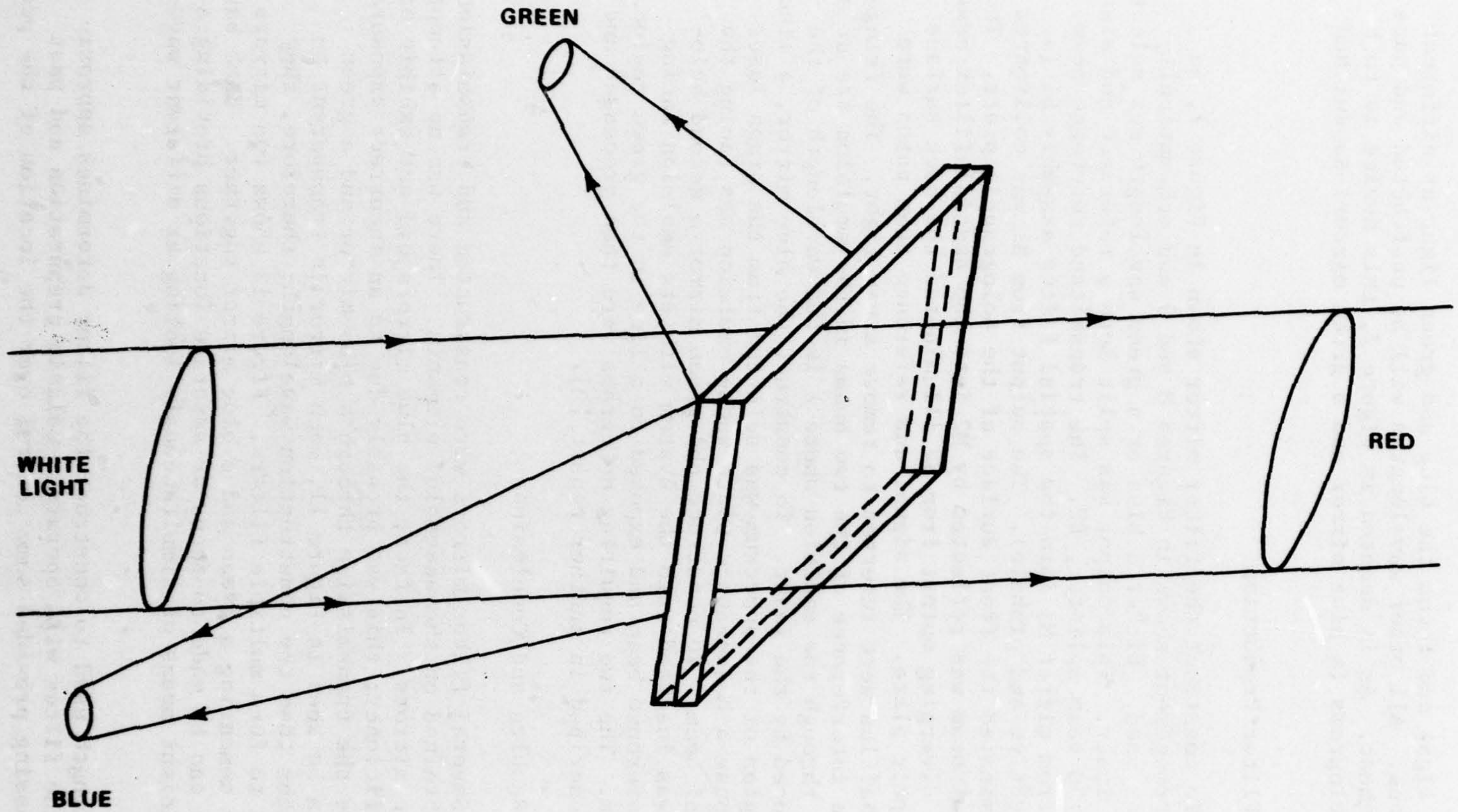

Figure 7. Holographic mirror.

blue and green light and focus the blue and green light at different spatial locations. All other wavelengths will be unaffected and pass through the element. As is denoted in Figure 7, this device is to be two separate holograms (a blue mirror and a green mirror) sandwiched together.

