NPS-52Po74051

NAVAL POSTGRADUATE SCHOOL
Monterey, California

ANALYSIS OF A MULTIPURPOSE
ELECTRO-OPTICAL SIGNAL PROCESSOR

John P. Powers

May 1974

Final Report for Period 1 May 1973 - 1 July 73

Approved for public release; distribution unlimited

red for: Naval Electronics Laboratory Center
San Diego, California 92152

NAVAL POSTGRADUATE SCHOOL
Monterey, California

ABSTRACT:

This report contains an analysis of the technology required for the operation of an electro-optical signal processor. The individual elements consisting of light emitting diodes, photographic transparencies and charge-coupled device (CCD) imaging devices were considered for feasibility of use and potential limitations to system response or applications. Primarily, the system frequency response and dynamic range is restricted by the CCD imaging device. Other trade-offs in the design and application of the system are also indicated.

This task was supported by: Naval Electronics Laboratory Center
Work Request WR-3-9123

NPS-52Po74051

September 1974

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: NPS-52Po74051
2. GOVT ACCESSION NO.:
3. RECIPIENT'S CATALOG NUMBER:
4. TITLE (and Subtitle): ANALYSIS OF A MULTIPURPOSE ELECTRO-OPTICAL SIGNAL PROCESSOR
5. TYPE OF REPORT & PERIOD COVERED: Final Report, 1 May 1973-1 July 1973
6. PERFORMING ORG. REPORT NUMBER:
7. AUTHOR(s): John P. Powers
8. CONTRACT OR GRANT NUMBER(s):
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Naval Postgraduate School, Monterey, California
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: WR-3-9123
11. CONTROLLING OFFICE NAME AND ADDRESS: Naval Electronics Laboratory Center, 271 Catalina Boulevard, San Diego, CA 92152
12. REPORT DATE: 20 June 1974
13. NUMBER OF PAGES:
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office):
15. SECURITY CLASS. (of this report): Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE:

16. DISTRIBUTION STATEMENT (of this Report): Approved for public release; distritution unlimited.
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report):
18. SUPPLEMENTARY NOTES:
19. KEY WORDS (Continue on reverse side if necessary and identify by block number):
    - electro optical
    - signal processing
    - charge coupled device
    - light emitting diode
20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report contains an analysis of the technology required for the operation of an electro optical signal processor. The individual elements consisting of light emitting diodes, photographic transparencies and charge-coupled device (CCD) imaging devices were considered for feasibility of use and potential limitations to system response or applications. Primarily, the system frequency response and dynamic range is restricted by the CCD imaging device. Other trade-offs in the design and application of the system are also indicated.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
(Page 1) S/N 0102-014-6601

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

TABLE OF CONTENTS

ANALYSIS OF A MULTIPURPOSE
ELECTRO OPTICAL SIGNAL PROCESSOR

INTRODUCTION

An electro optical signal processor under investigation at the Navy Electronics Laboratory Center (NELC) is schematically shown in Fig. 1.[1] Although the device can perform more general functions involving any form of matrix multiplication, one of the primary applications of the device is to perform integral transforms of electronic signals (e.g. the discrete Fourier transform). The primary features of the device are:

1) It takes advantage of the parallel processing capability of an optical signal to rapidly perform the operation. (Operating speed is limited by the switching speed of the imaging device or the modulation capabilities of the light emitting diode (LED).)
2) The device is compact. It could easily fit into a three-inch cube.
3) The device is reliable. Because the key elements of the system are solid state, it will be a rugged reliable device. (In making this statement, it is anticipated that within five years commercial CCD's will be well developed and will be able to fulfill the present expectations.)

The scope of this report is to investigate each of the elements in the system and to analyze them for possible sources of error in the output. Another purpose was to verify some of the implicit assumptions in the system design and to identify possible problem areas in the implementation of the working system. Since only a two month (May-June 1973) study was made, the analysis is not completely detailed but, rather, is of a preliminary nature.

OPERATION OF THE SYSTEM

The operation of the system is described for the case of performing a Fourier transform. Other operations can be performed by using another transparency.

The discrete Fourier transform can be considered as the following operation sequence:

1) Sampling of the electronic signal.
2) Multiplication by a matrix whose elements correspond to the value of the Fourier kernel.
3) Summation of the products.

Mathematically this is written as

$$A(n) = F\{x(j)\} = \frac{1}{N} \sum_{j=0}^{N-1} x(j)\, e^{+i \frac{2\pi nj}{N}}$$

$$= \left[\frac{1}{N} \sum_{j=0}^{N-1} x(j) \cos \frac{2\pi nj}{N} \right] + i \left[\frac{1}{N} \sum_{j=0}^{N-1} x(j) \sin \frac{2\pi nj}{N} \right]$$

where

$A(n)$ is the n_{th} (out of a total of N) Fourier coefficient

$F\{\ \}$ is the discrete Fourier transform operation.

$x(j)$ is the sampled signal (assumed real and positive).

N is the total number of signal samples and Fourier coefficients.

In the electro optic processor, the input signal can be either discrete (and synchronized with the detector switching) or continuous. If it is continuous, the discrete nature of the imaging device and the fact that it is switched both spatially and temporally samples the signal. Since an optical signal is required to be real and positive (since the detector is intensity sensitive), the processor generally would require four channels to complete the complex transform of a positive real input signal (as shown in Fig 2.). One set of two channels handles the real part, $x(j)\cos\frac{2\pi nj}{N}$, the other set of two handles the imaginary part $x(j)\sin\frac{2\pi nj}{N}$. Each set has one channel to handle the positive values and another for the negative values of the product. Hence, four parallel channels are required to obtain the complete complex Fourier transform of the signal. The result can be electronically manipulated to give the real and imaginary parts (or amplitude and phase) from the output terminals. It is noted that a bias term can be added to both the dc input and the transparency to eliminate the requirement for parallel processing of the positive and negative information.

$$a(n) = \frac{1}{N}\sum_{j=0}^{N-1}\left[x_o+x(j)\right]\left[1+\cos\frac{2\pi nj}{N}\right]$$

$$+\, i\,\frac{1}{N}\sum_{j=0}^{N-1}\left[x_o+x(j)\right]\left[1+\sin\frac{2\pi nj}{N}\right]$$

where x_o and 1 have been added to the input signal and the Fourier kernel respectively.

