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NONLINEAR REAL-TIME OPTICAL SIGNAL PROCESSING

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ABSTRACT

The results of a one-year research program in nonlinear real-time optical signal processing are described. Fast parallel nonlinear operations on signals with large time-bandwidth and space-bandwidth products are a need for many current and future information processing systems. Several approaches to the problem have been investigated. The first achieves nonlinearities by parallel filtering of a pulse-width modulated continuous level input. The pulse-width modulation is done by halftoning and hard-clipping with real-time optical input transducers. A real-time logarithm function has been achieved by this method, and a novel feedback processor explored to improve the necessary hard-clipping operation. Many results predicting degradations of non-ideal real-time devices and precompensation for these effects have been obtained. Another approach is to use the inherent nonlinear characteristics of real-time devices to directly achieve selected nonlinear functions without halftone preprocessing. A parallel optical analog-to-digital converter based on this principle is described. A last approach is to exploit the variable grating mode of liquid crystal light valves for the conversion of local input levels to different spatial frequencies. A nonlinear function is achieved by selective attenuation and recombination of these frequencies. Some comparisons and limitations of these systems are given. The project has been a joint effort between the University of Southern California Image Processing Institute (USCIPI) and the Hughes Research Laboratories (HRL), Malibu, California. The USC group has developed new systems and techniques for nonlinear optical processing and the HRL group has performed work on various real-time devices.

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1. RESEARCH PROGRESS

1.1 Introduction

This report summarizes the results of a one-year research effort in performing nonlinear operations in optical signal processing and achieving operation in real-time using various input transducers. Sections 1.1 and 1.2 are respectively, an introduction and project overview, and detailed descriptions of various specific results are contained in later sections.

1.1.1 Motivation

In many present and future Air Force systems, there is a great need for very general types of fast, parallel multi-dimensional operations on signals with large time-bandwidth and space-bandwidth products. The time-bandwidth and space-bandwidth product of a signal is a measure of its complexity or degrees-of-freedom, and in many applications, traditional analog or digital electronic hardware is overburdened or simply inadequate [1]. Some particularly difficult examples include terminal guidance, nonlinear tracking and signal filtering, imaging radar systems, image processing [2], image target and pattern recognition, and automated assembly [3,4]. In the area of image processing, the large dimensionality of the data and complicated nature of the operations now tax even the most powerful digital computers. A particular example is the maximum *a posteriori* (MAP) probability estimator, which is among the most effective in image restoration from degraded recordings [4,5]. This procedure is a

nonlinear multi-dimensional estimation technique. Other applications of nonlinear processing are in the solution of general systems of multi-dimensional equations [6]. These equations arise in the solution of nonlinear filtering and guidance problems, and currently are very time-consuming to solve digitally, even with a very limited number of data points. An important point is that the electronic systems to perform these operations are essentially serial in nature, so that only one operation can be performed at a time. Even though 10^6 digital instructions per second are currently possible, the only significant way to improve this is by the costly use of parallel hardware.

In recent years, the common mathematical structure of electrical signal analysis and optics has led to the development of optical information processing [7] and to the interaction of optical and electronic signal processing [1]. Both coherent and incoherent optical systems are well suited to high space-bandwidth work because they are inherently multi-dimensional and parallel in nature.

A fundamental difficulty with optical processing has been the limited range of operational "software" available [8]. Thus, general nonlinear operations such as logarithms, power law, and limiters have been very hard to implement. The usual types of coherent and incoherent optical processors are essentially limited to the linear operations of correlation, convolution, and filtering [7]. Many new techniques of signal processing and pattern recognition require nonlinear functions as part of their operation, and these functions

have been achieved digitally, although in serial form [2,4]. Certain particular optical nonlinearities have been achieved in the past using special techniques, but these methods are clumsy, hard to repeat and control, and often are limited in dynamic range.

A second major difficulty of optical information processing is the problem of input and output [9]. Recent developments have simplified the output problem: television and solid-state devices are available to efficiently make use of the two-dimensional processed output. In many situations, the human eye or observer is the end user of the information, so that optical systems with their inherent two-dimensional nature are ideally suited to process pictorial information intended eventually for the human observer. The major difficulty lies with real-time input to optical processors. Flexible real-time optical input modulators which can convert electronic or image information into a form for input to a processing system are badly needed, and significant research over the last several years has made progress on certain aspects of this problem. Thus, combined work on these two major limitations to optical information processing is the subject of this research.

1.1.2 State-of-the-Art: Nonlinear Processing

Recently, several techniques for general nonlinear optical information processing have been explored by various groups, with very promising results [10-27,34]. These methods are: a) halftoning; b) direct nonlinearities; and c) variable phase gratings.

Halftone Nonlinear Processing

The halftone method is the best developed of the three techniques. Although the use of halftone methods for performing nonlinear optical processing is quite new, there has already been a substantial amount of work in the area by various groups which have laid the groundwork for future development [10-27]. A wide variety of nonlinear, nonmonotonic functions have been experimentally implemented. These functions include logarithms [10,11,22], exponentiation [22], level slicing [16-19,22], multiple isophote generation [12-15,25], quantization [23], pseudocolor [26], and A-D conversion [12-15,34]. These experiments indicate the broad generality and flexibility of this nonlinear processing method.

The halftone method of nonlinear processing involves the conversion of an input signal with continuous levels to a pulse-width modulated binary input for use with an optical filtering system. One method of performing the pulse-width modulation is to use halftone dot screens combined with a high contrast binary photographic material or input device. This technique has been used for some time to control density transfer characteristics in incoherent systems, especially in photoreproduction and graphic arts. Halftone screens consist of a periodic array of identical continuous amplitude transmittance profiles, each varying continuously from opaque ($\underline{t}$=0) to transparent ($\underline{t}$=1). Preprocessing for pulse-width modulation occurs by imaging or contacting the continuous input data together with a halftone screen onto a high contrast medium. The product of the two transmittances is

clipped in the process, giving an array of binary dots whose size is a function of clip level, input transmittance, and halftone transmittance profile. Accurate control is possible because the process is binary, and the wide dynamic range of the input is mapped into dot size.

When placed in the usual coherent optical filtering system, multiple diffraction orders appear in the Fourier transform plane because of the sampled input. The procedure for producing general nonmonotonic nonlinearities involves the use of diffraction orders higher than the on-axis zero order component, combined with specially made halftone screens. The usual two lens coherent processor is used [7] and the filtered diffraction orders in the Fourier plane are inverse transformed to yield the continuous output data.

Omitting wavelength and geometrical factors for clarity, the general expression for the intensity output $I_{out}(0,0)$ obtained by passing only the lowest (0,0) diffraction term in the Fourier plane is

$$I_{out}(0,0) = \left(1 - \frac{b^2}{a^2}\right)^2 \qquad (1)$$

where the input is an infinite binary rectangular array of opaque squares of side b and period a. The intensity output from passing only the next highest (1,0) diffraction order is

$$I_{out}(1,0) = \frac{b^2}{\pi^2 a^2} \sin^2\left(\frac{\pi b}{a}\right) \qquad (2)$$

and the sinusoidal term indicates that nonmonotonic behavior can be expected. In both equations (1) and (2), b is restricted to the range

$0 \leq b \leq a$.

Because of the halftone preprocessing, the value of b in (1) and (2) is a function of the input amplitude to the system, or equivalently, a function of the transmittance of an input. Also the expressions (1) and (2) are considerably more complicated when input spatial variations are considered because the binary dots vary in size due to modulation by the low frequency image information. This is true even though the halftone process assumes sampling of the input at a rate sufficient to avoid aliasing. Nevertheless, these results describe the local nonlinear effects adequately if the desampling filters are chosen to pass the low spatial frequency information of the input.

Recently, a great deal of attention has been given to various aspects of halftone nonlinear processing methods. The important aspects include halftone screen synthesis algorithms [18,21-24], halftone screen fabrication techniques [12-15], and halftone recording and processing techniques [12-15]. Halftone screen synthesis algorithms have been extensively studied at USC [18,21-24]. The most important result of that work has been the development of a synthesis algorithm that generates the halftone screen profiles for the periodic cells of ordinary monotonic screens [18], or cell profiles which are nonmonotonic [20,21,23]. In order to implement highly nonmonotonic nonlinearities using a monotonic dot profile in the halftone screen it is necessary to select high diffraction orders in the spatial filtering process. However, the use of nonmonotonic cell profiles

creates the possibility of achieving arbitrary nonmonotonic functions using only the first diffraction order.

Ideally the recording material used in halftone processing should have a perfect hard-clipping characteristic and large saturation density. Problems with the use of non-ideal recording materials have been investigated in several studies [20,21,24]. Although the results were based on approximations, they showed that nonlinear functions with sharp jumps (such as thresholding or level-slicing) are the most sensitive to problems of low gamma and saturation density. The sharp jumps tend to increase their slope and the sharp kinks are rounded. For the transfer functions which are smoother, the effects of non-ideal media are less severe. More accurate methods of predicting non-ideal effects for real-time devices have been under study in this project and will be summarized in Section 1.4. For certain types of nonlinearities, it is possible to precompensate for materials that have a relatively low gamma by adjusting the halftone screens. The technique of precompensation is quite effective for smooth nonlinearities [24], and some improved methods currently under investigation are also described in Section 1.4.

Examples of Halftone Nonlinear Processing

Because the halftoning method is the most developed to date, many different nonlinear functions have been synthesized by this method, although nearly all experiments to date have used hard-clipping photographic film in the preprocessing step. Only limited attempts have been made with a real-time device [21].

The two-dimensional point logarithm [10,11,22] has been synthesized and it is particularly useful in a signal processing technique called homomorphic filtering [2,28]. Homomorphic filtering is useful for processing multiplied or convolved signals, with specific applications in radiography [10,11], speech processing, and image processing [2]. The most general homomorphic processing system also requires a monotonic exponential function, and this has also been achieved in previous work [22]. Other monotonic functions are valuable for the compensation of recording system nonlinearities such as a photographic response curve. With general monotonic point nonlinearities which can be user-specified, the response curve can be linearized. Although hardly ready for immediate application, the smooth monotonic nonlinear functions are the most advanced for practical use because techniques for compensation with non-ideal halftone recording materials have been studied [20,21,24].

Some of the most interesting nonlinear functions are nonmonotonic and have sharp thresholds in their characteristic curves. Among these is the level slice function [16] which passes only those input levels falling in a narrow range of values. This function is extremely useful for image analysis, and making it variable in real-time would provide an interactive capability. By sweeping the level slice through all possible gray levels and integrating the output, an estimate could be made of the first order histogram. The histogram operation is essential to many high-level picture processing operations, and its repeated use is an extremely tedious task for serial digital computers. Quantizing and intensity notch-filtering

have been achieved and described. Multiple isophote generation with several levels is a more complicated version of level-slicing, and an even more ambitious extension is an optical analog-to-digital (A/D) converter.

The parallel A/D converter would be an extremely valuable accessory for computer signal processing because it would eliminate the necessity of slow tedious serial image scanning of the input [12-15,34], and conceivably provide parallel conversion. Recent progress on this problem is described in Section 1.7. More complicated extensions of thresholding, including pseudocolor [26] have been reported.

Direct Nonlinear Functions

A second method for nonlinear processing is to directly use the inherent nonlinear characteristics of a recording medium or real-time transducer to achieve nonlinear functions without halftone preprocessing. In recent work (not done in real-time) a logarithmic nonlinearity has been achieved [27]. The general technique involves the proper biasing and selection of operating points on a nonlinear curve to directly achieve a point-by-point mapping. Although very little has been achieved to date by this method, it is the most exciting for the future because the processing could take place with incoherent illumination, avoiding the problems of speckle, phase noise and the possible necessity for a laser source. It also appears to require lower spatial frequency bandwidth on the real-time input device. One drawback is that the flexibility of this technique is

considerably more limited than halftoning. Detailed progress on this approach is contained in Section 1.7.