A. Filter Production

To construct the filter mirror shown in Figure 7, an experimental arrangement shown in Figures 8 and 9 and schematically in Figure 10 was used. Either a blue or a green wavelength was selected from the argon laser. This output was split into a reference and signal beam by the 50:50 beam splitter, B2. The transmitted reference beam was reflected from mirror M1 into the spatial filter assembly S1 (a microscope objective and pinhole). The output from S1 was collimated by L1 and illuminated the front surface of the holographic plate. The reflected signal beam was reflected by M2 into the spatial filter assembly S2 and the diverging output from S2 illuminated the back surface of the holographic plate. The signal and reference beam paths were equalized and baffles were inserted to remove stray light. The fringes produced by the interference of the two beams in the emulsion are at a spacing of $\lambda/2$ through the emulsion where λ is the wavelength of the radiation produced by the laser. To construct the blue mirror, a line in the blue region of the spectrum was selected from the argon laser and used to expose a holographic plate whose emulsion was facing the diverging signal beam. To construct the green mirror a second holographic plate was inserted into the system with its emulsion facing the parallel reference beam and exposed to a line in the green region of the spectrum. The two resulting holograms were then processed and assembled as described in another report [3].

B. Results and Conclusions

Several filter mirrors were constructed and transmission spectra were obtained on the assembled elements. There was no attempt to optimize the mirrors. In fact, the blue mirrors did not exhibit high diffraction efficiency; this was probably due to an incorrect exposure. Figure 11 shows the transmission through a blue mirror and a green mirror. As can be seen in Figure 11, each mirror is transparent to wavelengths other than the construction wavelength; therefore, they can be stacked to form multiple filters. Figure 12 shows two mirrors constructed by cementing a green and a blue mirror together. Each band of wavelengths can be made to focus at separate locations providing a cheap and efficient means of simultaneously looking at different wavelengths.

The wavelength used to construct the filter determines approximately where the filter will operate. Gelatin preparation and past exposure processing provides some control over the location of the peak

