DIGITAL/OPTICAL HYBRID SYSTEM (DOHS) FOR TWO-DIMENSIONAL SIGNAL PROCESSING

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ABSTRACT

A hybrid system consisting of a coherent optical computer and a general purpose digital computer is proposed for processing a two-dimensional signal. Such a system will have the speed and high information density of an optical computer and the decision-logic capability, flexibility and high accuracy of a digital computer.

The general plan of hybrid computation is that a given signal is first processed on the optical computer, which can perform all linear operations. A selected portion of the optically processed signal is further processed on a digital computer. The digital computer, in addition, controls the optical computer, makes decisions on the basis of processed signal and issues commands to the external devices for further action. It is shown that for successful implementation of the proposed hybrid system, we must have devices capable of real time input to the optical computer and devices capable of transmitting data from the digital to the optical computer and vice versa. *Furthermore, the optical system has to be further improved in order that the accuracy of computation improves by at least one order of magnitude.*

1. INTRODUCTION

Over past one decade a considerable work has been done in the field of coherent optical computing. An excellent text[1] has recently appeared which describes the present state-of-art in this important field of activity. An optical computer is an analog computer capable of parallel processing of a two-dimensional signal, such as an image or a photograph, or several, one-dimensional signals, say, from an array of detectors. An optical computer can perform several linear and space-invariant operations, among them the most important one is the Fourier transformation. The computation is literally instantaneous, but the detection takes a finite time. It is possible to achieve with the current technology a speed of 10^{14} multiplications per second[2]. One other feature of an optical computer is the extremely large space-bandwidth product, in the range of 10^9 to 10^{10}. It is, therefore, possible to store an enormous amount of information on a high resolution film and to feed to the optical computer for processing. All these features go to make an optical computer extremely fast, as for example, the University of Michigan built a precision optical processor having the highest data rate, 10^{12} bits/sec.

Despite all the above mentioned advantages of an optical computer, we find it has, as compared to a digital computer, some serious drawbacks. They are as follows:

(*a*) can perform only a small class of operations, *i.e.*, linear operation leaving all non-linear and logical operations;

(*b*) relatively low accuracy, 1–10% only;

(*c*) lacks flexibility.

Let us now illustrate how the above drawbacks make an optical computer inadequate for certain problems. Consider processing of radar signals from a phased array. An optical computer can do multiple beam formation, measure range and doppler shift at a speed much faster than a digital computer yet it cannot track a particular target nor can it issue a command, say, for interception in the event of an approaching enemy plane. This deficiency is mainly on account of its inability to perform logical operations. The situation may be improved if we use a digital computer in conjunction with an optical computer for the purpose of logical and decision-making operations. For example let a vidicon camera look at the output plane of the optical computer, and feed the scanned information to a digital computer. All decision-making including issuing commands is then done by the digital computer.

Thus, it would appear that in order to make on optical computer more useful, particularly, where real time processing is desired, we should combine a digital computer and an optical computer. Such a hybrid system will have the speed and information capacity of an optical computer, and decision logic and a wide range of mathematical operations that a digital computer can perform. The idea of hybrid system was first conceived by Huang *et al.*[3] An example of a working hybrid system is that of automatic microscopy for chromosome spread location at the University of Pittsburgh[4]. The system computes optically the Wiener spectra of a mitotic cell location. The digital computer then measures energy in two frequency bands, namely, 300–400 cycle/mm and 65–90 cycle/mm. For mitotic cells the energy is high in the 300–400 cycle/mm band and low in the 65–90 cycle/mm band. For non-mitotic cells it is low in both bands while for dust particles it is high in both bands. The digital computer compares the energy in these both bands and recognizes the mitotic cell.

There is yet no general purpose hybrid system. This introductory article essentially looks at how one would go about to design a general purpose hybrid system for the broad purpose of signal processing. The effort is mainly on the system design and performance of the proposed system.

2. GENERAL SYSTEM CONSIDERATIONS

Let us first list the projected signal processing capabilities of the proposed system.

(1) Fourier transform of one or two-dimensional signals

(2) Spatial filtering

(3) Matched filtering

(4) Deconvolution filtering

(5) Subtraction of a stationary scene from pictures taken at different intervals.

(6) Spectral analysis

(7) Maximum entropy deconvolution filtering, superresolution, and other advanced processing techniques

