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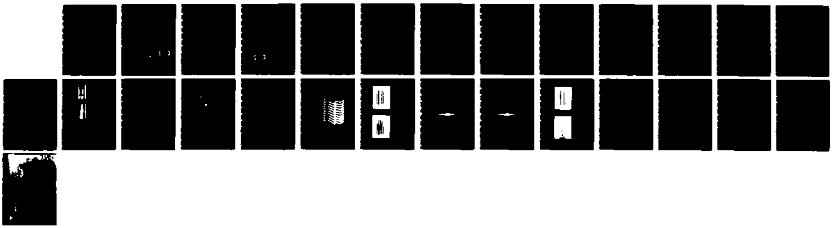

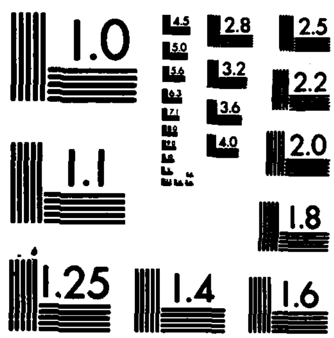

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NRL Memorandum Report 5318

Optical Signal Processing for Surveillance

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Applied Optics Branch
Optical Sciences Division

April 25, 1984

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Washington, D.C.

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Recent progress toward multichannel implementation of a time-integrating, acousto-optic Fourier transforming device is described. Various multichannel schemes are assessed, and advantages and disadvantages for each scheme given. A laboratory multichannel demonstration has been carried out successfully. It is shown that Fourier transformation of a simulated Gemini signal can be readily obtained. A special A-O demultiplexer is proposed to handle the data format proposed by Aerojet for the focal-plane detector array. Recommendations for future tasks are given.

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CONTENTS

OPTICAL SIGNAL PROCESSING FOR SURVEILLANCE

I. INTRODUCTION

A distinct feature common to high-resolution surveillance systems using focal-plane detector arrays is the amount of output signals one has to analyze before useful information can be extracted. A good example is the Gemini system under study by Aerojet ElectroSystems. To achieve high resolution and large field-of-view, a 240 row x 20 column focal-plane array is proposed. Digital data analysis techniques are proposed to handle the data reduction. This would involve a large number of electronic components for filtering and fast-Fourier transformation to provide information for discriminating the moving target (or targets) against the dense clutter. To reduce the number of components, the detector array in one scheme is so wired that the outputs of the 240 detector elements in each column are multiplexed to form a channel. There are 20 such separate channels. Even so, the still large numbers of filters and FFT devices would mean large volume and high power consumption. In addition, there is also the question of reliability of such a complex matrix of circuits. A more efficient signal processing technique is required.

Since 1982 NRL has developed several versions of a simple, reliable, real-time, Fourier-transforming device.[1,2,3] It is designed according to a chirp-transform algorithm using well-proven acousto-optic Bragg cells and long-life semiconductor diode lasers. The frequency analyzing range of the device can easily cover what is required in Gemini (< 200 Hz). Moreover, configurations suitable for compact design and parallel channel operation have been identified. To bring the acousto-optic Fourier-transforming device closer to being a practical alternative in a large system such as the Gemini, we have also addressed pertinent technical issues in various possible approaches to a subsystem having a very large number of parallel channels. The ultimate goal is to develop a subsystem architecture that is either totally compatible with the current Gemini signal processing concept or to suggest a different, but more efficient, new approach.

In the following, the basic principle of operation of the device will be explained, multichannel implementation concepts will be given, technical assessment of the possible components for multichannel implementation will be summarized, and finally, a unique choice of AO demultiplexer will be described to treat the multiplexed, sampled data coming from the 240 detector elements in each column of the Aerojet focal-plane array. Recommendations for future work are then given.

II. ACOUSTO-OPTICAL APPROACH TO THE ANALYSIS OF MULTICHANNEL SIGNALS

The operational principle of the single-channel, acousto-optic, Fourier transforming device has been well explained and demonstrated in Refs. 1,2,3 and a recent report.[4] Suffice it to say that the Fourier transform of a temporal signal applied to the light source (a diode laser) can be obtained by reading out the spatial charge distribution in the time-integrating detector array in a simple optical setup, using a single Bragg cell, as shown in Figure Figure 1. The role of the Bragg cell is to convert the RF chirp signal into the optical phase distribution required by the Fourier transform kernel, while the signal to be Fourier transformed is applied to the light source. It is, therefore, possible to allow the same chirp to be shared by all the channels,

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provided that the chirp bandwidth is set to cover all the frequency ranges of the individual signals. This realization means a high degree of simplification of the interferometer design, making possible, with simple addition of cylindrical lenses, adaptation of the two compact versions of the Fourier transforming device as reported in Refs. 2 and 3. For example, a two-channel demonstration using the Fig. 1 setup is shown in Fig. 2, where the optical beams of diode laser 1 and diode laser 2 are juxtapositioned in height normal to the plane of the Figure. The two independent outputs, separated in space, are displayed in Fig. 3. The concept can be easily extended to a large number of channels, when the input beams can be formed into separate parallel sheet beams. As shown in Figure 4, a suitable cylindrical lens is added in front of the beamsplitter, BS, to focus all the sheet beams to the Bragg cell. The output beams from the interferometer will then be properly scaled by another cylindrical lens (not shown) to match to the two-dimensional detector array. If the input sheet beams are intensity modulated at different frequencies f_1, f_2 ...., f_n, then, fringe maxima will be displayed in the images of the individual channels. The crux of this implementation is the production of these parallel or quasi-parallel, collimated input beams. Whether one can successfully couple the beams through the Bragg cell depends strongly on what type of light source and light modulators is chosen. We treat this point in Section III.

The advantage of using acousto-optic techniques is the maturity of this technology. High-quality Bragg cells are now commercially available. The Bragg cell is very rugged. With TeO_2 crystals, large diffraction efficiency (~ 50%/RF Watt) can now be achieved.

III. IMPLEMENTATION CONCEPTS AND ASSESSMENT

The optical interferometer configuration chosen takes either the form of the common-path, triangular one as described in Ref. 2, or that of the compact prismatic one as described in Ref. 3. Both are found suitable for our purposes. Efforts were concentrated in identifying the optimum multichannel light sources that would allow individual addressing and provide a set of light beams commensurate with our choice of interferometers. Two basic kinds have been investigated. The first is the linear diode laser array, each element emitting independently. The second consists of spatial light modulators illuminated by a common collimated beam. These two kinds of sources require different ways of coupling optical beams into the interferometer. In the case of multichannel spatial light modulators illuminated by an initially collimated beam, the coupling via either imaging or focusing to the Bragg cell in the interferometer requires only simple optics, in that the diffracted beams from the spatial light modulators are nearly parallel and collimated. In the case of the diode laser arrays, special optics is needed to both collimate and collect the cone-shaped laser emission. Since off-axis diode lasers give rise to phase-front tilts in the ensuing beams, these collimated beams are dispersed in angles proportional to the distance of the emitting laser to the optical axis. The problem is further compounded by the practical requirement to demagnify the images of the diode laser array so that the overall height of the image matches with that of the acoustic beam in the Bragg cell. The problem presents a severe challenge to optical designers.

To gain an understanding of the imaging problems for a large diode laser array and to see to what extent conventional off-the-shelf optics can perform in this imaging process, laboratory investigation was performed using the prismatic interferometer described in Ref. 3. The light source consists of two discrete diode lasers positioned 3 mm to either side of the optical axis to represent two outer elements in an array; the behavior of the interferometer with an axially located single diode laser is known (Ref. 3). A special TeO_2 Bragg cell was procured, having an apodized transducer to produce an acoustic field uniform along the propagation direction and over a vertical height of about 3mm. An f/0.75 optical system with 4mm back focal length and 15mm rear aperture was used to collect and collimate the laser beams without vignetting. However, even when all the difficulties of implementing this investigation were overcome, a fundamental problem was found in fitting the laser beam within the 3mm Bragg cell aperture. One solution is to fabricate a Bragg cell with even larger height to match the size of the overlapping image. In other words, design a Bragg cell to fit the images, rather than reduce the images to fit an arbitrarily narrow cell. According to one vendor, a Bragg cell with 20 mm usable height in the acoustic beam can be made with current technology using a TeO_2 crystal having the same performance as the 3 mm one used here.

We have also evaluated other multichannel modulator approaches. These fall into two major categories: one is the direct-modulatable, individually addressable array light sources such as light-emitting diodes (LEDs), monolithic diode lasers, discrete diode lasers with matching mini-collimating optics (Selfoc gradient-index collimating lenses or micro-spheric lenses), and discrete diode lasers with pigtailed single-mode optic fibers. The other is the light beam modulators external to a laser cavity, such as the array acousto-optic modulator, the acousto-optic demodulator which converts time-multiplexed (hence serial) electrical signals into parallel optical channels (hence parallel), and the electro-optic multi-channel modulator. We have alluded above that the second category, giving parallel diffracted beams, is much easier to implement with any kind of interferometer, except for the discrete diode lasers with Selfoc lenses, the first category requires special imaging arrangements. We have made the following assessments:

(A) LED ARRAYS: The advantages are: (i) arrays commercially available (ii) scalability (over 180 elements possible), (iii) direct-modulatable. Disadvantages are: (i) invidual light output is low (10μW each), (ii) large heat dissipation requires a cooling unit, (iii) incoherent light unsuitable for interferometric uses.