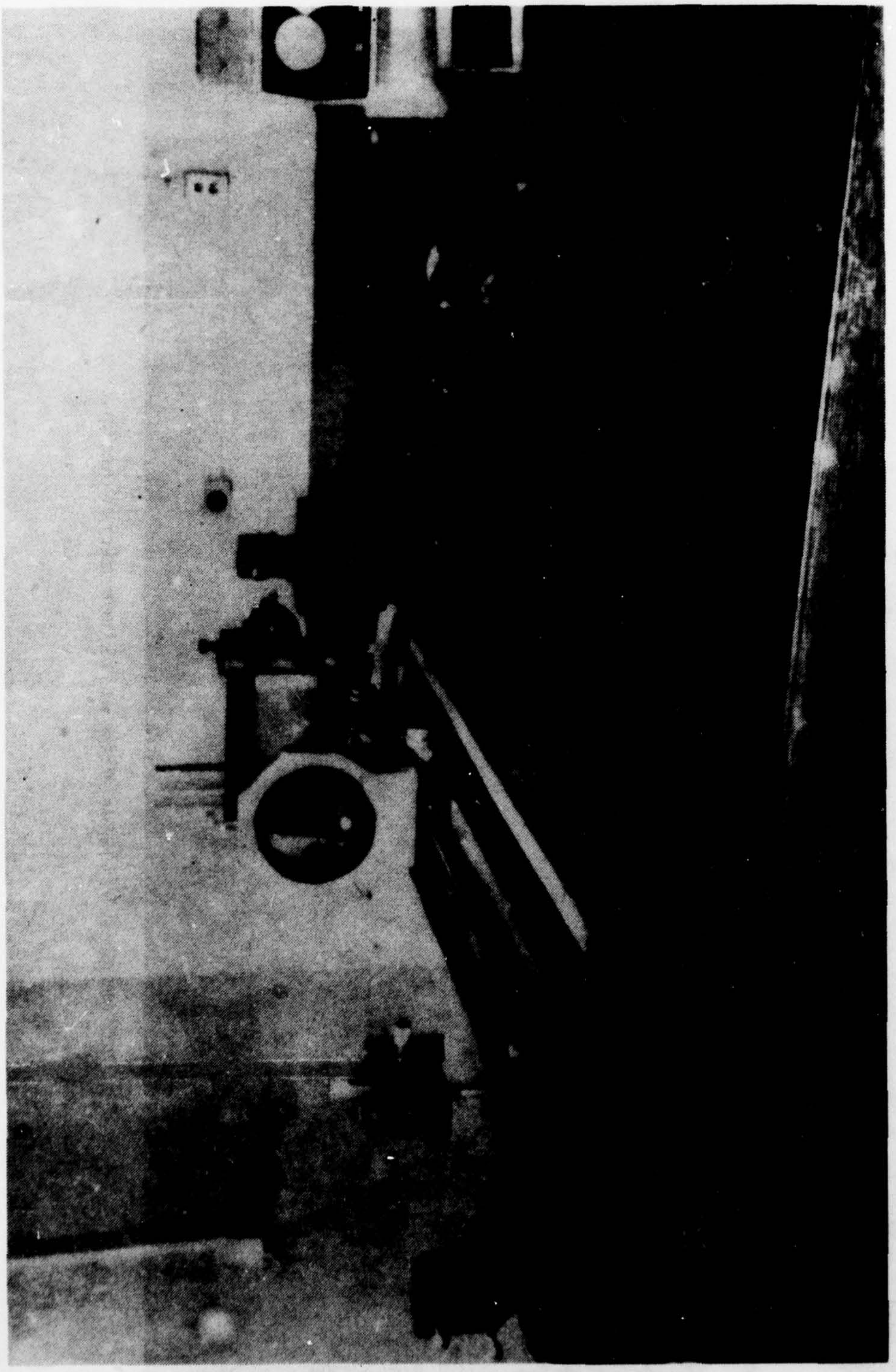

Figure 8. End view of filter mirror setup.