Variable Grating Mode Nonlinearities

A third method of nonlinear optical processing currently under study involves the conversion of different input levels to a local phase-modulated input whose spatial frequency is a function of the brightness. When the variable grating is placed in the front focal plane of a coherent Fourier transform processor, the difference in local spatial frequency should cause different input levels to be effectively placed at different points in the transform plane. By selective filtering and recombination of the transform components, various nonlinearities should be possible. Although this method has not yet been experimentally demonstrated, the liquid crystal component of certain liquid crystal light valve (LCLV) real-time devices has shown the variable grating mode in experiments [33]. Some details of this method are also described in Section 1.8.

1.1.3 State-of-the-Art: Real-Time Optical Devices

For ordinary linear optical processing a great deal of progress has been made recently in developing fast, sensitive and easily usable real-time controllable replacements for photographic film. There are many different materials and systems, each with its own particular characteristics and tradeoffs [9,29-32]. There is extensive literature on these real-time devices and much current research concerned with their development and improvement. One common

characteristic of nearly all current devices is that they are intended to operate essentially linearly with moderate contrast (photographic gamma of 2) over a broad dynamic range (densities of 0 to 2 or 3).

Of all the real-time techniques now under consideration, the liquid crystal light valve (LCLV) appears to be one of the most promising for the future [31,32]. This device has been extensively investigated by Hughes Research Laboratories and other groups. It offers the advantages of 1) relatively good modulation transfer function (to 50 or 60 cycles/mm); 2) fast, reusable, simple operation; 3) room temperature operation; and 4) physical compactness with little controlling electronics. As with nearly all other real-time devices, the LCLV has generally been optimized for linear operation.

The LCLV has been made in both electronically and optically controlled versions. The optical version serves as a real-time incoherent-to-coherent converter. Incoherent light impinges on a photoconductor, which in turn changes the electric field across a liquid crystal layer. The change in electric field alters the birefringence of the liquid crystal, which is placed between crossed polarizers. This sequence serves to modulate a coherent readout beam. Replacing the photoconductor with a layer of electrically addressed charge-coupled devices (CCD's) makes the LCLV electrically sensitive. The optical version is available on a production basis.

The desire to eliminate the photographic preprocessing has led to the possibility of using the LCLV for the initial step in halftone nonlinear processing [21-24]. It should be emphasized again that most

real-time systems have been optimized for the largest possible linear range, in contrast to the needs of halftone nonlinear processing. Some initial experimentation has been done by USC in cooperation with the Hughes Research Laboratories indicating the feasibility of using the LCLV in halftone nonlinear processing [21]. A real-time optical level slice has been attempted, and the results show an indication of the desired effect, even though the liquid crystal light valve used was not intended for high contrast hard-clipping. In recent work described in Sections 1.3 and 1.4, a logarithmic function has been achieved in a real-time system. Many different techniques for utilizing and characterizing LCLV's are currently under study and are described in these sections.

Another type of real-time device with promise is the Pockels Readout Optical Memory (PROM) developed by and commercially available from Itek Corporation (Lexington, Massachusetts) [30]. This device is operated by optically addressing a photoconductive, electrooptic single crystal ($Bi_{12}SiO_{20}$) placed between crossed polarizers. The control (input) wavelength is presently in the blue where the photoconductive quantum efficiency is near unity. Readout is accomplished in the red (the He-Ne wavelength is quite suitable) where the crystal is relatively insensitive. Electrically controlled versions are operated by scanning a modulated optical or electron control beam across the crystal. The PROM is characterized by an inherent long-term memory (hours), a selective erasure capability, high resolution, and numerous intrinsic image enhancement features (contour generation, contrast enhancement, contrast reversal, image

addition, etc.) which make it attractive for linear real-time processing applications. The possible use of PROM-type devices for direct nonlinear processing is described in Section 1.7.

1.2 Project Overview

This program has been a joint cooperative effort between the University of Southern California (USC) group and the Hughes Research Laboratories (HRL) in Malibu, California. Each group has participated together in the project since its beginning in April 1977 and a separate progress report is being submitted by HRL as a companion to this report.

Both USC and HRL have worked closely together in their particular areas of expertise towards the goal of extending optical processing to nonlinear functions in real-time. Because of the recent emergence of the two technologies of nonlinear processing and real-time input transducers, there is no single method or combination of methods that is clearly superior, and several alternatives have been explored during the first year's work. It was initially decided to begin work on two levels - long term and short term. The short term aspects are those that could work with existing LCLV devices or with devices having very elementary modifications in order to demonstrate the feasibility of the concept within the first year. The longer term aspects are those that involve newer methods of achieving optical nonlinearities and extensive device development.

The major expertise of the USC group lies in the development of techniques for nonlinear processing. The three major techniques of halftone processing, direct nonlinearities and variable phase gratings for nonlinear functions have all been considered in the study. A major goal has been to define fundamental limitations of each

technique by comparing accuracy, noise, space-bandwidth product, resolution and other parameters. These factors have been studied in terms of the particular processing technique chosen and in terms of current real-time parameters. This work has used computer modeling and simulation, and specific characteristic curves of existing real-time devices developed by Hughes are being analyzed. Many basic questions involving the characteristics of a non-ideal real-time device and its effects on the overall nonlinear transfer function have been resolved. These results show that jump nonlinearities such as level-slicing are degraded much more seriously than smooth nonlinearities such as logarithms.

Another USC effort which has continued throughout the first year is theoretical work on new methods of halftone nonlinearities, including binary screens, for example, and on better fabrication techniques for ordinary gray-level screens. Another effort in parallel with this has been the development of new types of nonlinear functions and innovative new techniques for achieving nonlinearities, including direct nonlinearities and variable phase grating techniques. An investigation into background material on real-time devices and liquid crystals has led to several ideas for new techniques that are described in subsequent sections. Because of the promise of these new ideas, this theoretical work will continue through the second year of the program.

The role of the Hughes Research Laboratory (HRL) in this program has been to extend nonlinear processing techniques to real-time

operation by developments and modifications of liquid crystal light valve (LCLV) technology. The HRL group is one of the leaders in this technology and has developed an advanced, commercially available transducer for linear processing. Some of the approaches used include: a) modifying existing LCLV's to provide a sharp threshold (higher gamma) and sharper toe and shoulder of the characteristic curve for use with halftone nonlinear processing; b) theoretically and experimentally studying LCLV's with variable grating mode (VGM) characteristics; and c) accurately measuring the transfer characteristics of existing devices to achieve certain halftone nonlinearities by precompensation and by direct utilization of the nonlinear characteristics.

Real-time device development has proceeded initially more slowly than the nonlinear technique part of this work due to its more experimental and developmental nature. In addition to modifying existing types of devices for threshold behavior, HRL has simultaneously begun to develop new devices with the required characteristics. After one year, some improvement in device parameters has been achieved, but to really optimize and develop the liquid crystal technology for the most difficult applications such as analog-to-digital conversion will undoubtedly need perhaps one to two years past the first year's work.

Because there are a great many tradeoffs and variable parameters in both nonlinear processing and real-time device technologies, the close contact of the USC and HRL groups has encouraged the optimum

utilization of these tradeoffs. New techniques of nonlinear processing such as the variable grating technique have been suggested by USC studies of liquid crystal characteristics. This is only an example of certain real-time device behavior which has been noted earlier, and then ignored because it did not suit the initial application of wide dynamic range, linear processing.

A combined system to demonstrate real-time logarithmic processing with halftone screens has been assembled and has been reasonably successful. As work progresses, more combined experimental work between USC and HRL can be expected. The following sections describe details of results in the several areas of nonlinear processing research.

1.3 Halftone Processing: Existing Devices and Simple Modifications

It was initially decided to work with an existing HRL linear LCLV to achieve a monotonic logarithm function. The logarithm is useful for homomorphic signal processing, a technique used to filter signals corrupted by multiplicative noise [28]. The log of two multiplied signals gives additive signals, and these can usually be separated by subsequent linear processing.

The linear LCLV used is a 45° twisted nematic hybrid field effect device currently used as an incoherent-to-coherent converter. Although the device has a smooth curve approximating that of photographic film with an effective gamma of 2 to 3, simulations (described in Section 1.4) showed that a smooth nonlinear function like a log could be achieved by the halftone method using a precompensated screen. Detailed measurements of device characteristics on several LCLV samples were made. The measurements initially found a hysteresis effect on the input-output characteristic that was previously unknown, and also some possible temperature dependence. The hysteresis effect was not seen in all samples of LCLV's tested however, and its presence may indicate a defect. The HRL report on this joint project contains details of the measurement procedure.

The particular LCLV cell with minimum hysteresis was chosen for experimentation, and its characteristic input-output curve is shown in Fig. 1. With this information, several specially precompensated halftone screens were theoretically obtained using the procedure

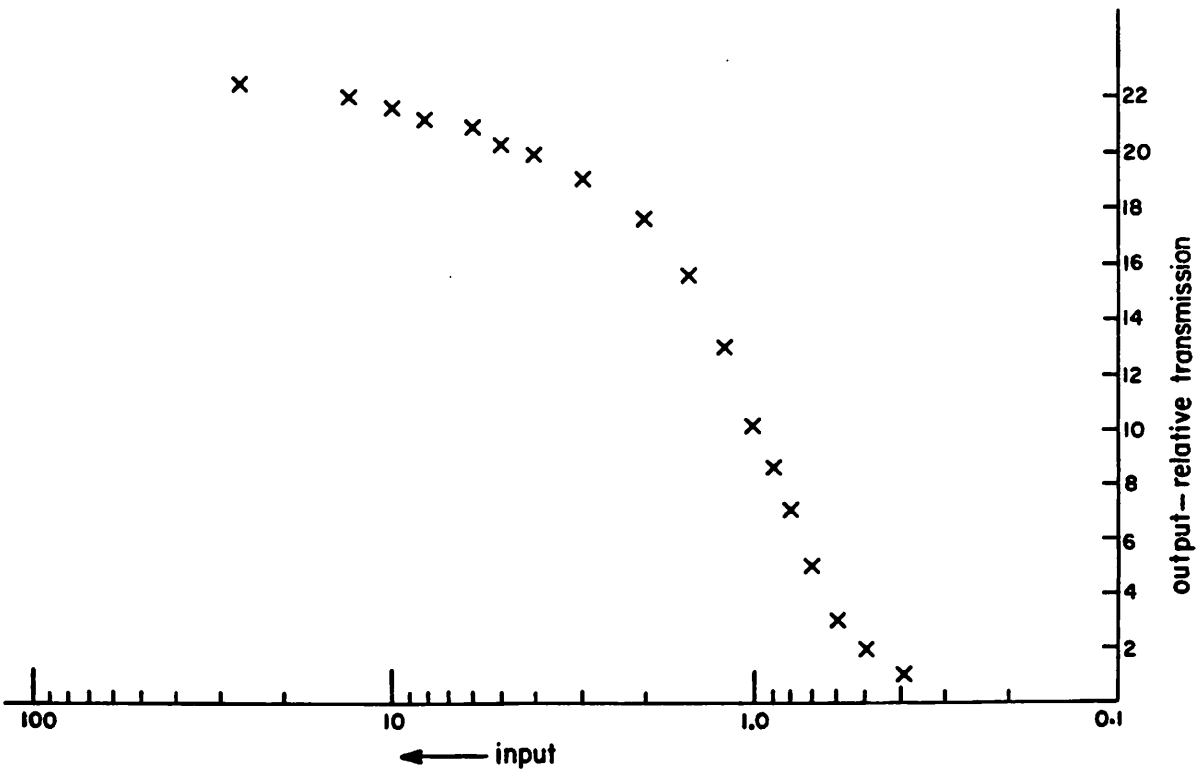

Figure 1. Transfer characteristics of the LCLV without the halftone screen.

outlined in Section 1.4. These screens were fabricated using a Dicomed computer-controlled plotter as described in Section 1.5 and used in the real-time optical processing setup shown in Fig. 2. An input test pattern illuminated incoherently was imaged through the halftone screen onto the control surface of the LCLV. Readout was performed coherently at 632.8 nm with a simple imaging system. A spatial filter on-axis in the Fourier transform plane blocked all but the zero-order information to produce the logarithmically transformed result. The effective transfer function with a precompensated screen is shown in Fig. 3. The input-output curve is considerably improved and now has less than 10% error over two decades. In another experiment, two crossed multiplicatively combined Ronchi rulings were used as the input. The period of these rulings was approximately 3 mm, much higher than the halftone screen period of 0.33 mm. The difference in Fourier spectra between multiplicatively and additively combined gratings [10,11] could easily be seen in this real-time experiment. Although these results are preliminary and can be refined considerably, they do demonstrate the effectiveness of the logarithm operation. The HRL report on this work contains additional experimental details [38]. Present work on extending this technique to exponential and smooth monotonic or nonmonotonic polynomial functions is currently underway. As characteristic curves of improved real-time devices are made available, additional precompensated screens will be specified and fabricated.