The real part becomes

$$\mathrm{Re}\{A(n)\} = \frac{1}{N} \sum_{j=0}^{N-1} x_o + x(j) + x_o \cos(\frac{2\pi nj}{N}) + x(j) \cos\frac{2\pi nj}{N}$$

$$= x_o + \overline{x(j)} + x_o \quad \delta(n) + F\{x(j)\}$$

where $\overline{x(j)}$ = the average value of the sequence

$$F\{x_o\} = x_o \quad \delta(n), \qquad \delta(n) = \begin{cases} 1 & n=0 \\ 0 & \text{otherwise} \end{cases}$$

Subtraction of $x_o + \overline{x(j)}$ would give the Fourier coefficient for all but $A(0)$ which would require subtraction of $2x_o + \overline{x(j)}$.

A similar expression holds for the imaginary parts. By proper electronic compensation of the output of the channels, only two parallel processing channels (Fig 3) are required rather than four, as previously described. However, the facts that the average of a sequence must be computed and that the compensation of the dc Fourier component is different from the others, complicates the electronic compensation technique.

The operation of the system as a Fourier transform is as follows. The detecting element is an NxN array of optical detectors with a light integration capability. Each row of N elements will provide one Fourier coefficient. The optical transparency is designed so that it also has NxN blocks that register with the NxN elements of the receiving array. Each block has a transmission factor that is proportional to the kernel of the transform. For example, the element in row n and column j of the transparency in the positive real channel will have the transmission factor

$$t_{nj} = \begin{cases} \cos \frac{2\pi n}{N} j & \text{if } \cos \frac{2\pi n}{N} j > 0 \\ 0 & \text{if } \cos \frac{2\pi n}{N} j < 0 \end{cases}$$

The design of the transparency is discussed in a later section.

The serial switching of the detector serves to break up a continuous signal into a sequence. By following the charge accumulation as it is switched laterally, it is seen that the Nth signal received from the n^{th} line is the summation of $x(j) \cos \frac{2\pi n}{N} j$ over the total of N elements. (The operation uses the switching and integration capabilities of the detector in a "step and add" fashion.) This is a scaled version of the real positive part of the Fourier coefficient. The negative real part and the imaginary parts are obtained from the other three channels of the device.

As this process continues in time, the time varying Fourier coefficients are obtained. In this mode of operation, the processor acts as a sliding temporal window in sampling the signal and the output is useful for obtaining a continuous picture of the time evolution of the spectrum. If nonoverlapping samples of the signal are desired, then the first N-1 signals from each line may be discarded with the Nth charge packet representing the Fourier coefficient for that sample. The process then repeats itself to determine the spectral coefficients for the next signal sample.

The elements to be considered for study are the LED, the transparency, and the CCD imaging device.

THE LIGHT EMITTING DIODE

(LED)

The following properties of LED's become important in the signal processing scheme envisioned.

1. Angular dependence of radiation.

It is desired to have a uniform illumination over all parts of the transparency to avoid weighting the elements due to irregularities in the beam. The angular spread of the uniform portion of the LED beam is easily computed from the geometry of Fig. 4. The height, H, of a typical CCD imaging device is .1" (2.54 mm). Since $\sqrt{2}\, H/2 = d \tan \theta$, a trade-off between element spacing and divergence of the LED is required. For an arbitrary spacing of 1" (2.54 cm), the half angle becomes 5°. This is well within the capabilities of current LED's to provide uniform illumination (e.g. the Fairchild FLV 101 and 102 have $I/I_o \simeq .99$ at ±5°.) At higher prices other devices can provide uniform illumination over very wide angles (e.g. Spectronics GaAs diode provides uniform illumination up to 60°.)

2. Linearity of the LED

It is desired to have the light follow the signal exactly. LED's have excellent linearity to the current driving the device. For some applications it might be necessary to have a linear voltage-to-current converter to drive the LED.

3. Dynamic range

The dynamic range of the light output of the LED's typically is in excess of two orders of magnitude (40 db), ranging from 10 ma of input current to 1 amp. At higher current levels the light becomes non-linearly dependent on the current due to thermal effects. To extend the dynamic range, lower current levels should be investigated to find at what point the light intensity deviates from being linear or that noise obscures the signal. It is noted that the linearity and peak current fall off with increasing junction temperature (important when considering CW operation about a dc bias current). The upper current limit on linear operation is determined by thermal dissipation limits of the device. Without elaborate cooling techniques, it would not be practical to extend the dynamic range of the device in the direction of higher currents.

4. Bandwidth

Present state-of-the-art devices have a maximum bandwidth of 10's of MHz. Research efforts are progressing to increase this frequency. It is noted, however, that first generation CCD imaging devices in their commercial form are expected to operate at 10 MHz. Hence, present LED's already have enough bandwidth capability. At present and in the near future, it is expected that the bandwidth limitations of the solid state imaging device will be the primary restriction on the system bandwidth rather than the light source. Hence, it is concluded that LED's present no limitations on the design and implementation of the system.

TRANSPARENCY DESIGN

The transparencies are required to be divided up into N×N elements that correspond to each of the imaging elements. Each element would have a transmission factor between 0 and 1. Two tecnniques are envisioned for achieving this: a binary mask or a grey scale photographic mask.

1. Binary mask

The binary mask uses observations of various amounts to control the amount of light falling on the detector element. As shown in Fig. 5 two designs are possible: one being a clear spot in an opaque element, the other being an opaque spot in a clear element. The transmission factor is simply determined by the ratio of the area of the clear portion to that of the entire element.

For the first design this would be (assuming square elements)

$$\tau = \frac{W'^2}{W^2} = \left(\frac{W'}{W}\right)^2$$

For the second design

$$\tau = \frac{W^2 - W'^2}{W^2} = 1 - \left(\frac{W'}{W}\right)^2$$

The advantages of the binary transparency are that it is easy to fabricate in prototype models and is amenable to computer-controlled fabrication. Since only two levels are involved--transparent and opaque--there are no problems with film nonlinearities.

The binary transparency is subject to errors due to misregistration of the transparency. The amount of the error introduced is dependent on the imaging element size, the design of the binary mask, the transmission of the element as well as the size and direction of the misregistration. The amount of the error for a given configuration is easily determined. The signal from the detector is proportional to the intensity of the incident light which in turn is determined by the overlapping areas of the detector and the transparent part of the transparency. The overlap of the areas is reminiscent of the spatial correlation of two-dimensional functions representing the transparency and the detector. This function is a maximum at zero offset (corresponding to optimum registration) and falls off with displacement of the transparency function. Computation of the relative decrease in signal level with displacement of the mask then can be computed by a graphical or analytical analysis of the correlation of the transparency and the detector. Investigations into the sensitivities of the error for the different binary designs could be done to minimize the errors. For example, the correlations shown in Fig. 6 show that for the binary design with a clear spot in an opaque mask, the output is more insensitive to small displacements for small transmission factors than for large transmission factors.

