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ELECTRO-OPTICS CENTER

Box 1084 • Ann Arbor, Michigan 48106
(313) 769-6400

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George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

by

Electro-Optics Center
Radiation Incorporated
P.O. Box 1084
2320 Washtenaw Avenue
Ann Arbor, Michigan 48106

ELECTRO-OPTICS CENTER

FORWARD

This report was prepared by the Electro-Optics Center of Radiation Incorporated, under Contract NAS 8-26360 with the NASA Marshall Space Flight Center, Huntsville, Alabama. This effort is monitored by Mr. G. A. Bailey. This report covers the work performed between 5 August 1970 and 30 January 1971.

The program manager for this project is Dr. A. Vander Lugt, Research Manager, who reports to Dr. A. Kozma, General Manager. Other contributors to this report are Dr. A. A. Friesem, G. E. Hoffmann, Dr. H. N. Roberts, R. G. Zech, P. J. Peters, and E. N. Tompkins.



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1. INTRODUCTION

1.1 Objectives of the Contract

The objectives of this contract are to design a read/write holographic memory system including a modifiable optical test bed and the following components: a laser system, acousto-optic beam deflectors, a block data composer, a read/write memory material, an output photo-detector array, and electronics to drive and synchronize all system components. The optical system configuration is to be arranged so that a variety of storage materials can be inserted for testing and so that other system components can be modified or replaced by newer components in the future. The optical test bed system is to be fabricated and delivered, along with the specifications for the components to be used with the test bed.

1.2 Summary of the Work Effort

During the contract period we analyzed the capacity of a holographic memory system in terms of the constructional parameters of the various system components and determined how these parameters are interrelated. The analysis was made for four possible memory configurations to cover any practical systems that may be developed. A similar analysis was made which relates the needed beam deflector optics to the constructional parameters of the system components, with special emphasis on the parameters associated with the acousto-optic beam deflectors. These two studies clearly indicated the correct procedure for designing an optimum memory system, given the operational constraints of available devices. The Gaussian optics for both the memory and the beam deflector optics were then specified. The results of these studies were given in the Quarterly Report.

Most of the optical components such as mirrors, microscope objectives, collimating lenses and polarization rotators are available as standard commercial items. Since the Fourier transform lens and the imaging lens are not standard items, we designed cemented doublets which are separately achromatic but unaplanatic. The design calculations for these lenses are given in Section 2 of this report. We have also simplified the beam deflector optics and established the constraints imposed by this system on the acousto-optic beam deflectors.

The layout of the optical memory and a description of its operation is given in Section 3. Special attention has been given to making the system as flexible as possible so that a wide variety of major system components can be fitted into the system for evaluation. For example, a rather simple modification will allow the system to operate in the Fourier transform rather than the Fresnel transform mode. The addition of just a few optical components will allow the system to work with manganese-bismuth as the holographic recording material with Kerr effect (reflection) readout.

The lasers to be used in the memory system are specified in Section 4. A helium-neon laser is recommended for use in the read/write mode and it, together with an argon-ion laser, is also used in the semi-permanent mode.

In Section 5 we discuss the work performed on the block page composer. We have reviewed the published literature and have based our design on the use of PLZT ferroelectric ceramic devices operating in the strain-biased mode, although other modes of operation have been also considered. We have fabricated some PLZT devices which allowed us to experimentally verify published performance data. The results of these experiments and a set of specifications for a 128 x 128 element device are given in this report.

The acousto-optic beam deflector specifications are reported in Section 6. The interaction medium is water and the deflector will be

capable of randomly accessing 80 x 80 hologram storage locations with a 13 μ sec access time. Both of the operating parameters and the design requirements have been specified.

Photoplastic material has been selected as the read/write storage material. We have constructed a clean box in which the photoplastic devices are fabricated, using dip-coating techniques. Extensive experiments with different sensitizers, thicknesses of both thermoplastic and photo-conductor layers, exposure levels, and development times have been conducted. Diffraction efficiency as a function of exposure and reference-to-signal beam ratios has been measured, and preliminary estimates of signal-to-noise ratio have been made. A scheme for attaching heating electrodes for a 5 x 5 array of holograms has been developed, based on experimental measurements of the current needed for development and erasing. Experiments to determine the recycling characteristics of the photoplastic material have been started. The work relating to the read/write material is reported in Section 7, along with specifications for the performance of the hologram array.

The photodetector array specifications are contained in Section 8. Based on the sensitivity of the photodetectors and estimates of the efficiency of the optical components, the total laser power needed for readout at a 1 MHz rate have been established; these power levels can be achieved by the lasers specified in Section 4. The specifications for the sense amplifier and the final array configurations have also been established.

Specifications for the electronics to drive and synchronize the system components have been established and are reported in Section 9.

2. DESIGN OF THE FOURIER TRANSFORM AND IMAGING LENSES

In the Quarterly Progress Report (8104-Q-1), we analyzed the capacity of a holographic memory system in terms of the constructional parameters of the various system components and determined how these parameters are interrelated. A similar analysis was made which relates the needed beam deflector optics to the constructional parameters of the system components, with special emphasis on the parameters associated with the acousto-optic beam deflectors. These two studies clearly indicated the correct procedure for designing an optimum memory system, given the operational constraints of available devices.

Of the four systems analyzed, we have chosen the imaging Fresnel transform system for use in the feasibility test bed system because it is flexible enough for use in both the read/write and semi-permanent modes of operation. The constructional parameters chosen are summarized in the list below:

1. Format of the block data composer: 128×128 electrically alterable apertures ($N = 128$).
2. Size of each bit element: $152 \times 152\mu$ ($d = 152\mu$).
3. Ratio of the bit spacing to the bit size: $c = 1.48$.
4. Format of hologram: 20×20 for the semi-permanent memory; 5×5 for the read/write memory ($\bar{N} = 20$ or $\bar{N} = 5$).
5. Size of each hologram: 1×1 mm ($\bar{d} = 1$ mm).
6. Ratio of the hologram spacing to the hologram size: $\bar{c} = 1.5$ for the semi-permanent memory; $\bar{c} = 6$ for the read/write memory.
7. Wavelength: $\lambda = 632.8$ nm for the read/write memory;
 $\lambda_1 = 632.8$ nm and $\lambda_2 = 488$ nm for the semi-permanent memory.

8. Focal length of the transform and imaging lenses: $F = 163 \text{ mm}$.
9. Aperture ratio of lenses: $R = 0.5$.
10. Magnification from block data composer to photodetector array:
 $M = -1$.

The optical system therefore requires the use of a Fourier transforming lens and an imaging lens having focal lengths of 163 mm and aperture ratios of 0.5. The lenses must be achromatic to work at both wavelengths and the entire system must be nearly free from distortion. Furthermore, the front and back focal planes of these lenses must be accessible with sufficient mechanical clearances. Since commercially produced lenses which satisfy these requirements are not available, we decided to design lenses especially for this application. The remainder of this section discusses details of the design of two cemented doublets that are separately achromated but not aplanatic.

2.1 Aberrations

The design procedure for achromatic doublets has been considerably simplified by Hopkins and Rao who have developed a method for the systematic design of two-component objectives.¹ The key to the method is a glass-selection procedure developed by Hopkins. The full details of this method has appeared in Reference 1; supplementary information appears in Reference 2. Most of the formulae used in this design can be found in these references.

Fundamental to the design of lenses are the Seidel aberration terms for the primary aberrations given by:

$$\left. \begin{aligned}
 \text{Spherical aberration:} \quad S_I &= \sum_1^k A^2 h \Delta \left(\frac{u}{n} \right) \\
 \text{Coma:} \quad S_{II} &= \sum_1^k AB h \Delta \left(\frac{u}{n} \right) \\
 \text{Astigmatism:} \quad S_{III} &= \sum_1^k B^2 h \Delta \left(\frac{u}{n} \right) \\
 \text{Petzval curvature:} \quad S_{IV} &= \sum_1^k H^2 P \\
 \text{Distortion:} \quad S_V &= \sum_1^k \frac{B}{A} \left\{ H^2 P + B^2 h \Delta \left(\frac{u}{n} \right) \right\}
 \end{aligned} \right\} (1)$$

where A is the angle that the principal marginal ray (PMR) makes with the normal at a surface, B is the angle that the principal pupil ray (PPR) makes with the normal to a surface, h is the incident height of the PMR, u is the angle that the PMR makes with the optical axis, n is the refractive index of a medium, H is the optical invariant, Δ denotes a difference at a surface, $P = \frac{1}{r} \Delta \left(\frac{1}{n} \right)$, r is the radius of a surface, and the summation is carried out over k surfaces of the system. Two additional aberrations of interest are:

$$\left. \begin{aligned}
 \text{Longitudinal chromatic variation of focus:} \quad C_L &= \sum_1^k Ah \Delta \left(\frac{\delta n}{n} \right) \\
 \text{Transverse chromatic variation of focus:} \quad C_T &= \sum_1^k Bh \Delta \left(\frac{\delta n}{n} \right)
 \end{aligned} \right\} (2)$$

where the symbol δ denotes the variation of index with wavelength.

The Seidel aberration terms are related to the wavefront aberrations coefficients by:

$$\left. \begin{aligned} {}^0W_{40} &= \frac{1}{8} S_I \\ {}^1W_{31} &= \frac{1}{2} S_{II} \\ {}^2W_{22} &= \frac{1}{2} S_{III} \\ {}^2W_{20} &= \frac{1}{4} (S_{III} + S_{IV}) \\ {}^3W_{11} &= \frac{1}{2} S_V \end{aligned} \right\} \quad (3)$$

$$\left. \begin{aligned} \delta {}^0W_{20} &= \frac{1}{2} C_L \\ \delta {}^1W_{11} &= C_T \end{aligned} \right\} \quad (4)$$

It is important to consider how the first order aberrations change as a function of the stop position. The aberration coefficients given by (1) and (2) are computed with the stop at the surface and are termed central aberrations. We define a variable $E = \bar{h}/h$ which is the ratio of the height of the PPR to that of the PMR at any surface. It can be shown that if the stop is moved to a new position in the system for which the new value of E is E' , then $\delta E = E - E'$ is fixed for all surfaces. The changes in the aberration coefficients as a function of δE are:

$$\delta S_I = 0$$

$$\delta S_{II} = (\delta E) S_I$$

$$\delta S_{III} = 2(\delta E) S_{II} + (\delta E)^2 S_I$$

$$\delta S_{IV} = 0$$

$$\delta S_V = (\delta E)(S_{IV} + 3S_{III}) + 3(\delta E)^2 S_{II} + (\delta E)^3 S_I$$

$$\delta C_L = 0$$

$$\delta C_T = (\delta E) C_L$$

(5)

Note that S_I , S_{IV} and C_L are independent of stop position. Coma is independent of stop position if $S_I = 0$. If both S_I and S_{II} are equal to zero (the aplanatic condition), S_{III} is also independent of stop position. Finally, if $S_{III} = -1/3 S_{IV}$ (the flat T-field condition) all the primary monochromatic aberrations are independent of the stop position. We also note that δS_{II} , δS_{III} and δS_{IV} are linear, quadratic and cubic functions of δE and that if all aberrations above a given term are zero, the aberration in question is independent of the stop position. Finally, for a lens system consisting of two separated doublets, each doublet must be achromatic if the overall system is to be achromatic.

In general, complete control of the primary aberrations of a separated system of two thin components can be achieved only if the components are separately achromatic ($C_L = C_T = 0$) and unaplanatic (either S_I or S_{II} not equal to zero).

2.2 Design Considerations

The design calculations will be carried out with reference to Figure 1. Lenses of power K_1 and K_2 are achromatized doublets that image the block data composer (BDC) into the photodetector array (PDA); in the first instance we shall set $M = -1$ so that $K_1 = K_2$. We begin by letting the stop position be at the first lens and we shall design the system for a flat T-field ($S_{III} = -1/3 S_{IV}$). The first step is to find the values of S_I and S_{II} for each of the two lenses. It is convenient to define normalized Seidel coefficients as

$$\sum_I = \frac{S_I}{h^4 K^3} ; \quad \sum_{II} = \frac{S_{II}}{Hh^2 K^2} \quad (6)$$

Further, we define

$$\gamma = \frac{h_2 K_2}{h_1 K_1} \quad (7)$$

and

$$\beta = d_{12} K_1 \quad (8)$$

We now have that

$$\left. \begin{aligned} \left(\sum_I \right)_1 &= \left(\frac{3+p}{\beta^2} \right) \left(\frac{h_2}{h_1} \right) \left[\left(\frac{h_2}{h_1} - \gamma \right) \right] + \frac{2}{\beta^3} \left(\frac{h_2}{h_1} \right)^2 \sum_V \\ \sum_{II} &= \left(\frac{3+p}{3\beta} \right) \left[2 \left(\frac{h_2}{h_1} \right) - \gamma \right] + \frac{1}{\beta^2} \left(\frac{h_2}{h_1} \right)^2 \sum_V \end{aligned} \right\} \quad (9)$$

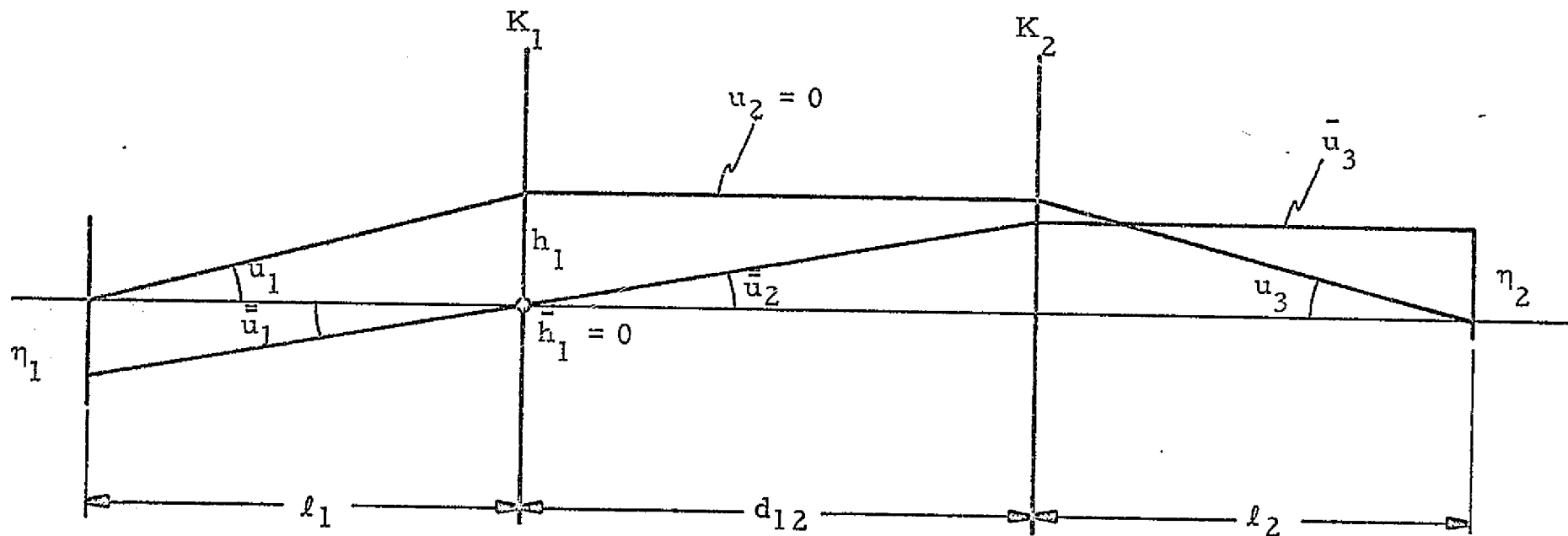


FIGURE 1: LENS SYSTEM GEOMETRY



$$\left. \begin{aligned} \left(\sum_I \right)_2 &= - \left(\frac{3+p}{\beta^2} \right) \frac{1}{\gamma^2} \left[\frac{1}{\gamma} \left(\frac{h_2}{h_1} \right) - 1 \right] - \frac{2}{\beta^3 \gamma^3} \left(\frac{h_2}{h_1} \right)^2 \sum_V \\ \left(\sum_{II} \right)_2 &= \left(\frac{3+p}{3\beta} \right) \frac{1}{\gamma} \left[\frac{1}{\gamma} \left(\frac{h_2}{h_1} \right) - 2 \right] + \frac{1}{\beta^2 \gamma^2} \left(\frac{h_2}{h_1} \right)^2 \sum_V \end{aligned} \right\} \quad (10)$$

where

$$\sum_V = \frac{h_1^2}{H^3} S_V = \frac{2h_1^2}{H^2} \left(\frac{\delta\eta'}{\eta'} \right)$$

is the residual distortion of the whole system, $(\delta\eta'/\eta') = S_V/2H$ is the fractional distortion at the edge of the field, and $p \approx 1/\mu$ is generally set equal to 0.7 for the initial calculations.

Since the BDC is in the front focal plane of the first lens, the light is parallel between the lenses so that $h_2 = h_1$. If $M = -1$, we have $K_2 = K_1$ so that $\gamma = 1$. The spherical aberration for each component (and for the whole system) is therefore zero if we set $S_I = 0$. Note that $(S_V)_I = 0$ because the central distortion is equal to zero by virtue of the fact that $B = 0$. After the design is completed, we shall check to see that S_V for the whole system is zero or nearly zero.

To gain symmetry for the overall system, we let $d_{12} = 2/K_1$ so that $\beta = 2$. From (9) and (10) we then have that $(\sum_I)_1 = 0$, $(\sum_{II})_1 = 0.61666$, $(\sum_I)_2 = 0$, and $(\sum_{II})_2 = -0.61666$. Thus we see that each doublet must be unaplanatic to achieve a system with zero primary aberrations.

Each doublet must, however, be achromatic. The question now becomes one of selecting glass types to achieve achromatic doublets having the prescribed values for $\sum_I$ and $\sum_{II}$. It is convenient to define the following parameters:

$$\rho = \frac{V_1 + V_2}{V_1 - V_2} \quad (11)$$

where V_1 and V_2 are the dispersions of the two glasses of the doublet and

$$Y = 1 + \frac{2u_1}{hK}, \quad (12)$$

where u_1 is the initial value of the PMR, K is the total power of the doublet, and

$$a = \frac{A_2}{hK} \quad (13)$$

is a shape factor which is equal to the incident angle with respect to the normal at the contact surface divided by the height of the PMR and the total power of the doublet.

If μ_1 and μ_2 are the refractive indices of the two glasses, the normalized primary spherical aberration of the doublet is

$$\begin{aligned} \sum_I = & \left\{ \frac{2}{\mu_1} \left(\frac{1+\rho}{2} \right) + \frac{2}{\mu_2} \left(\frac{1-\rho}{2} \right) + 1 \right\} a^2 \\ & + \left\{ \frac{3}{\mu_1-1} \left(\frac{1+\rho}{2} \right)^2 - \frac{3}{\mu_2-1} \left(\frac{1-\rho}{2} \right)^2 + (\rho-Y) \right\} a \\ & + \left\{ \frac{\mu_1}{(\mu_1-1)^2} \left(\frac{1+\rho}{2} \right)^3 + \frac{\mu_2}{(\mu_2-1)^2} \left(\frac{1-\rho}{2} \right)^3 \right. \\ & \left. - \frac{\mu_1}{\mu_1-1} \left(\frac{1+\rho}{2} \right)^2 \left(\frac{Y-1}{2} \right) + \frac{\mu_2}{\mu_2-1} \left(\frac{1-\rho}{2} \right)^2 \left(\frac{Y+1}{2} \right) \right\} \quad (14) \end{aligned}$$

and the normalized central coma is



$$\sum_{II} = \left\{ \frac{1}{\mu_1} \left(\frac{1+\rho}{2} \right) + \frac{1}{\mu_2} \left(\frac{1-\rho}{2} \right) + 1 \right\} a + \left\{ \frac{1}{\mu_1^{-1}} \left(\frac{1+\rho}{2} \right)^2 - \frac{1}{\mu_2^{-1}} \left(\frac{1-\rho}{2} \right)^2 + \left(\frac{\rho - Y}{2} \right) \right\}. \quad (15)$$

From the specified value of $\sum_{II}$ needed, (15) is solved for a for a range of μ_1 and μ_2 for various values of ρ . The range on μ_1 and μ_2 is from 1.50 to 1.80 and the range on ρ is from +2 to +8 or from -2 to -8 depending on whether the leading element has the higher or lower dispersion.

We have developed a simple computer program that helps to converge on the right values of μ_1 , μ_2 and ρ . The description of the program is easily made with the aid of an example. From the parameters given in the list, we find that

$$\left. \begin{aligned} \eta_1 &= -20.5 \text{ mm} \\ K_1 &= 1/163 = 0.006134 \text{ mm}^{-1} \\ u_1 &= -\bar{D}/2F = -0.1227 \\ h_1 &= -u_1 \ell_1 = 20 \\ H &= n_1 \mu_1 \eta_1 = 2.52 \\ E_1 &= 0 \\ E_2 &= 41/20 = 2.05 \\ Y &= -1 \end{aligned} \right\} \quad (16)$$

To begin the computer program, the values of $\sum_{II}$ and Y are entered. The program operates in one of three modes. In the first mode, we supply a value of ρ ; the computer prints values of $\sum_I$ and a for combinations of μ_1 and μ_2 falling within the range 1.5 to 1.8. This preliminary search gives the approximate values of μ_1 and μ_2 based on the turning point of $\sum_I$. If the turning point occurs at inconvenient values of μ , repeat for a different value of ρ . We also watch the calculated value of a — we want $A_2 = |ahK|$ to be less than one to avoid the introduction of higher order aberrations. The value of a is most strongly dependent on ρ .

From the parameters given above, we found that a $\rho = 3.5$ gave an a of approximately -5 which gives $A_2 = (-5)(20)/163 = -0.61$. The indices were $1.50 < \mu_1 < 1.60$ and $1.60 < \mu_2 < 1.70$.

In the second mode, we supply ρ as determined above, a range for μ_1 and μ_2 and an increment on μ_1 and μ_2 . This simply calculates (14) and (15) within a finer mesh. From this calculation we found that

$$\mu_1 \approx 1.52$$

$$1.62 < \mu_2 < 1.64$$

Finally, in the third mode, we supply μ_1 , μ_2 , V_1 and V_2 for candidate glasses. The computer prints out the value of $\sum_I$ and a ; we can quickly converge to the set of glasses for which $\sum_I$ is acceptably close to zero. From this calculation we found that we should have $\mu_1 = 1.52$ and $\mu_2 = 1.625$ for $\rho = 3.5$, giving a value for a of -5.1833.