(B) MONOLITHIC DIODE LASER ARRAYS.[5, 6, 7] The advantages are: (i) each element of the array has high output power (> 1mW CW), (ii) there exists a strong driving force for the development of this technology in the areas of laser recording and communication. They are being developed by major industrial research laboratories. (iii) compact size possible. Their disadvantages are: (i) High power dissipation in a closely-packed array may create temperature gradient that would create non-uniformity and thermal damage, (ii) there is the potential problem of cross-talk, which has not been adequately addressed, (iii) large angle output beam divergence requires special collimating lens, and (iv) the prospect of yielding a large number of consecutively-operational elements is still uncertain, and (iv) lack of commercially availability .[8]

(C) DISCRETE LASERS WITH MATCHING MINI-LENSES FOR COLLIMATION [9]

This refers to an array made of existing, discrete diode lasers, with, for example, Selfoc lenses on each laser. The advantages are: (i) they can be put together without extra technology development effort, (ii) lesser cross-talk potential, (iii) parallel output beam , (iv) since the array is less dense than in the monolithic case, dissipation can be treated without problem, and (v) collimated light beams are preferred in interferometic setups. The disadvantages are: (i) packing density is limited to a center-to-center spacing of 1 mm, due to the sizes of the Selfoc lens and any possible microlenses, hence the number of elements in a line array will probably not exceed 20, and (ii) cost for mounting matching lenses will be high.

(D) FIBER-COUPLED DIODE LASER ARRAY [9]. This is the case where the array is formed by the free ends of fiber-pigtailed diode lasers. The advantages are: (i) that a closely-packed fiber array is possible, (ii) that discrete lasers can now be mounted with convenient separation and configuration such that heat dissipation can be handled easily and optical and electrical cross-talks can be eliminated, (iii) even though the coupling between the single-mode pigtail fiber and the laser chip produces losses, efficiency of 50% is possible, and (iv) the output beam from a fiber end has a much smaller divergence angle than the laser itself (15° vs 40°) and a spherical wavefront so that the collecting optics system requirement is less stringent. The disadvantage lies in the fact that pigtailing requires precision in alignment, and automated alignment techniques have not been found. This translates into high cost for a large array (> $ 1K/ One pigtail mounting).

(E) ELECTRO-OPTICAL MULTICHANNEL LIGHT MODULATOR [10,11]

The optical arrangement of the multichannel light modulator is shown in Figure 6. The various channels correspond to the electrode finger pairs deposited on the silicon chip which is contacted to an optical prism made of an electro-optical material (e.g., $LiNbO_3$ or $LiTaO_3$) and shaped for total internal reflection. The diffracted light is single-sideband filtered by the Schlieren output optics and coupled into the interferometer.

This device has the advantages of: (i) parallel input format and (ii) memory ability (the information is held in each channel as long as the voltages are applied to the electrodes). The disadvantages are: (i) low light diffraction efficiency (ii) a cross-talk of about -20dB between adjacent channels, and (iii) low (~20dB) dynamic range. An 8-channel device has been procured from Xerox Corp. We have demonstrated multichannel operation with this device to evaluate overall optical system design. Details will be given later.

(F) MULTICHANNEL ACOUSTO-OPTIC MODULATOR

The device concept is illustrated in Fig. 7, where an array of transducers produces an array of parallel diffracted light beams, which can, in turn, be coupled into the interferometer via appropriate simple lenses. One such has been developed by Harris Corp. for wideband holographic digital recording and reproduction.[12] As a modulator, 16-channel, 32-channel, 64-channel, and 128-channel devices have been developed and tested. This device has advantages in (i) large diffraction efficiency (> 50%/RF Watt power,) (ii) low cross talk (-40 to -50 dB), (iii) large dynamic range (40 dB to 50 dB), (iv) parallel output beams, and (v) input format flexibility. Its disadvantage is its cost (> $ 1K/channel). Because of its well-proven technology, large dynamic range and low cross talk, this device is a good choice for parallel-input, multichannel Fourier transformation applications.

The final multichannel approach investigated, the acousto-optic serial-to-parallel demultiplexer will be described in detail in Section V, since its characteristice closely matches the present Gemini architecture.

IV. MULTICHANNEL DEMONSTRATION

To this point, we have discussed the implementation of multichannel Fourier-transforming devices without referring to a particular input signal format. Before discussing a particular system configuration for a particular signal format, it is important to demonstrate the validity of concepts and, in the process, gain understanding of the operational issues. It is the purpose of this section to show results of one recent demonstration. The optical setup is the same as that shown in Figure 4, which we had proposed as one of the two practical concepts. The quasi-parallel signal beams coming from the left are produced by the Xerox eight-channel electro-optic modulator. This modulator is a parallel input device where each channel has the following characteristics:

1. Frequency Range - DC-300 kHz

2. Risetime: < 75 nsec for input voltage greater than 1 volt.

3. Input impedance: 50 Ohms.

4. Power supply Requirements:
   (a) Voltage: 50 volt
   (b) Current: 30 mA per channel

5. Video input voltage:
   (a) Polarity: positive only
   (b) Operating range: 0 -3.5 volts
   (c) Maximum: 7 volts

6. Video output characteristics:
   (a) 0 - 50 volts
   (b) 30 mA max.
7. Dynamic range: > 15 dB but < 20 dB

8. Optical crosstalk: < 15 dB

9. Material: Lithium tantalate crystal

10. Illumination: 633 nm polarized laser light

11. Max. laser beam power = 0.082 Watt/cm^2

The optics for getting diffracted beams is the same as shown in Figure 6. The outputs from the interferometer are detected by a 100 x 100 detector array made by Reticon, and displayed on a scope. Fig. 8 shows two photographs of the typical display. The one on the left shows seven out of the eight channels (the eighth channel was illuminated by the weak wing of the Gaussian beam and hence did not produce enough exposure.) The RF chirp had been applied to the Bragg cell. Therefore, for those channels where no signals were applied one should see a sinc function centered at the zero frequency position. These channels show dark and bright bands on the right-hand sides of the bright traces. In one channel (the second from the top) where a 120 Hz sinusoidal wave was applied, an extra band shows up in the middle of that trace. When the bias voltage to channel 4 (4th from the top) was removed, the trace completely disappeared. This is shown in the picture on the right. Hence, one could not visually detect any optical crosstalk. Good crosstalk results require careful alignment and positioning of the imaging optics.

Some information from Aerojet ElectroSystems about the possible signal waveform from Gemini[14] was available. A typical wave form obtained by their computer simulation is shown in Figure 9. We have simulated the waveform in the laboratory, and it is shown in the left-hand picture of Fig. 10. When applied to the 5th channel of the Xerox light modulator, one obtained the Fourier transform of such signal. The location of the peak in channel 5 is proportional to the carrier frequency of the burst sinewave (~ 200Hz). Thus, the multichannel implementation and the ability of the device to analyze a Gemini-type signal are clearly demonstrated.

V. AN ARCHITECTURE FOR THE GEMINI SURVEILLANCE SYSTEM

To reduce the number of individual output channels in the postdetection data processing electronics, detector-element outputs are arranged so that the 240 elements in each of the 20 columns in the focal-plane array are to be multiplexed, after sampling at 400 Hz, to form a serial data stream. The detector array configuration and a burst sinewave corresponding to a moving target as seen by one detector element are shown in Figure 11, whereas the special data encoding scheme is illustrated in Fig. 12. To differentiate which detector output contains the sinewave, one must demultiplex the serial data into channels corresponding to individual elements and carry out the Fourier transformation of the sampled signals. Such a sampled signal will be similar to the one shown in Fig. 9, for which we have demonstrated Fourier transformation with our optical setup. For the demultiplexing, we propose the following scheme. As shown in Fig. 13, a Bragg-cell deflector of time-bandwidth product greater than the number of multiplexed detector elements N, (here, N = 240) is illuminated by a collimated coherent lightbeam from a pulsed diode laser. The serial data stream is applied to the tranducer of the Bragg cell after mixing with an appropriate RF carrier. A signal is also applied to pulse a diode laser after appropriate time delay. At the time the diode laser is pulsed, there are N acoustic wave packets in the window of the Bragg cell. A single light pulse would give rise to N diffracted beams, which are the input beams to the interferometer for Fourier transformation. Consecutive feeding of k such N-sample segments with k laser pulses would produce k-point Fourier transforms at the interferometer output plane. As shown in Fig. 4, N-channel outputs will be detected by a large two-diminsional detector array and can be displayed on a scope screen. The requirements for such a Bragg deflector are determined as follows:

Material:	TeO_2 crystal
Acoustic mode:	slow shear wave
Time window:	10 μsec
Data sampling rate:	50 kHz
Number of resolvable spots (or channels):	> 240 (for Gemini) (~ 40 nsec/channel)
Diffraction efficiency:	>10%
Acoustic beam shape:	Uniform in both horizontal and vertical directions using transducer apodization.