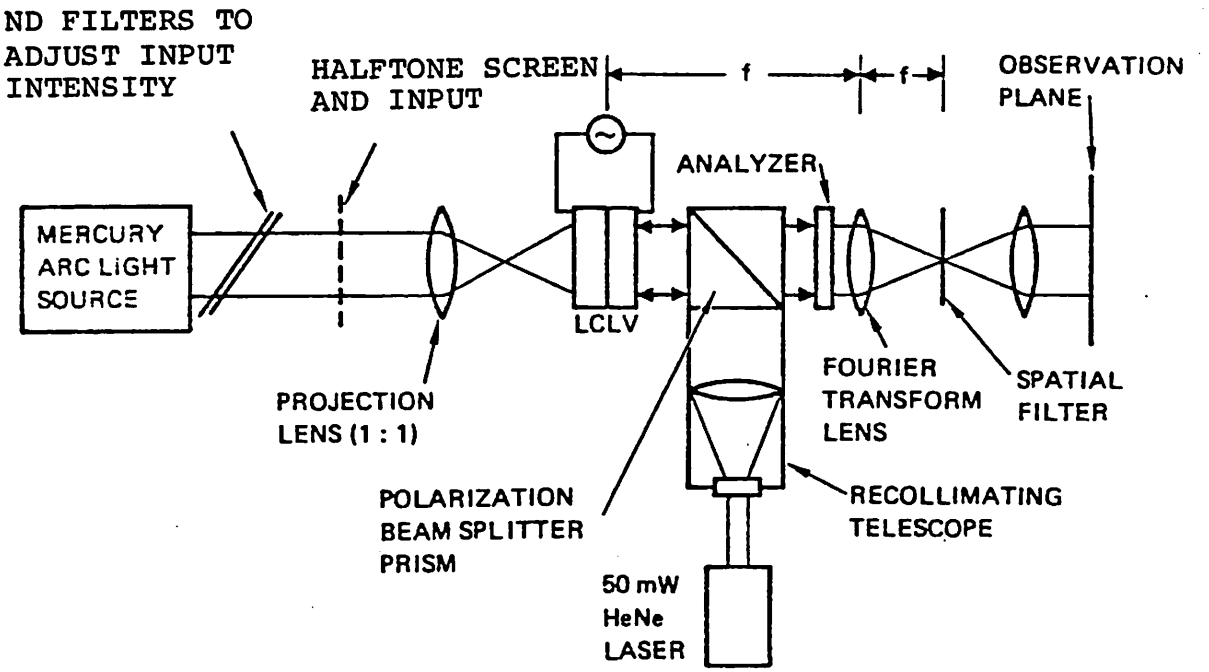

Figure 2. Experimental setup for real-time logarithmic filtering.

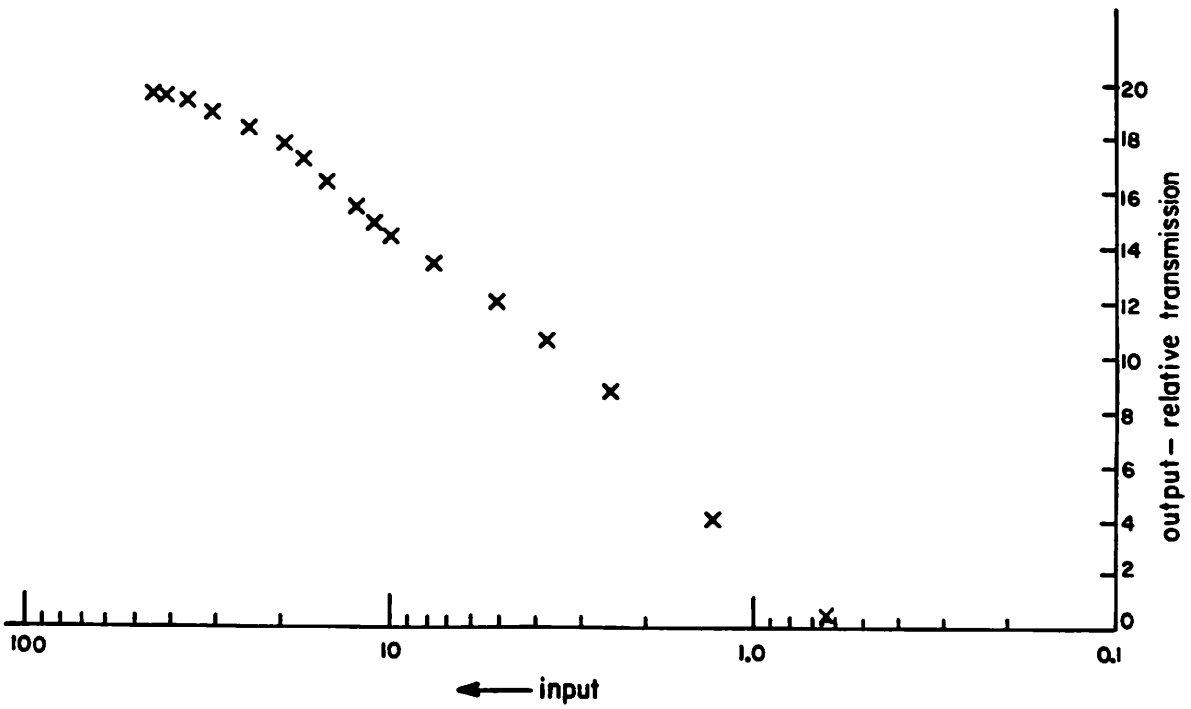

Figure 3. Transfer characteristics of the logarithmic LCLV system with halftone screen.

1.4 Halftone Processing: Non-Ideal Effects and Precompensation

The real-time device in the halftone method plays the role of a printing medium. Ideally the halftone method for nonlinear processing requires a printing medium that has a binary characteristic. Thus, the real-time device should have no output light if the input light intensity is below some threshold and should give its maximum output if the input light intensity is above the threshold. This is shown in Fig. 4.

If such an ideal device were available, the theoretical design of the halftone screen would follow from previous results [8,10-26]. Unfortunately all of the real-time devices that are available do not possess such a binary characteristic. Their characteristic curve looks like the one shown in Fig. 5a. This is the transmittance versus log exposure curve of the standard LCLV for linear processing. With such a nonbinary characteristic for the printing medium an analysis was performed to consider this property for the halftone process. Going through such an analysis the relationship

$$I_0(I_{in},k) = \left|\left[\frac{1}{L}\int_0^L g(\log I_{in}-f(x))e^{\frac{-j2\pi kx}{L}}\,dx\right]\right|^2 \qquad (3)$$

is obtained, where

$I_0(I_{in},k)$ = output intensity in the order k as a function of input intensity I_{in}.

$g(\cdot)$ = transmittance versus exposure characteristic of the printing medium.

$f(x)$ = density profile of the halftone screen over one period of length L.

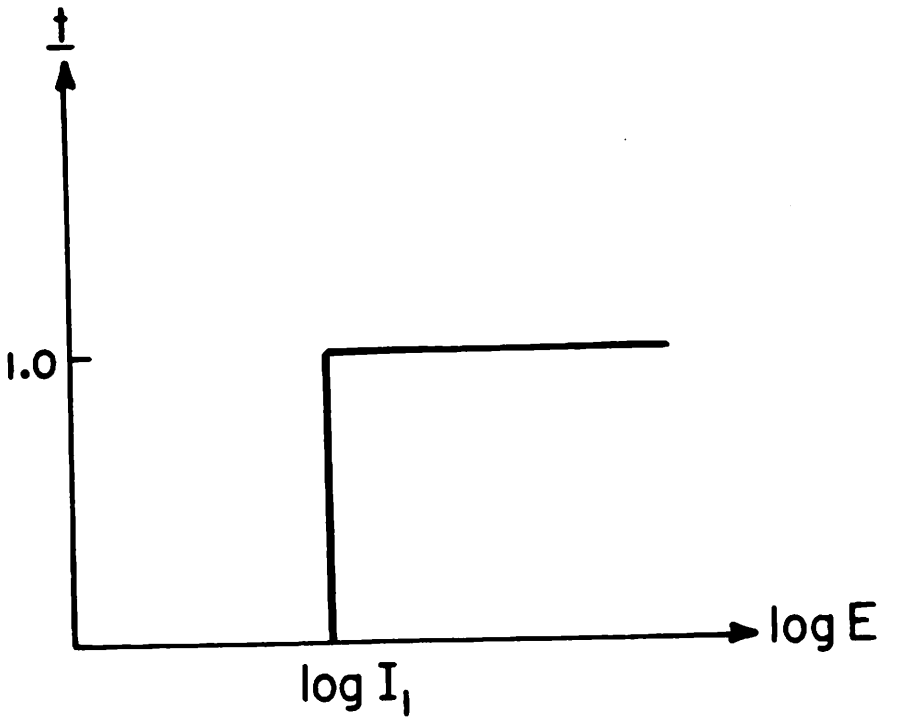

Figure 4. Ideal transmittance vs. log E characteristic.