The next step is to find glasses having the correct values of μ and V to satisfy the requirements. Sixteen possible glass combinations were then calculated, using mode 3. The residual spherical aberration ranged



from $\sum_I = 0.00693$ to $\sum_I \approx 0.5270$ with a being nearly constant. The minimum value of $\sum_I$ was achieved for the following glasses.

$\mu_1 = 1.51821$	$V_1 = 65.2$
$\mu_2 = 1.62237$	$V_2 = 36.04$
$\rho = 3.4719$	$a = -5.15061$
$\sum_I \approx 0.00693$	$\sum_{II} = 0.61666$

A similar procedure can be followed for the second doublet for which $\sum_{II} \approx -0.61666$ and $Y \approx 1$. Note that since the system is symmetrical we could let the second doublet be flint-leading rather than crown-leading as in the first doublet. The sign of $\sum_I$ does not change, however, so that the total spherical aberration of the system is proportional to $2\sum_I$. In some systems, the appropriate glasses for making $\sum_I$ acceptably small may not exist; the only recourse is then to make the second doublet of a different design so that $(\sum_I)_2$ is equal and opposite to $(\sum_I)_1$.

It is worthwhile making a preliminary estimate of the required value of $\sum_I$. The value of $\sum_I$ may be determined by the permissible level of spherical aberration or the permissible value of distortion. We will first find the bound on $\sum_I$ set by distortion and then check this value against that set by spherical aberration.

The fractional distortion $\delta\eta/\eta$ at the edge of the field is equal to $S_V/2H$. For a 100 x 100 element photodetector array, we have $\delta\eta/\eta \approx 0.0014$ if we are to keep any bit location to within 10% of its intended location. This means that $|S_V| < 0.0014(2H) \approx 0.00706$. From the stop-shift formulae (5), we see that $|S_V| = (\delta E)^3 S_I$ so that for $\delta E = 2.05$, which is the worst possible case, we have $|S_I| < 8.18(10^{-4})$, and $|\sum_I| < S_I/h^4 K^3 \approx 0.0221$.

The lens design is based on good aberration control over the entire 40 mm aperture of the system. The effective aperture as determined by the size of each hologram is, however, only 1/40th of the full system aperture. The aberrations are therefore reduced according to the following relationships: spherical aberration decreases as the fourth power of aperture, coma decreases as the cube of the aperture, and astigmatism decreases as the square of the aperture. Distortion is a linear function of aperture but is cubic function of the stopshift δE .

The amount of spherical aberration that leads to an acceptable amount of distortion is ${}_0W_{40} = 1/8S_I \approx \lambda/8$ which, even at full aperture, is acceptable. Note, however, that we will be operating each subhologram at an aperture that is 1/40 of the full aperture, so that the effective amount of spherical will be only $(\lambda/8)(1/40)^4$ which is totally negligible.

In a previous calculation we assumed that δE could be as large as 2.05 which implies that the stop is moved from K_1 to K_2 . Since the stop is to be located midway between K_1 and K_2 , and since S_V varies as the cube of S_I , we see that we can tolerate $(2.05/1.025)^3$ times the amount of S_I indicated before. In terms of $\sum_I$ this means that $|\sum_I|$ should be less than 0.1771 so that the preliminary design is well within this requirement, even if the symmetrical solution is used.

2.3 Further Design Calculations

We now calculate the curvatures of the lens components. For the first doublet we have

$$A_2 = ahK_1 \quad (17)$$



where A_2 is the angle that the incident ray makes at the interface with respect to the normal of that surface. We also have

$$h\tilde{K}_1 = \left(\frac{1 + \rho}{2} \right) hK_1; \quad h\tilde{K}_2 = \left(\frac{1 - \rho}{2} \right) hK_1 \quad (18)$$

and

$$\begin{aligned} A_1 &= A_2 + \left(\frac{\mu_1}{\mu_1 - 1} \right) h\tilde{K}_1 \\ A_3 &= A_2 - \left(\frac{\mu_2}{\mu_2 - 1} \right) h\tilde{K}_2 \end{aligned} \quad (19)$$

where $\tilde{K}_1$ and $\tilde{K}_2$ are the powers of the individual lenses in the doublet, K_1 is the power sum, h is the (common) height of the PMR at the lens and μ_1 and μ_2 are the indices of refraction. Using the appropriate values as developed earlier, we have

$$A_2 = (-5.15061) 20/163 = -0.631976$$

$$h\tilde{K}_1 = \left(\frac{1 + 3.4719}{2} \right) 20/163 = 0.27435$$

$$h\tilde{K}_2 = \left(\frac{1 - 3.4719}{2} \right) 20/163 = -0.15165$$

$$A_1 = -0.631976 + \left(\frac{1.51821}{.51821} \right) (0.27435) = 0.171792$$

$$A_2 = -0.631976 - \left(\frac{1.62237}{.62237} \right) (-0.15165) = -0.236617$$

The paraxial angles defined by $g = hc$ are given by



$$g_1 = A_1 + u_1$$

$$= 0.171792 + (-0.1227) = 0.049092$$

$$g_3 = A_3 + u_3$$

$$= -0.236617 + 0 = -0.236617$$

The formulae given in Reference 1 for obtaining g_3 are needlessly complicated and lead to inaccuracies in computation. A more accurate formula is

$$g_2 = (2a + \rho + Y) hK/2 \quad (20)$$

We then have

$$g_2 = [2(-5.15061) + 3.472 - 1] (20)/(163) (2) = -0.480346$$

The three curvatures are obtained by assuming $h = 20$ nm at each surface so that

$$c_1 = g_1/h = 0.002454 \text{ mm}^{-1}$$

$$c_2 = g_2/h = -0.024015 \text{ mm}^{-1}$$

$$c_3 = g_3/h = -0.011830 \text{ mm}^{-1}$$

and the radii are

$$r_1 = 1/c_1 = 407.5 \text{ mm}$$

$$r_2 = 1/c_2 = -41.64 \text{ mm}$$

$$r_3 = 1/c_3 = -84.53 \text{ mm}$$

We see that curvautre c_2 is very steep; in fact, r_2 is nearly one-half the free lens diameter which means that this must be a hemispherical surface. There are two ways to correct this situation. The first is to try to divide the powers more evenly between K_1 and K_2 by changing ρ , but this gain is offset by a higher value of A_2 . The second is to make the leading element a flint glass. We tried the second approach and found that the smaller value of ρ led to a lower value of a and a better set of curvatures. Sixteen more pairs of glasses were calculated; curvatures we calculated for six pairs of glasses that led to acceptably small aberrations. The two glasses chosen are a SF-4 ($\mu_1 = 1.75520$, $V_1 = 27.6$) and a K-10 ($\mu_2 = 1.50137$, $V_2 = 56.4$). The three radii are $r_1 = 123.77$ mm, $r_2 = 63.36$ mm, and $r_3 = -124.11$ mm. The value of ρ is -2.9423 and $a = 4.5143$.

The thickness d of a lens element can be obtained from the formula

$$d = \frac{R^2}{2} (c_1 - c_2)$$

$$= \frac{R^2 K}{2(\mu - 1)}$$
(21)

where R is the radius of the lens, K is the power, and μ is the refractive index of the glass. The radius of the lens is generally increased by at least 0.5 mm to give the needed free aperture. Equation (21) gives the center thickness of a positive lens or the edge thickness of a negative lens. The thickness of a positive lens is increased by 0.5 mm to give a surface at the edges and the thickness of a negative lens, at the center, is generally not less than $1/5$ of the free aperture.

The first lens (the flint) is a negative lens so that, for a lens diameter of 82.5 mm, the axial thickness is 8.25 mm; its edge thickness is $6.47 + 8.25 = 14.72$ mm. The second lens has an axial thickness of $19.73 + 0.5 = 20.23$ mm.



The next step is to trace a PMR and a PPR through the system to establish the position of the principle planes H and H'. The basic formula is that

$$n'u' - nu = hc(n' - n) \quad (22)$$

where the primes refer to indices and angles after refraction at a surface, c is the curvature of a surface (positive if convex to the incoming light) and h is any convenient intersection height. The basic formulae (22) is more conveniently put into the form

$$u' = \frac{nu + hc(n' - n)}{n'} \quad (23)$$

which, along with the transfer formula

$$h_{+1} = h - d'u', \quad (24)$$

serves to establish the path of a ray. We begin by finding H' by tracing a ray from left-to-right parallel to the optical axis. We found that the second principal plane H' lies 8.87 mm to the left of the last surface of the lens. The distance from the last surface to the back focal plane was found to be 156.5 mm. The first principal plane H lies 9.53 mm to the right of the first surface of the lens and the front focal plane lies 157.3 mm to the left of the first surface.

2.4 Performance Calculations

Having defined the glass types, the curvatures, and the positions of the principal planes, we are ready to evaluate the performance of the lens with a computer program. The program used was Words I (owned by

Wiley Optical, Melbourne, Florida), available on our time-shared system at Melbourne. This program is capable of generating spot diagrams, modulation transfer functions, and other information such as the plane of best focus. For this application the two most significant parameters are the spot size (the diameter of the image point containing 90 percent of the energy) and the distortion.

The preliminary design was evaluated for five object positions: an on-axis point, points ± 14 mm off-axis, and points ± 20.5 mm off-axis (the full field). The image spot diameter and location were then calculated for a 1 mm diameter hologram both on-axis and 20 mm off-axis. Although the lenses are not designed to be used at the full 40 mm aperture, calculations were also made at full aperture to be compared to the design calculations. All computations were done for 632.8 nm and 488 nm wavelengths.

The computations can be summarized by stating that the lenses are diffraction limited for all object positions and for all hologram locations (for the 1 mm hologram aperture) at both wavelengths. The maximum distortion encountered is 0.025 percent which is well within the design goal of 0.14 percent. All primary aberrations are, therefore, sufficiently small for this application.

At full aperture (40 mm) the performance dropped significantly, as expected. Distortion remained small, however, being 0.5 percent for the edge of field and 0.007 percent for an object point ± 14 mm off-axis.

The computer program also prints the position of the plane of best focus. Figure 2 shows the variation of focus as a function of field for the two wavelengths. Since the depth-of-focus for this system is ± 30 mm, the variation in focus of ± 0.4 mm is insignificant.

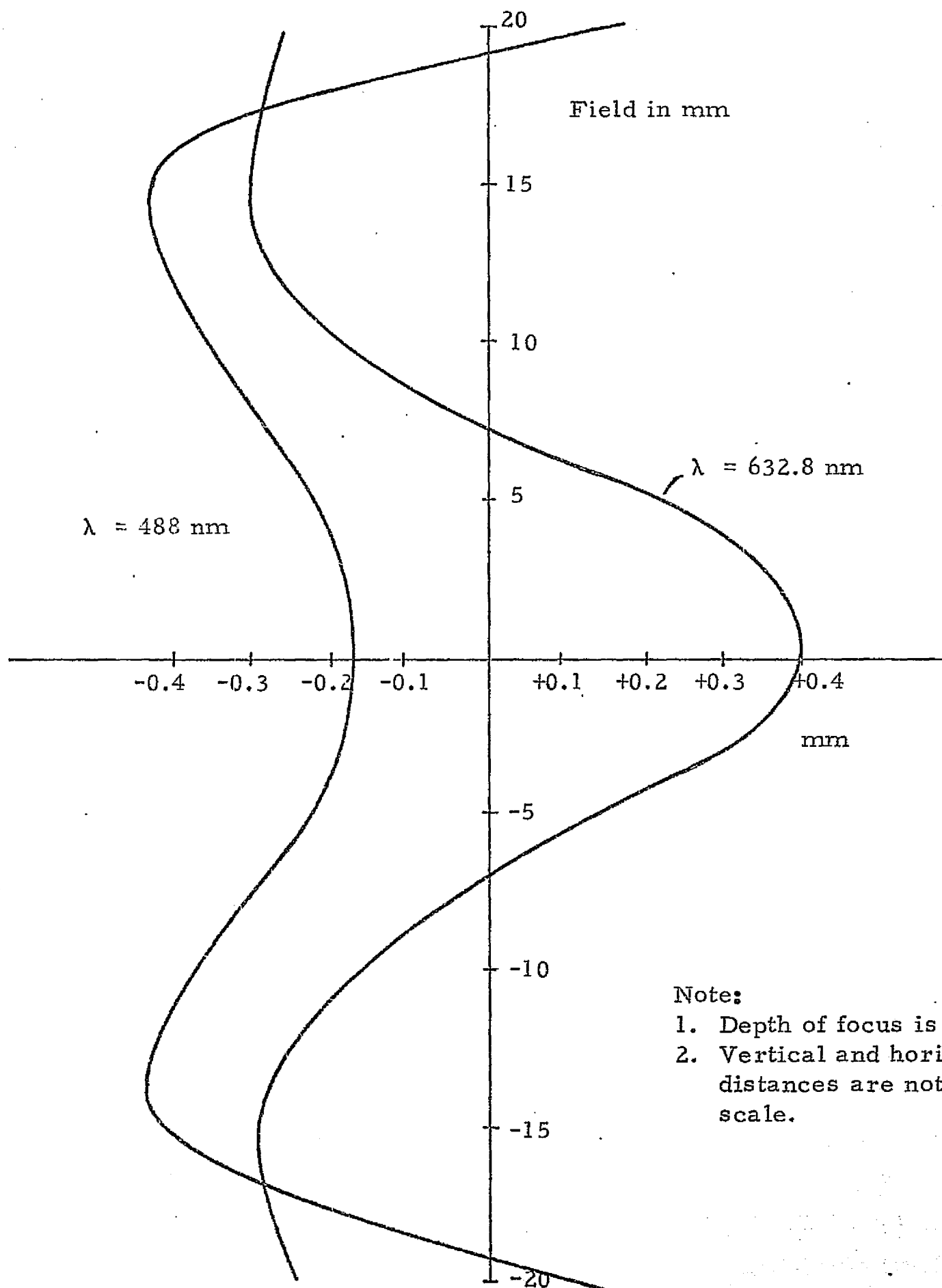


FIGURE 2: GAUSSIAN IMAGE SURFACES

The design proved, therefore, to be satisfactory in every respect. These two cemented doublets have been fabricated and mounted in the test bed system.

2.5 Beam Deflector Optics

In the Quarterly Report we gave an analysis of the beam deflector optics needed for the feasibility test bed system. That optical design was predicated on the requirement that the reference (and readout) beams be collimated; this requirement led to the design of a four lens system. The last two lenses in that system increased the beam diameter from 0.5 to 1.0 mm as it collimated the reference beam. Such a system will still be required in memories that use conjugate readout beams. We found, however, that only the first two lenses were adequate for memories where the readout and reference beams are identical.

The two lens system consists of an objective lens of focal length F_1 and a microscope objective of focal length F_2 ; the angular magnification of the system is therefore, $M_a = -F_1/F_2$. The beam diameter at the entrance pupil of the system (see Figure 3) is D and the beam diameter at the exit pupil, as calculated from Gaussian optics, is D/M_a . The actual beam diameter at the plane of the hologram is however, dictated by diffraction so that the diameter calculated from Gaussian optics is not valid. This also implies that the reference beam amplitude is not uniform at the plane of the hologram and we must specify a criterion for its diameter. We define the diameter of the reference beam as the diameter of the first dark ring of the diffraction pattern.

We shall assume that the beam entering the first lens has a uniform amplitude so that the light distribution at the focal plane is proportional to $\text{sinc}(\pi D \xi / \lambda F_1)$ whose first zeros occur at $\xi = \pm \lambda F_1 / D$, where ξ is the

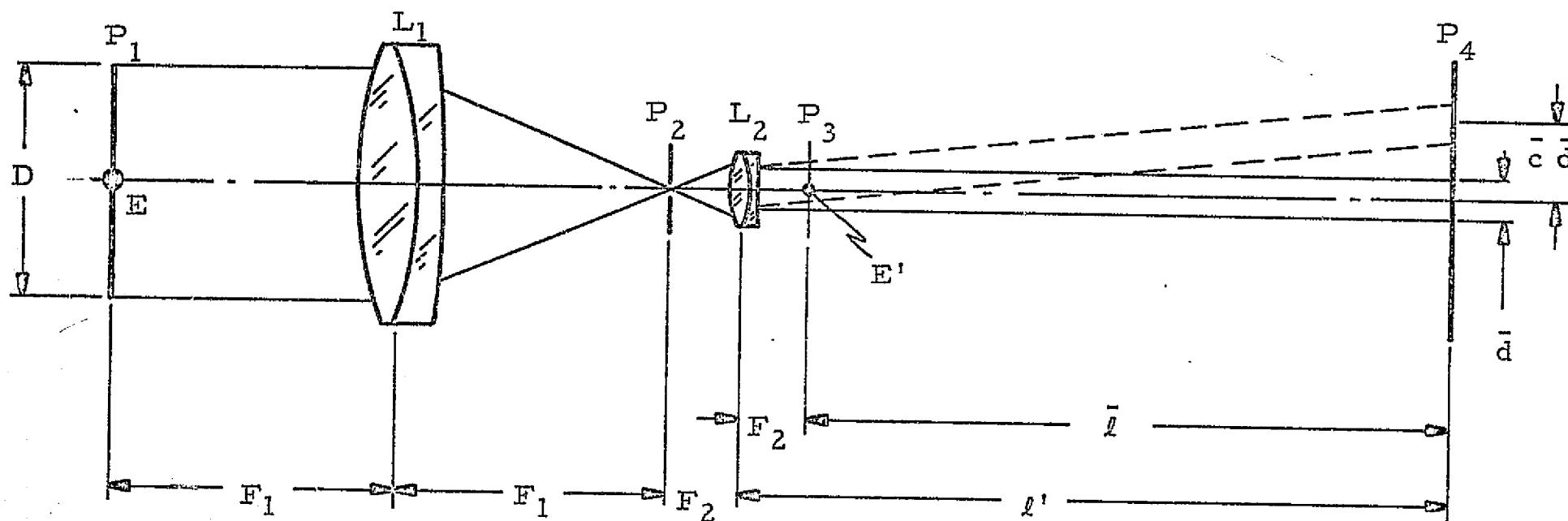


FIGURE 3: BEAM DEFLECTOR OPTICS



coordinate in plane P_2 . The light amplitude at the hologram plane will be either an image of the sinc-function or the far-field diffraction pattern of the exit pupil.

In the case where the light distribution at the plane of the hologram is the image of the light distribution in plane P_1 , we have that the distance from lens L_2 to the hologram is $\ell' = (1-M)F_2$ where M is the linear magnification associated with lens L_2 above. The first zeros of the sinc-function then occur at

$$|x| = M\lambda F_1/D \quad (25)$$

where x is the coordinate in the plane of the hologram. The distance from the exit pupil to the plane of the hologram $\bar{\ell}$ is equal to $\bar{\ell} = \ell' - F_2 = -MF_2$ so that (25) becomes

$$\begin{aligned} |x| &= \bar{\ell}\lambda F_1/F_2 D \\ &= M_a \lambda \bar{\ell}/D \end{aligned} \quad (26)$$

We now calculate the distance to the first zeros of the sinc-function when the two lens system is in the afocal (telescopic) arrangement. The far-field diffraction pattern is simply $\text{sinc}(\pi D x / \lambda \bar{\ell} M_a)$ whose first zeros are at

$$|x| = M_a \lambda \bar{\ell}/D \quad (27)$$

which is identical to (26). Thus, the hologram beam diameter $\bar{d} = |2x|$ is the same for the two cases.

We also note that the centers $\bar{c}\bar{d}$ must satisfy the relationship that

$$\bar{c}\bar{d} = (\Delta\theta) M_a \bar{l} \quad (28)$$

where $\Delta\theta$ is the incremental deflection angle produced by the AOBD. We can solve (27) and (28) to get that

$$D = \frac{2c\lambda}{\Delta\theta} \quad (29)$$

which relates the length of the AOBD to its deflection properties.

The design calculations for the AOBD are based on a time-bandwidth product of 80 double-Rayleigh resolution elements. The $\Delta\theta$ found is of the order of 0.05 mr and D was found to be 20 mm. We note that $\Delta\theta$ is a linear function of wavelength so that D is not a function of wavelength. Equations (26) and (27) show, however, that the reference beam size at the hologram plane is a function of wavelength because it is caused by diffraction.

What we must do, therefore, is to ensure that Equations (27-29) are simultaneously satisfied at the long wavelength. Since $\bar{d}$, $\bar{c}$ and λ are usually specified, we have four variables (D , $\Delta\theta$, M_a and $\bar{l}$) with which to solve these equations. If D is also fixed, we must make the product $M_a \bar{l}$ equal to $\bar{c}D/2\lambda$ which can be done for a fixed M_a by varying $\bar{l}$. The incremental angle $\Delta\theta$ must then be chosen to satisfy (29).

3. OPTICAL SYSTEM DESIGN

After designing the Fourier transforming and imaging lenses, we began the design of the remainder of the optics for the memory system. Figure 4 shows a layout of the optical portion of the memory system. The positions of the major system components to be fabricated on NAS-8-26672 are also shown for information (the lasers, the acousto-optic beam deflector, the block data composer, the holographic recording device, and the photodetector array); these components are not included in the optical test bed system developed on this contract. Specifications for these components are, however, given later in this final report.

The two lasers are the primary source of light. Since their exit beams are only 1-2 mm in diameter, two collimating assemblies are used to expand the light into larger collimated beams. The beam diameter (to the $1/e^2$ points) from the argon laser is 1 mm; the collimated beam must have a diameter of at least 28 mm. The beam is overexpanded, however, so that the beam intensity at the edge of the aperture is ± 30 percent of the intensity on axis. This over-expansion is required to make full use of the acousto-optic beam deflector (AOBD). The mirror gimbal mount is, in turn, mounted on a translation stage so that this beam can be made collinear with that obtained from the He-Ne laser. To achieve the desired beam, we have designed and fabricated a collimating assembly for the argon laser which consists of a 40 power microscope objective in a focusing mount, a pinhole in an x-y positional mount, a 160 mm focal length collimating lens, and a high reflectivity dichroic mirror, in a gimbal mount, which bends the collimated beam 90° .