2. Grey scale mask

The second technique of transparency preparation involves exposure of each element of the transparency film to enough light to create the proper grey scale. As long as the transparency elements are larger than the detector elements, the errors due to misregistration are minimized since the centering of the transparency element is not critical. The preparation of the transparency becomes more difficult, however. The individual elements must be exposed to a light source of correct intensity and time duration. Nonlinearities of the film response should be taken into account to obtain the correct transmission factor. The demagnified image of the light source would be required because of the small size of the transmission element. (A detector element on a CCD device is on the order of 1 mil on a side.) Since a large array of elements are required, a computer controlled process that governs the positioning and exposure (including the nonlinearities) would reduce the work to a tolerable level. Once a master mask was produced in this way, photographic copies could be easily and cheaply produced.

The two techniques then have offsetting difficulties. The binary transparencies are fairly easy to make but are somewhat sensitive to registration problems. Micro positioners would probably be required for accurate registration with the small imaging devices that are envisioned. The positioning requirement is not too difficult to this scale and can even be partially eased by using mask element sizes that are smaller than the detector elements. The grey scale transparencies, while more insensitive to registration, are much more difficult to make. The requirement for a grey scale adds a new dimension to the fabrication process. The fact that film is nonlinear makes this new problem even more difficult. In this case, the use of a computer controlled fabrication of a master transparency would be required to reduce the effort to a tolerable level. Once the master is made, other transparencies can be photographically duplicated at little cost. At present the binary technique appears to be the simpler.

THE IMAGING DEVICE

As described, it is desirable to have a small, reliable solid state sensing device that can combine the detecting capability with information processing. One such device obtaining technological prominence is the charge coupled device (CCD).[2] In the processor the CCD serves as a means of collecting the charge across various lines of the image at different points and different times. Hence, the integration can be done in both time and space across the device.

It should be noted that in the following discussions typical parameter values of available devices such as the Fairchild CCD 101 linear image sensor are used. Because CCD's are under intensive development, these values will be changing. Where trends and limitations exist, it will be noted. However, the values used are representative of commercially available devices in mid-1973. It is also noted that other devices such as the self-scanned photodiode array also are potential candidates for this application, but that the fundamental emphasis in the conceived design was on the applications of CCD's.

The limited dynamic range of present CCD's for imaging purposes (typically 10^3) is further reduced by the fact that one element is used for collecting the charge across one line of the device. The saturation level of each element must be reduced by l/n to avoid saturating the signal in the case of constant illumination. The noise currents are reduced by only $\sqrt{1/n}$ because of their statistical nature. Hence the dynamic range -- (saturation level/noise level) is reduced by $\sqrt{1/n}$ (or ~ 1/23) from the value used in imaging devices.[3]

In considering the frequency response of the signal one must consider both the desired application and the design of the CCD. Two designs of area imaging devices are anticipated: one involves a lateral movement of all lines followed by a vertical shift (as shown in Fig. 7). Allowing for equal exposures the individual elements give the time varying Fourier coefficients. When the time varying Fourier coefficients are not of interest, only the last column transferred out of the device is useful since only it will be full summation over N. The terms read out previously will be incomplete summations. Assuming that the array is 500 by 500, it is noted that the vertical transfer must operate at a frequency of 500 times that of the lines since 500 elements must be read out of the vertical shift register for each lateral shift of the columns. Since the maximum shifting frequency of the devices is anticipated to be on the order of 10 MHz for currently conceived ideas such as TV cameras and computer memory devices, the maximum signal frequency that can be processed is reduced by 1/N (N is the number of vertical elements). Hence audio signals (10 MHz/500 = 20 KHz) can produce 500 coefficients in this application of non overlapping signal samples.

The second technique to be used in image detectors is frame or field transfer. As shown in Fig. 8, 2N lines are used; the upper N are exposed to the light (image area) and then quickly transferred vertically to the lower N lines (storage area). While the upper frame is being exposed, the storage frame is read out by shifting the lines vertically and reading out sequentially the bottom line by horizontal shifting. Again the fastest clock frequency appears at the horizontal shift register, and the vertical frequency would be reduced by $\frac{1}{N}$ (N here is the number of horizontal elements). It is noted that in this scheme the integration would occur vertically and that the N Fourier coefficients for non-overlapping samples would be contained in the last row to be shifted out of the storage frame.

Simple modifications in the fabrication of the CCD can be made to achieve full use of the switching frequency of the CCD. Applications that use non-overlapping signal samples can use the time when the N-1 samples of each line are being discarded to read out the previously obtained value of the Fourier coefficient. In this way the signal bandwidth would be limited by the switching frequency.

The switching frequency itself can be raised by modifications in the design of the CCD. A new charge coupled data processing device called the peristaltic charge coupled device [4] has been recently developed and is capable of operating at frequencies of more than 100 MHz. Such a device, while now developed for signal processing rather than imaging, will provide a useful base when optical processing of high frequency signals becomes an important application of this technique.

In summary then the frequency response of the processor is:

1. When using a conventional commercial CCD with a switching speed on the order of 10 MHz two modes of operation are possible.

   a. The instantaneously time varying Fourier coefficients can be obtained by using every output signal. A 500 by 500 array operating at 10 MHz could produce 500 coefficients every 50 microseconds. This is equivalent to using a "sliding window" to sample the signal every 5 microseconds.

   b. When discrete non-overlapping samples of the signal are desired much of the information is discarded lowering the maximum signal frequency but still providing a large number of Fourier coefficients in a short amount of time (e.g. 500 coefficients every 2.5 milliseconds for the numbers assumed above. Minor modifications to the device design before fabrication can recover the full frequency response of the system and make it practical for a wider variety of signal processing applications.

2. Major modications to the device design appear technologically feasible to raise the frequency capability of the device. Research into high frequency devices has been promising.

Other problems presented by using devices and electronics developed for television use are easily circumvented. Removal of the interlace is accomplished by modifications to the driving electronics. As element sizes decrease to improve resolution capabilities more stringent registration of the mask will be required but this is well within the limits of simple micro-positioners. Also as previously noted, tolerances on mask registration can be somewhat related by making the masking elements smaller than the sensor elements.