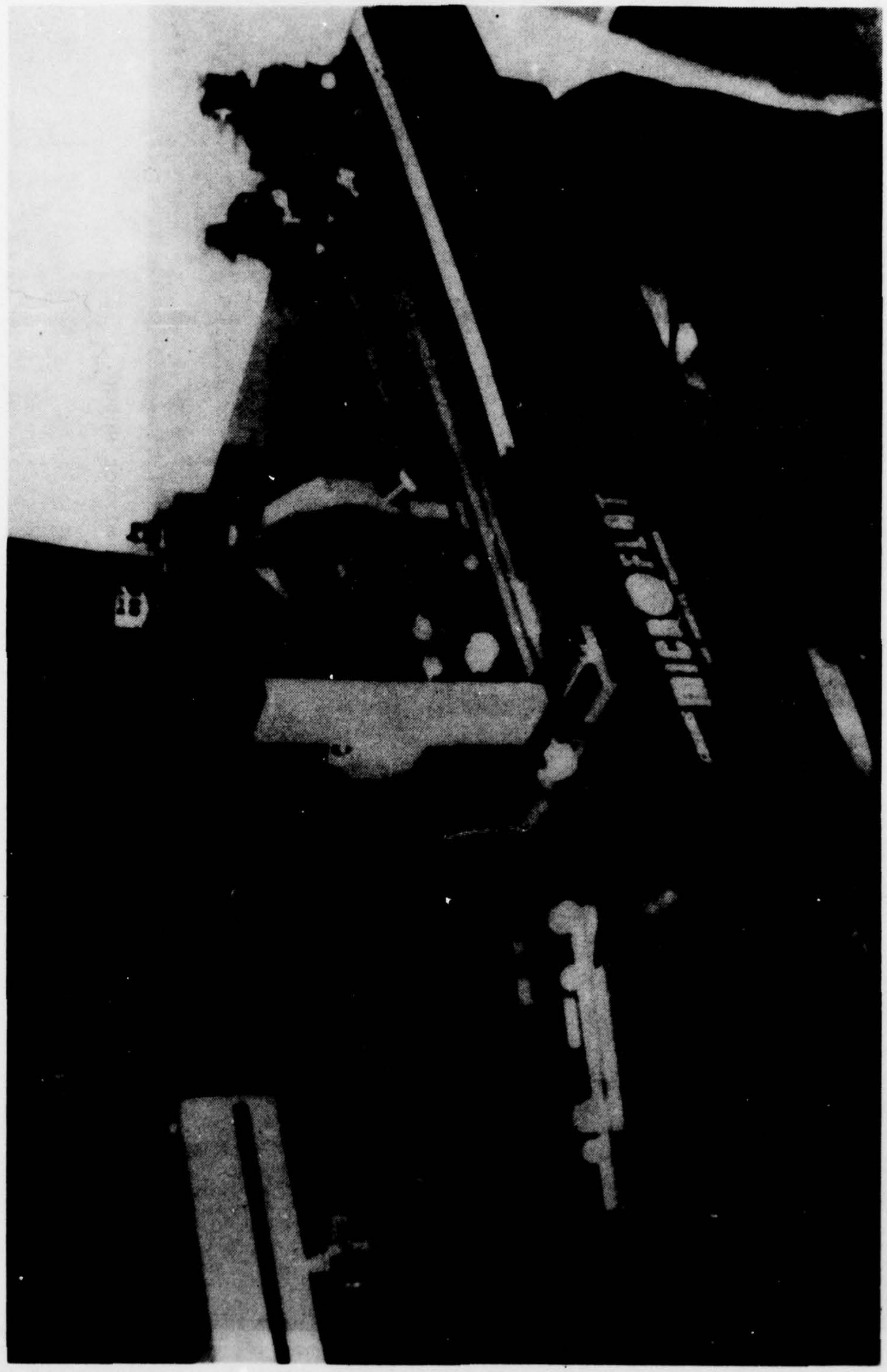

Figure 9. Side view of filter mirror setup.