The entrance beam diameter (to the $1/e^2$ points) of the helium-neon laser is 2 mm and, again, the exit beam diameter must be 28 mm. The collimating assembly for the He-Ne laser consists of a 21 power

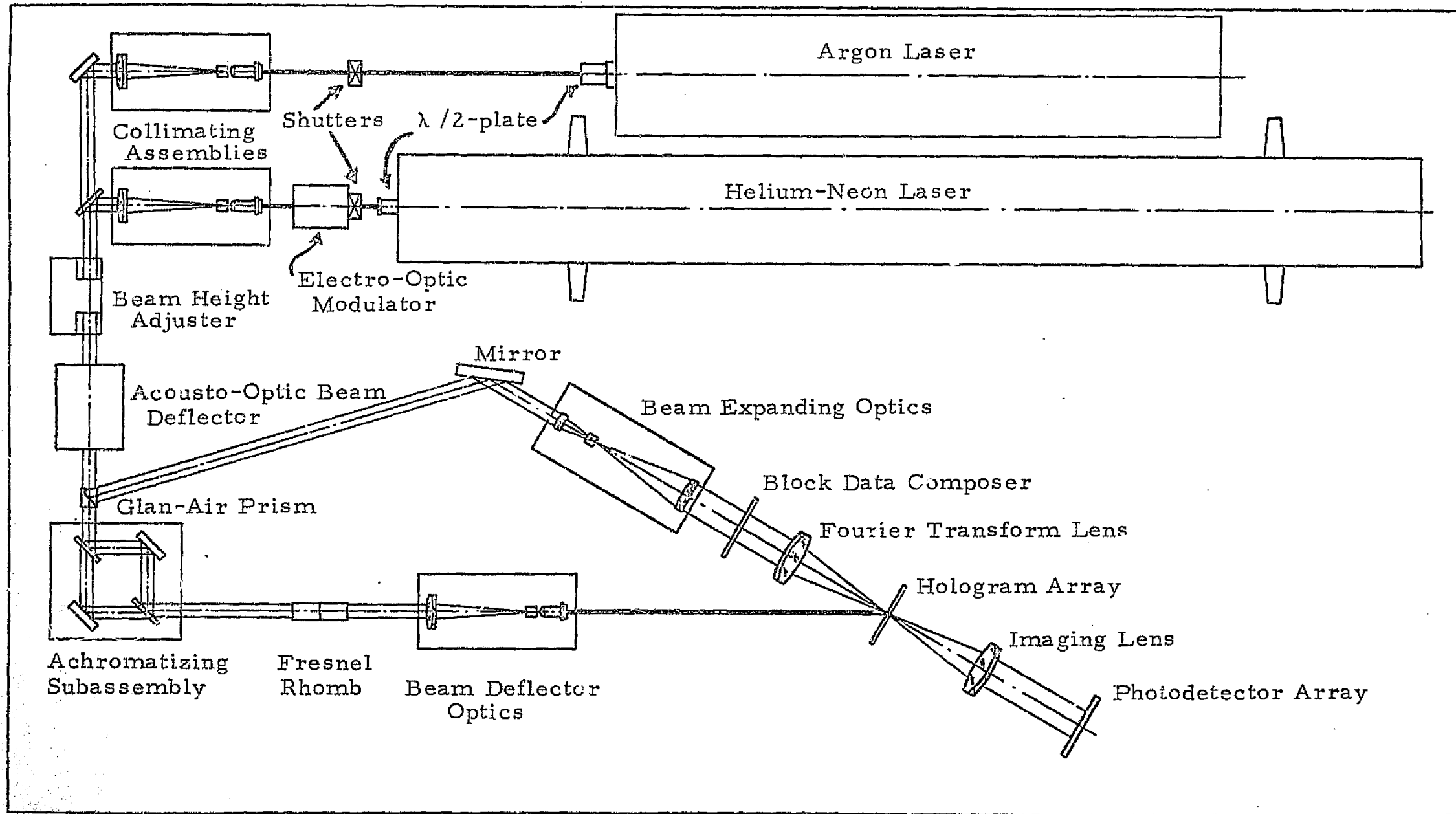


FIGURE 4: SYSTEM LAYOUT



microscope objective in a focusing mount, a pinhole in an x-y positional mount a 160 mm focal length collimating lens, and a dichroic mirror (red reflecting, blue transmitting) in a gimbal mount. This beam of light has the same relative intensity at the edge of the aperture as the beam from the argon laser.

The function of these two assemblies, then, is to produce and combine two 28 mm diameter collimated beams of coherent light. These combined beams then enter a beam height adjuster. Since the optical axis of the lasers are typically 254 mm above the table and since the remainder of the system can be centered on a 100 mm axis, the beam height adjuster drops the optical axis 150 mm by means of two broadband reflecting mirrors. The interferometric portion of the system which follows is therefore more stable and less sensitive to vibrations.

The mirrors are adjusted so that each beam enters the AOBD at the Bragg angle. After deflection, the beams enter a modified Glan-Air prism which functions as a polarizing beamsplitter. If the entering light is vertically polarized, all of the light is reflected at the interface and goes to the signal beam. If the light is horizontally polarized, all the light is transmitted and goes to the reference beam. The electro-optic modulator between the He-Ne laser and the collimating assembly is used to electrically control the plane of polarization so that an arbitrary ratio of reference-to-signal beam intensity can be obtained. Since the He-Ne laser is to be used in the read/write mode, rapid switching of the plane of polarization is needed. A polarization rotator, placed between the laser and the electro-optic modulator, is used to adjust the plane of polarization of the light entering the modulator. Since the argon laser is to be used only in the semi-permanent mode, a manually adjustable half-wave plate is used to obtain the desired reference-to-signal beam ratio.



The transmitted (reference) beam enters an achromatizing sub-assembly which makes the red and blue light collinear. The Bragg angle at the exit side of the AOBD is different for the two wavelengths and must be corrected. By adjusting the mirrors in this sub-assembly, both beams enter the beam deflector optics at the same angle. Figure 5 shows the Bragg angles (greatly exaggerated for clarity) at both the entrance and exit faces of the AOBD for the two wavelengths. This figure also clearly shows the purpose of the achromatizing sub-assembly. The principle pupil ray (PPR) for 632.8 nm is reflected by a dichroic mirror, by a red reflecting mirror, and by a second dichroic mirror. If the PPR is traveling vertically downward and if the three mirrors are at 45°, the PPR for the red light will be horizontal and thus define the optical axis of the beam deflector optics.

The PPR for the blue light passes through the first dichroic mirror and is reflected by a blue reflecting mirror. The angle of this mirror is rotated counterclockwise by $(\theta_r - \theta_b)/2$ and, by means of a translation stage under the fourth mirror mount, is made to exit the achromatizer collinear with the PPR of the 632.8 nm light. This subassembly of mirrors, therefore, makes the beam entering the beam deflector optics achromatic.

During the past quarter we experimentally tested the beam deflector optics design given in the Quarterly Report. We found that beam spreading due to diffraction was greater than anticipated so that the second pair of lenses used in that design is not needed to obtain a 1 mm diameter beam. The beam deflector optics, then, are particularly simple. The collimated light from the achromatizing sub-assembly passes through a Fresnel rhomb half-wave retarder which causes the polarization in the reference beam to be vertical so that it can interfere with light in the signal beam. The collimated beam then enters a 160 mm focal length objective lens and

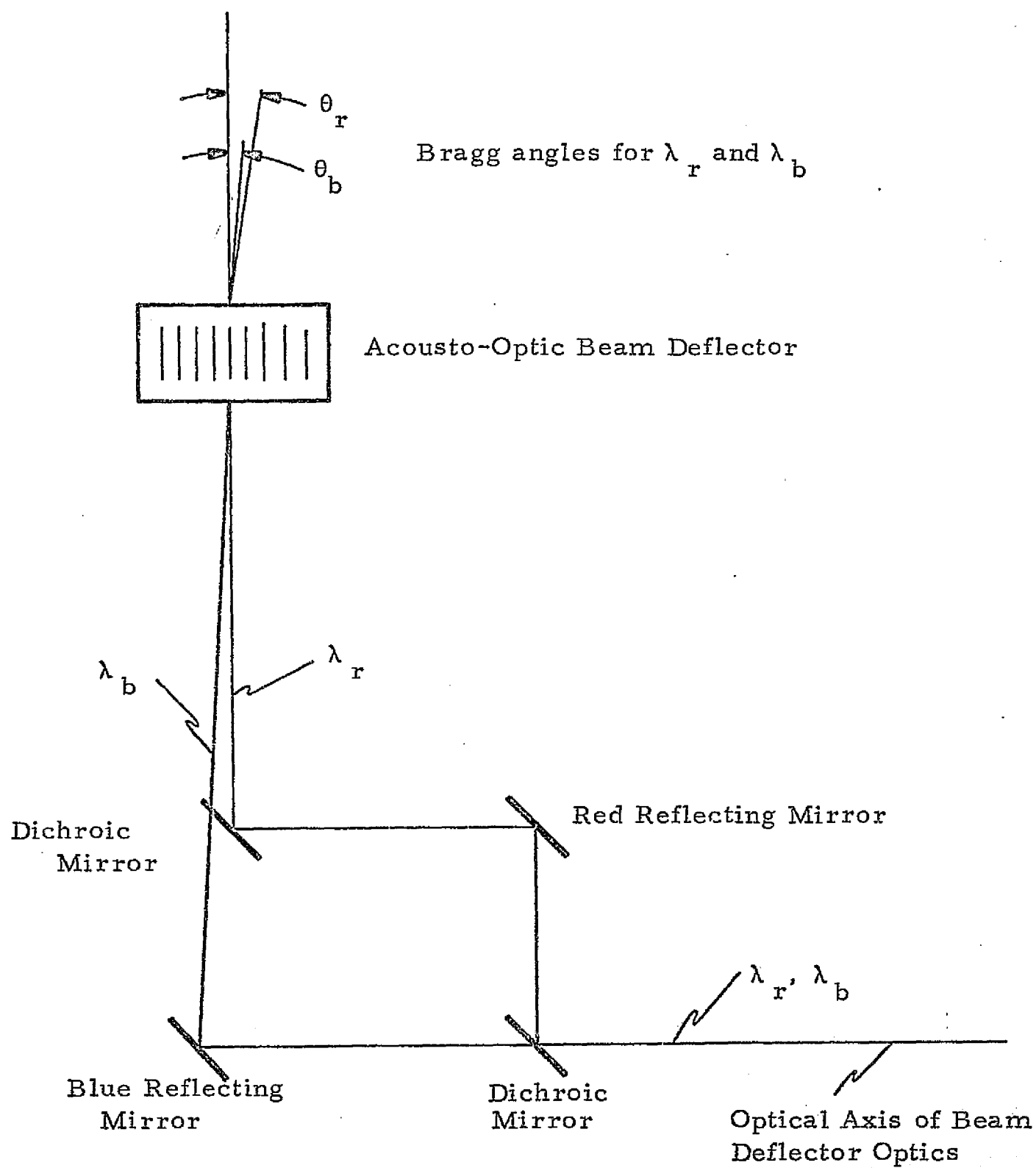


FIGURE 5: ACHROMATIZING SUBASSEMBLY



is focused at its back focal plane. A small aperture in this plane removes the unwanted d.c. light (light that is not deflected by the AOBD) while passing the desired deflected beams. A 40 power microscope objective in a focusing mount is then used to produce a 1 x 1 mm beam at the plane of the hologram. The beam deflector optics are mounted on a single plate that can be moved axially along the PPR of the system so that the proper beam spacing as well as the proper beam size can be obtained.

The beam reflected by the Glan-Air prism serves to illuminate the signal beam. This beam is chromatic because the beams generated by the AOBD do not have collinear PPR's. Even an achromatic beam entering the Glan-Air prism would be chromatic upon reflection (the transmitted beam, however, is achromatic if the entering beam is achromatic). Chromatism in the signal beam is not important in this application because the diffuser used in conjunction with the BDC scatters light over a broad range of angles. The slight differences in the angles of the PPR's are not, therefore, significant.

The light is reflected by a 2" x 4" broadband mirror and enters a 60 mm focal length objective lens. The beam entering this lens is approximately 20 x 20 mm in size and must be expanded to at least 40 x 40 mm in size. The variation in intensity across the aperture must also be reduced, so the focal length of the second lens in the expanding optics is 160 mm. The maximum variation in the illumination of the BDC is ± 20 percent. A spatial filter, placed at the common focal plane of this telescope, passes only the deflected portion of the light. Only the deflected portion of the light can be used because the AOBD shifts the frequency of the light by the frequency of its electrical excitation. The d.c. light (or light not deflected) is not shifted in frequency and, although it will interfere with the light in the reference beam, the interference fringe pattern will not be

stable. Fringe motion during the exposure times anticipated in this application will smear the recorded patterns and lead to degraded signal-to-noise ratios. The Glan-Air prism, which divides the light into the signal and reference beams, was placed after the AOBD so that both the reference and the signal beams experienced the same frequency shift.

The light modulated by the BDC is Fourier transformed by one of the cemented doublets whose design was discussed in Section 2. Although the light modulated by the BDC illuminates the entire hologram plane, only a part of it is recorded at a given location. The reference beam, deflected to a given hologram location by the AOBD, interferes with a portion of the light distribution created by the Fourier transform lens. After the exposure is made and the photoplastic hologram recording is fixed by heating, the entire process is repeated for each of the hologram locations.

The imaging lens is used only in the retrieval process. The read-out beam is directed to one of the hologram locations and a wavefront, corresponding to the wavefront present upon recording, is reconstructed by the hologram. The imaging lens then displays the related bit pattern at the plane of the photodetector array. The photodetectors convert the bit pattern into an electrical signal.

Figures 6 and 7 are photographs of the components fabricated under this contract mounted on a 4' x 8' aluminum honeycomb, air-suspension table. Adequate space has been left for mounting the major system components such as the lasers, the block data composer, the hologram storage device, the acousto-optic beam deflector, and the photodetector array. The drive electronics and the controller for these components can be mounted under the table.

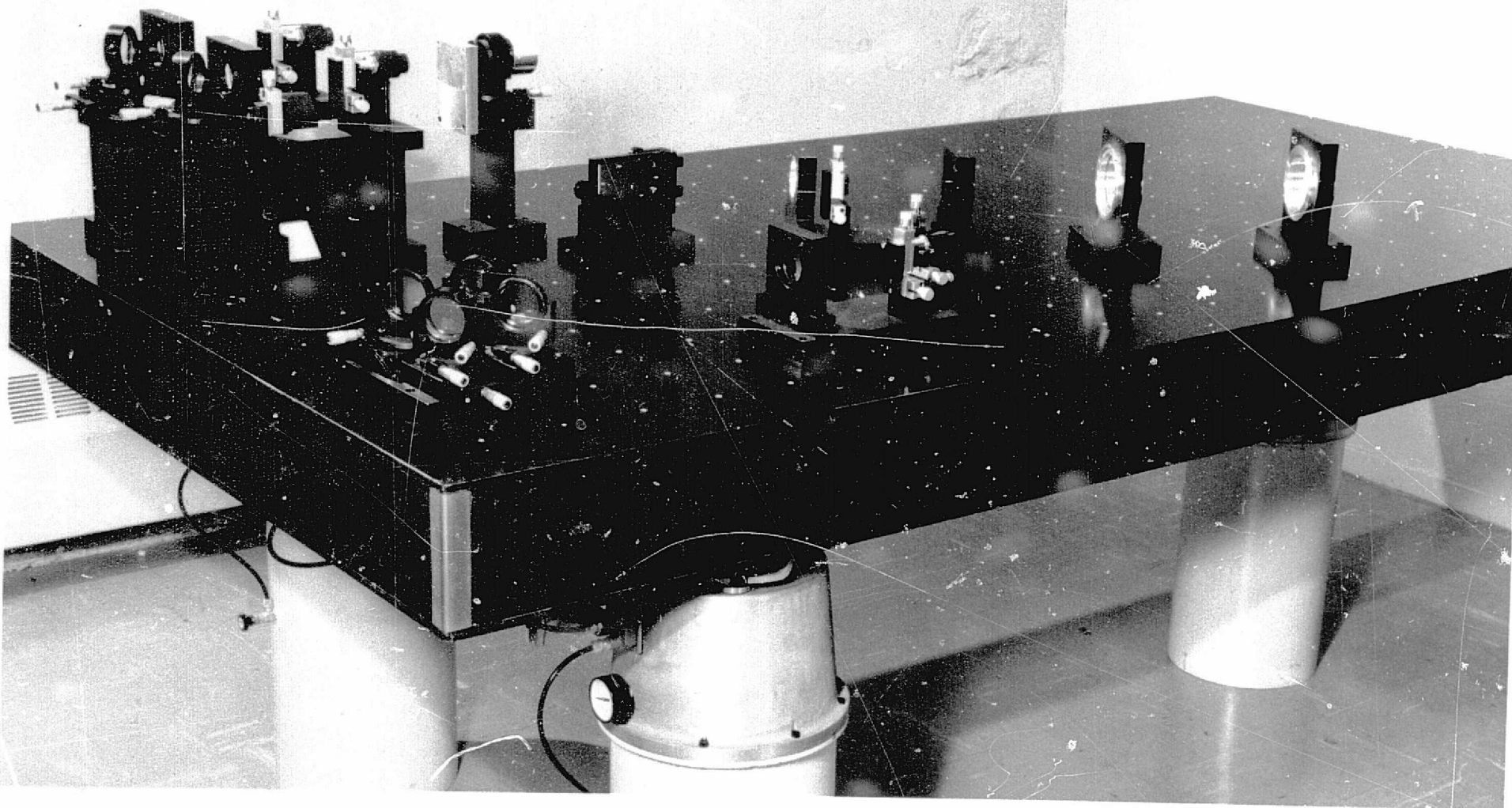


FIGURE 6

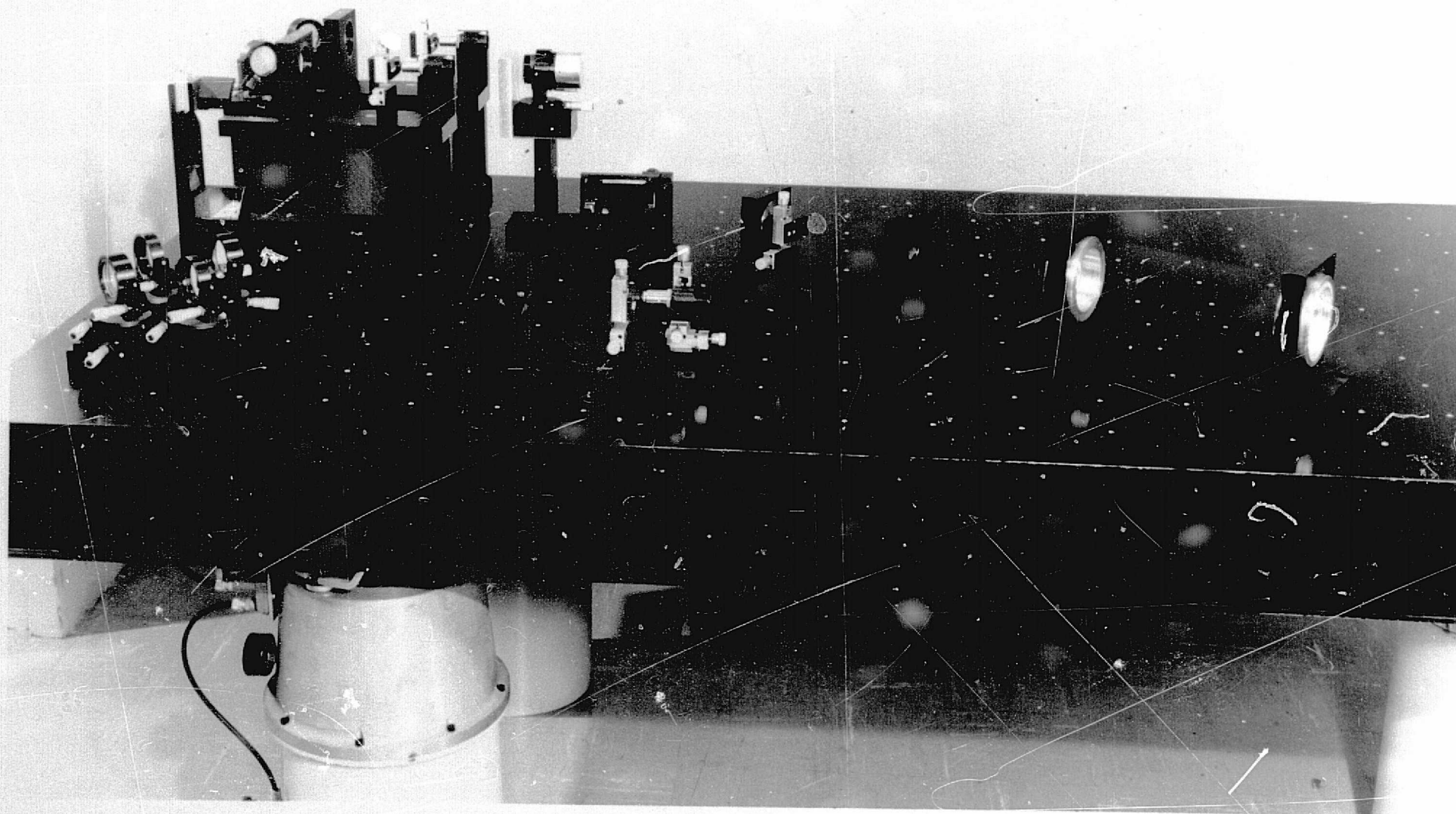


FIGURE 7

4. LASERS

The laser for the holographic memory must provide coherent light at more than one wavelength. Coherent light will be provided by two CW lasers operating in the fundamental (TEM_{00}) mode. The wavelength difference between the light emitted by these lasers will be sufficiently large so that multiwavelength holographic data storage can be achieved in the semi-permanent optical memory mode. A beam combiner, required to superimpose the individual laser beams, will allow the entire optical system to function with either of the laser beams so that an adjustment of optical components when switching between wavelengths will not be required. A wavelength selector will be used to select an operating wavelength and to provide a means for blocking both laser beams. The beam combining system and means for selecting the desired wavelength were discussed in Section 3.

The laser system will be specified within certain constraints and limitations imposed by the overall performance criteria for the holographic memory. The principal constraints are (1) the spectral response of the page composer, hologram recording material, and photodetectors, and (2) the laser power requirements defined by data flow rate, signal-to-noise ratio, and error rates. The lasers we specify are compatible with the goals of the overall system and will provide a satisfactory level of performance.