A light budget estimate for this multichannel acoustooptic processor has been carried out:

The assumptions are:

1 W pulsed diode laser (e.g., available from M/A-Com LDL as model LD-90-95)

20 nsec pulses (i.e., 20 nJ/pulse)

256 channels (k=256)

Demultiplexing Bragg cell diffraction efficiency: 10%

Chirp-loaded Bragg cell diffraction efficiency: 10%

Fourier Transform integration time: = 30 msec. (i.e. ~ 30 Hz resolution).

Detector Saturation exposure: 4.2×10^{-10}J

(e.g. Reticon 100x100 array)

The calculated light energy per channel for one integration cycle is 12×10^{-10}J, which is larger than the saturation exposure of the detector element. This indicates that even with a 1 W diode laser, there is enough energy to allow one to achieve the maximum dynamic range defined by the detector array, assuming reasonable losses in the optical train. One may note the 1 W output power from the diode laser and 10% Bragg cell diffraction efficiencies are very conservative conditions. Therefore, acoustooptic implementation of an efficient data processing subsystem is well within the current technologies.

VI. SUMMARY AND RECOMMENDATIONS FOR FUTURE WORK

A multichannel, acousto-optic, Fourier transform architecture has been devised for handling the multiplicity of detector outputs in the Gemini surveillance concept. The approach is based on an acousto-optic serial-to-parallel demultiplexer to reformat the serial, multiplexed, data for parallel computation of 240 transforms. Multiplexing requirements and light budget using commercially-available technology were calculated. A variety of other approaches for implementation of a multichannel processor have been examined including, LED arrays, Monolithic diode laser arrays, arrays of discrete lasers with individual collimating optics, fiber-coupled diode laser arrays, multichannel electro-optical light modulators, and multichannel acousto-optic modulators; advantages and disadvantages of each were discussed. An eight-channel electro-optical light modulator was used to demonstrate multichannel operation; tests inputs included CW tones and a simulated Gemini-type signal.

The following tasks are recommended specifically for the Gemini system requirement.

(a) Demonstrate the capability of the A-O demultiplexer to convert a serial data stream into parallel channels suitable for Fourier transforming interferometers. The number of channels will be made compatible to the most current Gemmini focal-plane detector configuration,

(b) Integrate the A-O demultiplexer into a Fourier transforming device for optimum performance,

(c) Demonstrate the full capability of this optical signal processor by using real or simulated Gemini signals for testing as soon as they are available,

(d) Address optical bench design criteria for a flight-worthy compact system based on Gemini's structural design, and

(e) Investigate other processing configurations for discriminating target(s) from a dense cluttered background using frequency-domain filtering. One possibility is the spatial lock-in detection scheme recently proposed by H.H. Barrett, et al[15] of the Optical Sciences Center of Univ. of Arizona. A microchannel-plate addressed membrane spatial light modulator under study at NRL may be a better device than the image orthicon tube employed by Barrett, since it promises both high spatial resolution and high frame rates (>1 kHz) simultaneously.

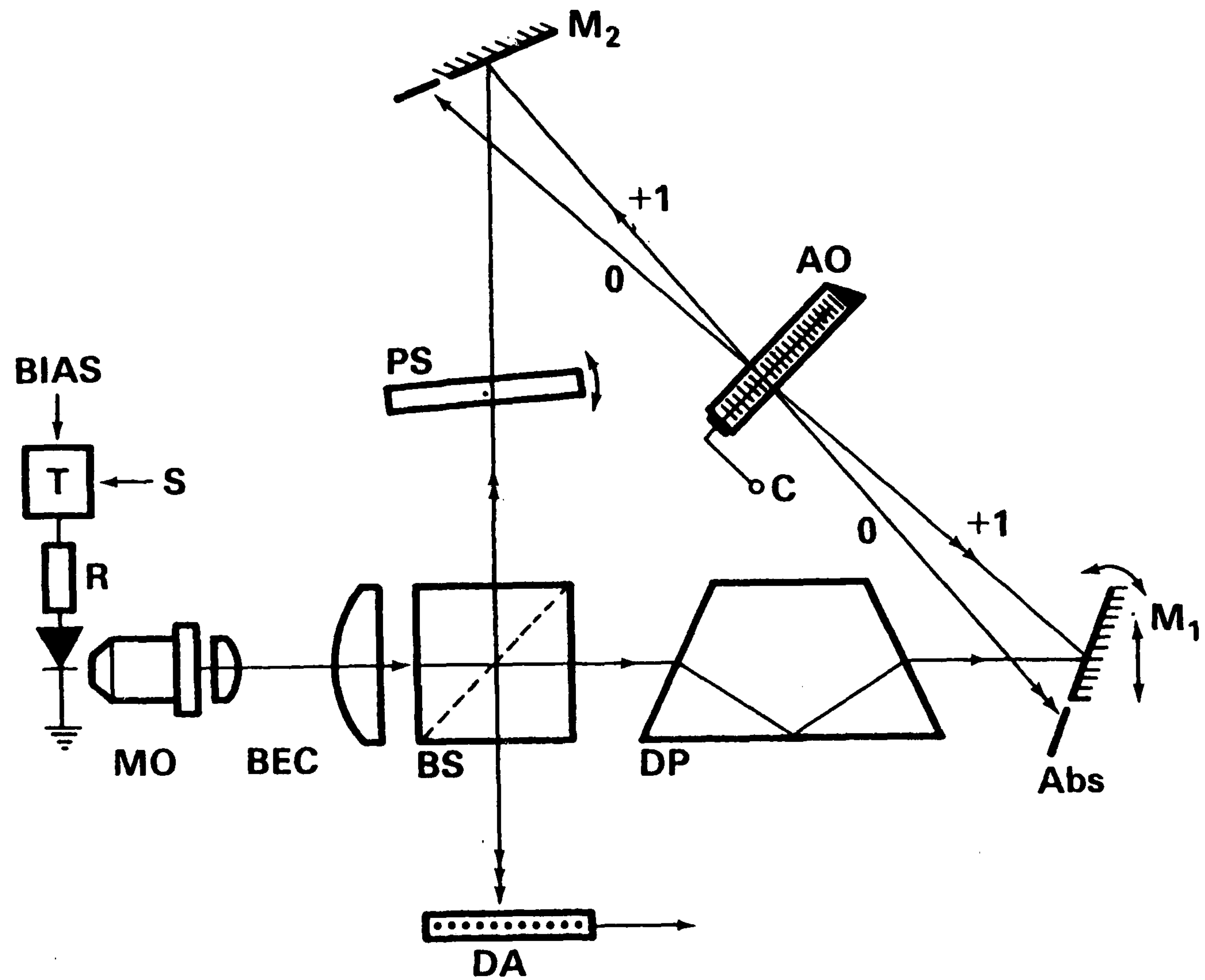


Figure 1. A Fourier transforming device employing diode laser light source, triangular, commonpath interferometer, a single Bragg cell, and a time-integrating linear detector array.