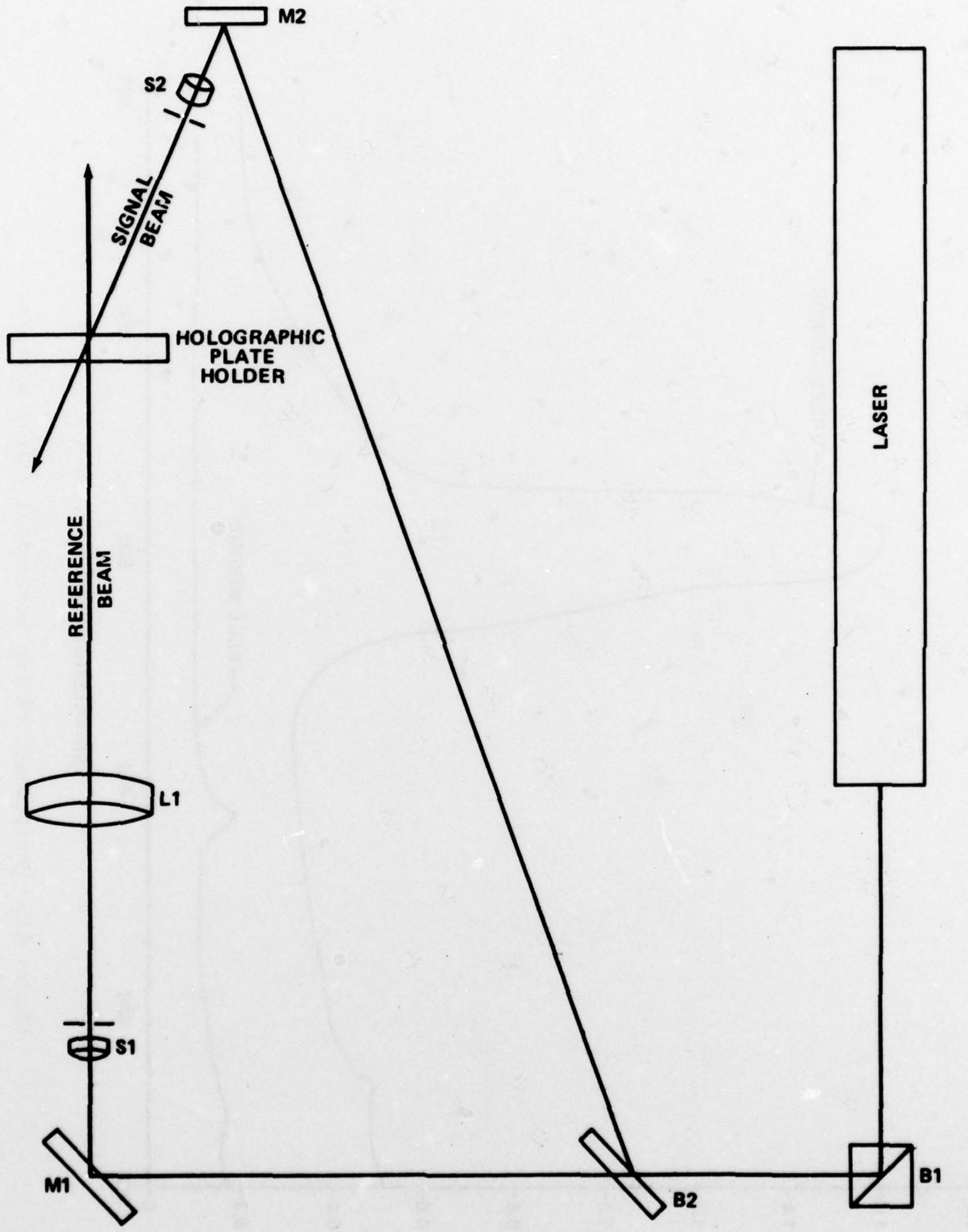

Figure 10. Schematic of setup for manufacture of holographic mirror.

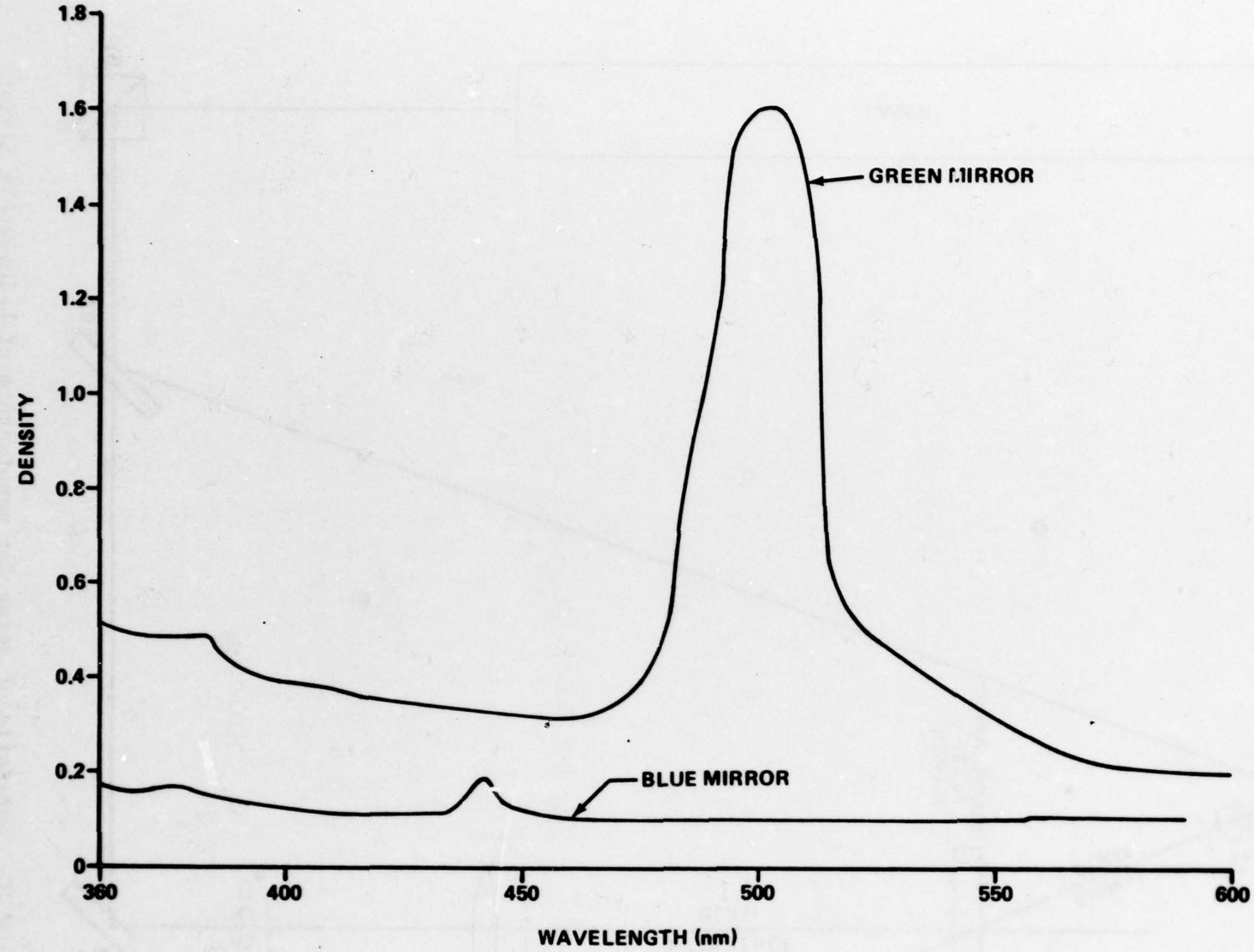

Figure 11. Performance of two individual filter mirrors.