At present the best lasers for this application are helium-neon lasers and argon-ion lasers. These lasers emit coherent light at 632.8 nm (red) and 488 nm (blue), respectively, giving a wavelength separation of about 155 nm which is sufficient for use with moderately thick recording materials. Due to an inherently higher gain, an argon laser will produce much more power than a helium-neon laser, a desirable factor to compensate for the reduced response of the photodetectors and other optical components in the blue part of the visible spectrum.



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At present, the best lasers for this application are the following. For the helium neon laser our choice is a Spectra Physics Model 125 laser. It is unequaled in terms of output power, quality, and reliability. The specification for this laser are as follows:

- (1) Wavelength: 632.8 nm
- (2) Output power: 50 mw
- (3) Linearly polarized to 1000:1
- (4) Beam diameter @ $1/e^2$ points: 2 mm
- (5) Beam divergence: 0.7 milliradians
- (6) Size: laser head - 75" long, 11" high, and 6 1/2" wide;
power supply - 12" deep, 6" high, and 16" wide
- (7) Weight: Laser head - 100 lbs., power supply - 45 lbs.
- (8) Prime power requirements: 115/230, 1 Φ , 60 Hz, 500 VA.

For the argon laser we recommend a Control Laser Model 901. The specifications for this laser are as follows:

- (1) Wavelength: 488 nm
- (2) Output power: 350 mw
- (3) Linearly polarized to 1000:1
- (4) Beam diameter @ $1/e^2$ points: 1 mm
- (5) Beam divergence: 0.8 milliradians
- (6) Size: laser head - 36" long, 5 1/2" high and 7 1/2" wide
power supply - 22 1/2" deep, 10 1/2" high and 9 1/2" wide
- (7) Weight: laser head - 50 lbs.; power supply - 90 lbs.
- (8) Prime power requirements: 208/240 V, 3 Φ , 35A/ Φ , 60 Hz
- (9) Coolant requirements: 1.5 gpm @ 35 psi (water).

5. BLOCK DATA COMPOSER

The holographic memory system is interfaced with digital electrical data by a block data composer (BDC). The BDC provides a two-dimensional spatial array of successive blocks of data extracted from the input data stream. Each array of data spatially modulates a laser beam which is directed to a storage location where it interferes with the reference beam to form a hologram.

We have designed a BDC having a 128×128 spatial array of modulating elements. The device will control each of the 128×128 positions by means of an electrode matrix bonded to a thin plate of PLZT (a transparent ferroelectric ceramic). Preliminary specifications and performance parameters for a BDC fabricated with PLZT were described in the Quarterly Progress Report. The physical, optical, and electrical properties of PLZT were also described and possible approaches for implementing a 128×128 BDC with PLZT, using strain-bias and a transparent electrode matrix, were outlined. In this section we describe the important fabrication steps and the drive electronics, and we present the final design parameters for the BDC using PLZT.

5.1 Block Data Composer Fabrication

The BDC consists of a polished PLZT plate with a transparent electrode matrix deposited on the two plate faces, plus a Plexiglas or glass plate to which the polished and electroded PLZT is bonded with a transparent epoxy. A fixed strain in a selected direction will be applied to the PLZT by bonding it to a prestressed plate. After the bond cures, the initial stress in the substrate will be released, thereby transferring a strain to the PLZT. This prestrained configuration is mounted so that the strain-bias can be



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changed by slightly flexing the substrate; small errors in the plate thickness or the amount of fixed strain can be compensated in the first devices fabricated.

Electrical contact with the electrodes on the exposed PLZT face will be made by directly attaching small flexible leads to the ends of each electrode strip by ultrasonic bonding or an equivalent technique. The electrode strips at the transparent bond interface will be pressure contacted at their ends to a matching set of electrode strips on the substrate; the substrate electrodes extend outside the interface region. Small flexible leads will be attached to the electrodes on the substrate and connected to terminal strips on the mount; more rugged leads will connect these terminals to the drive electronics through multiple conductor cables.

Techniques for lapping and polishing PLZT plates to thicknesses in the 2 to 5 mil range with an optical surface finish on both faces have been developed on an internal Radiation Incorporated program. The optical uniformity of the BDC will depend largely on the uniformity of thickness over the full area of the BDC; techniques for maintaining sufficient thickness uniformity exist and must be implemented during the device fabrication.

Transparent electrode matrices are routinely applied to polished PLZT plates and to Plexiglas substrates by vacuum evaporation of chromium and gold at Radiation Incorporated. Facilities for sputter depositing transparent indium oxide and tin oxide electrodes, as well as mask making facilities for fabricating metal masks with 128 or more parallel slits on 0.254 mm centers, are available at Radiation Incorporated.

We have developed procedures for mixing, applying, and curing transparent epoxy for bonding PLZT to Plexiglas and glass and we have used them successfully in preliminary devices fabricated in our optics shop. Electrical



access to the transparent electrodes on the PLZT at the bond interface has been made by pressure contact to matching electrode strips on the substrate which extend slightly into the interface region.

A jig for applying controlled strain (compression or tension) to preliminary BDC devices has been constructed and is in routine use. A sketch of an 8 x 8 element preliminary BDC is shown in Figure 8.

5.2 Block Data Composer Electronics

The BDC must provide 128 x 128 electrically alterable optical apertures in a planar array. The electronics to address matrix positions are fairly common, but the expected switching voltage levels of 100 to 300 volts, into relatively large capacitive loads, will present special design problems. Fast SCR switches which can handle tens of amperes when switched and can hold off several hundred volts are available. A power supply capable of supplying peak currents of hundreds of amperes at 100 to 300 volts for pulse lengths of several microseconds and duty cycles of about one percent will also be required; no fundamental problems are expected in this area.

A controller will supply signals to operate the read/write holographic memory system, including the BDC. The logic circuitry in the BDC receiving data and control signals from the controller will be TTL, or its equivalent. The TTL circuitry in the BDC will supply the appropriate control signals to the high voltage switches.

The controller operates with 12-bit, word-organized data. A random block of data can be generated by the controller at a maximum rate of one word every 10.25 microseconds (a 1.17 megabit/second rate) during a continuous flow of words. The controller can be programmed to provide signals at preselected intervals while reading a block of data into the BDC and to

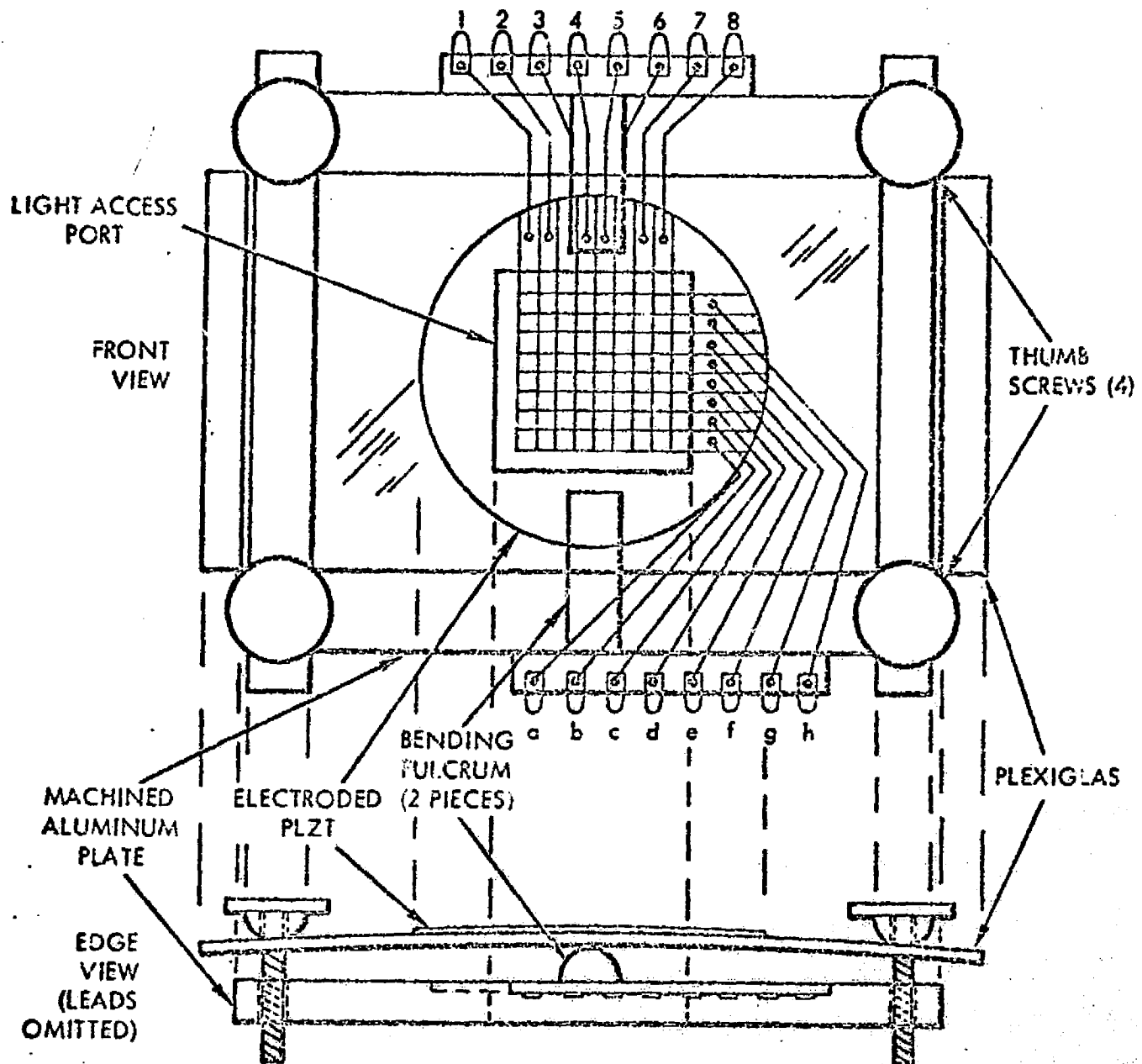


FIGURE 8: FRONT AND EDGE VIEWS OF A PLZT ARRAY MOUNTED IN A STRAIN-BIASING JIG



provide extra time between words at these intervals. These capabilities will be exploited to simplify the BDC electronics, as described in the remainder of this section.

Figure 9 shows the electronic logic, the switching circuitry, and the connections to the 128 rows (word lines) and 128 columns (bit lines) of the BDC. The input data feeds a 12-bit parallel-to-series converter (a 12-bit shift register). Each word is clocked from that register into a 128-bit series-to-parallel converter (sixteen 8-bit shift registers connected in series). The 10.25 microsecond interval between words is ample time to shift the data from the 12-bit register to the 128-bit register; a bit clock (BC) strobes the data into the 128-bit register.

A BDC word-line write-signal is supplied by the controller after a prescribed number of bits have been clocked into the 128-bit register (128 bits maximum). This word-line write-signal generates an output from each element in the 128-bit series-to-parallel converter and from each element in the 128 element word line commutator. All bit switches (BS) with a logical "1" supplied are switched to apply a potential V_s^+ to the corresponding bit lines; all other bit lines remain isolated from V_s^+ . Only one word switch (WS) receives a logical "1" and is switched to apply V_s^- to the corresponding word line; the data in the 128-bit register is written on this line. The word-line activate signal is advanced along the word-line commutator by one position for each write signal from the controller by a tapoff through a delay (see Figure 9). After the contents of the 128-bit register have been written, a new line of data is supplied and the sequence repeats until all word lines in the BDC have been filled.

A block of data would be composed on the BDC by the following sequence. A reset signal is supplied by the controller to simple TTL logic

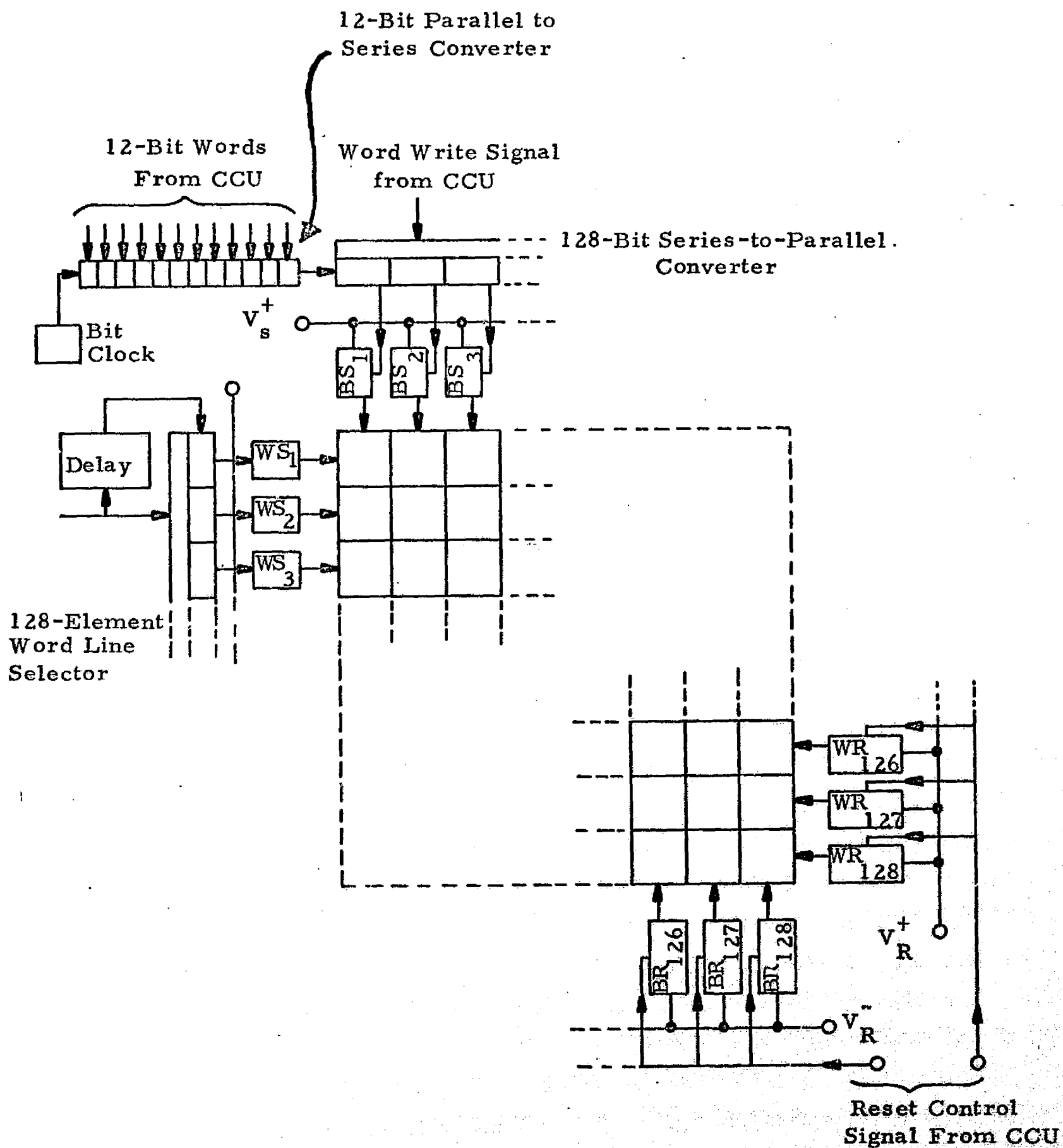


FIGURE 9: BLOCK DATA COMPOSER DRIVE ELECTRONICS



circuitry in the BDC (not shown in Figure 9). This signal initiates a reset or erase operation by activating all word reset (WR) and bit reset (BS) switches simultaneously; the potential difference $V_R^+ - V_R^-$ is applied simultaneously to all BDC positions and returns all positions to an OFF state. The reset signal is also used to clear all registers and to reset the word line commutator to the first BDC word line. After a pre-selected interval, the first group of words for the first word line are strobed in and clocked into the 128-bit series-to-parallel converter. As an example, suppose that 8 computer words (96 bits) are to be written on each BDC word line. After the controller supplies 8 words, it supplies a coded write signal to simple logic circuitry which distributes appropriate activate signals to the 128-bit series-to-parallel converter and to the 128 element word commutator. The first 96 bits are thereby written into the first word line. A tapoff from the word-line signal activates a delay generator which causes the word-line commutator to advance the enable signal to the next word line in preparation for the next word. A time interval longer than 10.25 microseconds can be provided between each group of 8 computer words if necessary to permit the PLZT to be properly switched. After this interval, the controller begins strobing in another 8 words; the cycle is repeated until all word lines have been activated or until the controller stops supplying data.

The potential along all unactivated lines will float. A potential difference will tend to accumulate across all unaccessed positions. These potentials are so-called half-select disturbance signals.

During a block writing sequence all BR and WR switches (see Figure 9) are maintained in an isolating or OFF state for obvious reasons. These switches must be able to hold off the corresponding bit-line and word-line write potentials. During a reset or erase sequence all BR and WR switches are activated and all BS and WS switches are maintained in an

OFF state. These switches must be able to hold off the corresponding bit line and word-line reset potentials.

All PLZT drive switches are assumed to be switchable by TTL voltage levels. If this is not the case, then two stages of switching with switching level amplification will be required since we are assuming that the controller will work exclusively into TTL circuitry when supplying control signals and data to the BDC.

The drive circuit concepts described here are representative of a class of concepts which are applicable. The overall design approach is sound, and essentially independent of the specific electronic drive scheme selected. The final circuitry may differ in some respects from that described here; engineering decisions based on yet to be determined electrical and optical operating characteristics of large PLZT arrays may affect the final choice.

5.3 Block Data Composer Design Parameters

The goals for the operation of the BDC using PLZT for the feasibility test bed system are described below:

1. Material: PLZT (lead zirconate-lead titanate with controlled amounts of lanthanum added) in hot-pressed ceramic form.
2. Operating Mode: Strain-biased with transparent electrodes.
3. Number of Bits: $128 \times 128 = 16,384$.
4. Center Spacings: 10 mils = 254 microns
5. Bit Size: 6×6 mils = 152×152 microns.
6. Overall PLZT Array Dimensions: 28.8×28.8 mm
7. Input Bit Rate: 10^6 bits/sec.
8. Peak Switching Voltage: ≤ 300 volts.
9. Extinction ratio ("contrast"): 100/1.



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10. Optical Efficiency: 30 percent (including analyzer).
11. Wavelength Range: 488.0 nm to 632.8 nm with 30 percent or less change in efficiency and contrast over this range (optimized for 632.8 nm).
12. Lifetime: $\geq 10^6$ cycles.



6. ACTOUSTO-OPTIC BEAM DEFLECTOR

The reference and readout beam angles in the holographic memory are controlled by a two-dimensional acousto-optic beam deflector (AOBD). The AOBD operates as a Bragg-mode deflector and produces x and y angular variation of an incident laser beam by the application of different frequencies to each of two independent transducers. The AOBD output beams are magnified by the beam deflector optics and projected onto the hologram plane as 1 x 1 mm beams. The AOBD is capable of producing 80 x 80 discrete beams at both 488 nm and 632.8 nm.

Preliminary specifications and performance parameters for the AOBD were described in the Quarterly Progress Report. The design is based on using water at a temperature of 74°C as the acoustic-optic interaction medium to minimize attenuation and the effects of temperature variation on beam position. In this section we analyze beam position stability and recommend a method for synthesizing the frequencies required for the memory.

6.1 Angular Stability and Settability Considerations

We examine the AOBD angular beam position tolerances by analyzing the effects of variations during hologram construction and during hologram readout. The tolerances permitted by the effects produced at the hologram and PDA plane are then translated into operating parameter variations such as oscillator stability and permissible temperature variation of the interaction medium. Two types of variation are considered: (1) short-term instability of the reference beam angle during hologram construction and (2) nonrepeatability of angular position during readout.



A short-term angular instability of the reference beam during hologram construction produces a fringe shift across the hologram which, if large enough, reduces diffraction efficiency and degrades the signal-to-noise ratio. Figure 10 shows the geometry used for the analysis. The signal beam from the BDC is directed along the optic axis while the reference beam is directed at a 30° angle with respect to the optic axis. The spatial frequency in the hologram plane is given by

$$\sin \theta_2 + \sin \theta_3 = \lambda \nu \quad (30)$$

where θ_2 is the angle of the reference beam relative to the optic axis

θ_3 is the angle of the signal beam relative to the optic axis

λ is the wavelength

ν is the spatial frequency of the interference fringes.