SUMMARY

The electro optic processor discussed is capable of processing electronic signals and producing processed data at a high rate by combining the parallel processing capability of optics and the integrating capability of optical detectors. It is emphasized that while this report has been framed in terms of Fourier transforms, any other discrete transform or multiply-and-add operation can be performed. The light emitting diode and mask fabrication present no technological problems. The efficient use of the frequency capability of the CCD calls for some ingenuity but the technological means are well in hand. Simple experimental confirmations of principles of operations have been obtained [1] and further development of the technique is desired and recommended.

REFERENCES

1. R. P. Bocker, K. Bromley and M. A. Monahan, "Incoherent optical data processing," presented at the 1973 Annual Meeting of the Optical Society of America, Rochester, N.Y., October 1973.

2. M. F. Thompsett, "Charge transfer devices," J. Vac. Sci. Technology., 9 (4):1166-1181, 1972

3. Keith Bromley, private communication, April 1974.

4. "CCD hits megahertz speed," Electronics 46 (25) "63, December 6, 1973

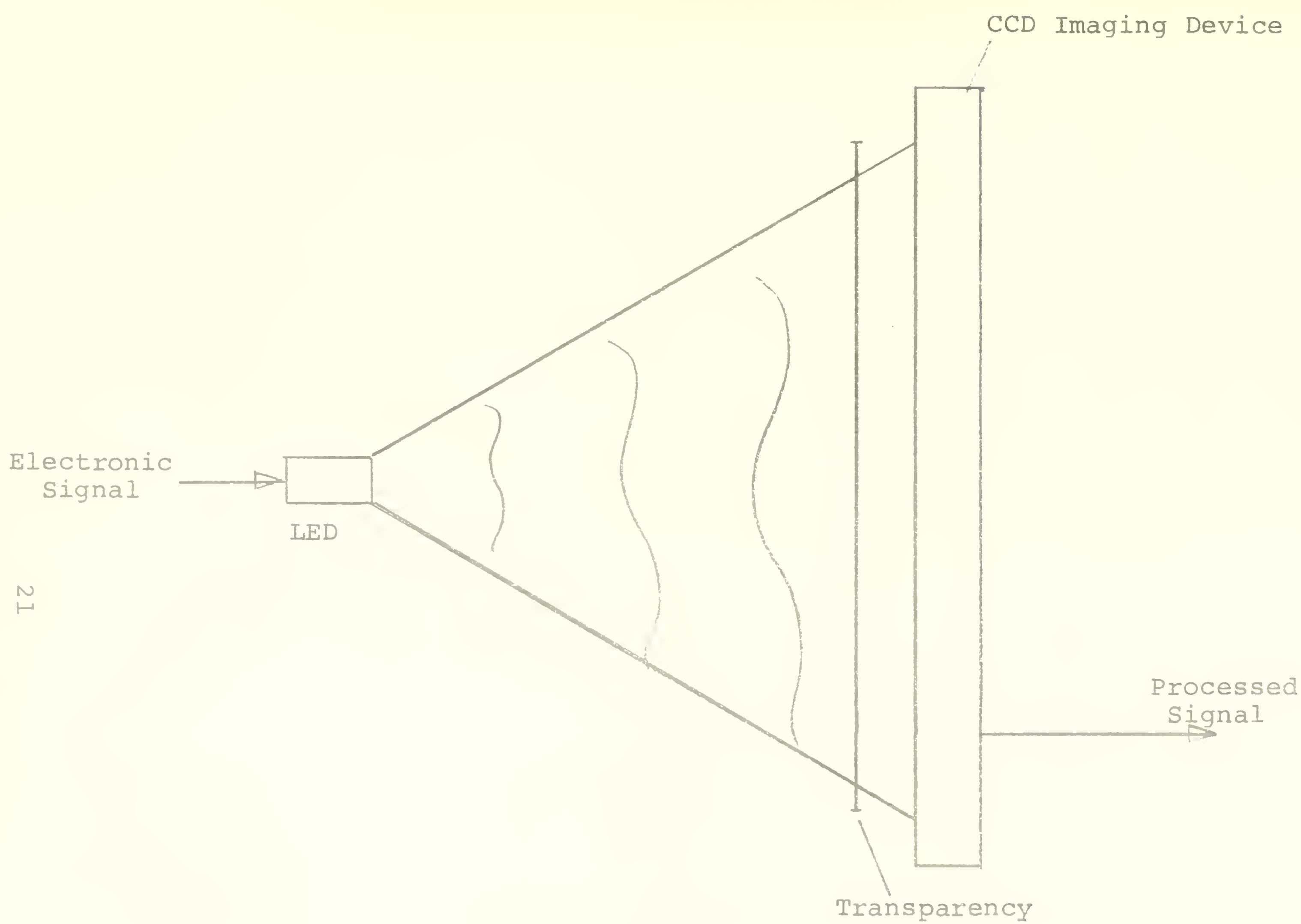

Fig. 1. Schematic of one channel electro-optic signal processor

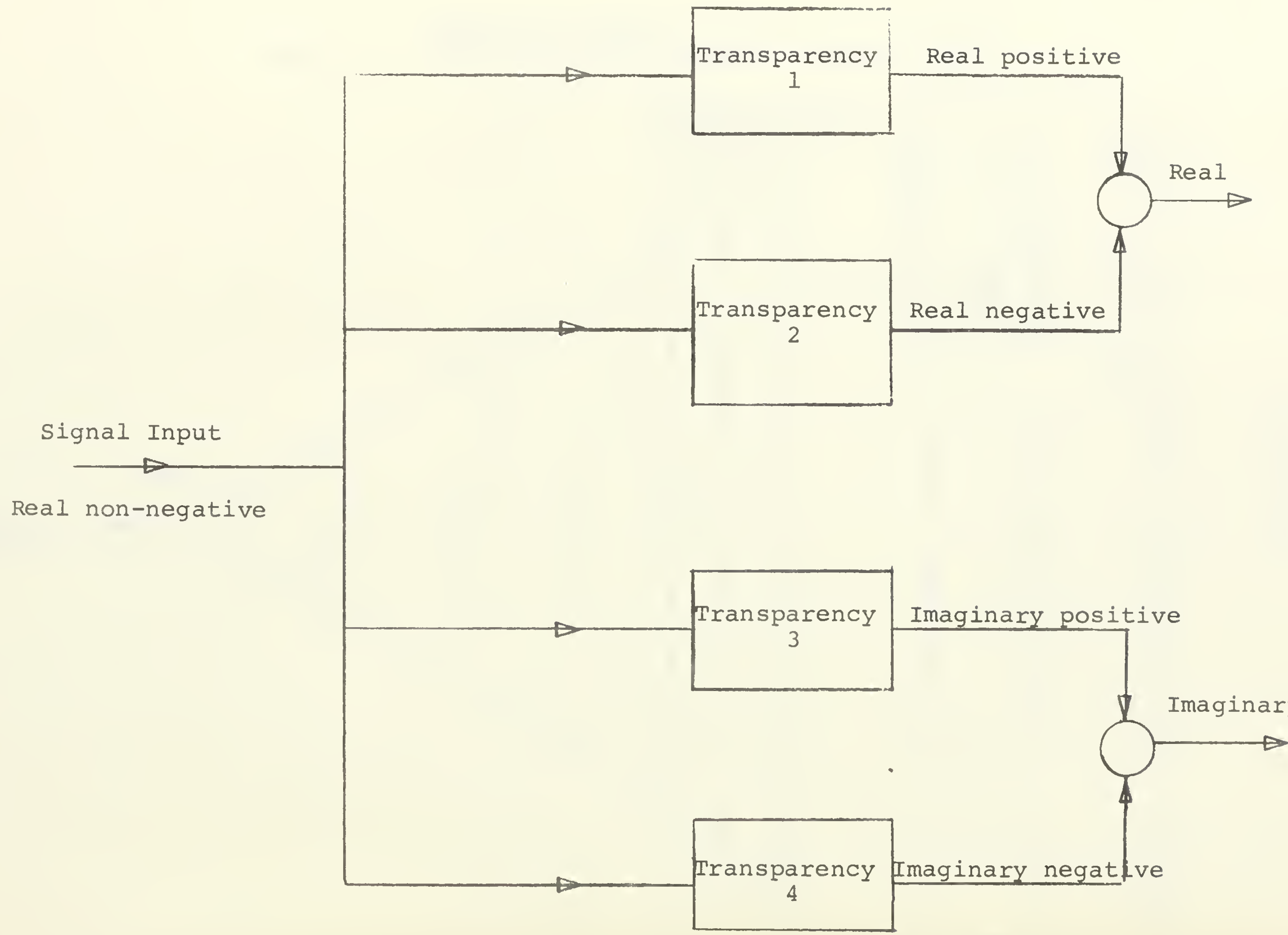