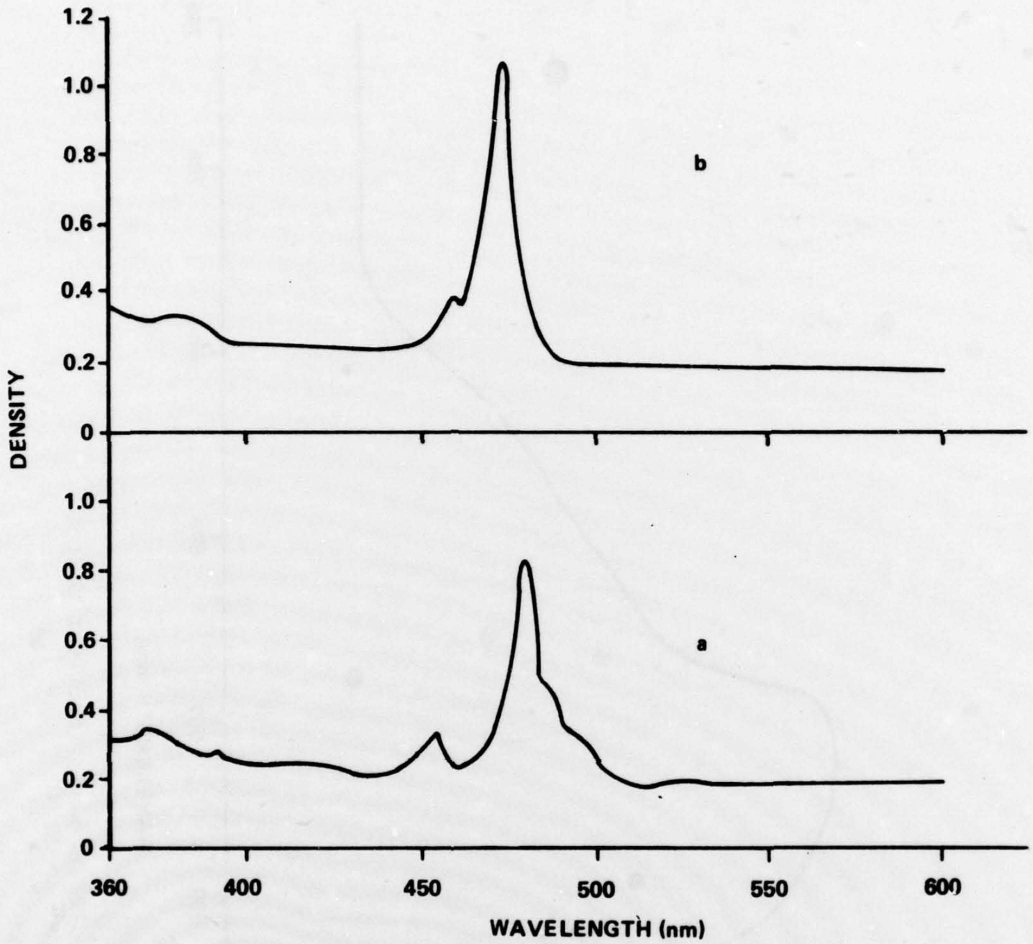

Figure 12. Performance of combined filter mirror.

response and the width of the filter bandpass. Figure 13 shows a broad-band green filter. To increase the bandpass and to shift the center wavelength toward the red, the last two steps in plate processing are modified in the following way. Before removing the filter from the 100% isopropyl alcohol bath, the gelatin is covered by a glass plate. This assembly is then placed on a hotplate. After the assembly warms to near the hotplate temperature (~169°F), the glass cover plate is removed causing a rapid drying of the gelatin.

Future efforts will be directed toward developing processing techniques to allow accurate production of filters with prespecified bandpass characteristics. The gelatin and the filters constructed did not exhibit absorption out to 1.5 μm; thus, extention of filter construction into the red will be made by using a dye laser together with dye sensitized dichromate gelatine plates.