Equation (30) can be written in terms of the total number of cycles (C) recorded across the hologram as:

$$\sin \theta_2 + \sin \theta_3 = \frac{\lambda C}{\bar{d}} \quad (31)$$

where $\bar{d}$ is the hologram diameter. Solving for C yields

$$C = \frac{\bar{d}}{\lambda} (\sin \theta_2 + \sin \theta_3) \quad (32)$$

and taking the derivative with respect to θ_2 yields

$$dC = \frac{\bar{d}}{\lambda} \cos \theta_2 d\theta_2 \quad (33)$$

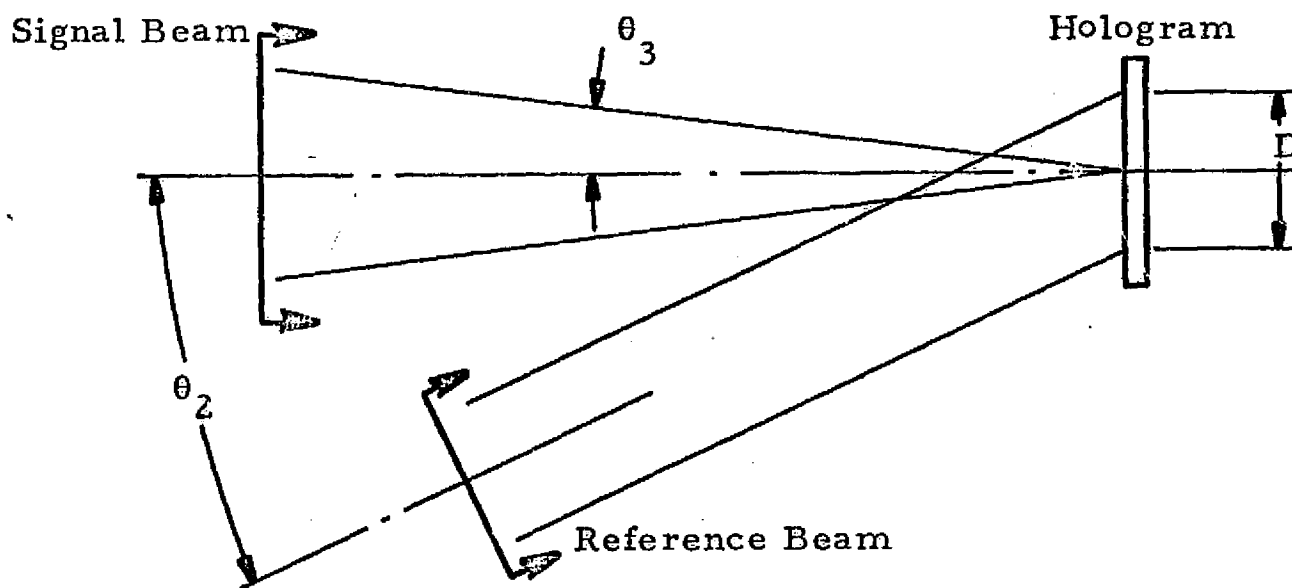


FIGURE 10: HOLOGRAM CONSTRUCTION GEOMETRY

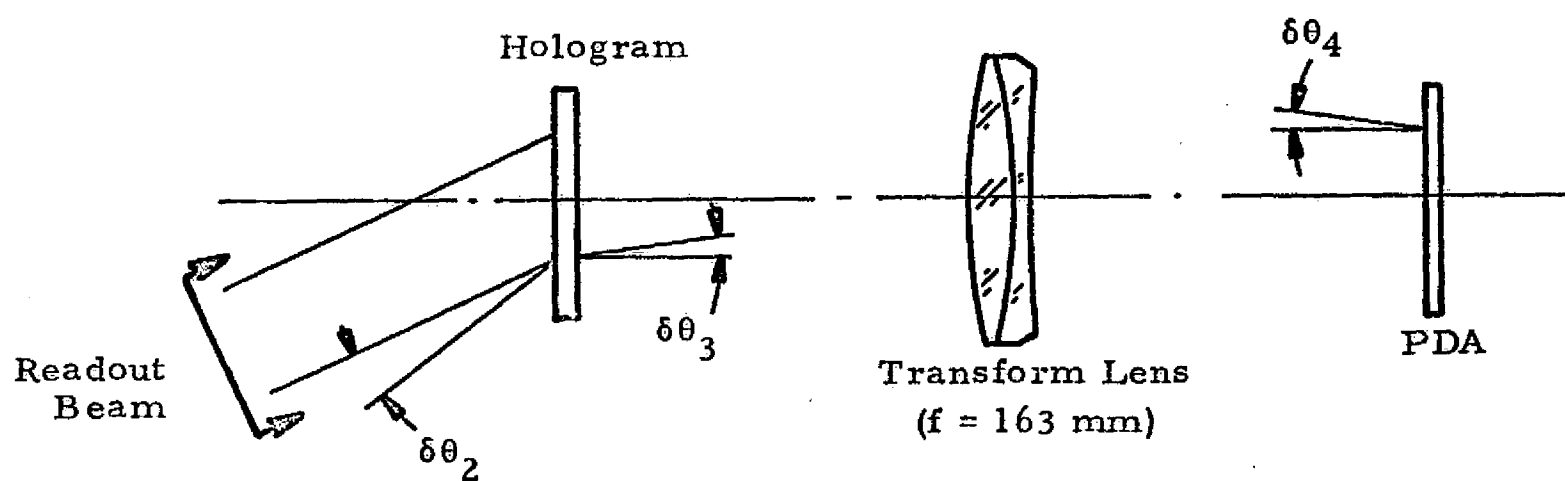


FIGURE 11: HOLOGRAM RECONSTRUCTION GEOMETRY

The fractional variation of C is therefore

$$\frac{dC}{C} = \frac{\cos \theta_2}{\sin \theta_2 + \sin \theta_3} d\theta_2 \quad (34)$$

For $\theta_2 = 30^\circ$ and $\theta_3 = 7^\circ$ we find that

$$d\theta_2 = 0.72 \frac{dC}{C} \quad (35)$$

and that $C = 1000$ for $\bar{d} = 1$ mm from (3). To determine the allowable tolerance on θ_2 we assume that the reference beam is directed to produce the nominal spatial frequency at the center of the hologram and that a variation of ± 0.1 cycle is permissible at the edges of the hologram. Therefore, the stability of θ_2 over the exposure time is

$$\Delta\theta_2 = 0.72 \left(\pm \frac{0.1}{500} \right) = \pm 0.144 \text{ milliradians} \quad (36)$$

The required angular repeatability of the reference beam for readout of the hologram is analyzed by referring to Figure 11. We consider two factors which can contribute to degradation of performance — the effects of variations on diffracted intensity for readout and the effects of variations on location of the bit pattern in the PDA plane.

The expression for angular orientation sensitivity of thick materials is derived in a paper by Friesem and Walker [3]. The internal half-power width in air, $\Delta\theta_{\frac{1}{2}}$, of the diffraction pattern is given by:

$$\Delta\theta_{\frac{1}{2}} = \left(\frac{\ln 2}{\pi} \right)^{\frac{1}{2}} \cdot \left(\frac{2\lambda}{t_o} \right) \cdot \frac{(n^2 - \sin^2 \theta_r)^{\frac{1}{2}} (n^2 - \sin^2 \theta_s)^{\frac{1}{2}}}{\cos \theta_r [\sin \theta_s (n^2 - \sin^2 \theta_n)^{\frac{1}{2}} + \sin \theta_r (n^2 - \sin^2 \theta_s)^{\frac{1}{2}}]} \quad (37)$$

where λ is the wavelength in air,
 t_o is the material thickness,
 θ_r is the reference beam angle,
 θ_s is the signal beam angle, and
 n is the refractive index of the hologram.

For the materials and geometry of the memory, $\lambda = 0.488 \mu\text{m}$,
 $t_o \approx 45 \mu\text{m}$, $\theta_r = 30^\circ$, $\theta_s \approx 0^\circ$, and $n \approx 1.5$. Substituting these parameters
into (37) yields:

$$\Delta\theta_{\frac{1}{2}} = \Delta\theta_2 \approx 0.0248 = \pm 12.4 \text{ mrad.} \quad (38)$$

To determine the effects of angular orientation on bit location we refer to Figure 11 and note that an angular variation $\delta\theta_2$ produces an angular variation $\delta\theta_4$ in the PDA plane. The PDA consists of photo-detector cells spaced on 0.250 mm centers. For this analysis, we require that effects of readout beam variation should not displace the reconstructed bit by more than 10% of the center-to-center spacing, or 0.025 mm.

The lens takes the Fourier transform of the holographically recorded data and forms an image of the reconstructed bit pattern in the PDA plane. Therefore, the angular tolerance at the PDA is

$$\Delta\theta_4 = \Delta\theta_3 = \pm \frac{0.025}{163} = \pm 0.156 \text{ mrad.} \quad (39)$$

The angular tolerance at the hologram is analyzed by examining (30) where θ_3 represents the diffracted angle as well as the signal beam angle. By solving (30) for θ_3 and taking the derivative with respect to θ_2 we get



$$\frac{d\theta_3}{d\theta_2} = \frac{-\cos \theta_2}{1 - (\lambda \nu - \sin \theta_2)^2} = \frac{-\cos \theta_2}{1 - \sin^2 \theta_3} \quad (40)$$

Since the value of θ_2 is 30° and the maximum value of θ_3 is 7° , we have

$$\frac{d\theta_3}{d\theta_2} = -0.874$$

Therefore, the settability of the reference beam incident on the hologram during reconstruction is

$$\Delta\theta_{2R} = \frac{\pm 0.178}{-0.874} = \pm 0.178 \text{ mrad.} \quad (41)$$

A comparison of (38) and (41) shows that bit location accuracy in the PDA plane is the dominant constraint. A comparison of (36) and (41) shows that angular stability during exposure is roughly equal to angular settability for readout.

To relate the angular sensitivity of the reference beam at the hologram plane, $\Delta\theta_2$, to angular sensitivity in the AOB plane, $\Delta\theta_1$, we divide by the angular magnification of the beam deflector optics ($M_a = 40$). Therefore, the stability during exposure is

$$\Delta\theta_{1E} = \frac{1}{40} \Delta\theta_{2E} = \pm \frac{0.144}{40} = \pm 0.00360 \text{ mrad} \quad (42)$$

and settability at reconstruction is

$$\Delta\theta_{1R} = \frac{1}{40} \Delta\theta_{2R} = \pm \frac{0.178}{40} = \pm 0.00445 \text{ mrad.} \quad (43)$$



To obtain fractional tolerances on the AOBD frequency and propagation velocity parameters, we write the expression for the nominal diffraction angle and obtain fractional variations with respect to frequency and velocity.

$$2\theta_B = \theta_1 = \frac{\lambda}{\Lambda} = \frac{\lambda f}{v} \quad (44)$$

and

$$\frac{\Delta\theta_1}{\theta_1} = \frac{\Delta f}{f} - \frac{\Delta v}{v} \quad (45)$$

The left side of (45) is evaluated by substituting the nominal operating values of the AOBD and the tolerances calculated in (42) and (43) above.

For water at 74°C, $v = 1.56 \times 10^6$ mm/sec, $f = 36$ MHz and $\lambda = 0.6328 \times 10^{-3}$ mm, so that

$$\frac{\Delta\theta_{1E}}{\theta_1} = \pm 24 \times 10^{-5} \quad \text{and} \quad (46)$$

$$\frac{\Delta\theta_{1R}}{\theta_1} = \pm 30 \times 10^{-5}; \quad (47)$$

which is the total allowable fractional variation for changes in both frequency and velocity.

Frequency stability is easily held to $\pm 5 \times 10^{-5}$ over a temperature range of -55°C to +105°C by using uncontrolled quartz crystals. Over the expected ambient temperature range of 15°C to 35°C, frequency variation can easily be held to $\pm 2 \times 10^{-5}$ of the nominal frequency with quartz crystals.



Consequently, we can eliminate frequency variation as a major contributor to angular variation and concentrate on the effects produced by velocity changes.

The velocity of propagation of water as a function of temperature is shown graphically in Figure 12. Note that the temperature coefficient is zero at 74°C temperature. A parabola produces a fit to within $\frac{1}{2}\%$ of this curve over the 0°C to 74°C temperature range and yields the following expression for velocity as a function of temperature:

$$v = -0.025 (T - 74)^2 + 1560 \text{ meters/sec.} \quad (48)$$

where T is in °C and 1560 is the nominal velocity at 74°C in m/s. The fractional variation of velocity with temperature is therefore

$$\frac{v - 1560}{1560} = \frac{0.025 (T - 74)^2}{1560} = \frac{0.025 (\Delta T)^2}{1560} \quad (49)$$

which must equal [from (36) and (37)] $\pm 24 \times 10^{-5}$ during exposure and $\pm 30 \times 10^{-5}$ for reconstruction repeatability. Solving for ΔT yields:

$$\Delta T_{\text{exposure}} = \pm 3.9^\circ\text{C} \quad (50)$$

and

$$\Delta T_{\text{reconstruction}} = \pm 4.3^\circ\text{C} \quad (51)$$

i.e., beam position stability during both exposure and reconstruction will be within acceptable limits if temperature variations in the water are maintained to within $\pm 3.9^\circ\text{C}$ at a nominal temperature of 74 C.

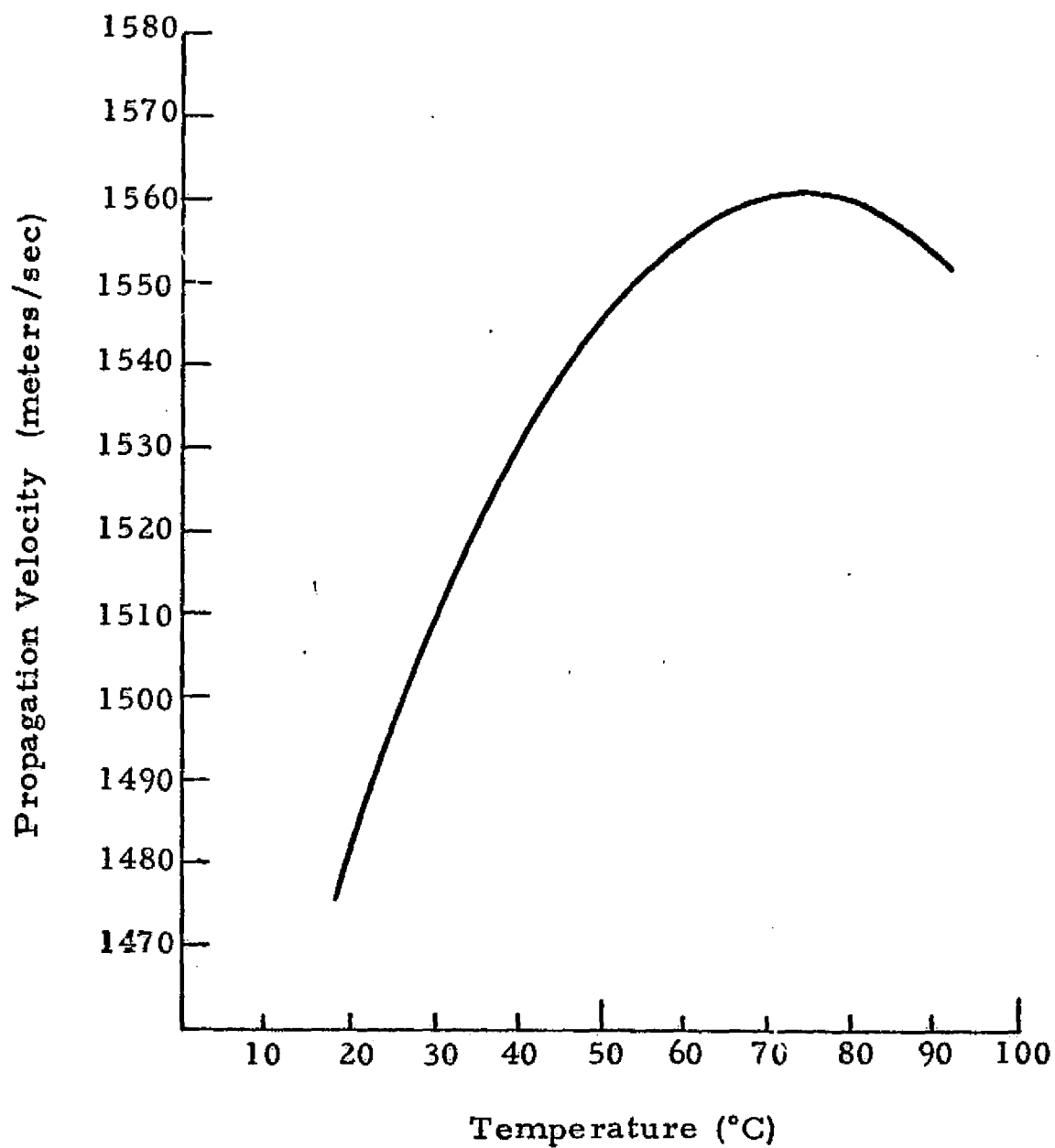


FIGURE 12: ULTRASONIC PROPAGATION VELOCITY IN WATER AS A FUNCTION OF TEMPERATURE



6.2 Frequency Generator

In Section 2.2 we show that the incremental angle generated by the AOBD must satisfy Equation (29) at the longest wavelength λ_L . Solving for $\Delta\theta$ yields

$$\Delta\theta = \frac{2\bar{c}\lambda_L}{D} \quad (52)$$

which is also given by

$$\Delta\theta = \frac{\lambda}{v} \Delta f \quad (53)$$

Solving for Δf in terms of the quantities in (52) yields

$$\Delta f = \frac{2\bar{c}\lambda_L v}{D\lambda} \quad (54)$$

By substituting $\bar{c} = 1.5$, $\lambda_L = 0.6328 \times 10^{-3}$ mm, $v = 1.56 \times 10^6$ mm/sec., $D = 20$ mm, and $\lambda = 0.6328 \times 10^{-3}$ and 0.488×10^{-3} mm, we get

$$\Delta f \Big|_{.6328} = 232.9 \text{ kHz}$$

and

$$\Delta f \Big|_{.488} = 302 \text{ kHz}$$

for the incremental frequencies required to access adjacent holograms at both wavelengths. For the read-only mode, 20 by 20 holograms must be accessed; for the read/write mode, 5×5 holograms must be accessed.

Several techniques for generating the required frequencies have been investigated. The stability and repeatability requirements derived in Section 6.1 show that temperature variations in the acoustic medium is

dominant factor if frequency stability is maintained by using crystal oscillators. If oscillator stability is not held to $\pm 2 \times 10^{-5}$, then more stringent constraints must be placed on temperature control of the interaction medium. To eliminate oscillator stability as a source of error, we concentrate on those techniques which use quartz crystals as the reference source.

One obvious approach is to use 20 individual crystals for each wavelength and gate these to the AOBD by digital addressing schemes. This requires 40 oscillators and an RF gating structure operating near 36 MHz, which is impractical.

Phase-locked loop digital frequency synthesizers can easily generate the nominal 36 MHz frequencies separated by 200 kHz. The advantage with this approach is that only one stable oscillator is required. Frequencies are generated by programmable counters and a voltage controlled oscillator connected in a feedback loop. Two such systems would be required for the memory, one for the "x" deflector and one for the "y" deflector. The principal drawback to this approach is the excessive lock-up time required to obtain stable output, i.e., about 2 milliseconds. Since a total access time of 50 μ sec is sought, phase-lock loop techniques are eliminated from consideration.

The third and recommended technique consists of using several lower-frequency crystal oscillators operating at approximately one-half of the desired carrier frequency and mixing these together to obtain sum and difference frequencies. To generate the twenty frequencies for each laser wavelength, we use two banks of oscillators, one containing five oscillators and the other containing four oscillators. The five frequencies required for the read/write mode are obtained by mixing the frequencies from the bank-of-five with one of the frequencies from the bank-of-four.



The oscillators operate continuously and are gated to a mixer through logic gates. Access time for a specific frequency is therefore a fraction of a microsecond so that the access time for achieving beam position is determined primarily by the 12.7 μ sec delay time of the acoustic cell. Figure 13 shows one possible configuration for the "x" channel frequency synthesizer. Frequencies for the "y" channel are generated by using the same oscillators shown in Figure 13 and duplicating the multiplexers and mixer. The entire synthesizer consists of 18 oscillators, two 16-line multiplexers, two 8-line multiplexers and two mixers with associated bandpass and high pass filters.

6.3 Acousto-Optic Beam Deflector Design Parameters

The goals for the operation of the AOBD in the feasibility test bed system are summarized below:

1. Interaction Medium	Water at 74°C
2. Temperature Control of Medium	$\pm 3.9^\circ\text{C}$
3. Cell Dimensions	20 mm cube
4. Center Frequency	36 MHz
5. Transit Time	12.7 μ sec.
6. Efficiency (2 dimensional operation)	30%

	$\lambda = 488 \text{ nm}$	$\lambda = 632.8 \text{ nm}$
7. Frequency increment between adjacent beams*	302 KHz	232.9 KHz
8. Bragg angle, θ_B (external)	5.66 mr	7.35 mr.
9. Angular Increment between adjacent beams*	.094 mr	.094 mr.
10. Bandwidth (for 20 positions)*	6.04 MHz	4.66 MHz
11. Bandwidth (for 80 positions)*	24.16 MHz	18.64 MHz

*Assumes beam deflector optics angular magnification of 40 and 1 mm diameter holograms located on 1.5 mm centers.

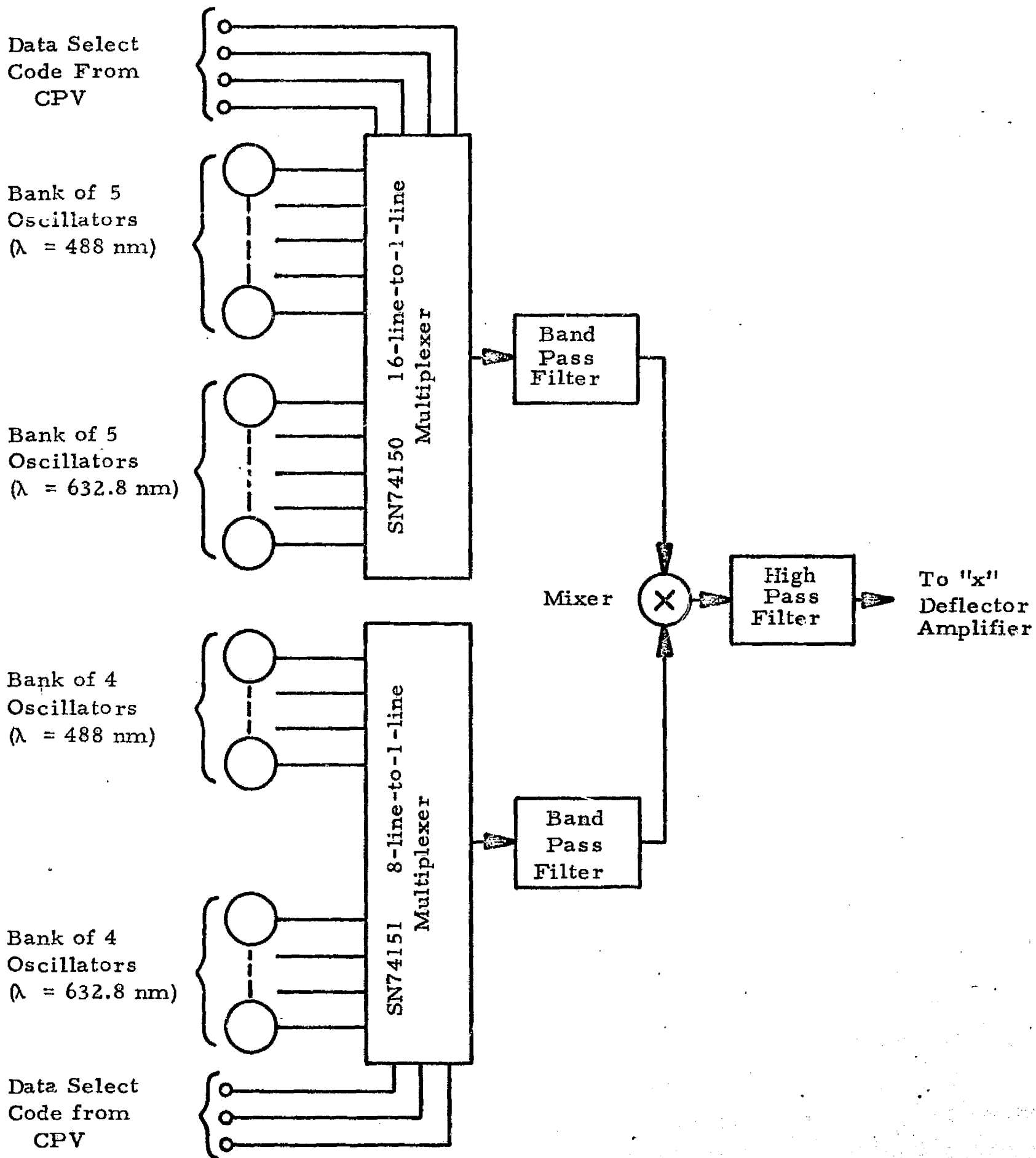


FIGURE 13: BLOCK DIAGRAM OF FREQUENCY GENERATION ELECTRONICS



7. HOLOGRAPHIC STORAGE MATERIAL

One of the objectives of this contract is to study the feasibility of using photoplastics as an interim read/write storage material in holographic memories. We have investigated the composition, the preparation, and various configurations of photoplastics, as well as techniques for recording and erasing the holographic information. The results of these investigations allow us to specify the type of material, the operating parameters, and the hologram array format for use in the memory.