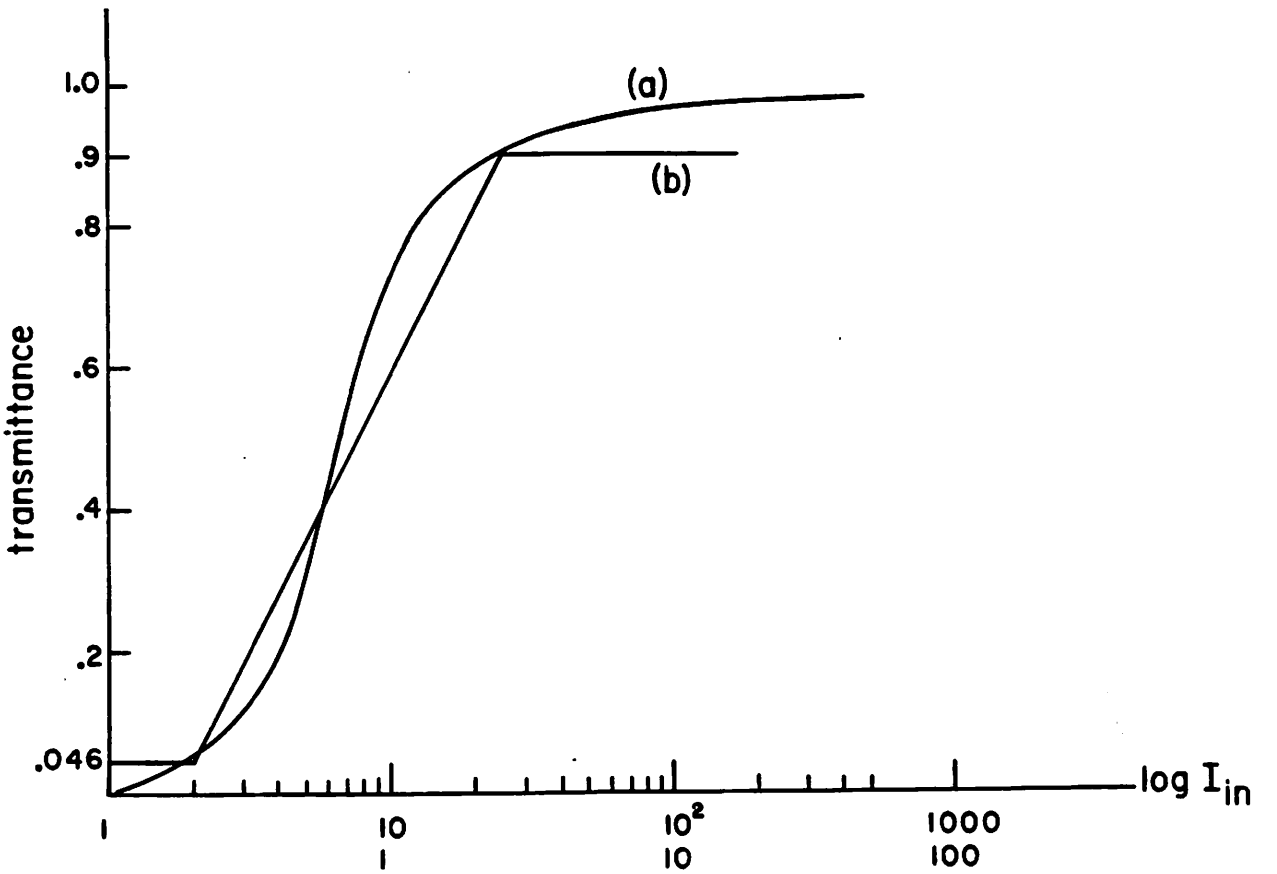

Figure 5. a) Transmittance vs. log I_{in} characteristic of the standard light valve.

b) Piecewise linear approximation to a).

The above formula predicts the output intensity in any diffracted order given the density profile of the halftone screen. The results for logarithmic and exponential transfer functions are shown in Fig. 6 and Fig. 7. These results are obtained assuming the halftone screen has been designed for an ideal printing medium. They show the deviation from the desired nonlinearity due to nonbinary characteristic of the printing medium.

As can be seen, the amount of degradation is unacceptable for any practical purpose. Thus, an effort was made to compensate for them by designing a halftone screen suitable for a nonbinary printing medium. To do so, a piecewise linear approximation to the real characteristic of the printing medium, shown in Fig. 8, was used in Eq. (3). The next step was to find f(x) from that equation for any specified nonlinearity and diffraction order. The problem reduces to a nonlinear integral equation which is, in general, hard to solve. To simplify the problem the zero order only was considered. This restricts the problem to monotonic nonlinearities since nonmonotonic nonlinearities are not possible in the zero order with monotonic halftone cells. Given the desired relationship between the output intensity and the input intensity, namely $I_0(I_{in},0)$, and using the piecewise linear characteristic approximation of Fig. 8 for g(log E) in Eq. (3), the relationship

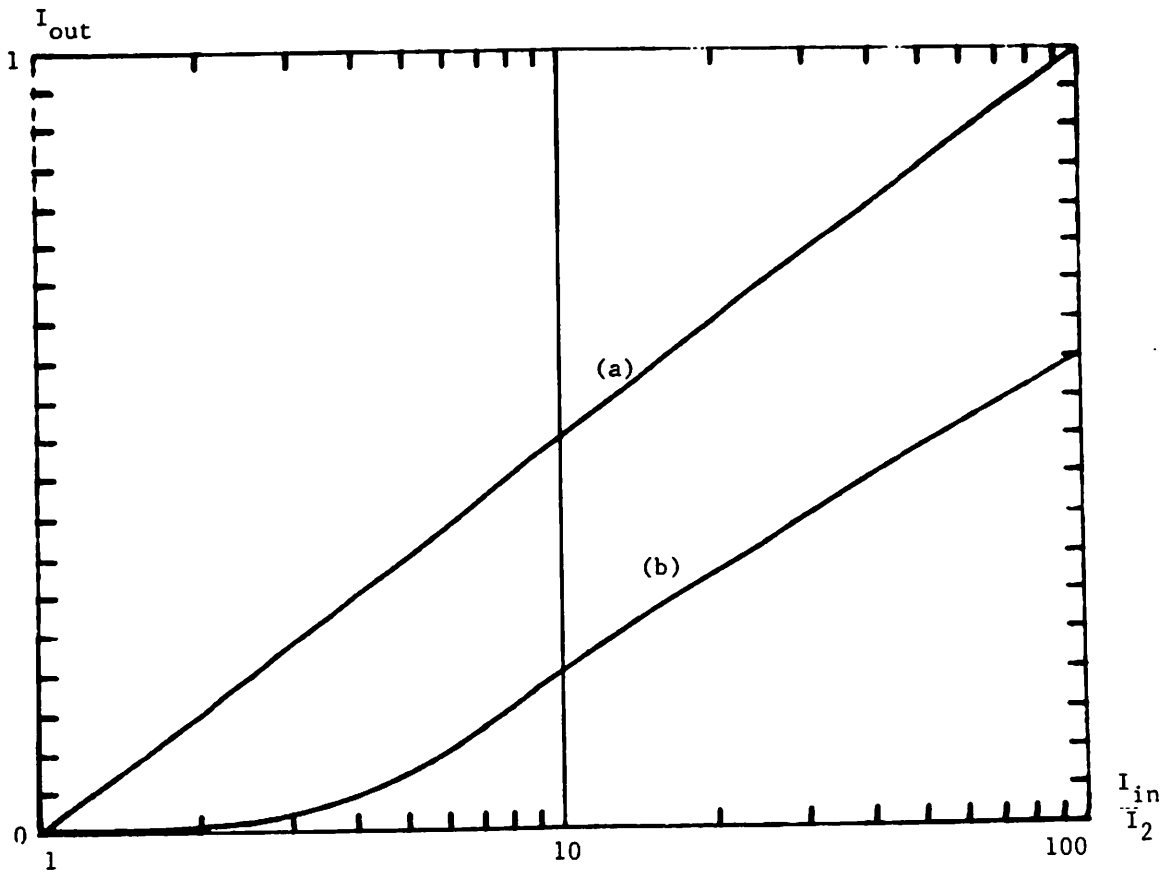

Figure 6. Logarithmic transfer function.

a) Ideal printing medium.
b) Standard light valve as the printing medium.

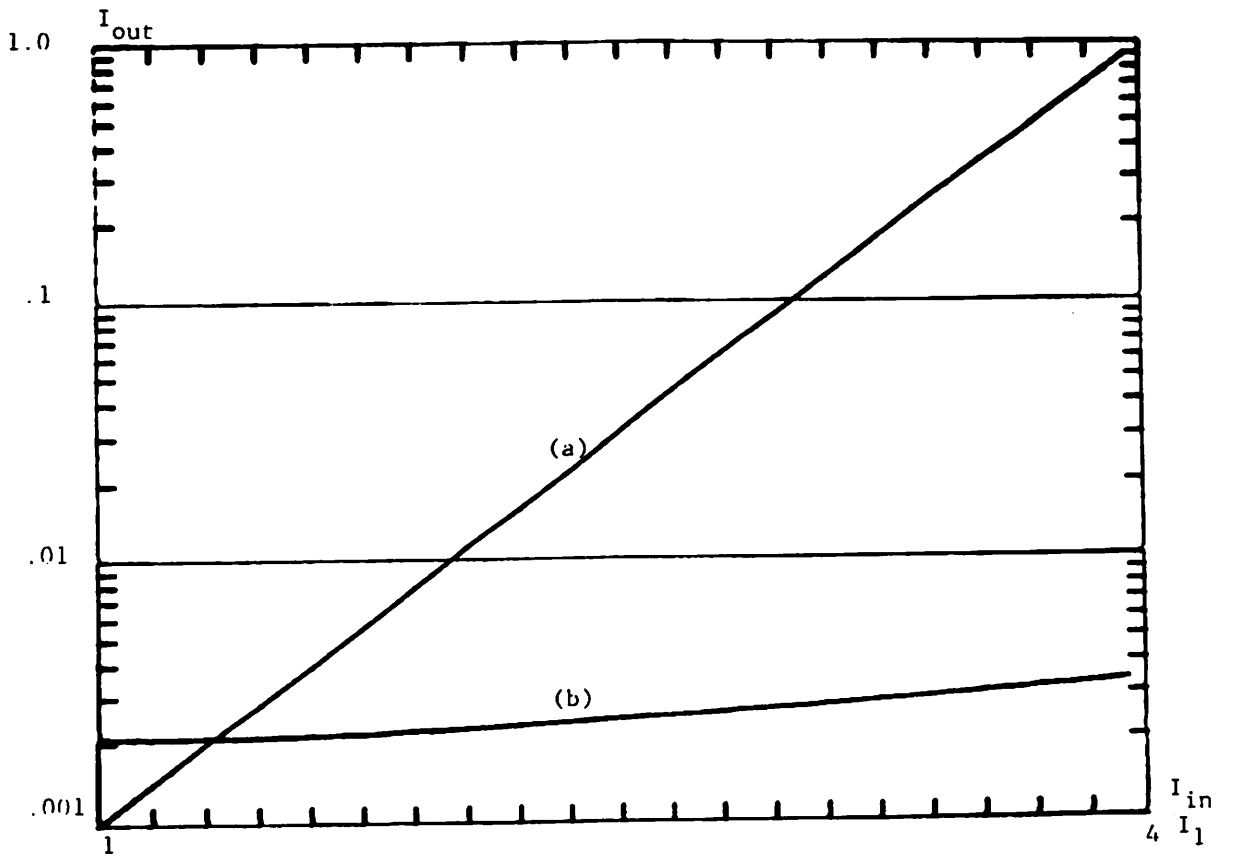

Figure 7. Exponential transfer function.

a) Ideal printing medium.
b) Standard light valve as the printing medium.