Fig. 2. Four Channel Parallel Processor

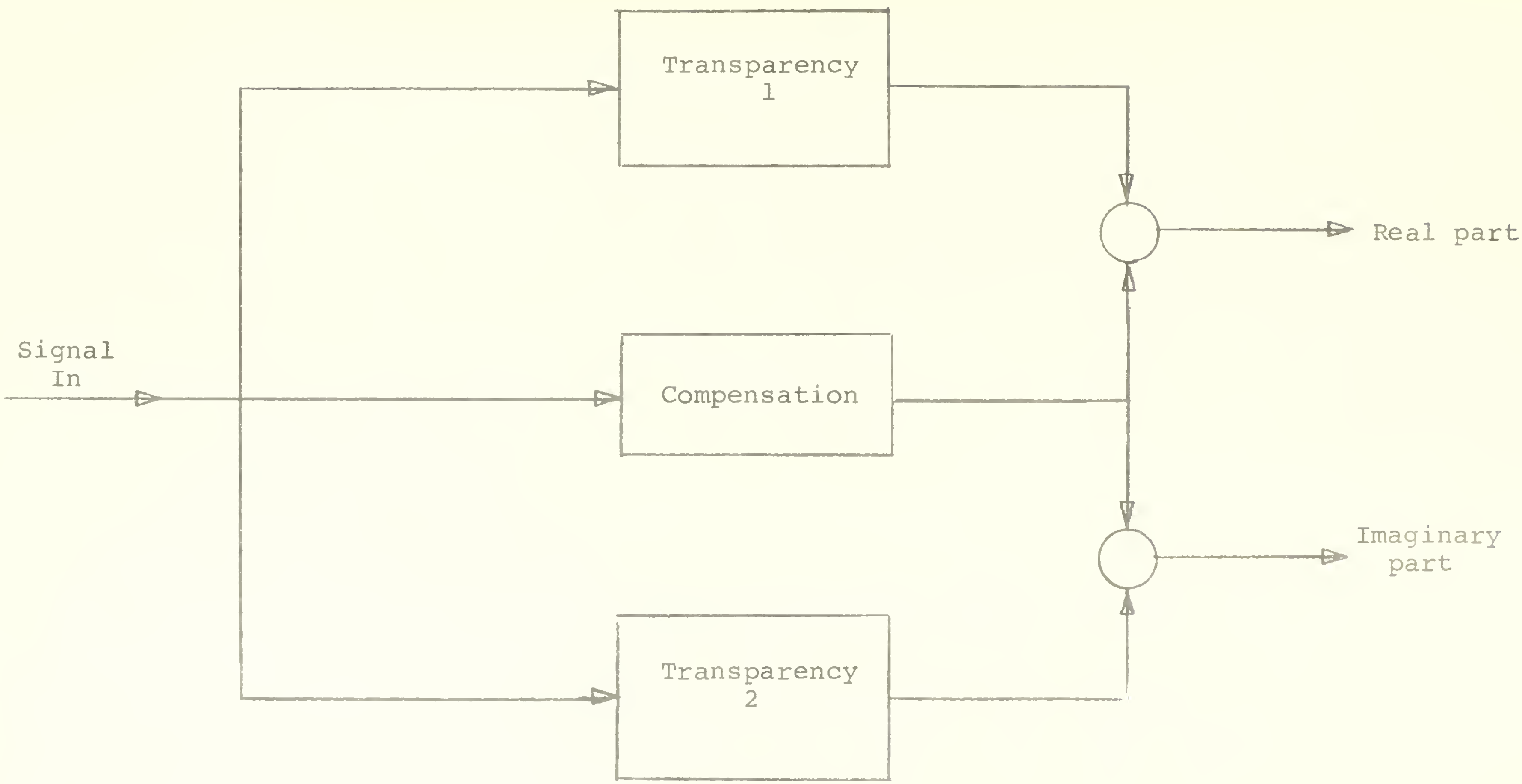

Fig. 3. Two Channel Processor

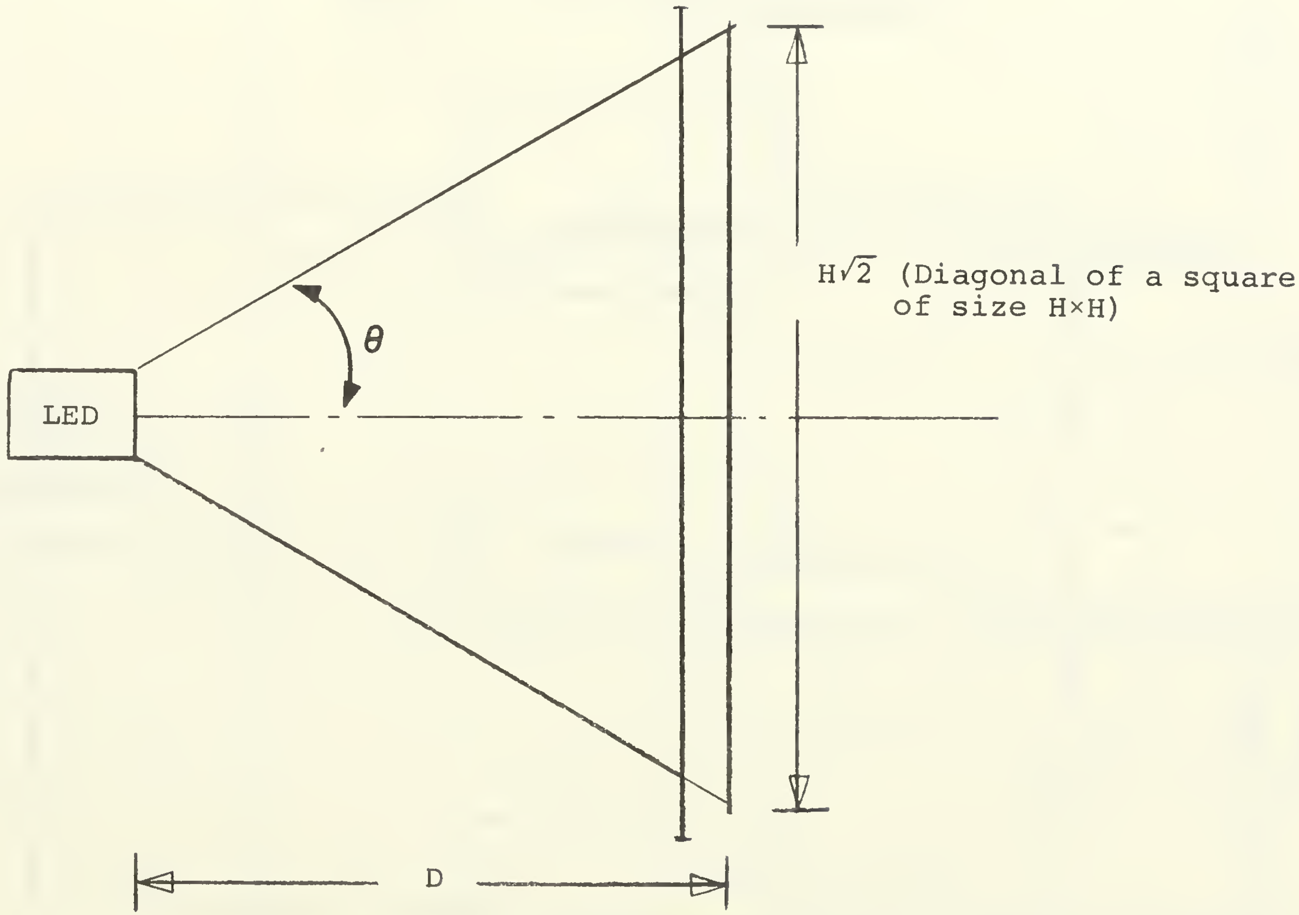

Fig. 4. Geometry of LED Illumination

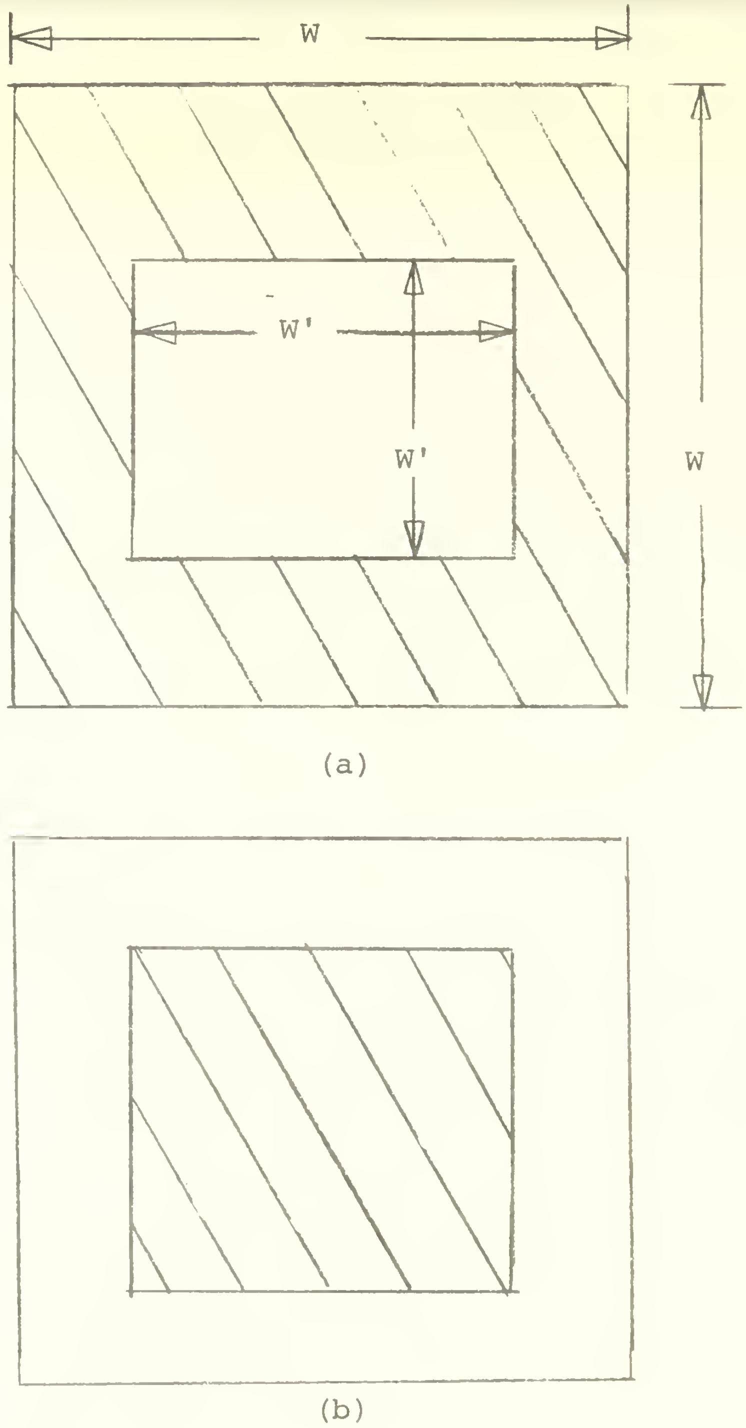

Fig. 5. Two designs of a binary mask

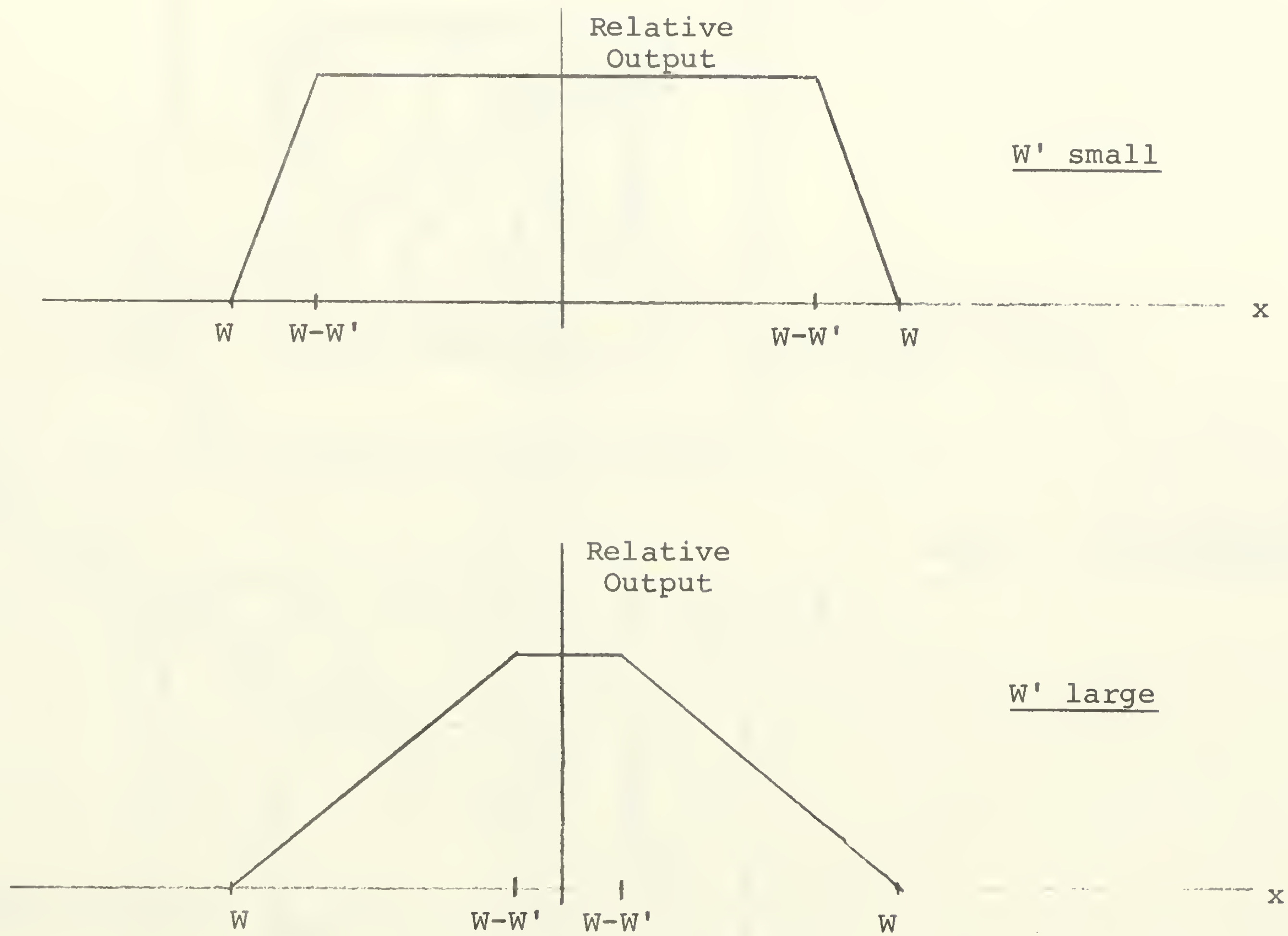

Fig. 6. Relative output vs registration for two different transparencies (assuming square imaging element of width W)