In the Quarterly Report we described the basic mechanism of holographic storage and erasure in photoplastic materials, the details of material preparation, preliminary experimental procedure and results, and a possible hologram array format. During the past quarter we performed additional experiments designed to define the operating parameters which will allow for better reusability of the photoplastic materials, we designed and tested timing circuits for use in development and erasure of photoplastics, and we designed a new hologram array format with total electrical isolation and, consequently, more flexibility. The results of these recent investigations are summarized in the following paragraphs along with specifications for fabricating an operable 5 x 5 holographic storage array and its operating parameters.

7.1 Operating Characteristics

During the past quarter we performed experiments designed to determine the effects of various parameters on the operation and reusability of photoplastic materials. The results of this experimental program, performed on an internal Radiation Incorporated program, are reported here for completeness.

(1) We observed that the exposure sensitivity is a nonlinear function of the surface charge deposited by the corona device. In particular, by increasing the surface charge by 50 percent, the exposure sensitivity was increased by a factor of 5. However, an increase of the surface charge corresponds to an increase of the scattering noise. Because the noise is expected to be a more serious problem than sensitivity, the surface charge will be kept at relatively low level. We determined that, for a best combination of sensitivity and signal-to-average noise characteristics in the reconstructed image, a nominal exposure value of 200 microjoules/cm² should be used.

(2) We determined that a stationary corona device can uniformly charge the surface of the photoplastic. The amount of surface charge is controlled either by varying the spacing between the corona device and photoplastic surface or by varying the voltage applied to the corona device.

(3) We determined that the corona device can be active during the entire sequence of exposure-development without adversely affecting the holographic recording. A simultaneous rather than sequential charge-exposure-recharge mode eliminates the need for switching networks to control the charging mechanism and simplifies the recording procedure.

(4) In earlier experiments we noted that erasure does not completely neutralize the electrostatic charges so that a latent image of an earlier recording appears in subsequent holographic recordings. This latent image obscures the desired information and degrades the S/N ratio of the reconstructed image. We also found that the latent image is particularly intense after the photoplastic material was reused a number of times, typically after 10 recordings. We have determined that the intensity of the

latent image can be reduced with several erasure pulses rather than just one pulse. This technique, however, is not satisfactory because it extends the duration of the record-erase cycle, and is useful only for a limited number of cycles.

A better solution for the elimination of the latent image is to charge the photoplastic during application of the erasure pulse. We hypothesize that this addition of charges during erasure eliminates the surface charges of earlier recordings and leaves a uniform charge distribution at the surface. We also determined that this technique produces more consistent results when the erasure is made with a longer duration pulse of the same voltage as the development pulse rather than at a higher peak voltage. This erasure technique was tested with several photoplastic materials. The testing sequence for recording and checking for latent image was to exposure-develop-erase-develop, measure the intensity of the image, and then repeat the cycle. We found that no latent image could be observed even after 100 recordings.

(5) In the Quarterly Report we noted that many photoplastic samples had limited reusability. Some samples could be recycled 25 times with little observable degradation; however, some samples began to deteriorate after only 3 or 4 cycles and the degradation in the reconstructed image became objectionable after 10 cycles. After introducing the erasure technique described above, we observed a significant improvement in reusability of the photoplastic materials; many samples could be reused for over 100 cycles with adequate S/N ratio. There was, however, a continual degradation in the noise characteristics as the number of recording cycles increased. We attribute this degradation primarily to dust which is attracted to the surface of the material during the development and exposure process. To improve the S/N ratio we plan to enclose the photoplastic and charging device in a dust free atmosphere.

(6) We determined that a practical operation sequence for recording each hologram is to

- a. energize the corona discharge device.
- b. apply an erasure heat pulse for 500 milliseconds.
- c. pause for 1.5 seconds to allow for cooling the substrate.
- d. expose
- e. pause for 1.5 seconds to allow for recharging the photo-plastics surface.
- f. apply a development pulse for 150 milliseconds.

7.2 Fabrication of Array

Figure 14 shows a new geometrical arrangement for recording 25 independent holograms. It differs from the array described in the Quarterly Report in that it allows complete electrical isolation between holograms. The storage geometry is a 5 x 5 array of independent holograms each capable of storing 10^4 bits.

The substrate for the array is a commercially available glass plate with a transparent conductive coating of tin oxide. The substrate is etched with zinc powder and hydrochloric acid to leave a 5 x 5 array of isolated 3.5 mm by 3 mm rectangular pads. The center spacing between adjacent pads is 6 mm. The conductive pads are used for electrical heating and also serve as ground plane for the charges deposited on the surface of the thermoplastic.

Aluminum electrodes are deposited through a mask forming the electrode structure shown in Figure 14. There is one electrode common to all pads and 25 independent electrodes for controlling each pad separately. The width of each electrode is 0.5 mm, leaving a workable aperture of 2.5 mm by 3 mm, larger than the required hologram

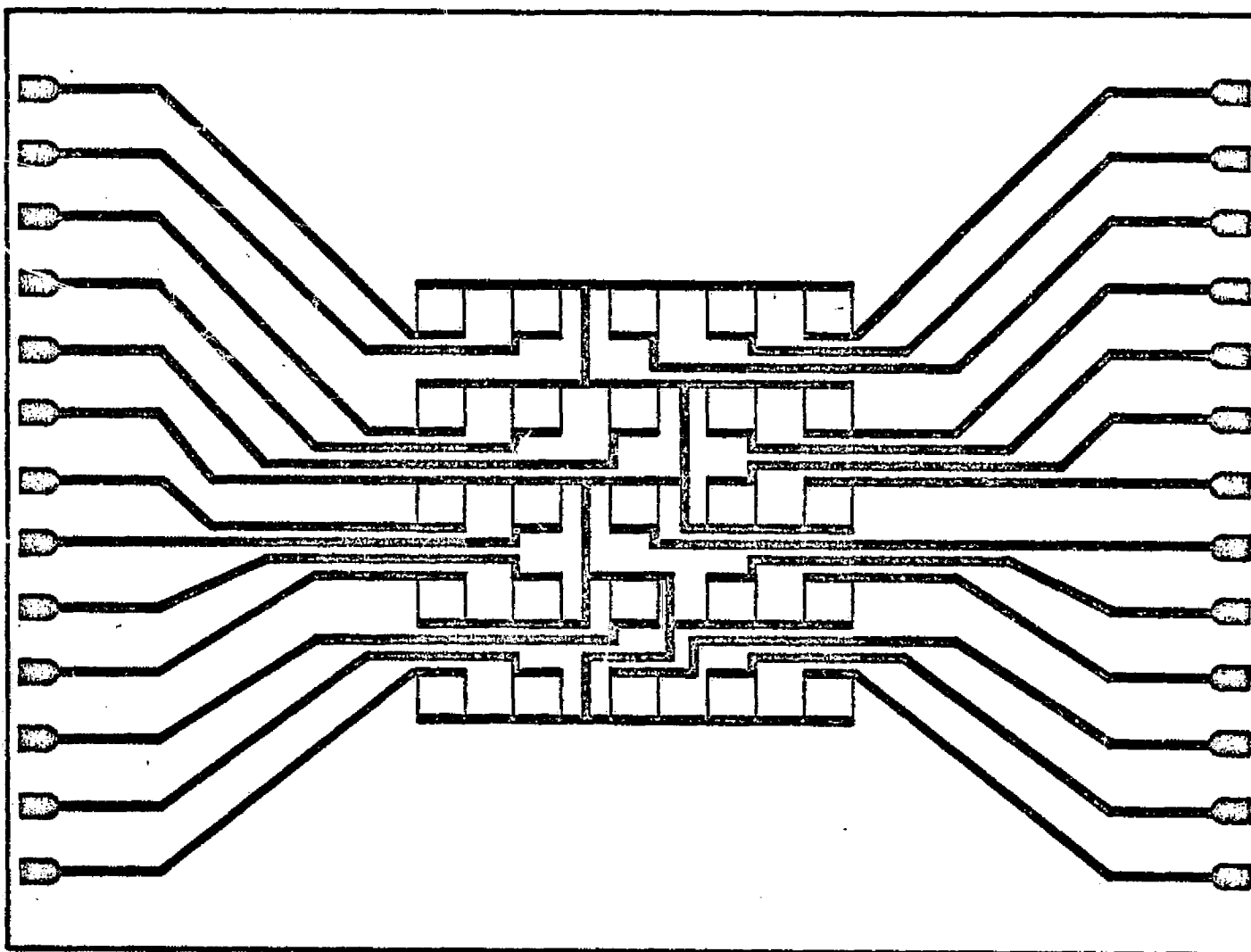


FIGURE 14: GEOMETRY OF HOLOGRAM ARRAY



aperture. The electrodes are then wired to a 25 position selecting switch for electrically addressing each pad.

The prepared substrate are then chemically cleaned and coated with a layer of organic-polymeric photoconductor and a layer of thermoplastic. The photoconductor consists of poly-N-vinyl carbazole polymer sensitized with 2, 4, 7-trinitrofluorenone. By mixing the polymer (typically 8 percent) with an equal mixture of p-dioxane and dichloromethane we obtain a photoconductive solution which is coated on the substrate to a thickness of 3 microns. The ambient temperature during the coating is held at about 40°C to prevent crystallization and to promote a smooth layer.

The thermoplastic is a wood resin called STAYBELITE, dissolved in naphtha in the ratio of 25 grams of resin to 100 cc of naphtha. The solution is used to coat a 0.6 micron thick layer of thermoplastic on top of a photoconductor layer. The substrate and composite layers are then baked in an oven at 60°C for about an hour to evaporate the solvent. The coated plates are then removed, cooled, and stored in a dust free container until used.

7.3 Electronics

A stationary corona discharge device charges the photoplastic material. The device consists of a single loop of 4 mm diameter wire and an electrically grounded shield. The loop is sufficiently large to surround the entire hologram array; the distance from the wire to the outermost holograms is approximately 15 mm at angle of 45 degrees. A voltage ranging from 3 to 10 KV, depending on the required charge density, is applied to the corona discharge device.

Development and erasure of each hologram is achieved by a resistive heating of each pad in the array. A pulsed 60 cycle voltage is applied across the electrodes of a selected pad. To avoid overdevelopment due to residual heat stored in the glass and to keep the write/read/erase cycle within reasonable limits, we use pulse lengths of 150 milliseconds for development and 500 milliseconds for erasure.

The complete circuit for generating the appropriate development pulse is shown in Figure 15. A switch, an RC network, and a diode produce a narrow positive pulse to trigger the silicon controlled rectifier (SCR) 2N3328. This triggering excites a timing network with a 30 volt d.c. voltage. The timing network, consisting of a unijunction transistor and passive components, generates a pulse whose length is controlled by an RC network; the pulse duration is 150 milliseconds. By increasing the 80 K ohm resistor to 260 K ohms the duration of the pulse increases to 500 milliseconds. The pulse triggers the output SCR and allows the positive portion of the ac voltage to pass through the rectifier for the pulse duration. The rectified voltage is then used to heat the hologram pads.

7.4 Design Goal Parameters

The investigations of photoplastic materials for the memory was performed with samples of one, two, and three hologram pads. The results of these investigations will guide the fabrication of the final 5 x 5 array of hologram pads.

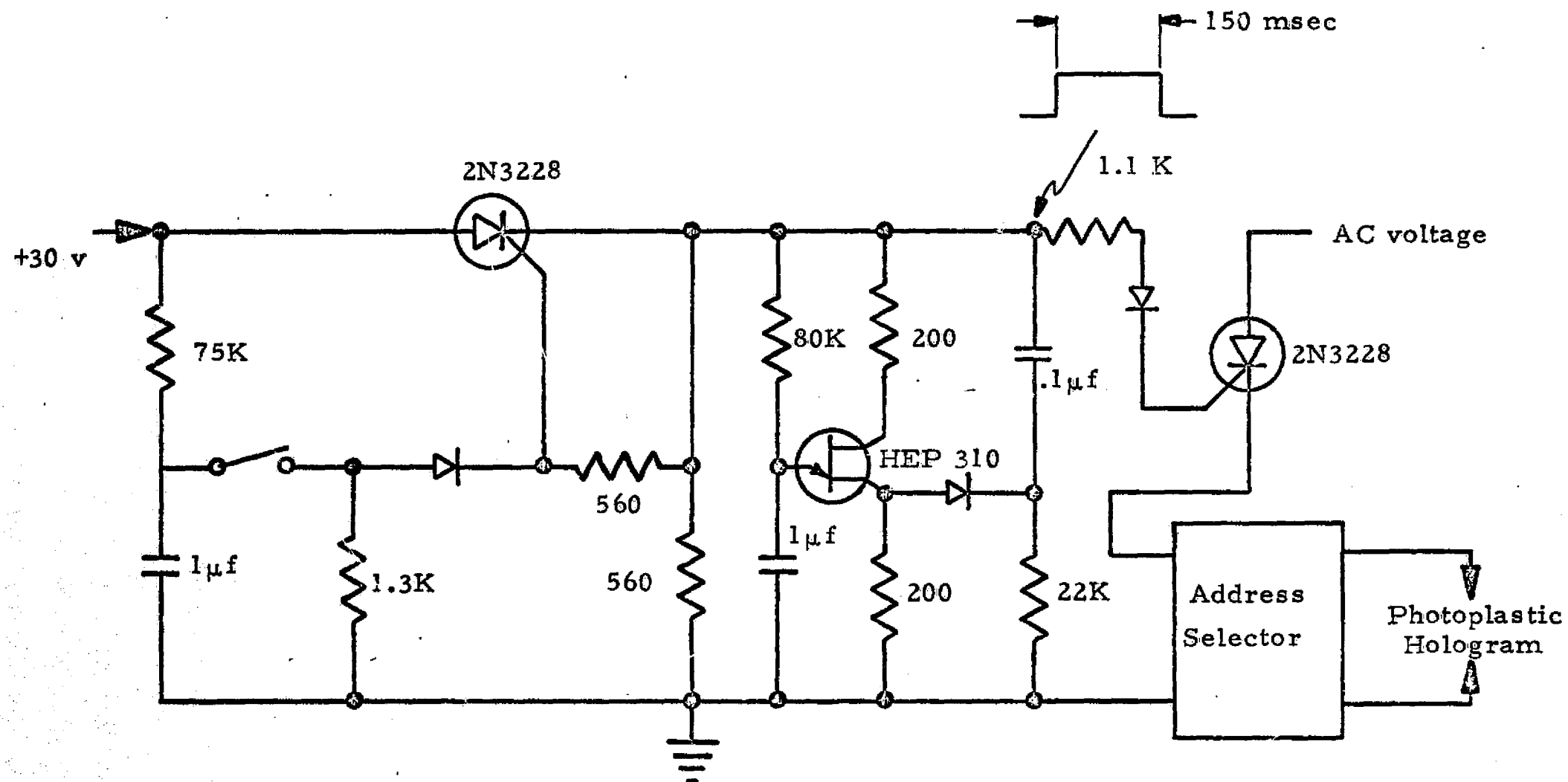


FIGURE 15: TIMING CIRCUIT FOR DEVELOPMENT AND ERASURE



The design goals for the photoplastic storage device are summarized below:

1. the storage geometry will be a 5 x 5 array of independent holograms, each capable of storing $1.6 (10^4)$ bits,
2. the center spacing between adjacent holograms will be 6 mm,
3. the aperture of each recorded hologram will be 1 mm x 1 mm,
4. the exposure sensitivity will be 200 micro joules/cm² or better at an illumination wavelength 632.8 nm.
5. the holographic diffraction efficiency will be at least 5 percent,
6. the contrast of the holographic readout image will be within 6 dB of the original input signal contrast,
7. the time duration of a complete recording sequence for each hologram will be approximately 5 seconds, and
8. the number of recording cycles will be greater than 100.



8. PHOTODETECTOR ARRAY

The hologram array, addressed by a deflected laser beam, produces a real image of the digital data pattern at a fixed position in space regardless of the position of the hologram on the array. The presence or absence of light dots is detected by a photosensitive detector array with one photo-detecting element corresponding to each bit in the digital data pattern. A solid state photodetecting array is most suitable as a readout device because it has those advantages attributed to integrated circuit devices; i.e., reduced weight, volume, and power consumption, plus greatly increased reliability and environmental immunity. Solid state photodetector arrays perform the functions of a pickup tube without the necessity for high voltages, magnetic fields, vacuum envelopes, filament power, and protection against mechanical shock. The addressing of individual portions of the photosensitive array can be achieved by random or sequential digital address of rows and columns in the array.

Current approaches to solid state detection use arrays of diodes, diode-diodes, diode-transistors or hybrid elements consisting of MOS devices and transistors. For the feasibility test bed system, we recommend that a portion of the 128 x 128 element photodetector array be fabricated by accurately locating submodule arrays of phototransistors at selected positions on the detector array plane.

A phototransistor array is a form of diode-diode structure in which the structure is fabricated to produce transistor action through the two junctions. The structure is nearly identical to a diode-diode structure and the readout approach is generally similar. The addressing rows of transistor elements have a common low impedance collector strip and the emitters of the transistors in a column are connected by a metalized strip and attached to sense amplifier inputs. With phototransistor arrays, the variation in



current gain of the devices produces the effect of varying responsivity between elements of the array; however, for a digital detecting device, this will be of little consequence because the inherent current gain at the amplifying junction of the transistor is expected to improve the signal-to-noise ratio at the output of the array. Another configuration for the phototransistor array consists of fabricating a dual emitter device with the collectors of all transistors attached to a common substrate. One set of emitters is attached to the rows for addressing the array whereas the other set of emitters is attached to the columns for readout as shown in Figure 16. This approach minimizes the effects of h_{fe} variations and permits switching times in the 50 to 100 nanosecond range. A configuration for the memory detector array using dual-emitter phototransistors is discussed in detail below.

The decision to use phototransistor arrays was based primarily on the high cost of developing a defect-free, fully populated array exhibiting the desired characteristics in a reasonable small format. The selected configuration, using five commercially available Fairchild FPA-304 arrays, is shown in Figure 17a. The submodules consist of a 16×16 dual-emitter phototransistors which have an element active area of 25 mil^2 and a center-to-center spacing of 10 mils. The five submodules are located in each corner and in the center of 128×128 element photodetector plane. The entire active photodetector plane is 1.28 inches by 1.28 inches which is determined by the 128 elements separated by 10 mils. The overall outside dimension of the detector plane is 1.60 x 1.60 inches.