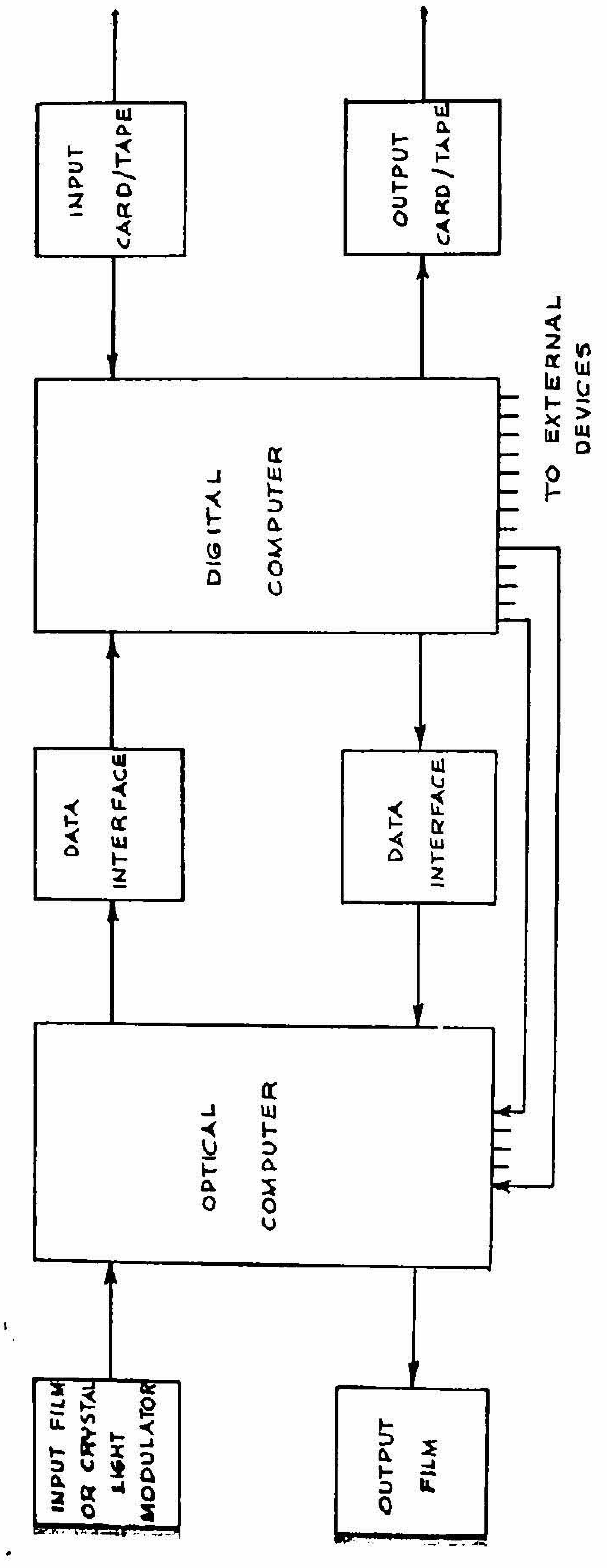
(9) Probability density function estimation

(10) Decision logic.

The philosophy of the system design will be wherever possible preliminary processing is first done optically and the results are carefully examined by a digital computer. A decision is made regarding the need for further refined and high accuracy processing, and if it is required over what portion of the signal. At this stage the digital computer takes over the processing operation. Either the original signal or optically processed signal is fed to the digital computer. The computer finally issues commands for initiation of other actions, if required.

A schematic block diagram of the proposed system is shown in Fig. 1. It consists of the following subsystems.

1. Optical computer consisting of arithmetic and Fourier transformation unit and memory.
2. Digital computer
3. Data interface between the optical and digital computers
4. Input/output devices.



DIGITAL / OPTICAL HYBRID SYSTEM (DOHS)

FIG. 1

Let us consider the broad specifications of the subsystems mentioned above. The optical computer must have as large a space-bandwidth product as possible. This would enable to process large format images or signals from a large array. It should be amenable to digital computer control, that is, at the command of a digital computer it should be possible to add or remove a given optical component. This would enable one to perform variety of arithmetic operations under the control of digital computer. Finally, since the speed of optical computation largely depends upon the light power, the system design should aim at maximum utilization of the available light. This would require use of a fewer and better optical components.

The digital computer most suited for the present task is any small general purpose process control computer. It should have several data channels (roughly six analog channels and ten digital channels). The core memory may not be very large (about 16K words). A data interface device enables the transfer of data from the optical computer to the digital computer and *vice versa*. A large number of such devices are commercially available or in active development stage. The most important consideration in the choice of a particular device is space-bandwidth product which should be comparable to that of optical computer. The other considerations are speed of scanning, linearity, grey levels, etc.

Finally, since the preliminary processing is to be done by the optical computer, the input must be to the optical computer. Very often the input signals are in form of electrical signals. The chief difficulty or challenge lies in transforming in real time the electrical signals into optical signals. The output, however, does not pose any problem. A good T.V. display of the output of optical and digital computers should be available.