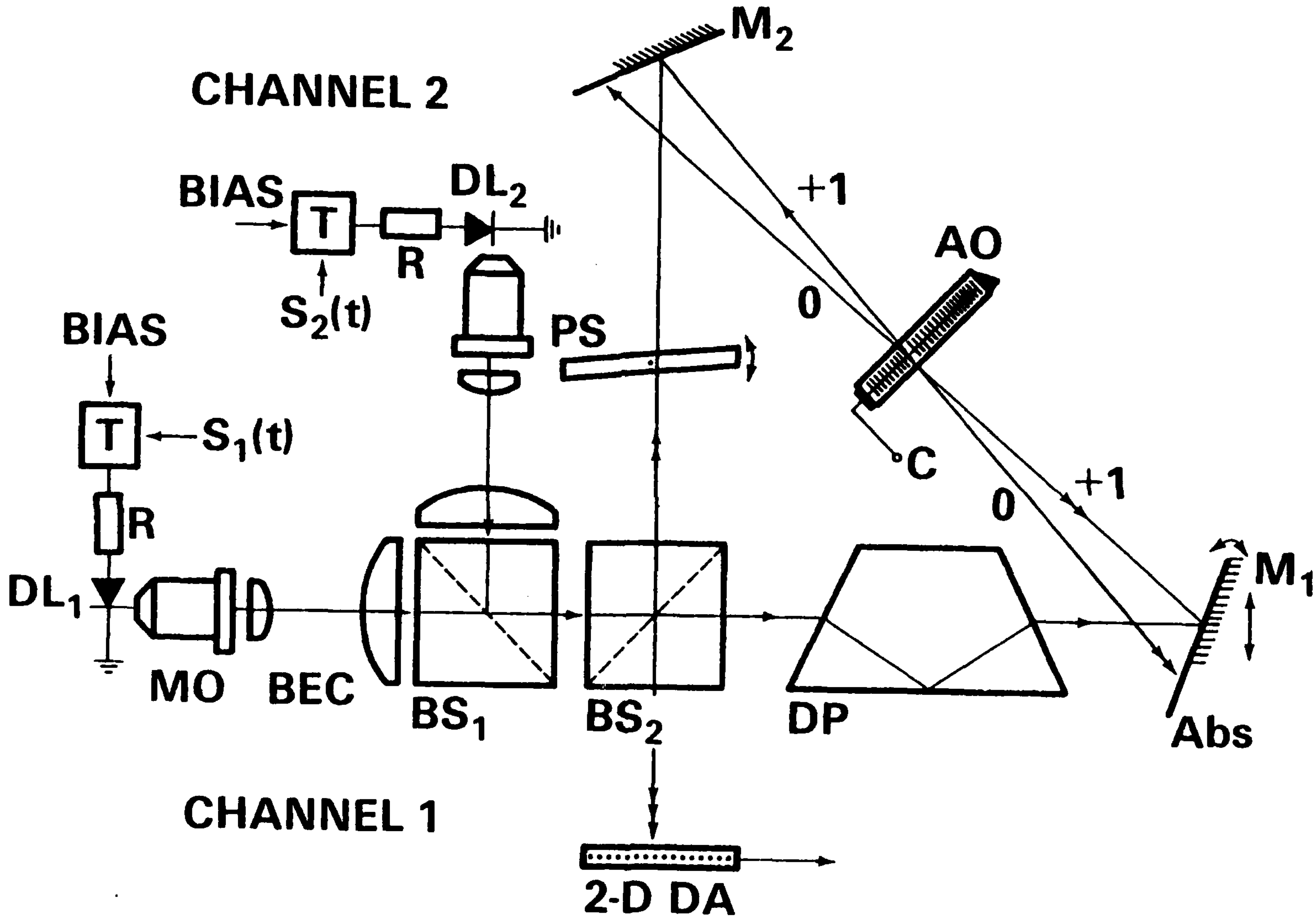
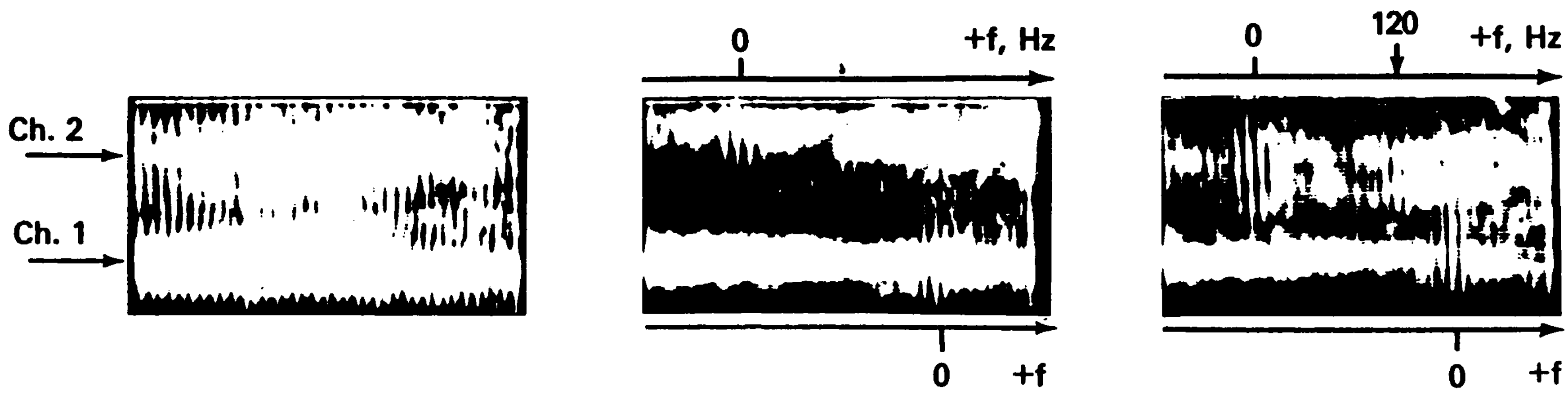


Figure 2. Experimental setup to demonstrate independent two-channel Fourier transformation as a first step toward multichannel implementation.



(a)
CW Fringes

(b)
Chirp Autocorrelation
in both channels

(c)
Fourier transform
of 120 Hz sinewave
in Channel 2.

Figure 3. Results showing achievement of two independent channels as recorded by a 100x100 Reticon detector array.

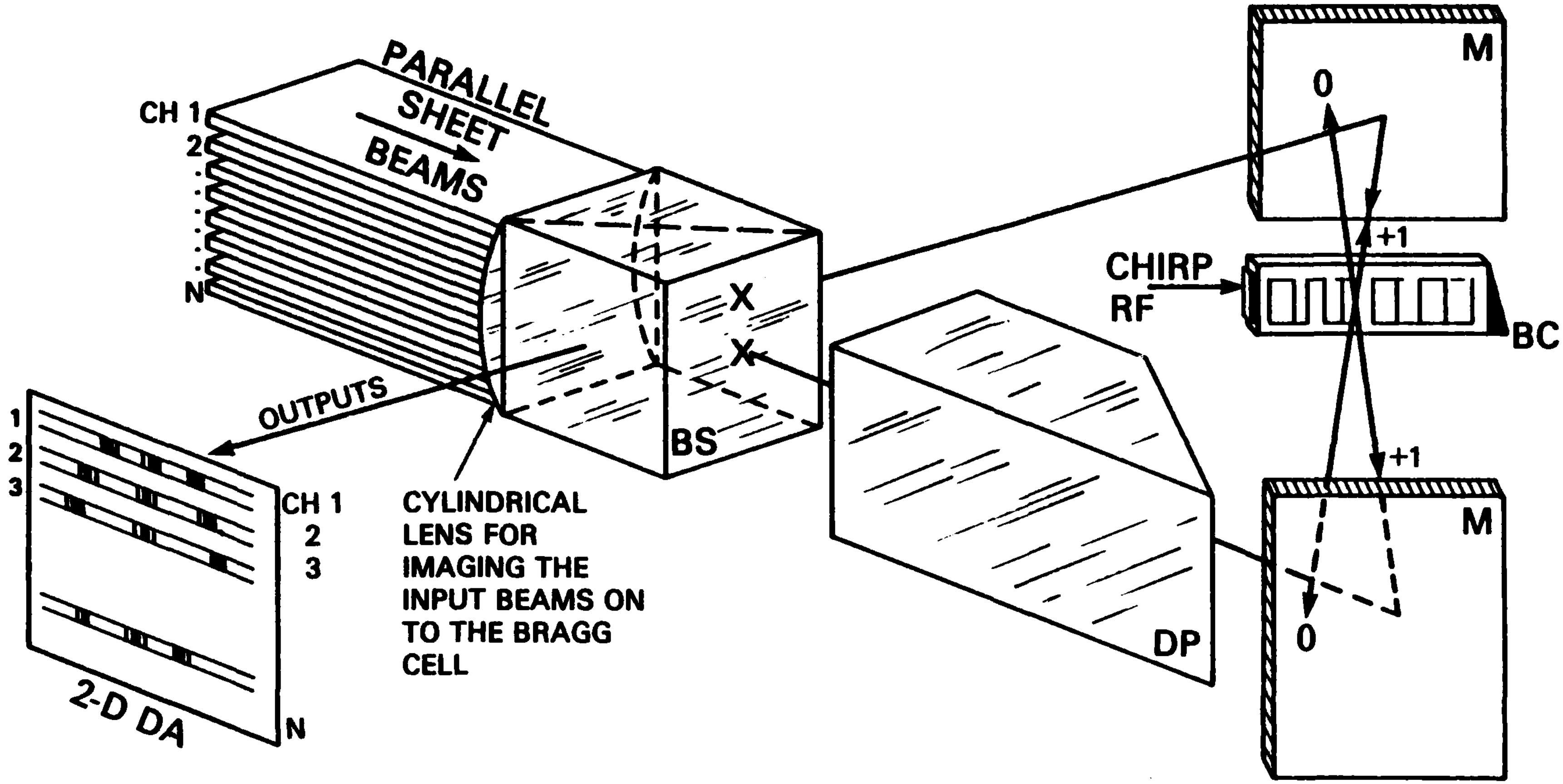


Figure 4. Multichannel implementation concept based on the arrangement of Figure 1.