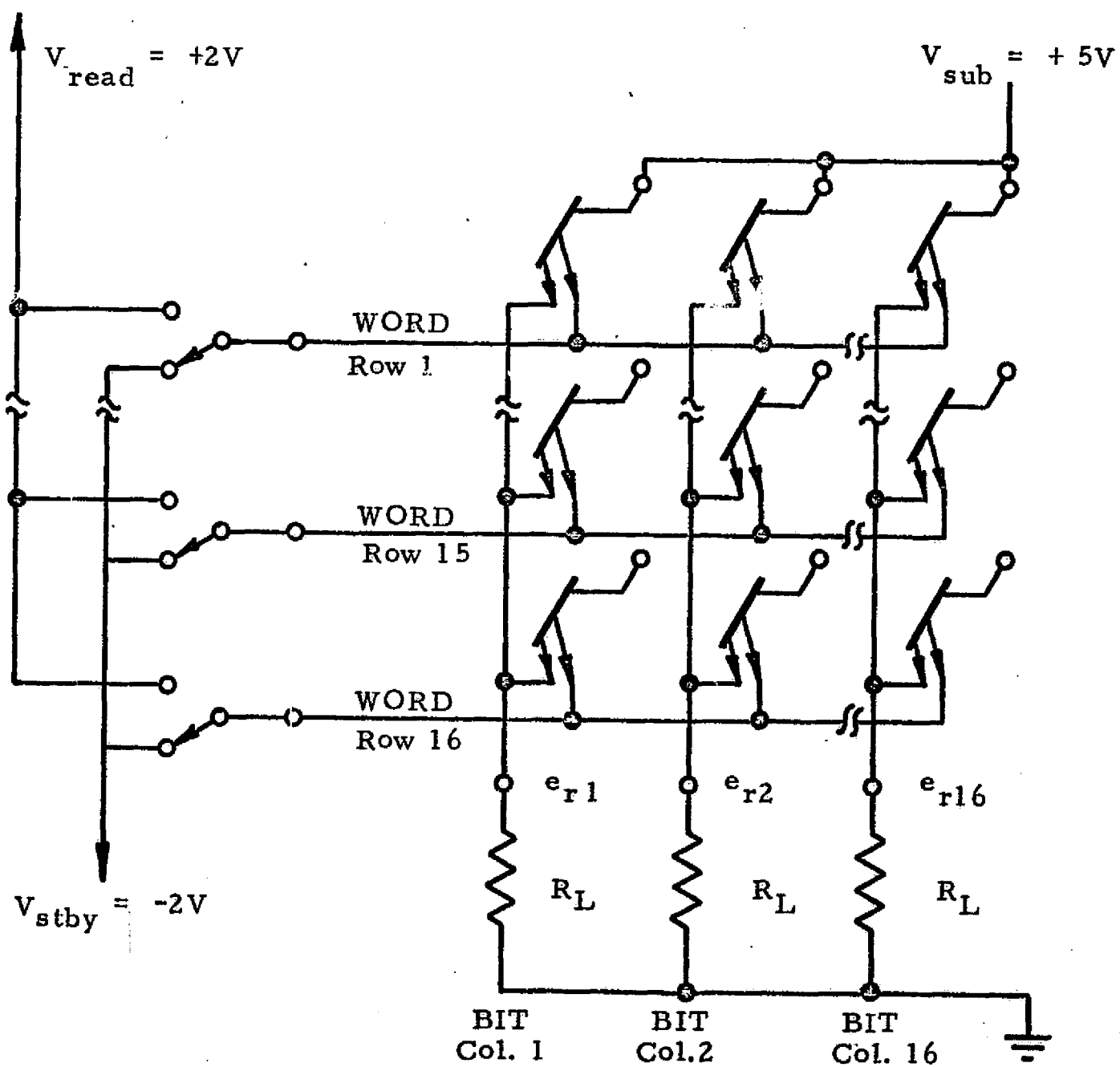


FIGURE 16: Equivalent Circuit of Phototransistor Array

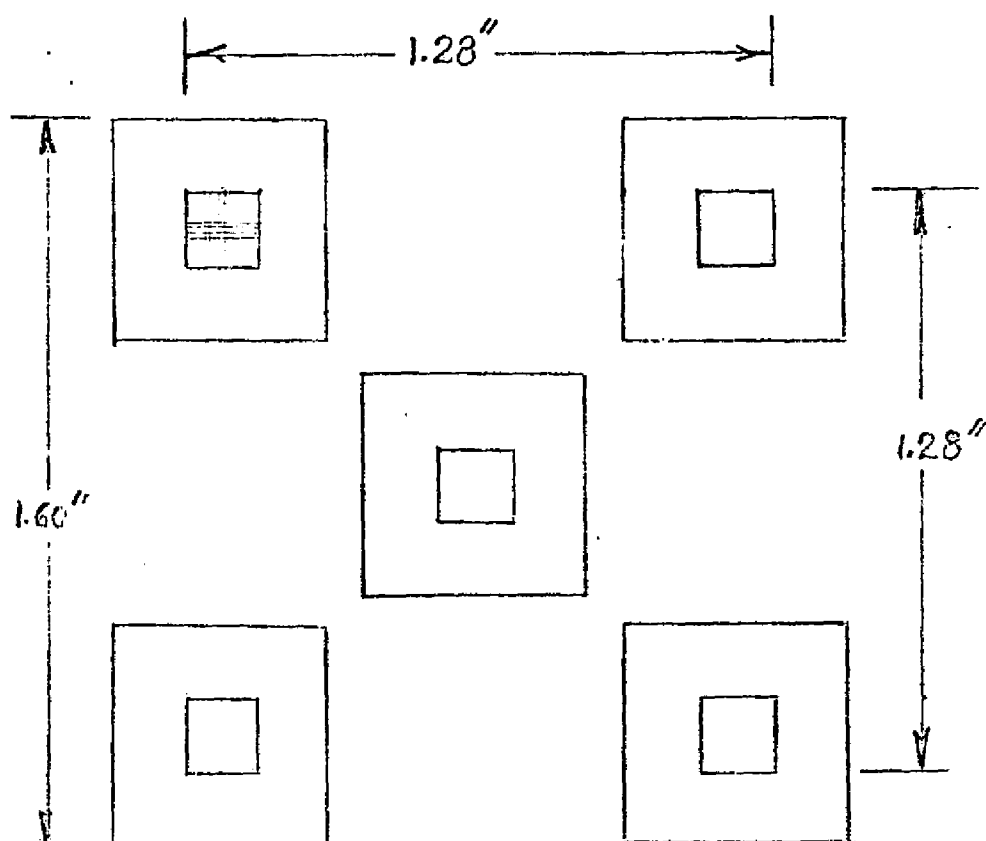


FIGURE 17a:
Layout for Semi-
Populated Detector
Array

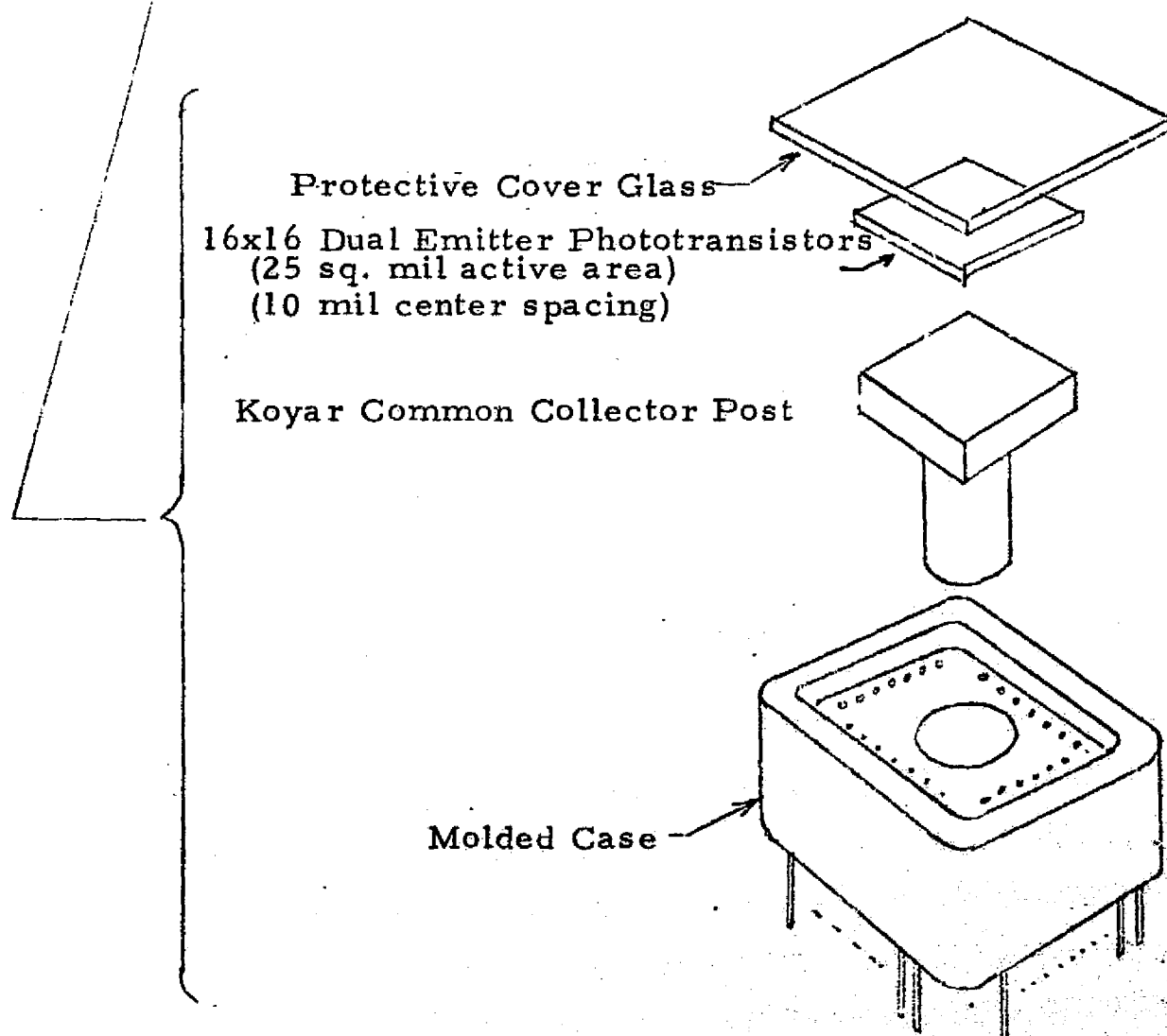


FIGURE 17b: Exploded View of 16 x 16
Phototransistor Construction

An exploded view of each submodule array is shown in Figure 17b. The dual-emitter leads are attached to the pins located at the base of the molded case and the n-type substrate, which form all collectors, is attached to the Kovar post. The submodules will be mounted in the detector plane so that small alignment adjustments can be made to correspond to the page composer format. Wires attached to the case pins will be connected to cross-wire grid structure located behind the photodetector plane to provide electrical signals to and from the photodetector array.

We now consider the flux density (irradiance) required on each reconstructed bit and the signal currents generated by this flux. For the fully populated array of 16 x 16 submodules, the worst case condition is 8 columns in series so that the dark current generated in this line is the sum of 128 elements. For the fully populated area this will be maximum of 0.004 μ A which will be simulated, in the semi-populated array, by adding a leakage resistor.

Phototransistors are commonly specified with a responsivity related to a tungsten source operated at a color temperature of 2870°K. Since the spectral response of the source and the detector are not the same, a response integral must be evaluated. In terms of the flux density of the source and the spectral response of the detector we determine an effective flux density on the detector by:

$$H_e = \int H(\lambda) Y(\lambda) d\lambda \quad ,$$

where $H(\lambda)$ is the absolute flux density distribution of the source and $Y(\lambda)$ is the spectral response of the detector. To find the efficiency ratio H_e/H we also evaluate H which is given by

$$H = \int H(\lambda) d\lambda \quad .$$



For a 2870°K tungsten source and a silicon p-n junction detector, we find that the efficiency ratio is 0.255, i.e., the response of the detector at the peak of its spectral response curve is approximately four times higher than that for a 2870°K tungsten source at the same radiometric flux density. Consequently, the worst case responsivity of the dual-emitter phototransistor is converted from 0.2 amps/watt for 2870°K tungsten to 0.8 amps/watt at 900 nm. By using the spectral response curve shown in Figure 18, we find that this corresponds to 0.28 amps/watt at 632.8 nm and .096 amps/watt at 488 nm. If we take into account reflection loss at the photosensor, h_{fe} , and the fall-off of detector response at reduced flux density, we get the often quoted peak sensitivity for a silicon p-n junction of 0.5 amps/watt.

To find the minimum required power per bit we must calculate the equivalent noise current due to the dark current and thermal noise of the load resistance. These are given by

$$\left(I_{\text{Noise}} \right)_{\text{DC}} = \sqrt{2q I_{\text{dc}} \Delta f}$$

and

$$\left(I_{\text{Noise}} \right)_{\text{Thermal}} = \sqrt{4KT \frac{\Delta f}{R_L}},$$

where q is the charge of an electron, Δf is the bandwidth, K is Planck's constant, T is temperature in °K, and R_L is the load resistance. By reading out 16 data bits in parallel we have an allowable read cycle time of 16 μ sec so that we can still maintain an average readout rate of 1.0 MHz. Thus Δf should be of the order of 125 KHz. To calculate the maximum allowable load resistance, we use the worst-case column capacitance for a

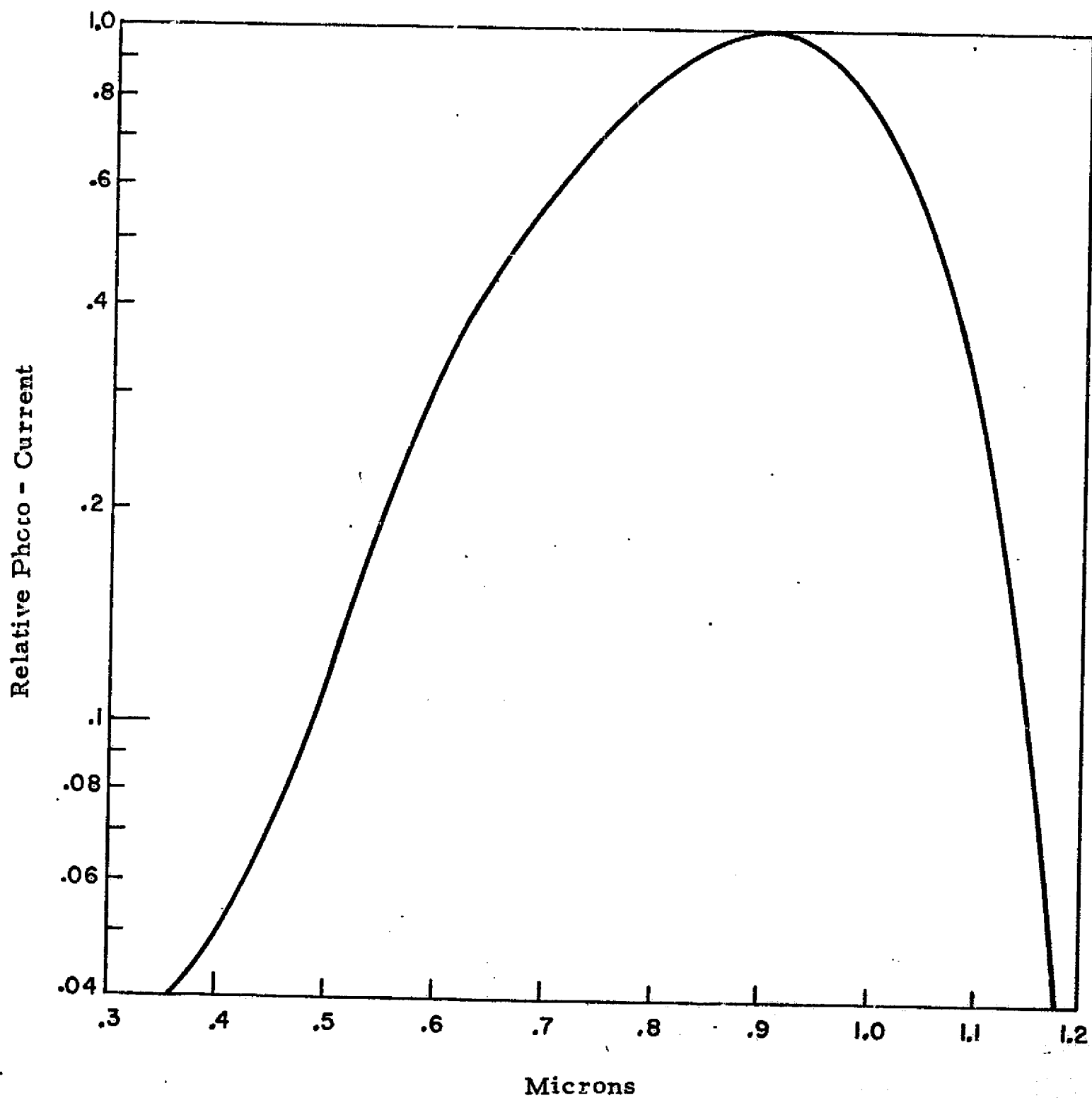


FIGURE 18: Typical Spectral Response of Phototransistor

16 x 16 subarray of 50 pf. By using a maximum allowable time constant of 4 μ sec with 8 subarray columns in series, we get a maximum load resistance of 10^4 ohms. Substituting these values into the above equations gives

$$\left(I_{\text{Noise}} \right)_{\text{DC}} = 1.2 \times 10^{-11} \text{ amps and } \left(I_{\text{Noise}} \right)_{\text{Thermal}} = 4.5 \times 10^{-10} \text{ amps.}$$

If we choose a signal-to-noise current ratio of 30:1, the required signal current is approximately 1.5×10^{-8} amps. If we use 632.8 nm and 488 nm for the two wavelengths of the system, the required power per bit is 5.3×10^{-8} watts and 15.6×10^{-8} watts respectively.

To find the system laser power required for readout the following component efficiencies were used: beam combining optics 80%; all glass surfaces 65%; beam deflector 33%; and hologram 10%. These combine to give total system light efficiency of 1.70%. The total laser power for detecting a 128 x 128 element array reconstructed from a hologram is then $0.95 (10^6)$ times the minimum power required per bit. Thus the total laser power for readout is 50 mw at 632.8 nm and 149 mw at 488.0 nm. These power levels are obtainable using Spectra-Physics Model 125 and Control Laser Model 901 lasers.

The specifications of the photodetector array as configured for readout of $1.6 (10^4)$ data bits per hologram are:



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1.	Photosensitive Area	25 mil ²
2.	Center-to-center Spacing	10 mils
3.	Maximum Dark Current per Column (8 subarray columns in series)	4×10^{-9} amps
4.	Minimum Sensitivity (632.8 nm) (488.0 nm)	0.28 amps/watt 0.096 amps/watt
5.	Uniformity within Subarray	$\pm 20\%$
6.	Uniformity between Subarrays	$\pm 35\%$
7.	Substrate Voltage	2.0 to 13.0 volts
8.	Address Voltages (V_{read}) (V_{STBY})	1.0 to 7.0 volts -7.0 to -1.0 volts
9.	Minimum Signal (632.8 nm) (488.0 nm)	5.3×10^{-8} watts 15.6×10^{-8} watts
10.	Signal-to-noise ratio	30:1
11.	$R_L = 10^4$ ohms	
12.	$\Delta f = 125$ KHz	
13.	Maximum Word Switching Time (10% to 90%)	8 μ sec



9. ELECTRONICS FOR DRIVING AND SYNCHRONIZATION

9.1 Introduction

The electronic control system for the holographic memory must be able to control, drive, and synchronize all system components. These include the laser, acousto-optic beam deflector, block data composer, storage medium processor, and photodetector array. The control system must coordinate these subsystems to generate the appropriate read and write cycles, and have the flexibility to allow optimization of these read/write cycles. In addition, it must be able to monitor the holographic memory performance.

Our recommended electronic control system consists of a Digital Equipment Corporation PDP-8/E as the central control unit (CCU) and the necessary interface equipment to control the storage medium processor, acoustic deflector, laser, block data composer, and photodetector array. This configuration is shown in Figure 19.

9.2 Central Control Unit

The PDP-8/E is a fully parallel, 12-bit random access, 4096-word core memory system. It performs general-purpose computations and process control operations. Transistor-transistor logic integrated circuits make it a compact, economical, and rugged system that is easy to interface and maintain. It is a single-address, fixed-word-length system that uses 2's complement arithmetic. The basic PDP-8/E system includes the central processor, a 4096 word core memory, input/output transfer facilities, an operator console and a teletype.

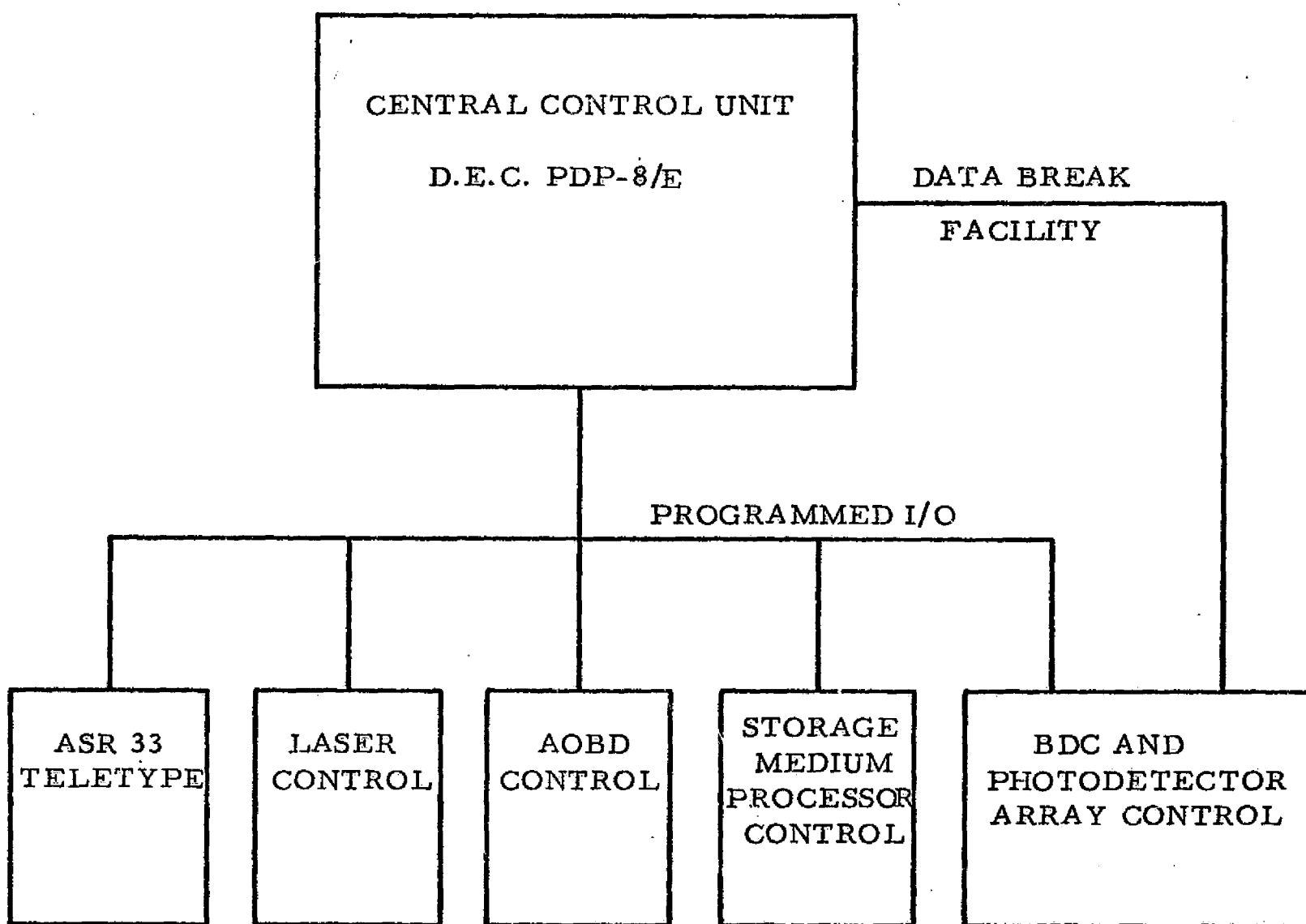


FIGURE 19: BTBS ELECTRONIC CONTROL SYSTEM WITH A PDP-8/E BEING USED AS CENTRAL CONTROL UNIT.



Central processor rewiring permits another 4096-word of core to be plugged into the standard cabinet. Six additional core memory blocks can expand the PDP-8/E memory capacity up to 32,768 words. Peripheral and interface devices are connected to the PDP-8/E through a versatile input/output bus. A built-in instruction skipping capability provides a convenient method for checking the status of peripherals. Data is transferred between the PDP-8/E and the bus-connected device through program interrupts, programmed data transfers, or data break transfers. The most efficient method of transferring data depends on the peripheral and interface servicing requirements.