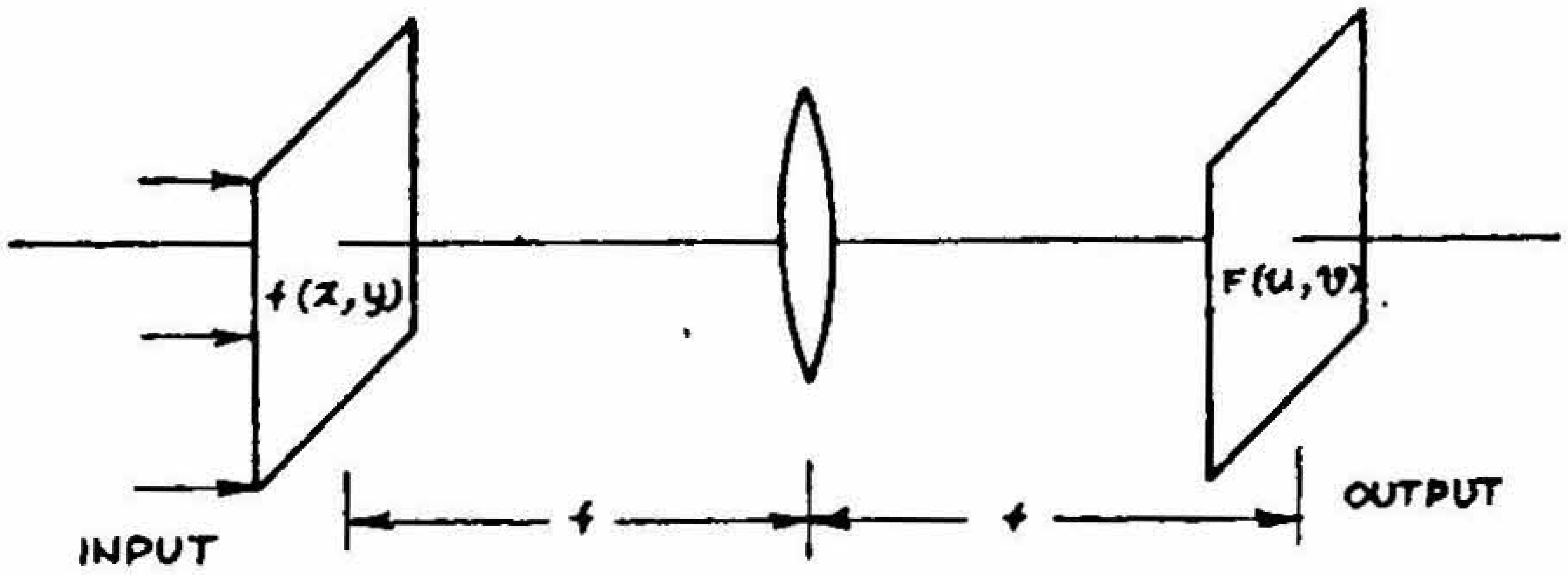
3. OPTICAL COMPUTER

The following arithmetic operations may be performed on an optical computer.

1. Fourier transformation
2. Multiplication
3. Division
4. Subtraction
5. Addition.

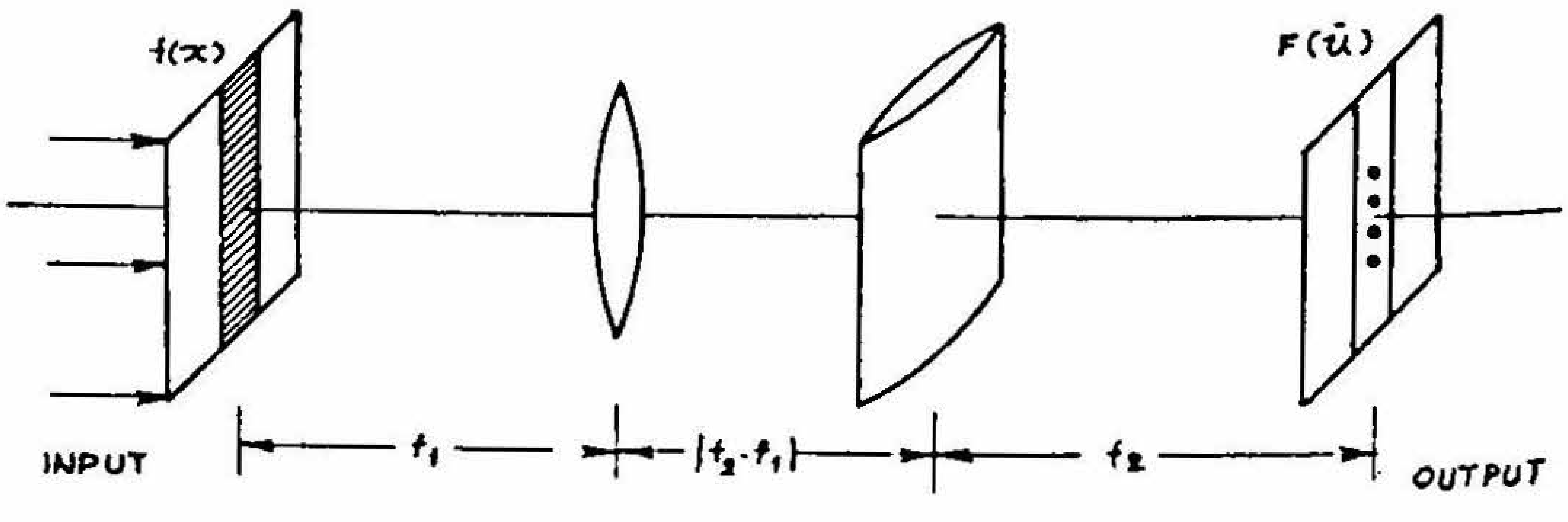
The complexity of the experimental set-up increases as one goes from Fourier transformation arrangement to that for addition. In Figs. 2 to 4 we show the basic set-ups for performing above operations. It is important to note that the configurations shown in the above figures are not the only possible ones. For example, one may use a paraboloidal mirror [5] for Fourier transformation. The set-up for multiplication may be much simplified if one were to use a holographic input. Thus, there exists a good scope for optimization. The main guiding factors should be (*a*) use as few optical components as possible. (*b*) Overall dimensions of the system should be small so that the mechanical stability is better. (*c*) A single set-up with minor alteration or change of a few components should perform all the five

$$f(u,v) = \frac{1}{4\pi^2} \iint f(x,y)\, \exp\,(i(ux + uy))\, dx\, dy$$



(a) FOURIER TRANSFORM (in two dimensions)