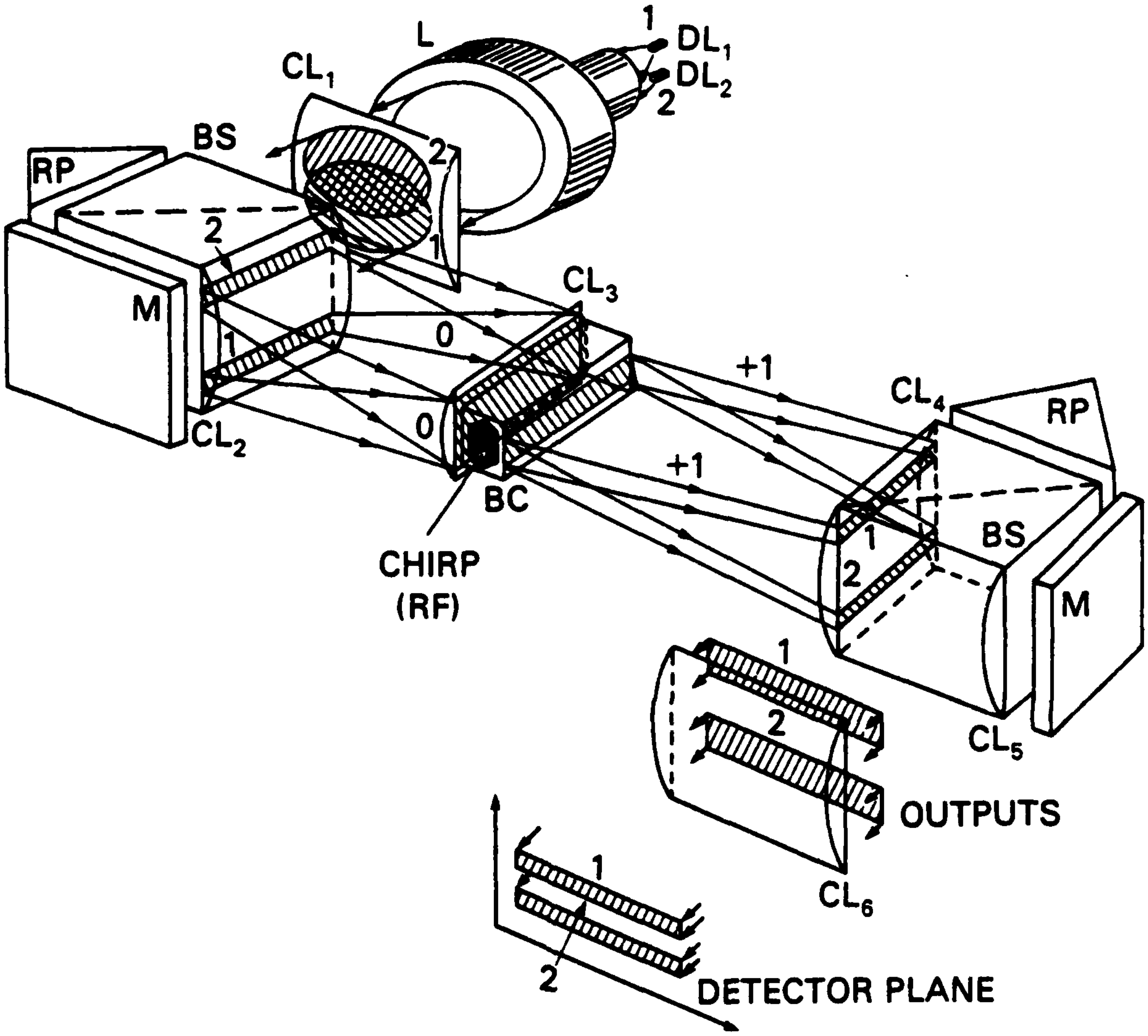


Figure 5. Experimental setup to illuminate the imaging process when laser diodes are considered as light source. This interferometer is the compact verison of the Fourier transforming device.

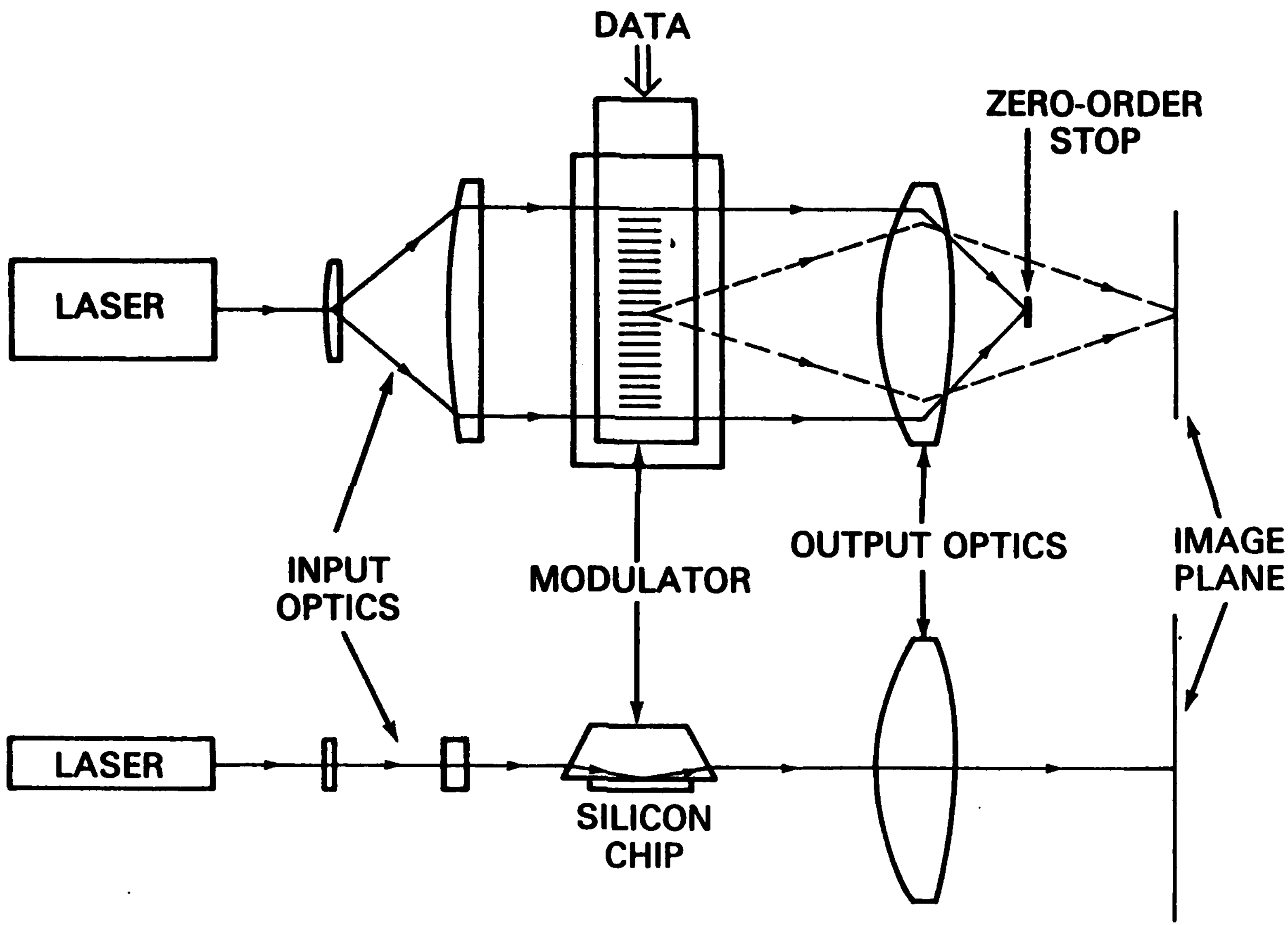


Figure 6. Xerox electro-optic light modulator configuration. It is a possible scheme using multichannel light modulator with one laser source for multichannel processor implementation.