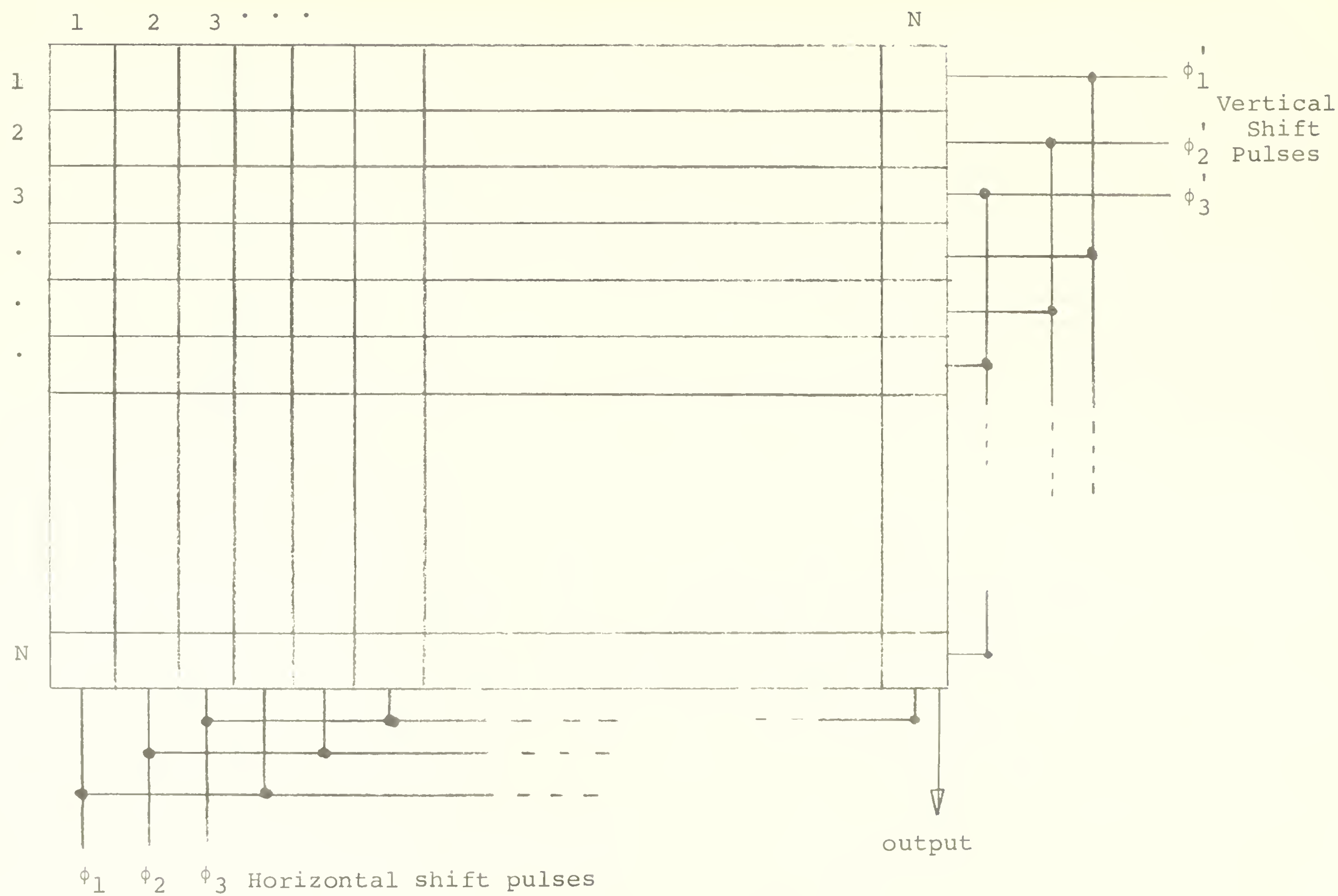

Fig. 7. Sequential shift imaging device

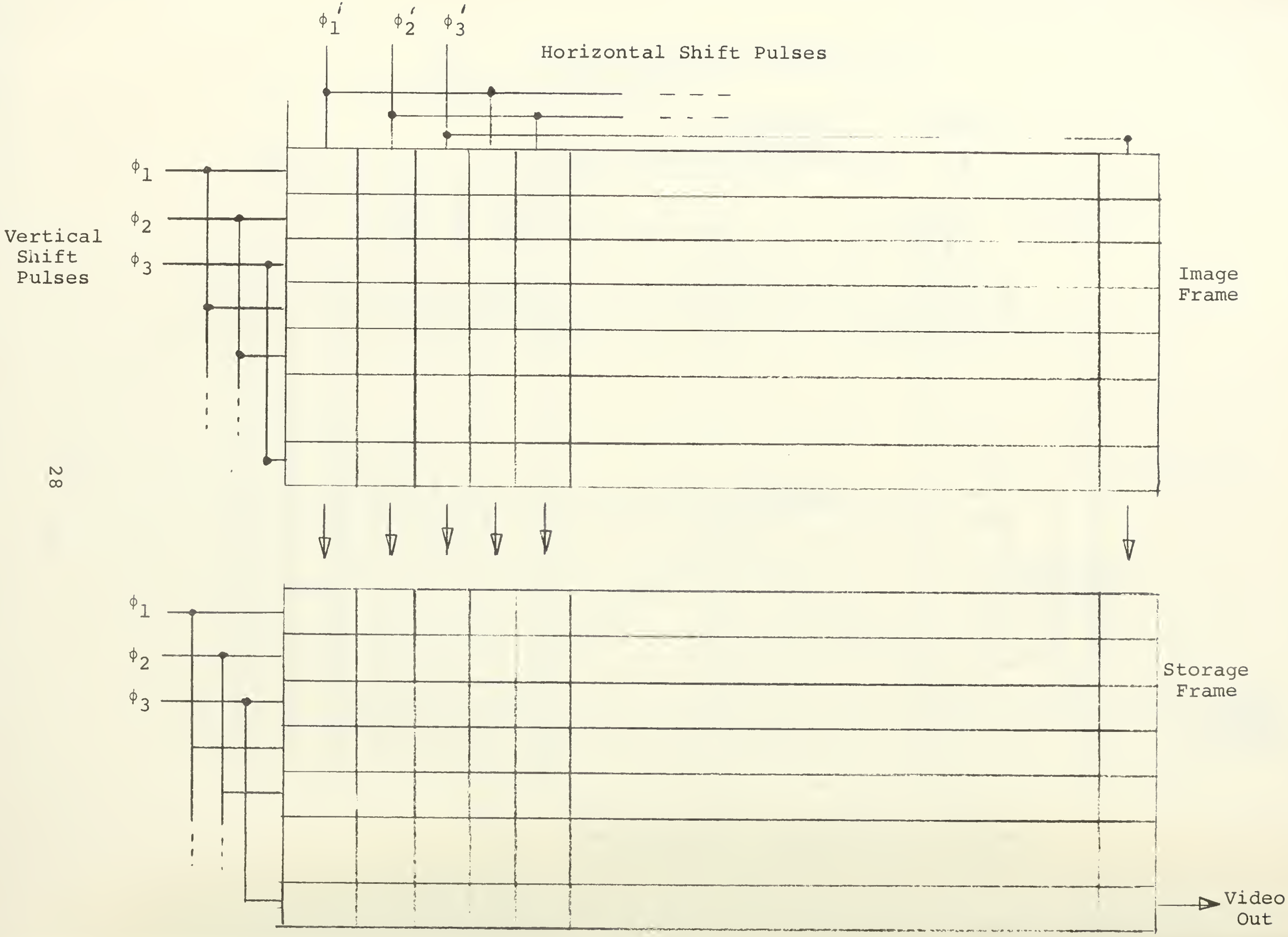

Fig. 8. Frame storage imaging device

INITIAL DISTRIBUTION LIST

		No. Copies
1.	Library, Code 0212 Naval Postgraduate School Monterey, California 93940	2
2.	Dean of Research, Code 023 Naval Postgraduate School Monterey, California 93940	2
3.	Mr. William Dejka, Code 4300 Naval Electronics Laboratory Center 271 Catalina Boulevard San Diego, California 92152	2
4.	Mr. Richard Bocher, Code 2500 Naval Electronics Laboratory Center 271 Catalina Boulevard San Diego, California 92152	3
5.	Dr. Sydney R. Parker, Code 52 Naval Postgraduate School Monterey, California 93940	1
6.	Dr. Glen Myers, Code 52Mv Naval Postgraduate School Monterey, California 93940	1
7.	Dr. John Powers, Code 52Po Naval Postgraduate School Monterey, California 93940	2
8.	Defense Documentation Center Cameron Station Alexandria, Virginia 22314	12