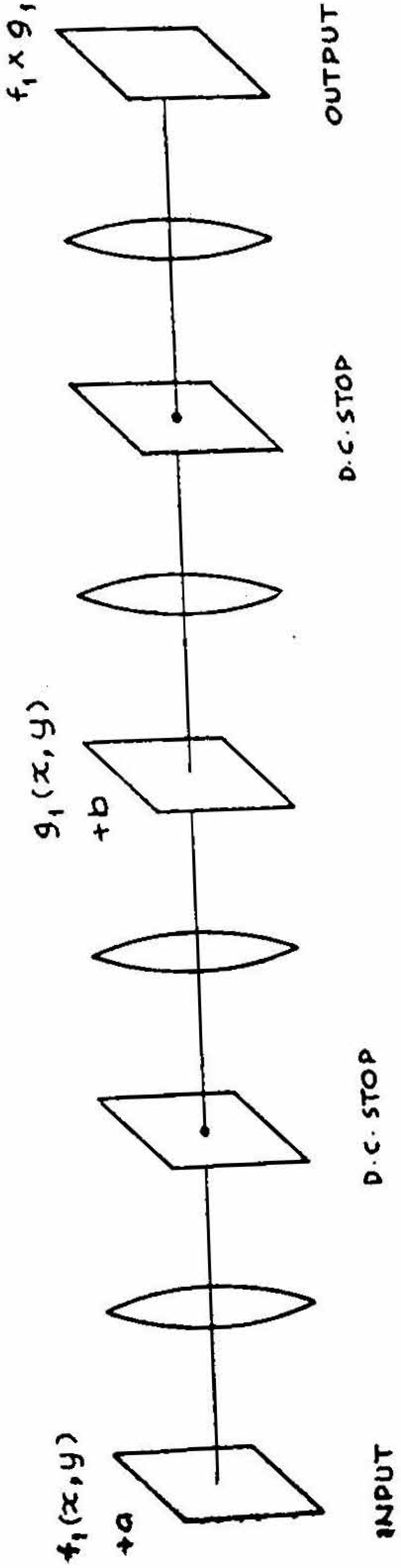
$$f(u) = \frac{1}{2\pi} \int f(x)\, \exp\,(iux)\, dx$$



(b) FOURIER TRANSFORM (in one dimension)

FIG. 2

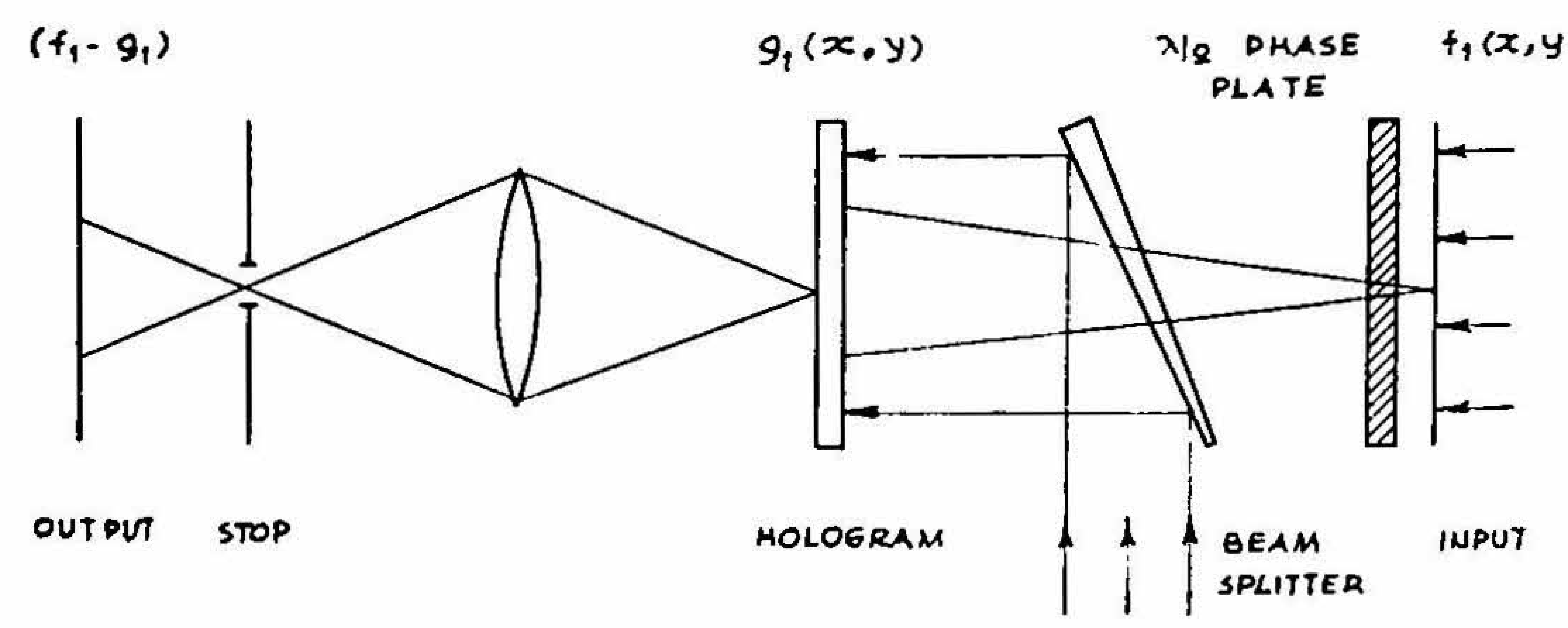
arithmetic operations. (*d*) Computer control of the system, especially for translating, removing, or bringing in a new optical component.