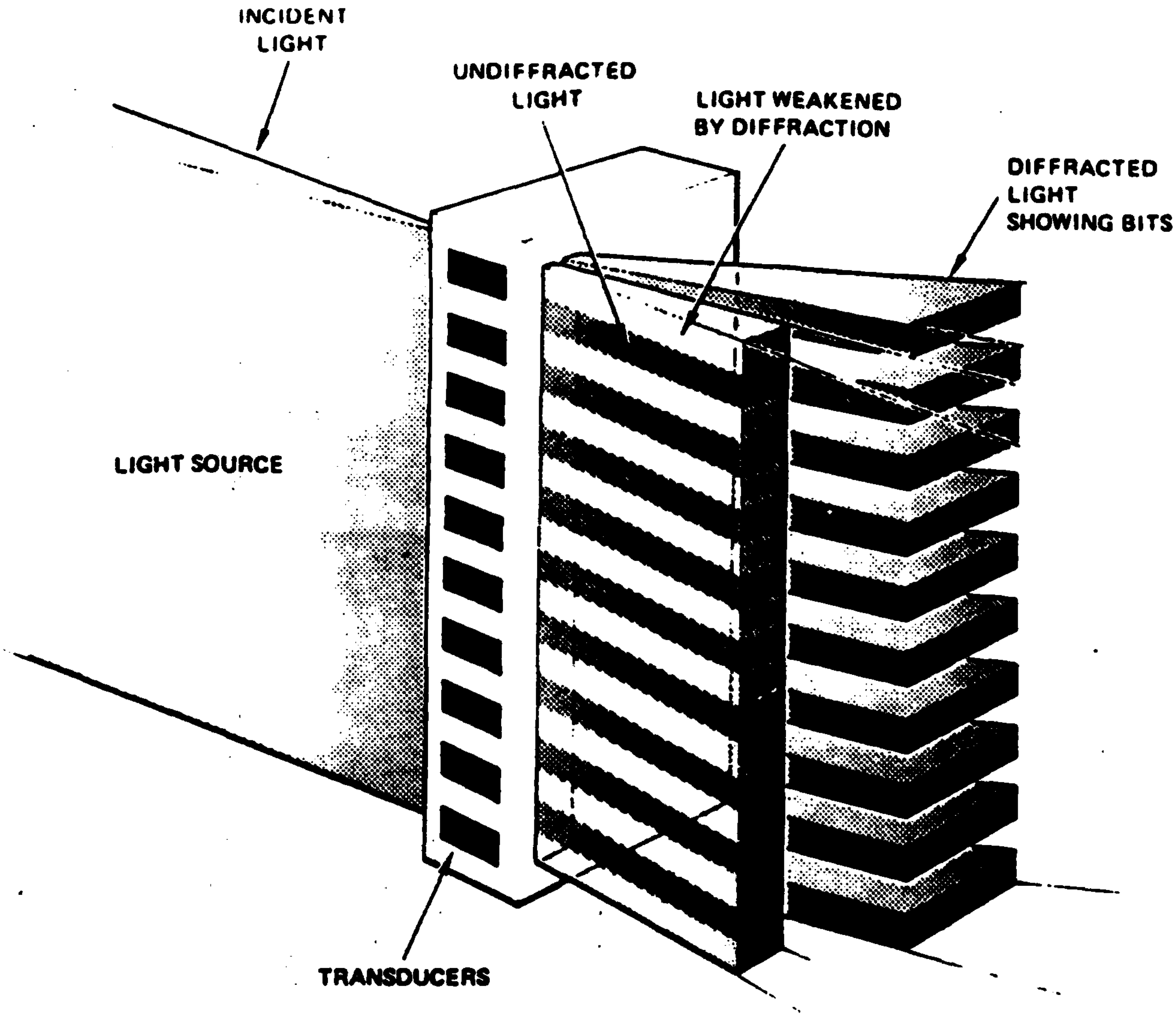


Figure 7. Multichannel acousto-optic light modulator. Another possible scheme.

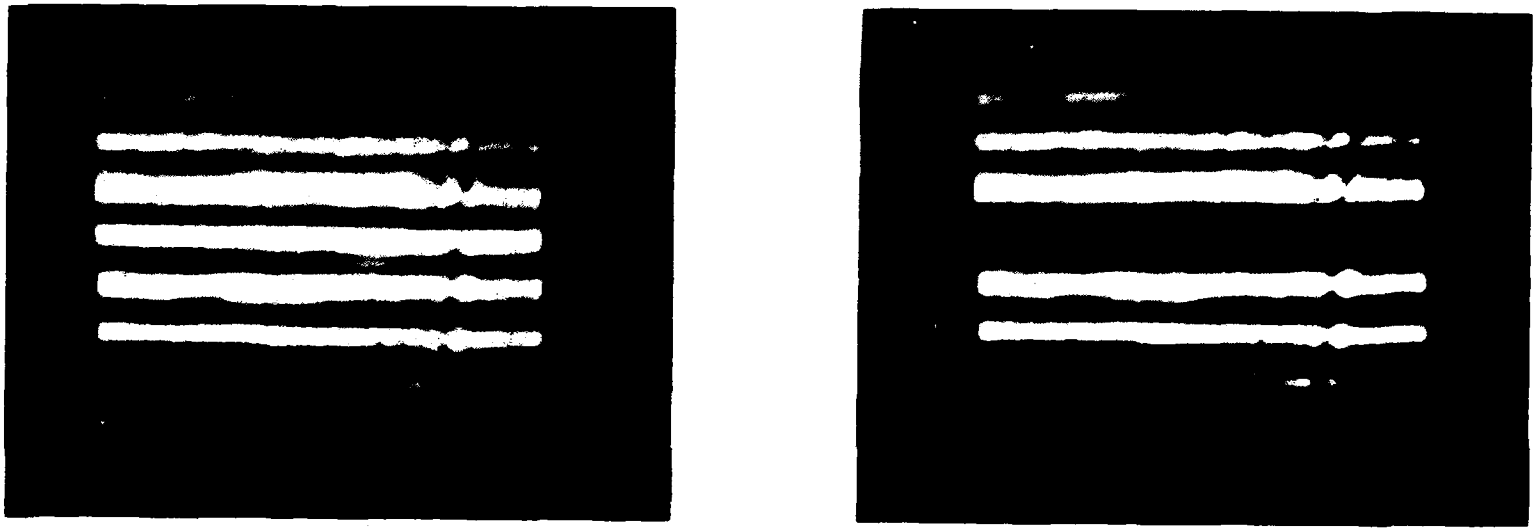


Figure 8. Results of a demonstration of multichannel operation in a setup similar to Figure 4 above. The light modulator is the electro-optic type provided by Xerox Corp. The left-hand picture showing 7 of the eight channels. The dark bands to the right of these traces are fringe locations for the DC (0 Hz) components of the Fourier transforms. A fringe pattern in the middle of the trace of channel 2 is the Foruier Transform of a 120 Hz signal applied to that channel and that channel alone. The picture on the right is the same as the one on the left, except that channel 4 is deactivated. No visible crosstalk is observed.

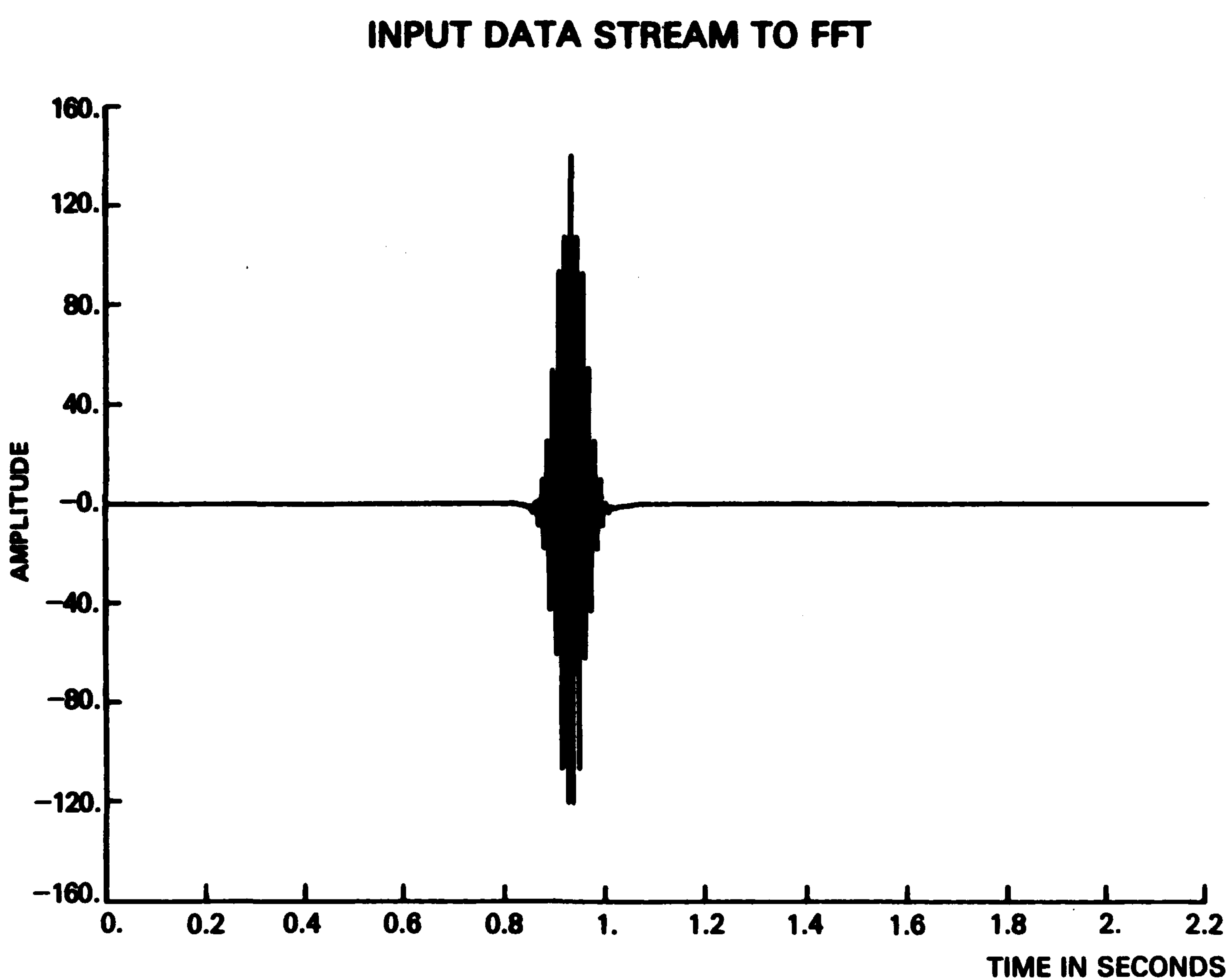


Figure 9. Gemini signal waveform (a sinewave burst) as provided by Aerojet Electro Systems.