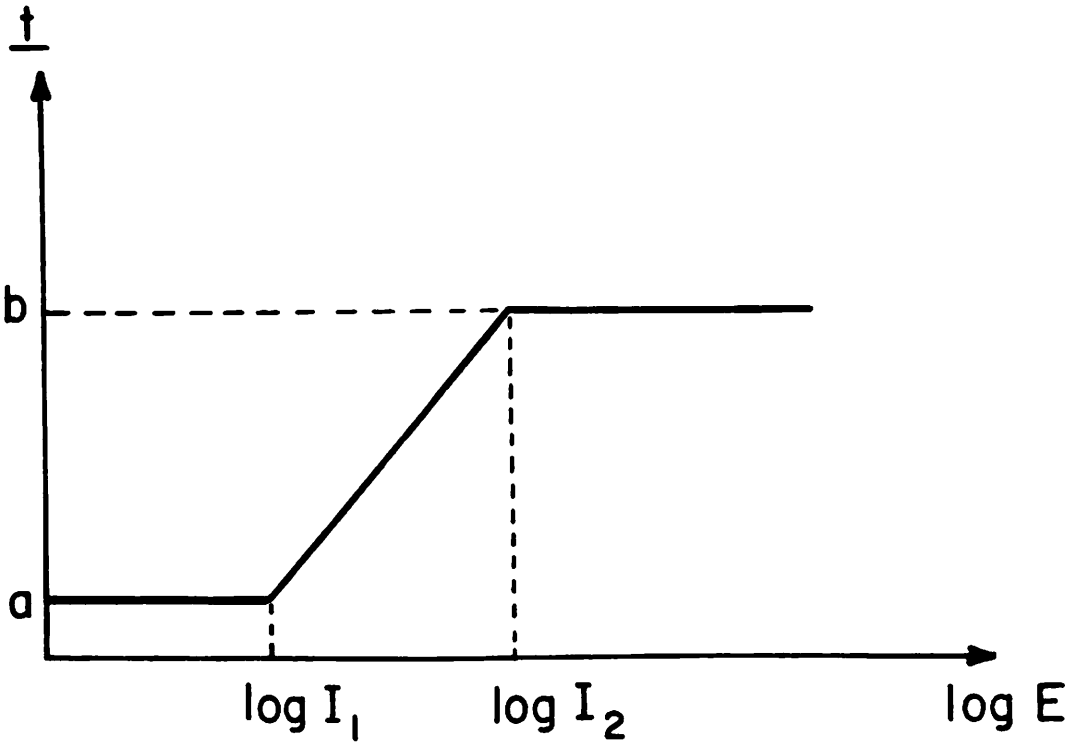

Figure 8. Piecewise linear characteristic printing medium.

$$f^{-1}\left(\log\frac{I_{in}}{I_2}\right) = \frac{L}{b-a}\left[\sqrt{I_0(I_{in},0)} - \left(\log\frac{I_{in}}{I_2}+\log\frac{I_2}{I_1}\right)\frac{d\sqrt{I_0(I_{in},0)}}{d\log(I_{in}/I_2)} - a + \frac{b-a}{L\log(I_2/I_1)}\int_{f^{-1}\left(\log\frac{I_{in}}{I_2}\right)}^{f^{-1}\left(\log\frac{I_{in}}{I_2}\right)+\frac{L}{b-a}\left(\log\frac{I_2}{I_1}\right)\frac{d\sqrt{I_0(I_{in},0)}}{d\log(I_{in}/I_2)}} f(x)\,dx\right] \quad (4)$$

can be derived. Using a recursive method, the form of f(x) was found from Eq. (4). For the initial guess it is appropriate to use the result of the ideal case. This has been done for the logarithmic transfer function and the density profile of the suitable halftone screen has been obtained. Figure 1 shows the transfer characteristics of the LCLV without the halftone screen, and Fig. 2 shows the experimental set up with the screen that was made using the given data. The result of this experiment is shown in Fig. 3. It is seen that a logarithmic transfer function with an accuracy of less than 5% error over one decade and less than 10% error over another decade can be synthesized.

Equation (4) becomes simpler if the range of usable input intensities is smaller than the range over which the characteristic curve of the printing medium is linear. This property is true for the exponential transfer function. In this case, Eq. (4) becomes

$$f^{-1}(\log(I_{in}/I_1)) = \frac{L}{b-a}\log\left(\frac{I_2}{I_1}\right)\frac{d\sqrt{I_0(I_{in},0)}}{d\log(I_{in}/I_1)} \quad . \qquad (5)$$

Using the above formula the screen for the exponential transfer function has been made and the experiment on the LCLV with this screen is now in progress.

1.5 Halftone Screen Fabrication

The Dicomed Image Recorder of the Image Processing Laboratory has been used to make the required halftone screens. It can plot up to 4096 x 4096 discrete points in a 4" x 4" area. There are 256 x 256 different intensity levels for each exposure setting of the machine. To plot any pattern on the film with this machine, the film density for each input intensity level must be known for different exposure settings. To determine the above relationship, a grey level test pattern was plotted by the Dicomed on Kodak SO-115 film for different exposure settings. This resulted in a series of curves that represented the final density on SO-115 film versus the intensity level for different exposures. From those sets of curves one that covered the density range of our halftone screen was selected. To check the calibration, a test pattern was generated by the Dicomed on a separate film under the same exposure setting each time a screen was made. If any deviations were observed, the exposure setting was re-adjusted and the experiment was repeated. The screens that have been made so far have 16 different levels of density for each halftone cell and hence have a fundamental spatial frequency of 3.0 cycles/mm.

1.6 Optical Feedback

The key element in the halftone nonlinear optical processor is a real-time liquid crystal threshold device. In order for the processor to approach theoretical performance, it is required that the threshold device exhibit a binary transfer function, i.e. infinite gamma at a finite input threshold level. The standard liquid crystal light valve operating in a high resolution mode exhibits a gamma on the order of 2-3. This can be increased somewhat by operating the device at a lower bias frequency at the expense of reduced spatial resolution. A typical plot of the liquid crystal transfer function is shown in Fig. 9.

While efforts are currently being made to improve the gamma of the device by altering the chemistry of the liquid crystal layer as well as the structure of the photoconductor, it appears evident that a finite gamma will always remain, although improved from the standard liquid crystal cell. In light of this, efforts were initiated to improve the gamma by taking advantage of the fact that the liquid crystal device exhibits an optical gain characteristic. The method being pursued incorporates positive optical feedback around the liquid crystal cell. The major portion of the readout light is fed back to the input of the cell via a series of beamsplitters, mirrors, and lenses. The actual configuration is shown in Fig. 10. To be consistent with the spectral response of the CdS photoconductor used in the input of the cell, the read illumination must be the same wavelength as the image input illumination. The green line at 514.5

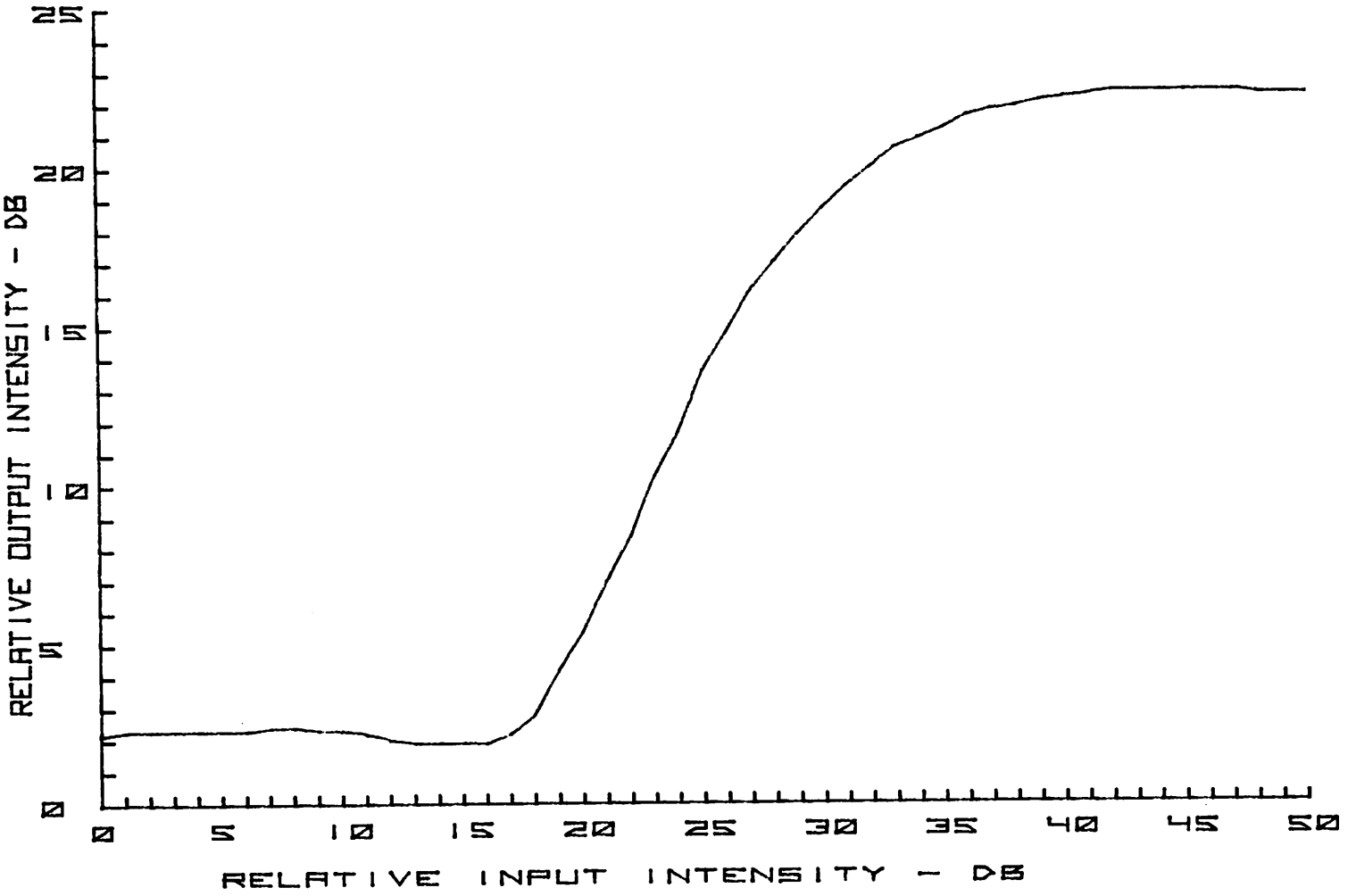

Figure 9. Liquid crystal light valve open loop transfer function.

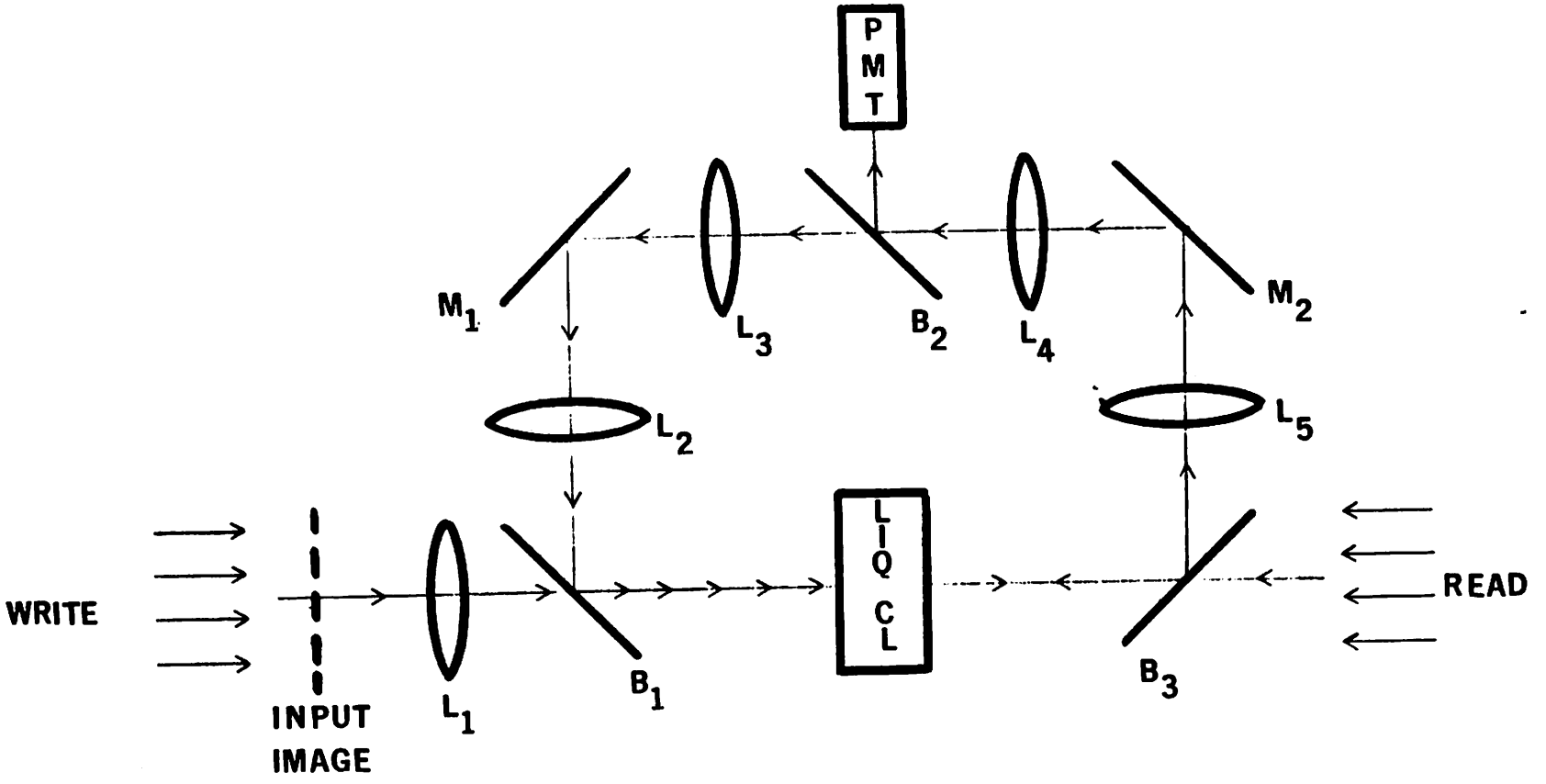

Figure 10. Optical feedback system.

nm derived from an argon ion laser was used for both read and write illumination in the feedback system.