MULTIPLICATION / DIVISION

FIG. 3

In Fig. 5 we present a schematic lay-out of an optical system capable of performing all five operations. In brief the system consists of two data processing lenses (L_1 and L_2) two input devices and one output device. Two input devices are required for two input functions. The second input device carries the hologram of one of the functions. A reference beam travels parallel to the axis of the optical system and is branched off at various points for the purpose of holographic recording. The wedge-shaped beam splitter provides proper inclination to the reference beam. First, one of the input functions is holographically recorded into the second device. This may be done in two different ways. First, the function is introduced into the first input device and a hologram is recorded optically in the second input device. In the second method the hologram may be generated on a computer, and this hologram is recorded on the second input device by means of a scanning electron gun. The relative positions of various subsystems, that is, input devices, data processing lenses and output device must be controllable externally at the command of a digital computer. For example, for matched filtering, the positions must be such that the distance between any two subsystems is equal to one focal length. The total length of the system shall be $4f$ to $5f$. Note that this length is half of that for multiplication shown in Fig. 3. Finally, for addition of two functions it is necessary to introduce a half wave plate at the input plane.



ADDITION / SUBTRACTION

FIG. 4

To illustrate how the system works let us consider the operation of addition of two functions, $f(x,y) + g(x,y) = h(x,y)$ (*see* Bromley *et al.*

[6]). First we optically record a Fourier transform hologram of $g(x, y)$ in second input device. The hologram may be represented by

$$\begin{aligned} t(x, y) & \\ &= t_0 + \gamma t_e \,|\, G(u, v) \,|^2 + \gamma t_e A_{\mathrm{R}} \,|\, G(u, v) \,| \\ &\quad \times [\exp\big(i(ka\mu - Q(u, v))\big) + \exp\big(-i(kau - Q(u, v))\big)] \end{aligned} \tag{1}$$

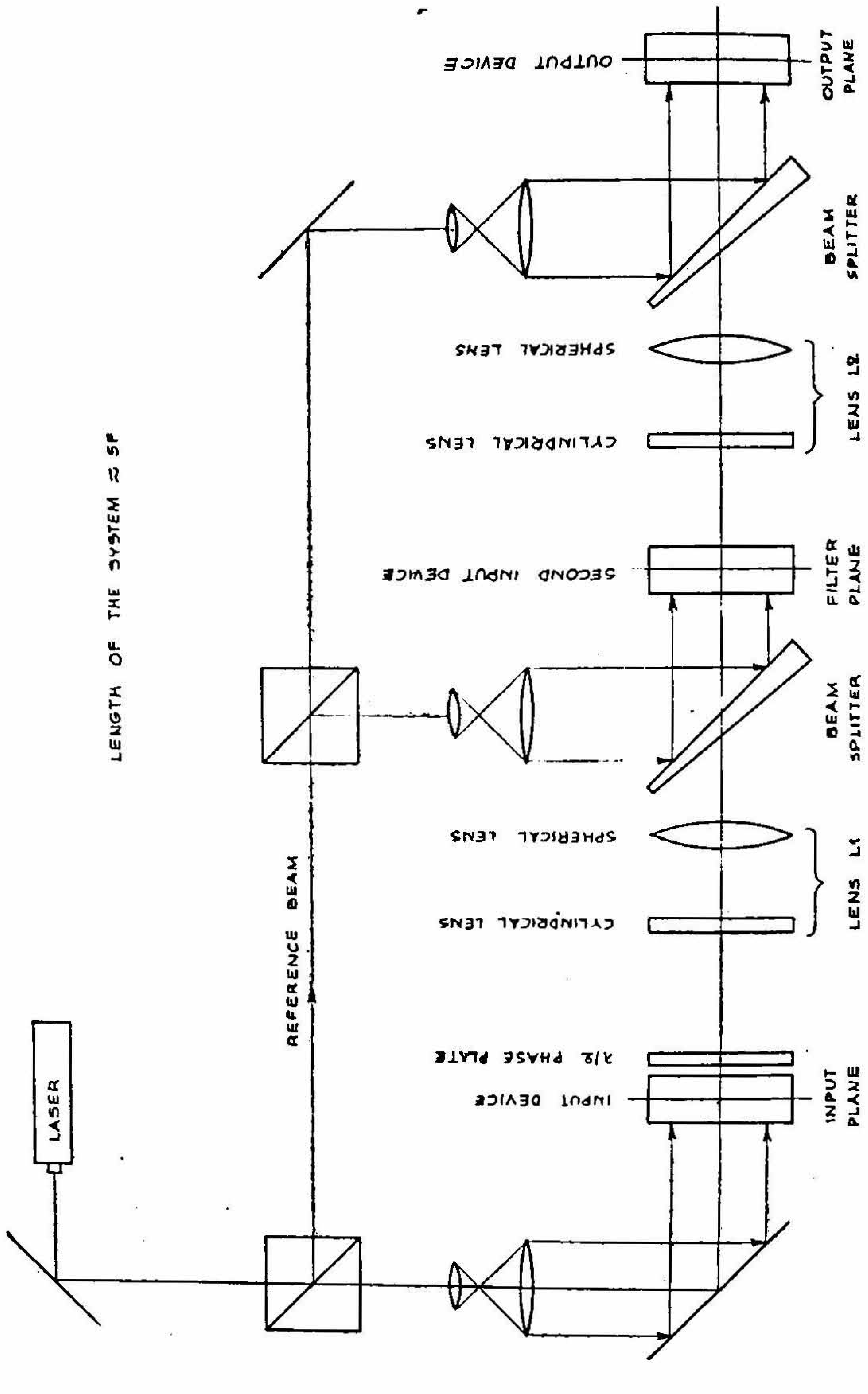
where the reference wave is represented by $A_{\mathrm{R}} \exp(ikau)$, γ is slope of the transmittance exposure curve measured in the linear region, t_0 is the operating point on T.E. curve, $t_0 = t_e A_{\mathrm{R}}^2$ where t_e is exposure time. Note that γ is negative. The hologram is reconstructed by illuminating with $\exp(i\pi)$ $F(u, v) + A_{\mathrm{R}}' \exp(ikau)$. The light amplitude emerging from the hologram is given by