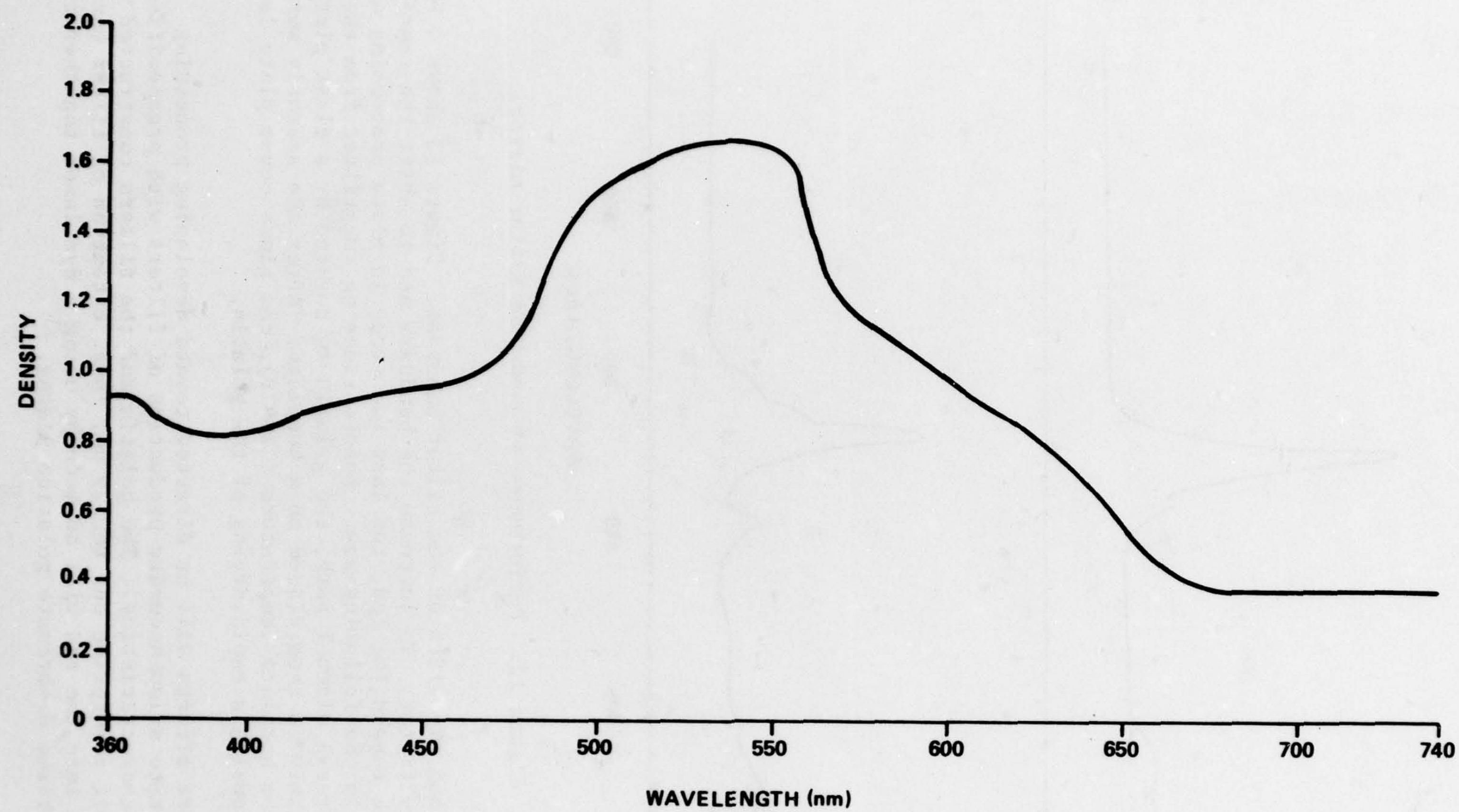

Figure 13. Performance of filter mirror.

IV. CONCLUSIONS

The examples of holographic optical elements constructed in this report demonstrate the feasibility of using holography to solve some of the optical design problems associated with missile guidance. The ability to replicate holographic optical elements without the need for highly trained technicians is the most appealing characteristic.

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