9.3 Peripheral Control Devices

All peripheral control devices sample the select code generated by the computer during Input/Output Transfer (IOT) instructions and, when selected, are capable of producing sequential command pulses in accordance with computer-generated Input/Output Perform (IOP) pulses. Each device receiving output data from the computer contains gating circuits at the input of a receiving register which strobes the accumulator signal information onto the register when this device has been selected. Each device supplying data to the computer contains gating circuits at the output of the transmitting register which are capable of sampling the information in the output register and strobing this data onto the computer input bus when triggered by the proper command pulse.

9.3.1 Acousto-Optic Beam Deflector Control - The AOBD control consists of a device selector decoder and a 14-bit input buffer register used to store each address of an 80 x 80 array of holograms.



9.3.2 Laser Control - The laser control is a device selector decoder which controls the appropriate electro-mechanical shutter for selecting the desired laser beam during hologram read and write cycle. Timing of these shutters is controlled by variable programmed delays. Also contained in the laser control unit is a KDP electro-optic modulator for controlling the relative amounts of power in the reference and signal beams (the K-ratio). The laser control unit contains a buffer for storing digital words whose magnitudes are proportional to the voltage required by the electro-optic modulator. A digital to analog converter transforms this buffer word into an analog voltage which is amplified and used to drive the modulator

9.3.3 Storage Medium Processor Control - The storage medium processor control is a device selecting decoder that controls the proper recording material processing sequence. When using a thermoplastic recording medium, it controls current pulses to the photoplastic heater.

9.3.4 BDC and Photodetector Array Control - The BDC and photodetector array control consists of a device selecting decoder, a 12-bit input data register, a 12-bit output data register and a 12-bit word address register. The input data register is used as a buffer between the CCU accumulator and the BDC while the output data register is used as a buffer between the photodetector array and the CCU accumulator. The address register controls the word addressing process in both the BDC and the photodetector array.

9.4 Electronic System Operation

The two major functions of the electronic control system are to generate read and write sequences for the holographic memory and to

monitor the holographic memory performance. We now describe typical read and write sequences and error checking routines generated by the CCU.

9.4.1 Write Cycle - Figure 20 shows a typical write cycle for recording a hologram on photographic film. The CCU stores, in its core memory, a block of data that is to be recorded on a hologram. Recording this data as a hologram requires that the AOBD must deflect the reference beam to the appropriate hologram position, the data must be read into the BDC, and the photographic film must be properly exposed.

The reference beam is deflected to the appropriate hologram by transferring the hologram address from its location in core to the AOBD address buffer via the accumulator. The desired K-ratio is transferred to the K-ratio buffer in the laser control. At the conclusion of this part of the program the reference beam has been deflected to the new hologram position and the proper intensity ratios have been set.

The next step in the program is to transfer the data to be recorded on the hologram to the block data composer. The BDC is sent a command which resets every location to zero. The BDC requires that the data be transferred one line at a time to minimize disturbances due to half select voltages. After initializing the line count and the word count, the program assembles data for one line and then sends the BDC a write command. The CCU continues to assemble data and transmit write commands until the last line has been completed. The time required for composing a block of 1024, 12-bit words is 14.8 msec. The CCU then sends a command to the laser control opening the proper electro mechanical shutter. The program goes into a counting loop which controls the exposure time, the maximum count being controlled by teletype input command. After the program has counted up to the maximum count a command to close the shutter is sent to the laser control, thus completing the hologram write cycle.

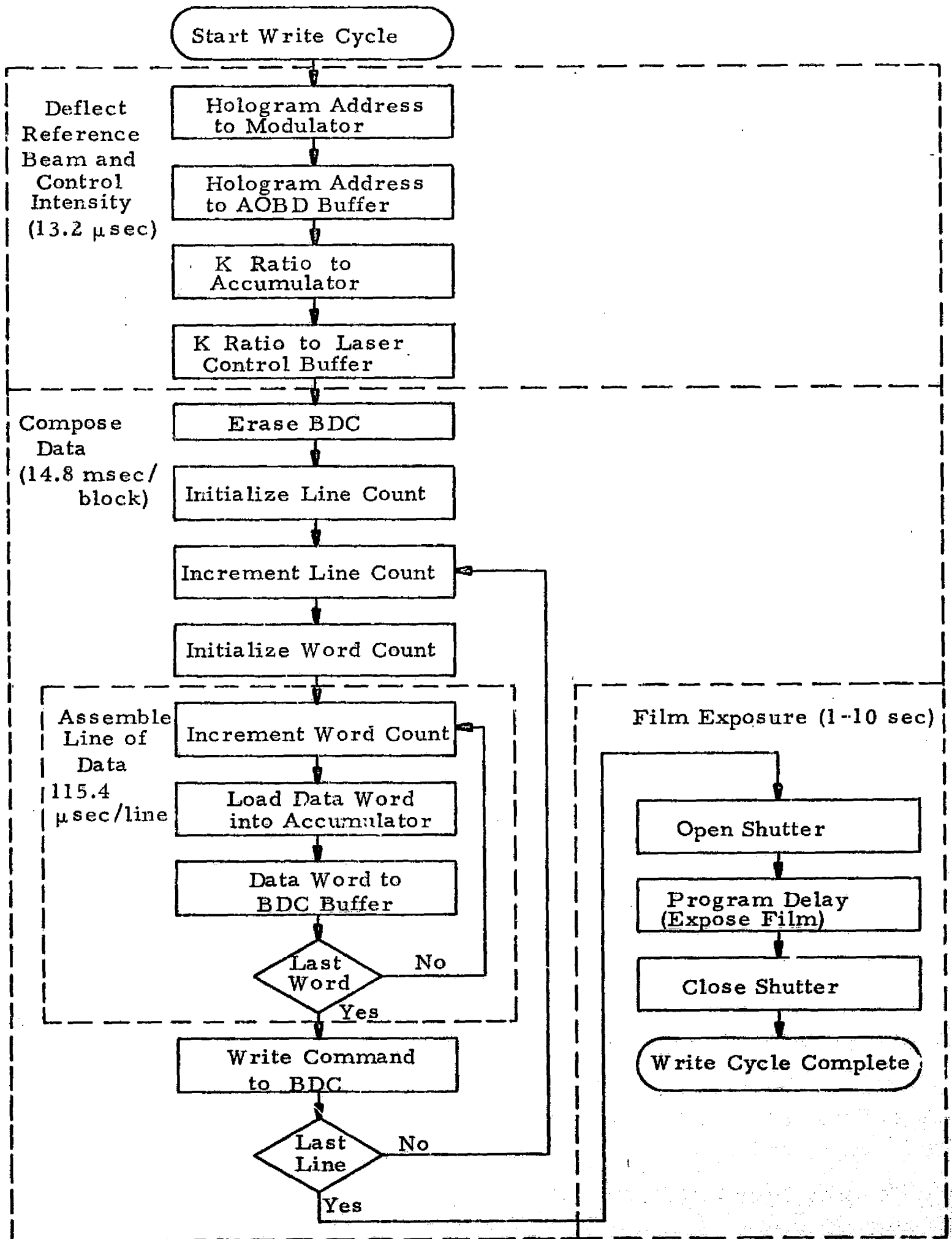


FIGURE 20: WRITE CYCLE (PHOTOGRAPHIC FILM)



9.4.2 Write Cycle (Thermoplastic) - The flow diagram for the thermoplastic write cycle is shown in Figure 21. This write cycle is identical to the photographic film write cycle except for the processing required by the thermoplastic as described in Section 7. The erase cycle is begun in step one and continues for approximately 0.5 sec. During this time the reference beam is deflected to the selected hologram address and the BDC is completely loaded. The remainder of the erase cycle is filled by a program delay. At the end of the delay the heat is turned off and another program delay allows the thermoplastic to cool. The shutter is then opened and the exposure time controlled during a third program delay. The shutter is then closed and another delay is begun to allow for proper charging of the thermoplastic. The heater is then turned on for approximately 150 msec to record the hologram. Another program delay allows the thermoplastic to cool to the point where further exposure to light will not decrease the S/N of the reconstruction.

Since less than 15 msec of the 5 sec needed to record the data on the thermoplastic material are actually used for useful control operations, we can use the program interrupt capability of the machine to allow an external counter to do the counting and to turn on the interrupt system at the end of the delay. This would allow the CCU to perform other tasks, such as error checking, during the programmed delays.

9.4.3 Read Cycle - The flow diagram for a typical read cycle is shown in Figure 22. The read cycle consists of two parts, deflecting the laser readout beam to the proper hologram and interrogating word locations in the PDA. The PDA is interrogated by sending word-address information to the photodetector word-address register and then strobing the data from the output data register onto the Input/Output bus. Total

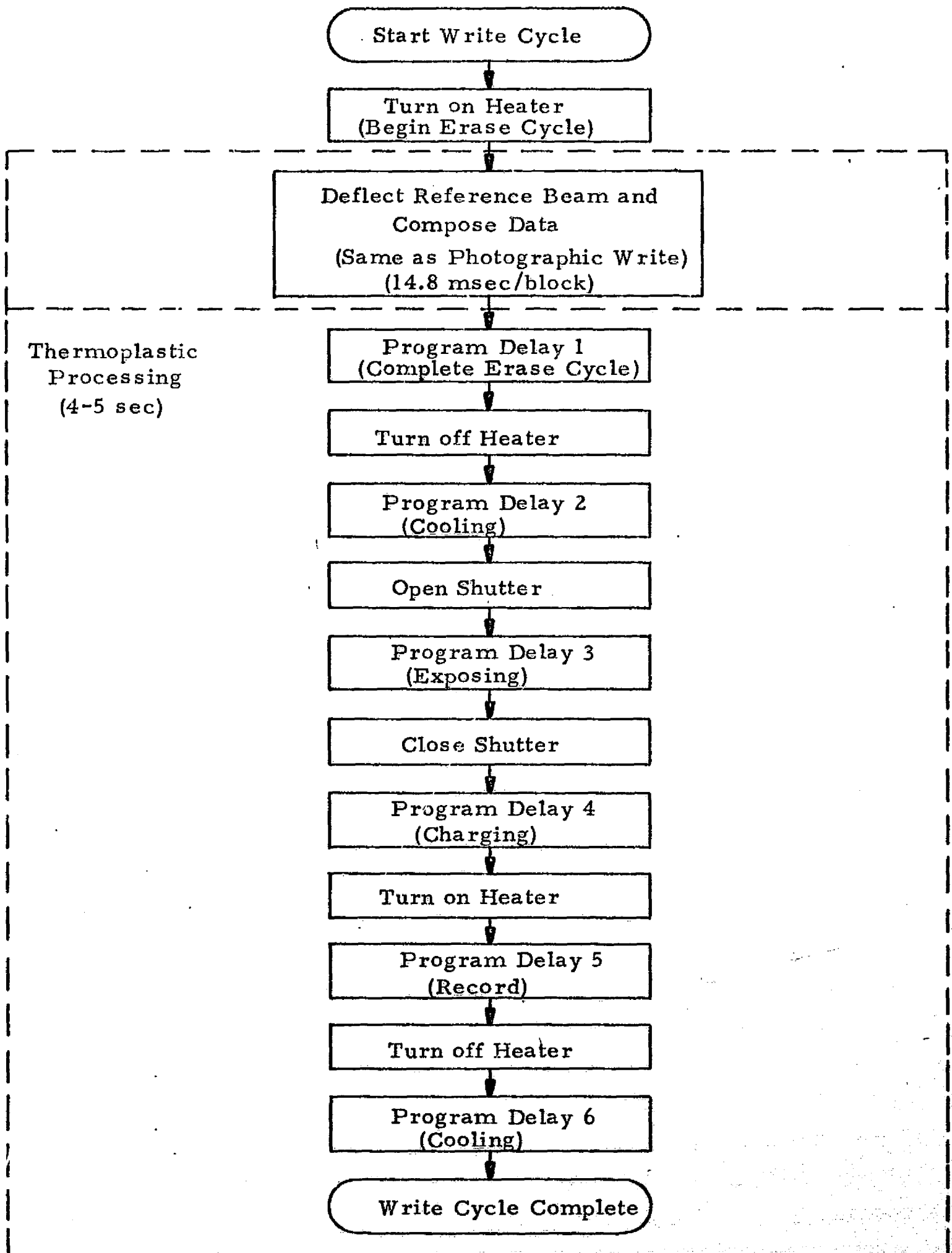


FIGURE 21: WRITE CYCLE (THERMOPLASTIC)

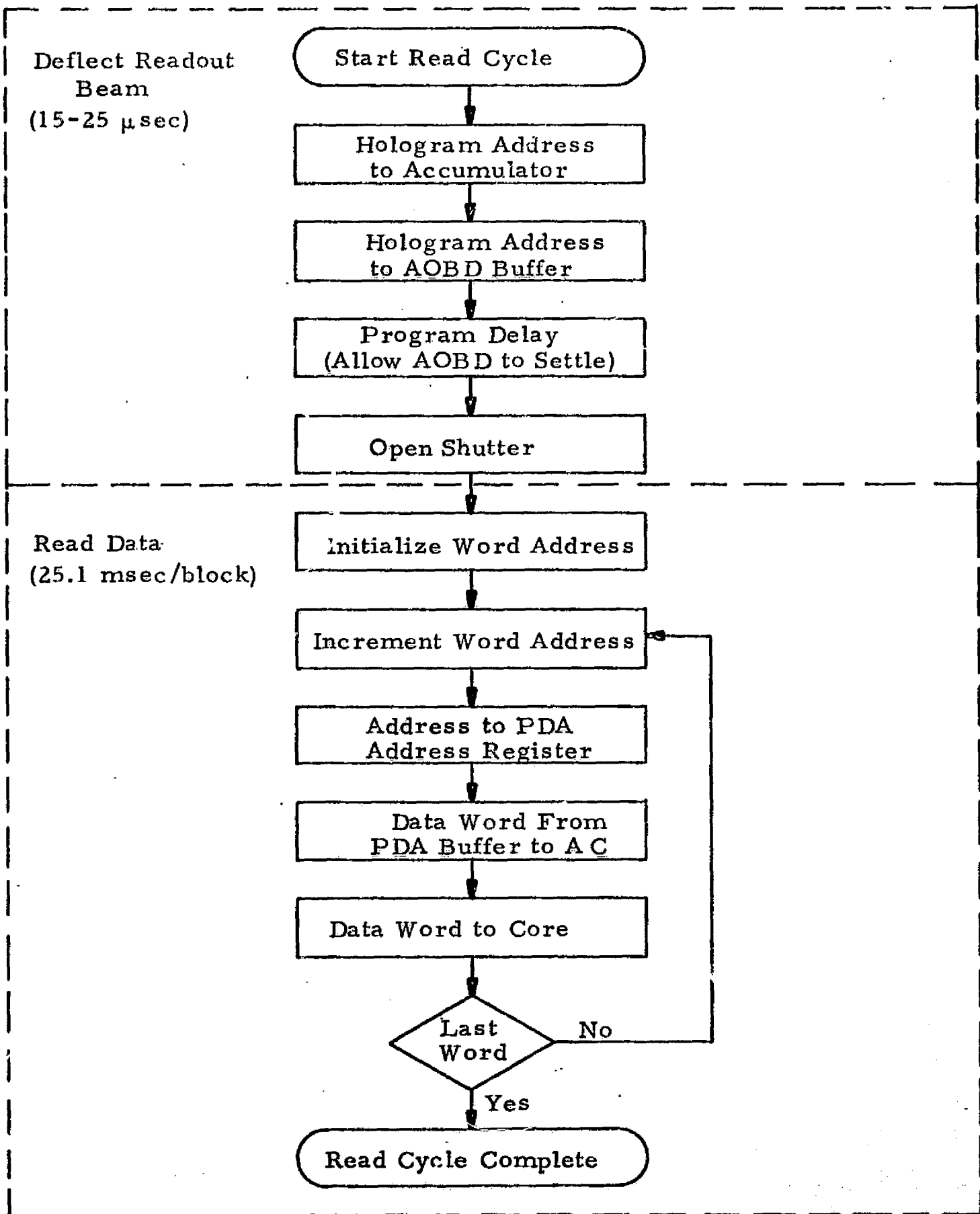


FIGURE 22: READ CYCLE



time required for reading a 1024 word block is 25.1 msec plus time required for readout beam deflection.

In the future, the readout rate of the holographic memory could be increased by using the data break facility of the PDP-8/E. Using the data break readout mode the entire 1024 word block would be sequentially strobed onto the I/O bus without the CCU interrupting between words for address. The data break mode allows bit rates as high as 8 MHz to be obtained.

9.4.4 Error Checking - Another major function of the CCU is to monitor the performance of the holographic memory. This essentially means comparing data input to the memory with data readout of the PDA. The flow chart in Figure 23 shows a technique for comparing input and output data. This particular approach makes use of the exclusive-OR function which is given by $A\bar{B} + \bar{A}B$. This function gives a "1" output if $A \neq B$ and a "0" output if $A = B$. The first part of the program initializes addresses, the second part calculates the exclusive-OR function and the third part stores the error and the address where the error occurs. The total time required to check a 1024 word block is 55.7 msec.

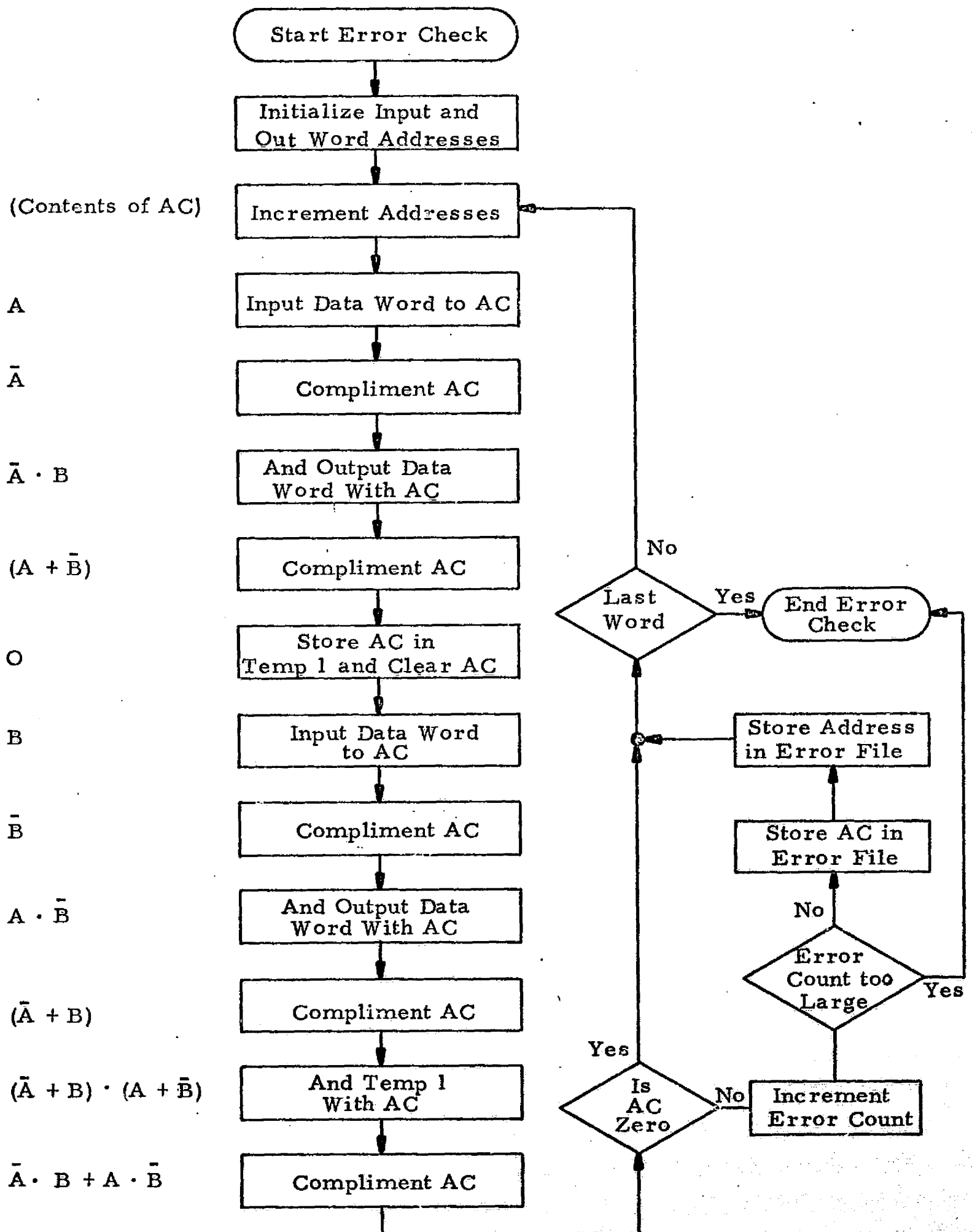


FIGURE 23: ERROR CHECK ROUTINE 55.7 msec/block



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10. REFERENCES

1. H. H. Hopkins and V. V. Rao, *Optica Acta*, 17, 497 (1970).
2. H. H. Hopkins, "Wave Theory of Aberrations", Clarendon Press, Oxford, England, 1950.
3. Friesem, A. A. and Walker, J. L., *Applied Optics*, 9, 201 (1970).



11. NEW TECHNOLOGY

There are two new technologies developed during this program.

1. Lens Design Program

The key problem in the design of achromatic lenses has been the selection of glasses having certain dispersions and refractive indices. An analysis due to Hopkins and Rac (see reference 1) makes the selection of glasses fairly routine given the appropriate design parameters. We have written a computer program which reduces the time needed to select the appropriate glasses and to check the selected glasses against the design parameters. The program incorporates an improved method for calculating the contact curvature.

2. Achromatizing an Acousto-Optic Beam Deflector

When an acousto-optic beam deflector operates in the Bragg mode (to achieve maximum efficiency) at more than one wavelength, the Bragg angles at both the entrance and exit faces are linear functions of wavelength. In the memory system described in this report, the Bragg angles at the exit face must be made colinear (achromatic) at the two wavelengths. Although this can be achieved by changing the electrical drive frequency, the bandwidth of the device must be increased appreciably. We have developed a device consisting of two dichroic mirrors and two reflecting mirrors which allow us to achromatize the acousto-optic beam deflector at two wavelengths without increasing electrical bandwidth of the deflector. The same center frequency is used to drive the deflector at both wavelengths.