$$\begin{aligned} U(x, y) & \\ &= [t_0 \exp(i\pi/1) F(u, v) + \gamma t_e A_{\mathrm{R}}' A_{\mathrm{R}} G(u, v) \\ &\quad + \gamma t_e \,|\, G(u, v) \,|^2 F(u, v) \exp(i\pi)] \\ &\quad + [t_0 A_{\mathrm{R}}' + \gamma t_e \,|\, G(u, v) \,|^2 A_{\mathrm{R}}' + \gamma t_e A_{\mathrm{R}} \exp(i\pi) \\ &\quad \times F(u, v)\, G^*(u, v)] \exp(ikau) \\ &\quad + [A_{\mathrm{R}} \gamma t_e G(u, v) \times F(u, v) \exp(i\pi)] \exp(-ikau) \\ &\quad + [A_{\mathrm{R}} A_{\mathrm{R}}' \gamma t_e G^*(u, v)] \exp(izkau). \end{aligned} \tag{2}$$

All four bracketed terms propagate in different directions. The first and second brackets in the above equation are of interest. Note that, since $A_{\mathrm{R}} \gg F(u, v)$ or $G(u, v)$ and $t_0 = t_e A_{\mathrm{R}}^2$ the third term in the first bracket may be neglected. We are left with first two terms,

$$\begin{aligned} & A_{\mathrm{R}}^2 t_e \exp(i\pi) F(u, v) + \gamma t_e A_{\mathrm{R}}' A_{\mathrm{R}} G(u, v) \\ &\quad = A_{\mathrm{R}}^2 t_e [\exp(i\pi) F(u, v) + A_{\mathrm{R}}'/A_{\mathrm{R}}\, \gamma G(u, v)]. \end{aligned}$$

In general the slope is negative in the linear region, hence, let $A_{\mathrm{R}}'/A_{\mathrm{R}}\, \gamma = -\alpha$. In order to achieve addition we will have to choose the reference wave amplitudes such that $\alpha = 1$. For subtraction, it is enough that a half wave plate is removed so that the exponential term is not present. The third bracket is also of interest. It is a product term with a positive sign. In the final output plane all four terms will occur in different portions of the output plane. It is possible to arrange such that they do not overlap.



OPTICAL COMPUTER

FIG. 5

Finally, the space-bandwidth product of the optical computer is controlled by input aperture. $f_0 = l/F\lambda$ where f_0 is cut off frequency, l is diameter of the input aperture, F is focal length and λ is wavelength. Let us take some typical values, $F = 10^3$ mm, $\lambda = 6 \cdot 2 \times 10^{-4}$ mm (red light) and $l = 70$ mm. Then, $f_0 = 110$ lines/mm and the space-bandwidth product would be of the order of 6×10^9.

4. DIGITAL COMPUTER

The main functions of the digital computer are to control the optical computer, in the sense that some of the optical components be brought in or out as per the programmed instructions, to control the second input device, and to sense the output plane of the optical computer. In addition, the computer may be called upon to do more advanced type of processing, such as non-linear filtering, maximum likelihood processing, etc. Thus, the desired computer must have the capability of closing and opening a number of relays, a number of data channels some of them should cater to analog input/output of the data, and must have fast data transfer rate. Real time processing capability must also be present. Since most of the photographic data is limited to 8 bits (256 levels) a 16 bit word is more than adequate. Any small process control computer will have the above-mentioned facilities. The size of core memory will largely depend upon the size of matrix on which the sophisticated processing is required to be done. Surely, the entire matrix, for example, 80000 × 80000, handled by the optical computer cannot be processed on the digital computer. A reasonable choice is 64 × 64 or 128 × 128 point matrix. However, we must have adequate back-up memory to store a good fraction of the original matrix handled by the optical computer.