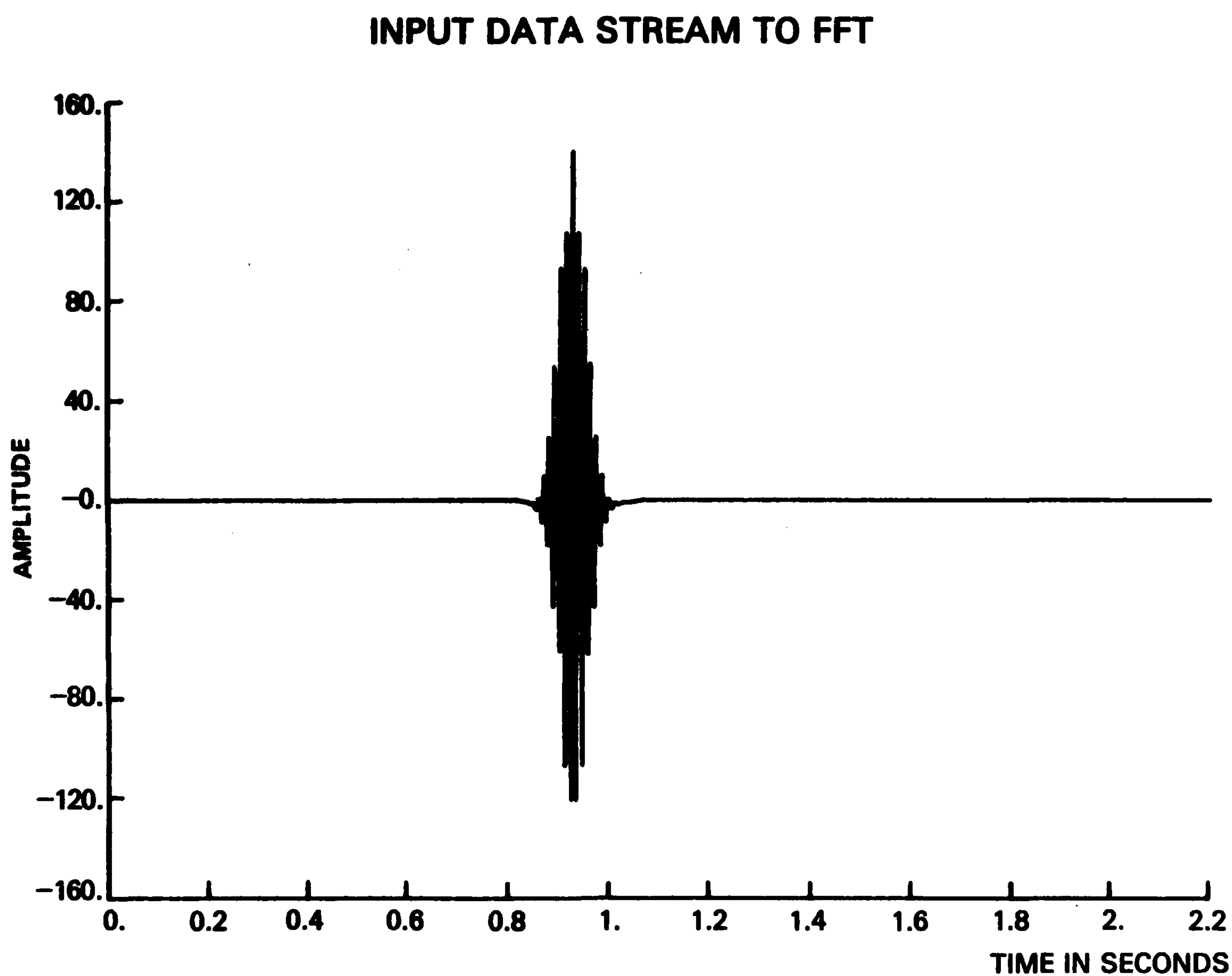


Figure 9. Gemini signal waveform (a sinewave burst) as provided by Aerojet Electro Systems.

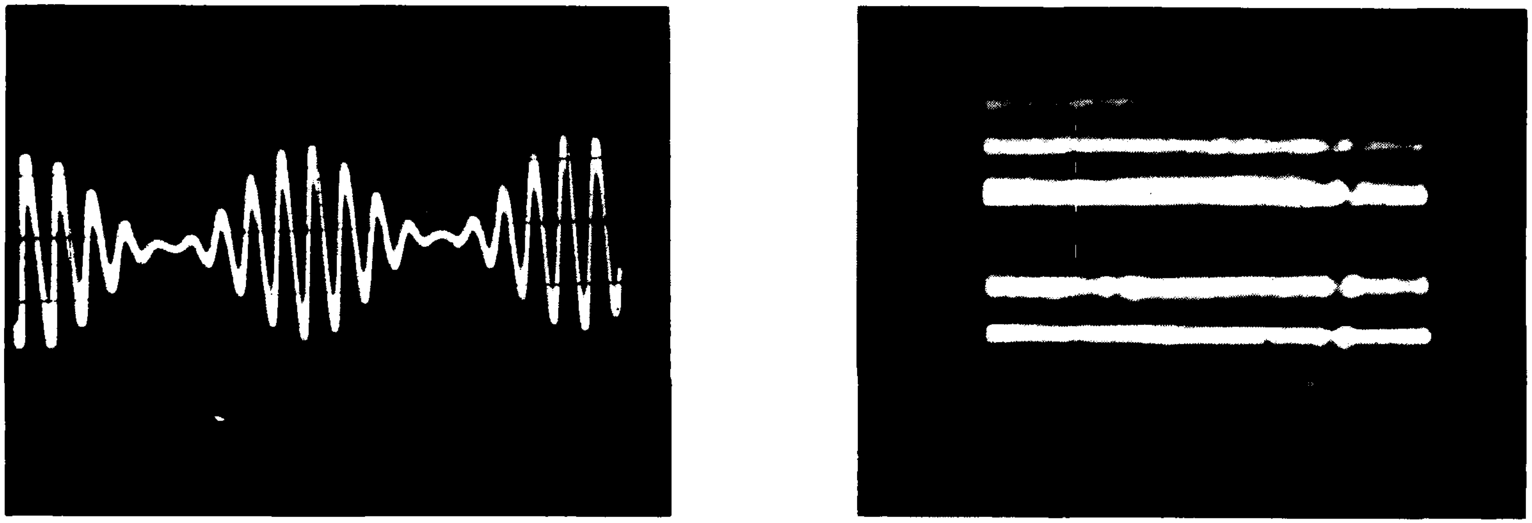


Figure 10. The picture at left is our simulation of the Aerojet Gemini signal to be applied to one of the channels in the light modulator. The picture on the right showing the Fourier Transform of this signal as it was applied to channel 5. The fringe to the left of that trace is the Fourier Transform. The location corresponds to the 200 Hz carrier in the simulated signal. (Note 120 Hz remains in channel 2).

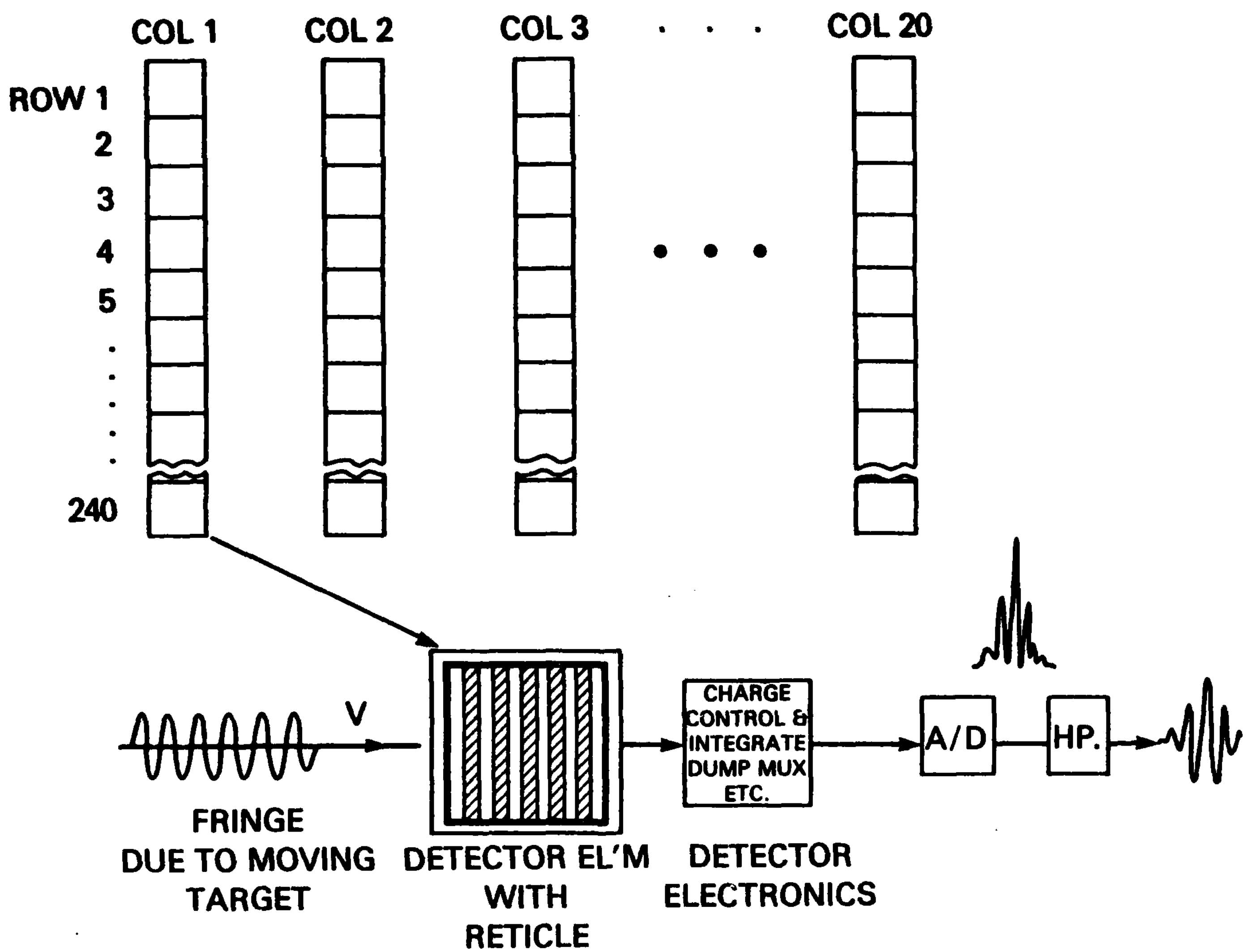


Figure 11. Schematics showing the Gemini focal-plane detector array and how the signal is acquired.