Operation of the system is as follows: with the cell initially off, i.e. no input illumination, the transmission at the readout side of the device is zero. Thus there exists no feedback component and the device remains in the off state. As the input illumination is increased, the energy in the readout beam and therefore the feedback path will change as determined by the device transfer characteristics shown in Fig. 9. Operation will continue in a normal manner until the input illumination is sufficient to place the operating point at the lower knee or threshold point of the transfer curve. At this point the transmission at the readout side of the device increases allowing a portion of the readout illumination to be fed back to the input. Since the optical gain of the device is greater than unity at this point, regenerative action occurs and with no further increase in input intensity the device turns itself on. This in effect simulates an infinite gamma for the device. Regeneration continues until the operating point reaches the level on the transfer curve where the gain again falls below unity. This level is near the upper knee of the transfer curve. Figure 11 shows experimental results obtained from the feedback system. The curve represents data taken by illumination and feedback over an area of approximately 10 sq mm of the device. Although obvious improvements remain to be made near the saturation level of the device, a marked improvement in both gamma and discernable threshold can be seen from the data. Improvements in maintaining the high gamma at the upper end of the curve can only be

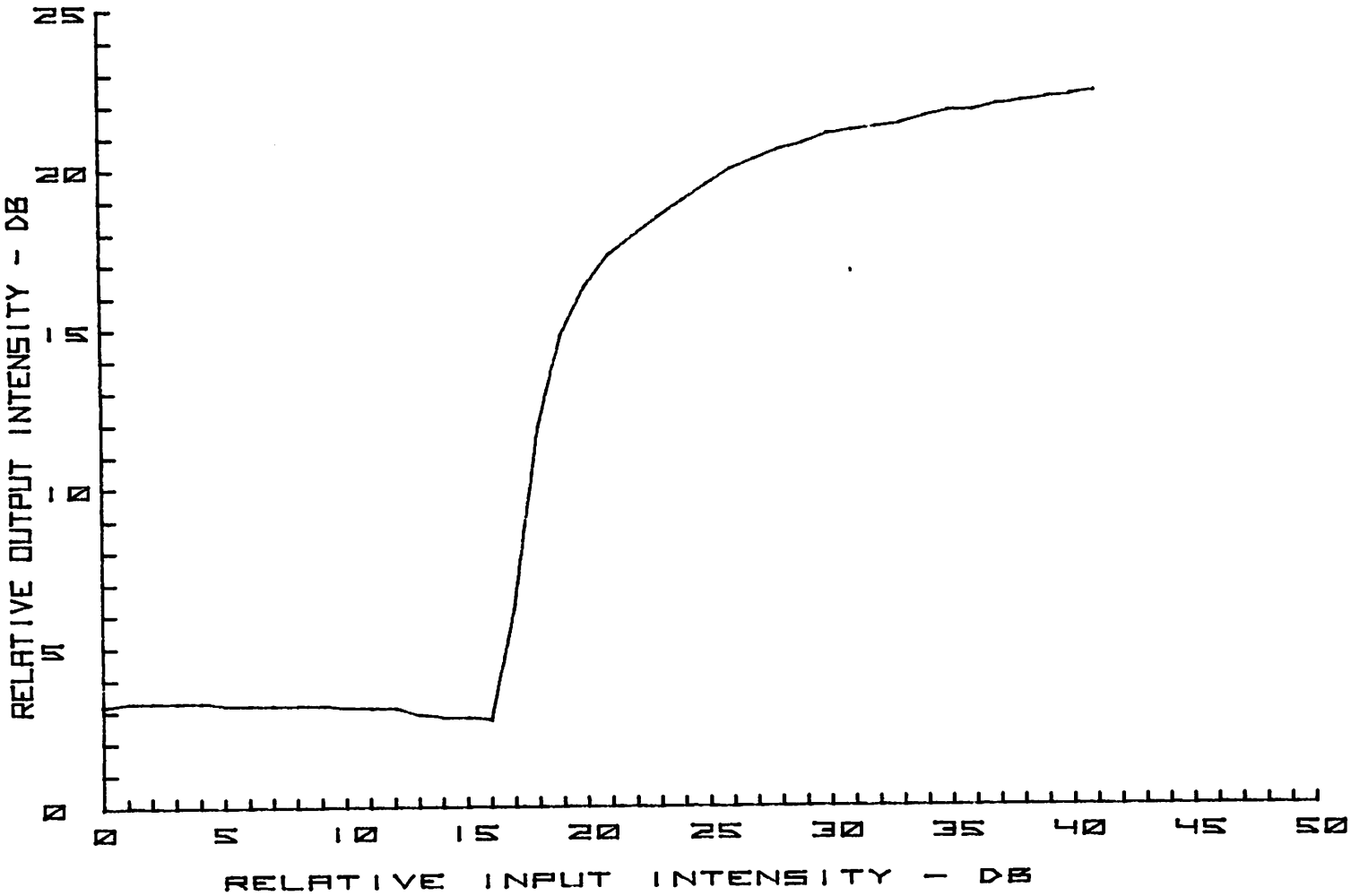

Figure 11. Liquid crystal light valve closed loop transfer function.

realized by increasing the gain of the device in this region such that the overall loop gain exceeds unity. The aforementioned physical changes in the liquid crystal device to improve gamma will satisfy this requirement. Further, the device currently being used in the experimental setup suffers from extreme nonuniformities across the aperture. This precludes presently using the feedback system to process entire images. As more uniform devices with a higher characteristic gamma become available, further experimentation can proceed to investigate the merits of the feedback system in nonlinear optical image processing.

1.7 Direct Nonlinear Functions

Some methods of nonlinear processing which rely on the inherent nonlinear characteristics of real-time devices have been studied. This method has the advantage of eliminating the halftone screen and requires less device resolution than the halftone method. The halftone method achieves nonlinearities by trading gray levels for binary spatial resolution via pulse-width modulation. The sharp edges on the binary dots require device resolution conservatively estimated at five times that needed for continuous tone recordings. The tradeoff is that the flexibility of nonlinear halftoning is lost, although it appears that several important functions could be achieved with the direct approach.

Tai, Cheng and Yu [27] have achieved a logarithm (although not in real-time) by using selected portions of a nonlinear photographic film curve. The nonlinear nature of electro-optical devices such as the LCLV or Pockels Read-Out Memory (PROM) suggests that these transducers may be directly useful for certain nonlinear functions. Both these two devices and many other real-time optical input transducers rely on electro-optically controlled birefringence to produce a selective linear differential phase retardation along two axes of a crystal. When the crystal is placed between crossed polarizers, a sinusoidal variation of intensity transmittance with voltage is produced as shown in Fig. 12. This nonlinear nonmonotonic behavior is the basis for many possible optically controlled nonlinear functions. By placing a photoconductor near the crystal surface, (as in the LCLV) the local

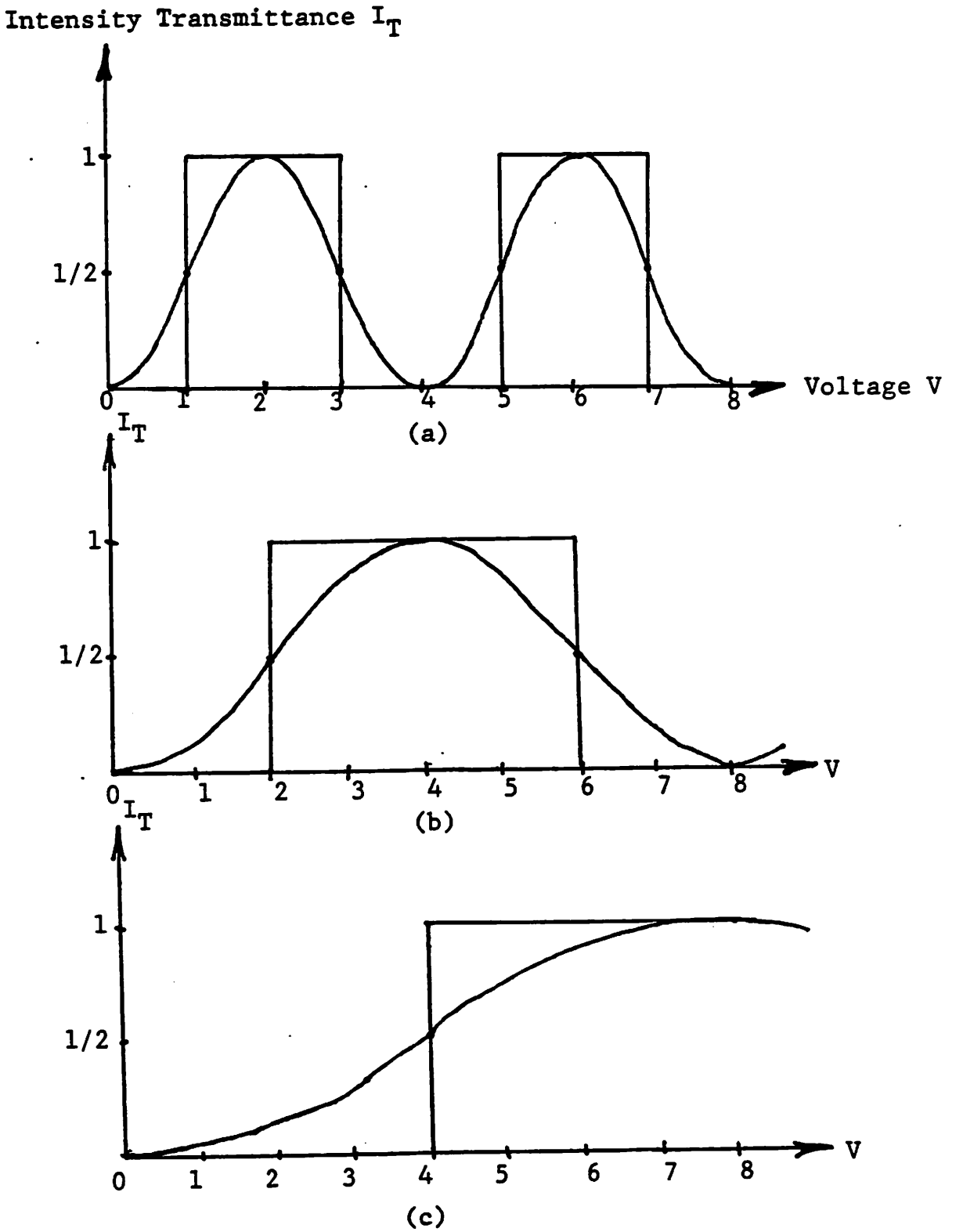

Figure 12. Analog-to-digital converter bit planes for 3 bit Gray code.

voltage is variable in a two-dimensional manner by applying a control image. In the PROM device, the crystal itself is a photoconductor at certain control wavelengths. The particularly interesting fact is that the system can be controlled and operated in strictly incoherent light. No diffraction or Fourier transforming is needed. Also, the spatial frequency resolution requirements are much lower because sharp edges of binary dots as in halftoning do not have to be maintained.