5. INPUT/OUTPUT

Input to the optical computer is through a film or a real time light modulator and that to the digital computer is through tape or cards. While the spatial resolution of a film is high (1000 lines/mm), the amplitude resolution is usually limited to 8 bits (256 levels). If the entire system is to work in real time, the input to the optical computer must also be in real time. This type of requirement exists in the processing of radar data, in particular, phased array radar. The film input is evidently too slow. Real time light modulators such as acoustic light modulators have been used [7]. A typical acoustic light modulator is shown in Fig. 6 (*a*). There must be as many light modulators as the number of channels. Assuming each channel to be 5 mm, no more than 14 channels can be packed within the input aperture

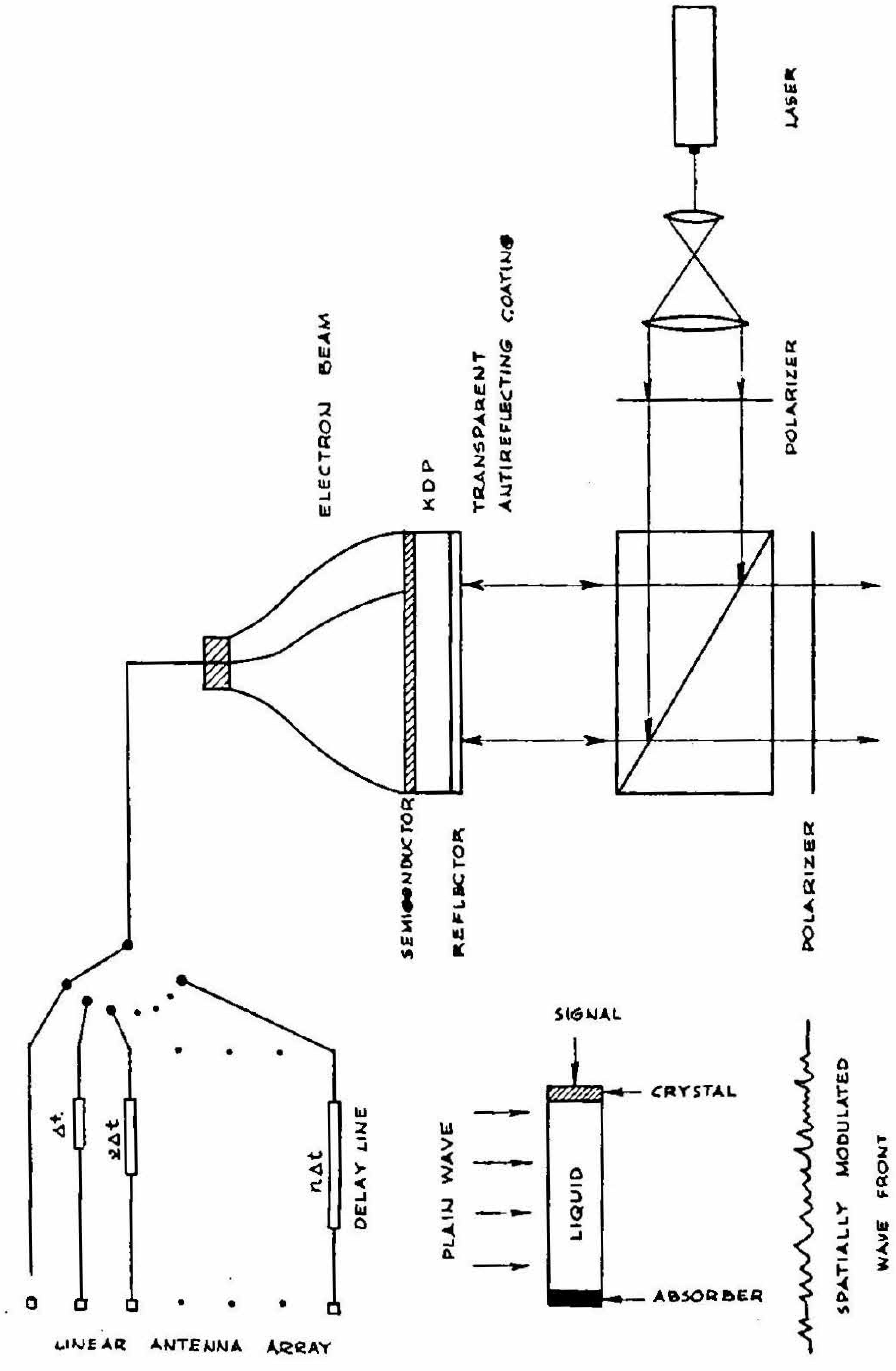


FIG. 6*a* VAN ARDANNE LIGHT VALVE

ACOUSTIC LIGHT MODULATOR

of 70 mm. This figure is obviously too low as far as any practical phased array radar system is concerned.

There are special types of solid state light modulating devices, one of this kind is known as Vanardanne light valve [8]. In this a KDP crystal is used to modulate the incoming laser beam. The optical properties of the KDP crystal are changed by changing the charge pattern on the face of the crystal by means of a scanning electron beam. The intensity of the electron beam is modulated by the radar signal. If there are N sensors, each sensor is connected to the electron beam sequentially after an interval Δt where Δt is equal to the duration of the signal. While any one of the sensors is being serviced the signals from the other sensors are kept waiting by means of delay unit. The light modulator must store the information for at least $N\Delta t$ seconds. Let us consider a problem of tracking a moving target by sampling the target trajectory every 100 m.s. Then, $N\Delta t \leqslant 100$ m.s. Let the duration of radar pulse be, $\Delta t = 100\,\mu$s, then, $N \leq 1{,}000$. In other words the light modulator can handle a linear array of one thousand antennas. The storage time of such a device is of the order of a few seconds to hours [9]. The resolution that can be achieved in such a device is in the range of 10 to 20 TV lines/mm for KDP crystal and 100 TV lines/mm for $Bi_{12}SiO_{20}$. Over an aperture of 70 mm, it is easily possible to pack 1,000 channels. The length of each channel will be equal to 1,400 to 2,800 points. This would correspond to 7 to 14 MHz bandwidth. Hence, it would be necessary to shift the radar signal frequency to mega-cycle range.