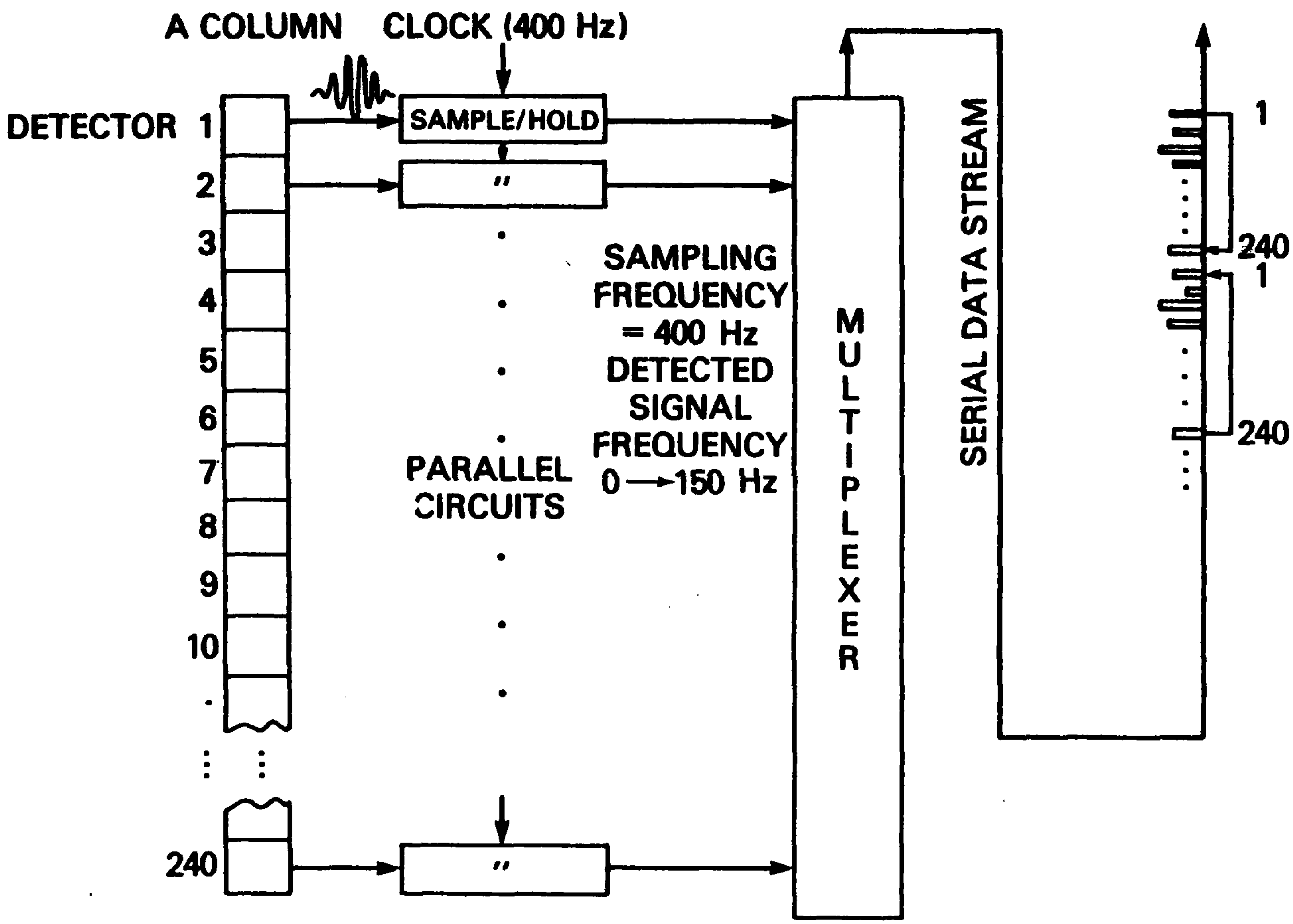


Figure 12. A parallel-to-serial Gemini data encoding scheme by a multiplexer.

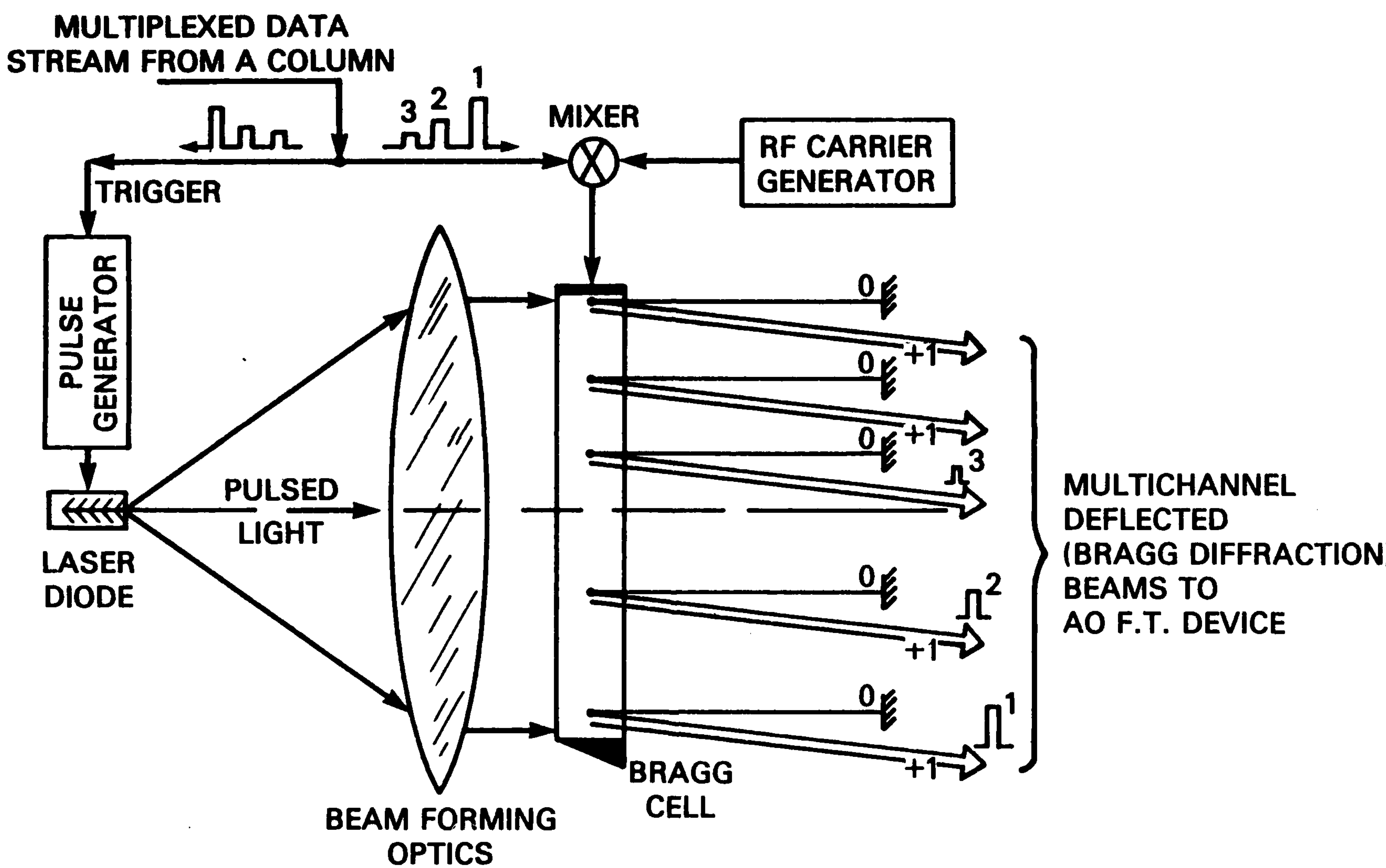


Figure 13. Acousto-optic demultiplexer for converting the Gemini data to parallel channels suitable for our AO Fourier Transform processor.

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