The direct nonmonotonic nature of the device is useful for some very limited approximations to certain polynomial or other smooth nonmonotonic functions. The rise on the first period of the device curves itself (for example the curve from V=0 to V=4 on Fig. 12b) is similar to an H and D curve. The device is kept from overshooting the value for V=4 for strong input light by using a saturating photoconductor. This is the basis for the Hughes LCLV in its production version (wide dynamic range linear operations).

A particularly useful function is the optical parallel A/D converter. Here an array of parallel electronic thresholding devices in the output plane of the system is needed to sense the separate bit planes of a binary output. If thresholds were set at 1/2 in the three device curves of Fig. 12, then a one output would be produced above threshold and a zero output below as shown by the square jump functions plotted. This electronic thresholding is easily done by a parallel array of light detectors and sensors, and is an essential part of the system replacing the optical thresholding as in halftoning. The three curves of Fig. 12 represent the three bits of

an optical A/D converter whose output is in the reflected binary or gray code. Note that any continuous input between 0 and 8 gives a unique three-bit code. The system could operate in parallel with an interlaced array of detectors matched to a periodic attenuating grating as shown in Fig. 13. The grating contains strips with transmittances of 1, 1/2, and 1/4 periodically repeated. If the period of this grating were finer than the smallest spatial detail on the continuous tone input, each of the three interlaced channels will sample approximately the same continuous value.

The A/D system could also operate serially using the characteristic of Fig. 12a. Using the full dynamic range (0 to 8) gives the least significant bit. The input light over the whole input is then attenuated by a factor of 1/2 (to the range 0 to 4) so that the effective response is the same as Fig. 12b. The final (most significant) bit is obtained by using an attenuation of 1/4 so the curve of Fig. 12c is the effective result. Other A/D code conversions such as the usual straight binary code can be achieved by translating these curves left or right along the V axis. This can be done by introducing phase retardation plates with different delays along orthogonal axes into the crossed polarizer system. Similar ideas have been used for electro-optic A/D conversion [35,36], but none have been achieved in an optically controllable device. An important point about this technique is that LCLV's, PROM's and many other optical real-time devices have similar characteristics and could conceivably be used for such a system. These aspects of direct nonlinear processing will be investigated in more detail in forthcoming work.

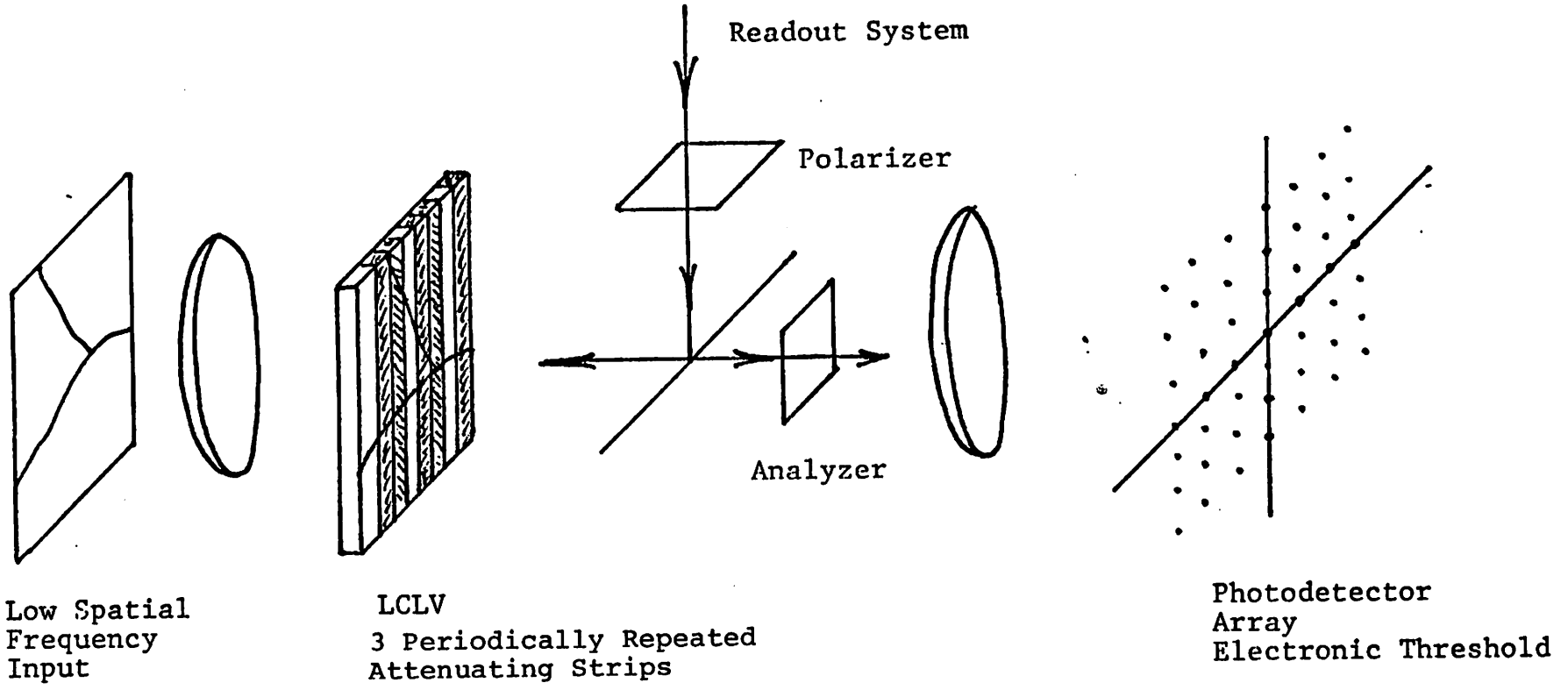

Figure 13. System for parallel analog-to-digital conversion.

1.8 Nonlinear Processing Utilizing the Liquid Crystal Variable Grating Mode

One of the major consequences of this cooperative effort between USC and the Hughes Research Laboratories (HRL) has been the identification of the variable grating mode (VGM) [33,37] effect in liquid crystals as a potentially powerful new tool in optical processing. Although the VGM effect is known to most people doing research in liquid crystal devices, it has received relatively little attention since it is not useful in normal display applications. It has been found that such a device could have very important applications in optical processing, in particular for the direct implementation of arbitrary nonlinear functions in real-time. Using this approach, it should be possible to implement an arbitrary nonlinearity without the use of halftone techniques. The extent to which this can be used depends upon the exact character of the VGM effect which is being studied by HRL.

The idea behind utilizing the VGM effect for nonlinear processing is quite simple and is shown in Fig. 14 and Fig. 15. Under certain conditions a linear, phase grating structure can be established in a liquid crystal (LC). The period of this grating can be varied by changing the externally applied voltage across the LC. By adding a photoconductive electrode to the LC cell, the effective voltage, and thus the grating frequency, should follow the intensity variations of an image projected onto the photoconductor. Thus the device would act like an intensity-to-spatial frequency converter capable of operating

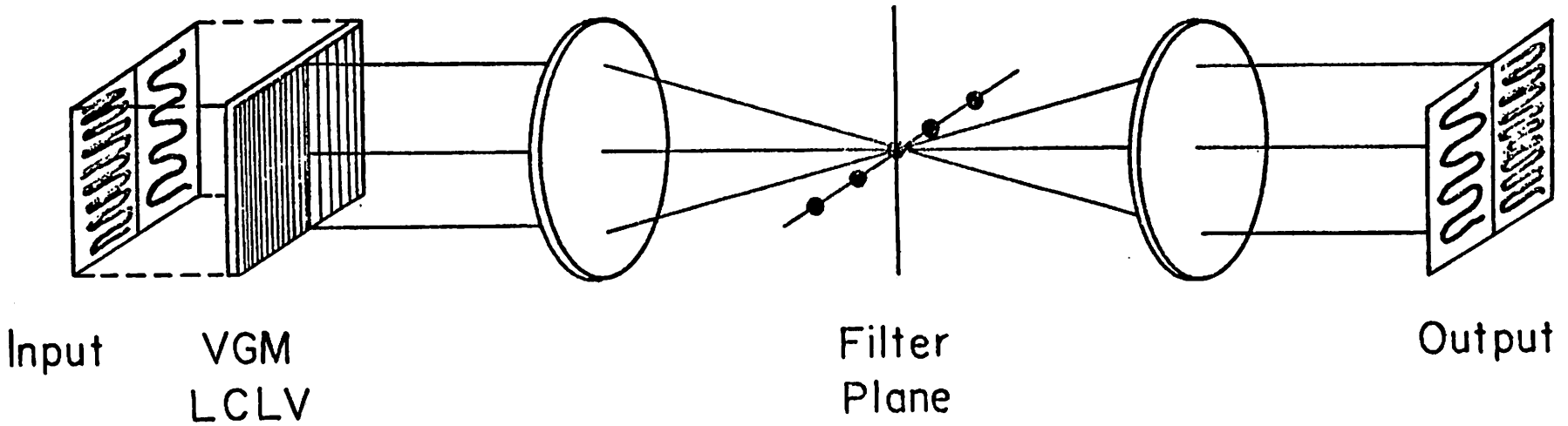

Figure 14. Filtering setup for variable grating mode. The input intensity modulates the spatial frequency on the VGM device. Each spot in the filter plane corresponds to a different input intensity. A filter can be used to attenuate these in an arbitrary fashion.