6. DATA INTERFACE

The purpose of a data interface device is to provide a means of transmitting data from the optical computer to the digital computer and *vice versa*. The optical data is in the form of light amplitude/phase variation whereas the data from the digital computer is in the form of numbers. It is easy to convert the light amplitude/phase variation into electrical signals using a vidicon camera whose output is then fed to the digital computer through A/D converter. Since the vidicon is a square law detector it is necessary to use a reference beam in order to preserve the phase information. Commercial high resolution image sensing cameras can achieve a resolution of the order of one hundred lines/mm and amplitude resolution of 256 grey levels. The scanning speed is about half a mega hertz/sec. It would take 560 m.s. to scan a matrix of 128 × 128. A much higher resolution can be achieved by RCA development type vidicon camera, for example C23084F has 5,000 lines space-bandwidth product.

With the modern developments in integrated circuits it has been possible to fabricate solid state photodiode and photo-transistor arrays, for example, Westinghouse has developed 400 × 500 phototransistor array [12]. Commercially a rectangular array of 50 × 50 or a linear array of 512 diodes are available. The photodiode array has higher sensitivity, stability and linearity than a vidicon camera. The scanning speed is also much higher, about 5 MHz/sec. These have a resolution comparable to that of a commercial vidicon camera.

The problem of converting digital data into optical data is much more difficult. The input from the digital computer to the optical computer is required whenever the spatial filter in the optical computer is calculated by the digital computer. The spatial filter is introduced in the second input device shown in Fig. 5. One method of doing this is to present the output of the digital computer on a high resolution CRT and use a device to convert incoherent image to coherent image such as the one developed by Nisenson [11] where Pockel effect in a $Bi_{12}SiO_{20}$ crystal is used. A resolution of 100 lines/mm has been achieved.

The second method involves use of thermoplastic. A charge pattern proportional to a given function is deposited on the surface of a thermoplastic. It is then subjected to heating followed by rapid cooling. The charge pattern gets transformed into surface undulations. Such a film is then used for modulating a light beam. A resolution of the order of a few hundred lines to a thousand lines/mm can be achieved, however the amplitude resolution is merely 8–10 grey levels. The advantages of the thermoplastic are two fold. The speed of recording is high, equivalent to 25–30 ASA and the processing takes only a few seconds. A thermoplastic film is reusable approximately 100,000 times. A device called Lumatron [13] has been built using a thermoplastic for real time input. One important drawback in the use of thermoplastic device, for that matter any other phase modulating device, is that a much larger bandwidth is required for the optical computer [7].

7. DISCUSSION

From the above discussion it is clear that the proposed hybrid system is feasible within the existing technology, yet there are many areas where further development is required to make the proposed system reasonably effective. The deficiency exists in the following areas :

(*a*) The computational accuracy of the optical computer.

(*b*) Real time input to the optical computer.

(*c*) Data transfer from the digital to optical computer.

(*d*) Computer control of the optical system.

A continued effort in the areas of optical device development, and optical system and component development will be required to overcome the deficiencies in the above areas.

The hybrid system described above will find its application in the following areas:

(*a*) Real time or near real time processing of two-dimensional signals·

(*b*) Real time processing of channellized phased array radar or sonar signals.

(*c*) Interactive processing of previously taken photographs such as aerial photographs for military and earth resources applications, etc.

Real time picture processing is rather far fetched at the present time, but in future a need for real time picture processing would arise as for example, in unmanned exploration of planets, biomedical studies, etc. Assume that a roving vidicon camera is transported to say, Mars. Pictures sent out by the camera should be processed in real time so that the scientist sitting in the control room can direct the camera to interesting targets. Similarly a doctor would like to continuously monitor the growth and decay of a tumor or observe the action of a drug.

The most interesting application of the hybrid system lies in the area of real time radar or sonar signal processing, particularly for the phased array or synthetic aperture radar. The optical computer can easily perform the usual tasks of beam formation, pulse compression and doppler shift measurement. The digital computer looks after book keeping work, sensing the output plane, and issuing commands to the fire control equipment. Because of the high speed of computation and large storage capacity of the optical medium it should be possible to handle hundreds of channels in parallel and perform all the operations in real time at substantially lower cost.

Lastly, let us examine how this system works for interactive type of picture processing. Aerial pictures are taken for the military, earth resources, and other applications at frequent intervals with the purpose of identifying the changes in the scene, for example, a new military installation not present in the previous frame or a new crop disease not noticed in the previous frame. In order to detect the change it is necessary to subtract the previous frame from the present. This operation may have to be repeated using many of the previous frames so that it may be possible to trace back the birth of the new feature.

The entire concept of hybrid system is very much in the developing stage. It appears to possess challenging applications in the field military intelligence, space exploration and environmental studies. Considerable work need to be done particularly in the field of input/output systems, data interfaces, and computer control of the optical system.

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