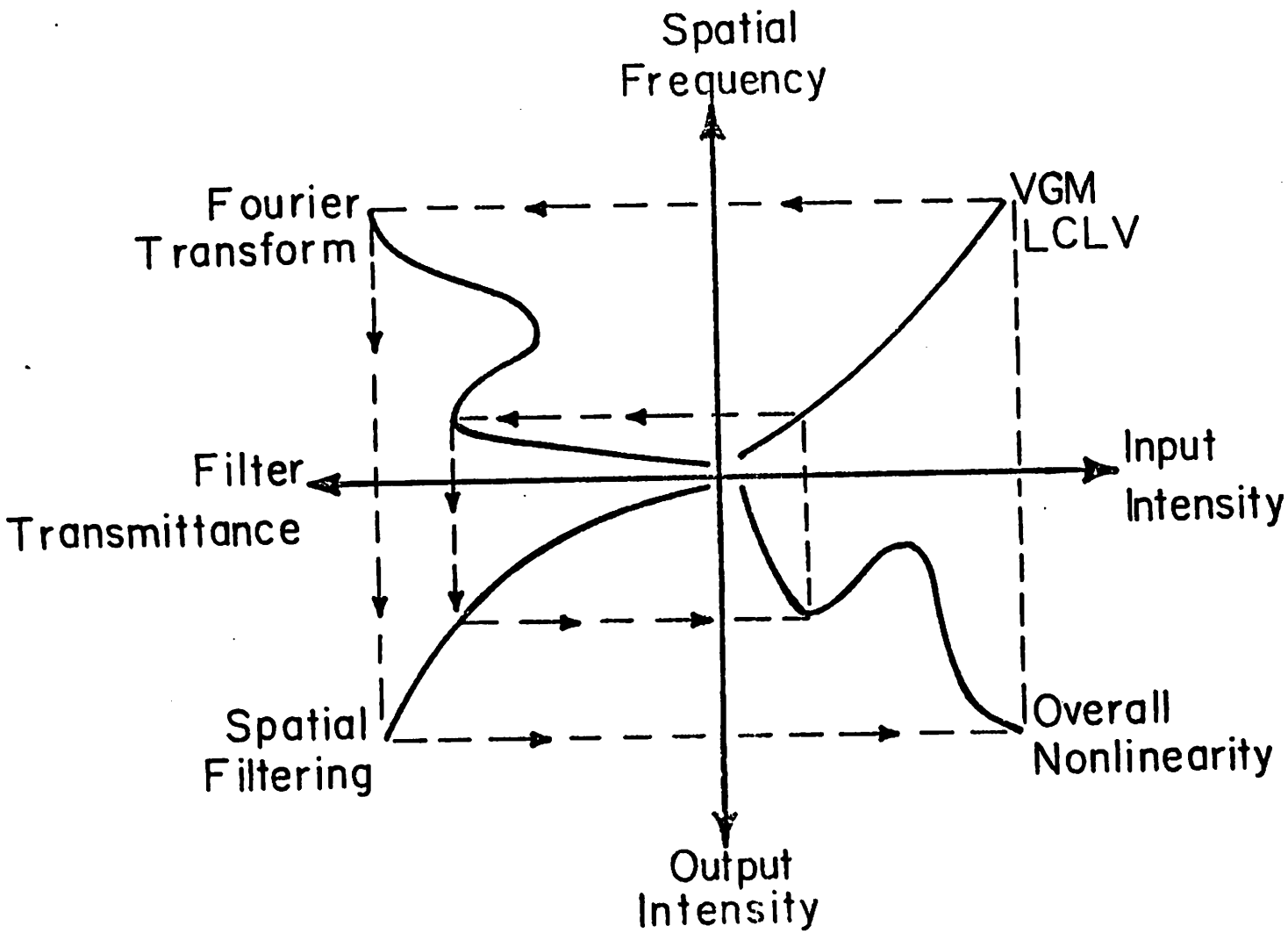

Figure 15. Graphical description of variable grating mode nonlinear processing. The input intensity variation is converted to spatial frequency variation by the characteristic function of the VGM device (upper right-hand quadrant). This spectrum is modified by a filter in the Fourier plane (upper left-hand quadrant). Finally, the intensity is observed in the output plane (lower left-hand quadrant). Taken together these yield the overall nonlinearity (lower right-hand quadrant).

on two-dimensional images. If this VGM encoded image were the input to an optical spatial filtering system, the different spatial frequency components would appear at different locations in the frequency plane and could be filtered to produce an output with any desired nonlinear relationship to the input frequency, and thus to the original input intensity.

1.8.1 Theoretical Analysis of VGM as an Optical Processing Device

The following preliminary theoretical analysis shows how the VGM could be used. We can consider the grating structure to be described by the Fourier series

$$g(x,y) = \sum_{n=-\infty}^{\infty} a_n e^{2\pi i n \nu_0 x} \tag{6}$$

where ν_0 is the fundamental frequency of the grating structure and the a are the Fourier coefficients. If this grating is placed at the input to a spatial filtering system, then in the filter plane of the system we would have an amplitude distribution proportional to $\tilde{g}(\nu,\mu)$, the Fourier transform of the input grating, given by

$$\tilde{g}(\nu,\mu) = \sum_{n=-\infty}^{\infty} a_n \delta(\nu - n\nu_0, \mu) \tag{7}$$

Thus we get a diffraction pattern consisting of a series of discrete diffraction orders located at $(n\nu_0, \mu)$.

With the VGM effect, we can alter ν_0 by changing the applied voltage, or equivalently by changing the incident intensity. Thus the location $(n\nu_0, \mu)$ of each diffraction order can be shifted by varying the input intensity. As a simple example assume the relationship

between ν_0 and incident intensity I_0 is

$$\nu_0 = \alpha + \beta I_0 \tag{8}$$

(In actuality the relationship may not be this simple, but a more complex relationship will not alter the basic ideas presented here.) Then the position of the first diffraction order along the ν-axis is simply given by $\alpha+\beta I_0$, i.e. its position is proportional to the input intensity. The input intensity will have a limited range, say between I_1 and I_2 as expresssed by

$$I_1 \leq I_0 \leq I_2. \tag{9}$$

Therefore the location of the first diffraction order is given by

$$\alpha+\beta I_1 \leq \nu_0 \leq \alpha+\beta I_2 \tag{10}$$

and the second diffraction order falls in the region

$$2(\alpha+\beta I_1) \leq 2\nu_0 \leq 2(\alpha+\beta I_2). \tag{11}$$

If we want to avoid any overlap of these two diffraction orders, then we must have

$$\alpha+\beta I_2 < 2(\alpha+\beta I_1) \tag{12}$$

or

$$I_2 < \left(\frac{\alpha}{\beta}\right)+2I_1. \tag{13}$$

This condition of course will be different if our simple model of Eq. (8) is not accurate. The important point is that we can define a range of input intensities for which the diffraction orders do not overlap. Assuming the diffraction orders do not overlap we can design a filter $\tilde{f}(\nu,\mu)$ that blocks out all but the first (or in general the

nth) diffraction order if we set

$$\tilde{f}(\nu,\mu) = \begin{cases} h(\nu), & \text{if } (\alpha+\beta I_1) \leq \nu \leq (\alpha+\beta I_2) \\ 0 & \text{, otherwise .} \end{cases}$$

Thus the filtered amplitude will be

$$\begin{aligned} \tilde{g}(\nu,\mu)\cdot\tilde{f}(\nu,\mu) &= a_1 h(\nu)\delta(\nu-\nu_0,\mu) \\ &= a_1 h(\nu_0)\delta(\nu-\nu_0,\mu). \end{aligned} \tag{14}$$

The output amplitude v(x,y) is then

$$v(x,y) = a_1 h(\nu_0) e^{2\pi i \nu_0 x} \tag{15}$$

and the output intensity is

$$\begin{aligned} I(x,y) &= |a_1 h(\nu_0)|^2 \\ &= |a_1 h(\alpha+\beta I_0)|^2. \end{aligned} \tag{16}$$

Thus the output intensity is related to the input intensity through h^2 (h will normally be a real function). But h can have any arbitrary nonlinear form.

A simple example is a nonlinearity associated with generating bit planes for optical analog-to-digital conversion shown in Fig. 16. The filter $\tilde{f}(\nu,\mu)$ that implements this nonlinearity is simply a pair of slits positioned to pass spatial frequency components corresponding to the intensity ranges 1/8 to 3/8 and 5/8 to 7/8.

From the above discussion it is clear that the VGM effect has a very great potential for nonlinear processing. However the extent to which this potential can be realized can only be judged once the effect has been carefully characterized. There are several questions that must be answered by experimental measurement. After these uncertainties are resolved, a much more detailed and complete theory

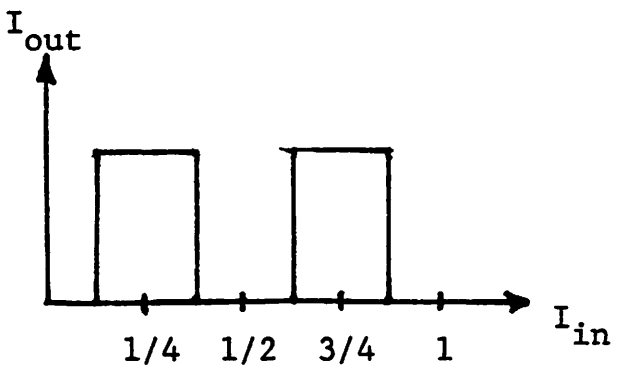

Figure 16. Nonlinearity associated with the third bit plane for a Gray code A/D conversion.

than the above simplified analysis can be constructed.

1.8.2 Advantages of Nonlinear Processing with a VGM Device

There are several advantages to this system over the halftone process. The most obvious is that it does not require a halftone screen. The production of a screen with a large bandwidth and the extremely accurate gray-scale resolution necessary for halftone processing is a major difficulty associated with the halftone approach. Typical spatial frequency ranges for the VGM gratings has been observed to be 150-300 cycles/mm. If this were implemented in an LC cell that was only 10 mm on a side, one could process images with a space-bandwidth product up to around 10^6. With this approach, it is also very easy to change the nonlinearity to be implemented. With the halftone technique, one generally needs a different halftone screen for each nonlinearity and perhaps a different filter also. With the VGM approach, one simply changes the filter. The filters inherently require only modest resolution as opposed to the halftone screens. Since the pertinent portion of the spectrum is isolated around the first diffraction order of the grating, several different filter functions $h_i(\nu)$ could be placed on one circular disc. With such a system, the nonlinearity could be changed by simply rotating the disc.

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3. Armand R. Tanguay, Jr., Assistant Professor, Departments of Electrical Engineering and Materials Science.
4. Ahmad Armand, Research Assistant, Ph.D. Candidate, Department of Electrical Engineering.
5. David Drake, Research Assistant, Ph.D. Candidate, Department of Electrical Engineering.
6. Jerry D. Michaelson, Research Assistant, Ph.D. Candidate, Department of Electrical Engineering.
7. Isaiah Glaser, Visiting Scientist, Image Processing Institute.
8. Gerard Ashton, Senior, Department of Electrical Engineering.

3. PUBLICATIONS

This section lists written publications resulting from AFOSR support from the initial starting date.

1. S.R. Dashiell and A.A. Sawchuk, "Nonlinear Optical Processing: Analysis and Synthesis," Applied Optics, Vol. 16, pp. 1009-1025, (April 1977).

2. S.R. Dashiell and A.A. Sawchuk, "Nonlinear Optical Processing: Non-monotonic Halftone Cells and Phase Halftones," Applied Optics, Vol. 16, pp. 1936-1943, (July 1977).

3. S.R. Dashiell and A.A. Sawchuk, "Nonlinear Optical Processing: Effects of Input Medium and Precompensation," Applied Optics, Vol. 16, pp. 2279-2287, (August 1977).

4. A. Armand, D. Boswell, A.A. Sawchuk, B.H. Soffer and T.C. Strand, "Real-Time Nonlinear Optical Processing with Liquid Crystal Devices," Proceedings 1978 International Optical Computing Conference, London, (September 1978).

5. A. Armand, D. Boswell, A.A. Sawchuk, B.H. Soffer and T.C. Strand, "Approaches to Nonlinear Optical Processing in Real-Time," Proceedings International Commission for Optics Congress, Madrid, Spain, (September 1978).

6. A.A. Sawchuk and T.C. Strand, "Nonlinear Image Processing," in Applications of Optical Fourier Transforms, H. Stark, ed., Academic, New York, (1978).

4. ORAL PRESENTATIONS

This section lists oral presentations at meetings and conferences describing research supported by this grant.

1. A. Armand, D. Boswell, A.A. Sawchuk, B.H. Soffer and T.C. Strand, "Approaches to Nonlinear Optical Processing with Liquid Crystal Devices," to be presented at the 1978 International Optical Computing Conference, London, (September 1978).

2. A. Armand, D. Boswell, A.A. Sawchuk, B.H. Soffer and T.C. Strand, "Approaches to Nonlinear Optical Processing in Real-Time," to be presented at the International Commission for Optics Congress, Madrid, Spain, (September 1978).