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FOURIER PLANE FILTERS

Donald S. Oliver, Ralph E. Aldrich, and Francis T. Krol
Itek Corporation
Central Research Laboratories
10 Maguire Road
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November, 1972
Final Project Report

Prepared for
GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland 20771

(NASA-CR-130185) FOURIER PLANE FILTERS
Final Project Report (Itek Corp.) 64 p
HC $5.25
CSCL 20F
N73-19670
Unclas
G3/23 65395

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1. Report No.	2. Gov. Accession No.	3. Recipient's Catalog No
4. Title and Subtitle FOURIER PLANE FILTERS		5. Report Date November 1972
7. Authors D. S. Oliver, R. E. Aldrich, F.T. Krol		6. Performing Org. Code
9. Performing Organization Name and Address Itek Corp., Central Research Laboratories 10 Maguire Road Lexington, Mass. 02173		8. Performing Org. Report No. Project 9656
12. Sponsoring Agency Name and Address James Strong, III Goddard Space Flight Center Greenbelt, Maryland 20771		10. Work Unit No.
		11. Contract or Grant No. NAS 5-11475
15. Supplementary Notes		13. Type of Report and Period Covered Final Project Report June 1971-Oct. 1972
		14. Sponsoring Agency Code

16. Abstract

An electrically addressed liquid crystal Fourier plane filter capable of real time optical image processing is described. The filter consists of two parts, a wedge filter having forty 9^{o} segments and a ring filter having twenty concentric rings in a one inch diameter active area. Transmission of the filter in the off (transparent) state exceeds fifty percent. By using polarizing optics, contrast as high as 10^{4}:1 can be achieved at voltages compatible with FET switching technology. A phenomenological model for the dynamic scattering is presented for this special case. The filter is designed to be operated from a computer and is addressed by a seven bit binary word which includes an "on" or "off" command and selects any one of the twenty rings or twenty wedge pairs. The overall system uses addressable latches so that once an element is in a specified state, it will remain there until a change of state command is received. The drive for the liquid crystal filter is $\pm$ 30 V peak at 30 Hz to 70 Hz. These parameters give a rise time for the scattering of 20 msec and a decay time of 80-100 msec. A complete description of the operational parameters of the device will be given and the results of several filtering experiments discussed.

17. Key Words (Selected by Author(s)) liquid crystals - Fourier plane filter Real time optical processing	18. Distribution Statement
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified
21. No. of Pages 57	22. Price 5.25

PREFACE

The objective of this project was to develop an electrically alterable two-dimensional light modulator to be used in the Fourier plane of a coherent optical processor for performing spatial filtering of light images. The filtering device was to consist of a set of electrically controlled wedges and rings (see Figure 3-1) covering an active circular area of about one inch diameter. Each ring and wedge element was to be capable of being set into either an "opaque" or "transparent" state by the application of binary electrical signals. Placing the ring and wedge sections in optical tandem would therefore provide various combinations of filtering patterns. The scope of the work included the development, fabrication, testing and delivery of three liquid crystal ring/wedge filter assemblies and associated filter element selection logic and buffer memory. All of the filters operated in accordance with the work statement (see Section 5-1) and Figures 5-4 and 5-5 give photographic evidence of their ability to perform realtime Fourier plane filtering of coherent images. A number of recommendations were made (see Section 8) which would lead to an improved device in terms of reduced thickness, higher contrast, increased speed of response, and a larger number of addressable ring/wedge segments. These improvements could be made possible by utilizing various new fabrication and addressing techniques currently under development at Itek.

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1. INTRODUCTION

1.1 Electrically Alterable Fourier Plane Filters

The basic requirements for a Fourier plane filter (FPF) are high contrast, uniformity, high transmission and operating speed. The requirements of NASA/Goddard were contrast greater than 100:1, uniformity better than 8 percent, transmission greater than 12 percent, and cycle time less than 100 msec. These parameters were achieved using liquid crystals and appropriate polarizing optics. It has been observed that if the electrode surface is properly prepared, e.g., by scrubbing the surface uniformly in one direction, the molecules all lie parallel and in the plane of the electrode. In this case, the scattering intensity when a voltage is applied is a strong function of the direction of light polarization relative to the direction of the molecular axis for voltages less than 50V/mil. High contrast is achieved when the polarizer and analyzer axes are both parallel with the molecular axis. This is indicated by Figures 5-1 and 5-2. The former shows the contrast as a function of voltage for various polarization conditions while the latter shows the contrast as a function of the f-number of the optical system. The contrast is proportional to the square of the f-number when polarized light is used, and for small (> f/100) collection apertures contrast in excess of 5000:1 is possible. Analysis of the data shows that one plane of polarization is scattered into a cone (half angle 9^{o} at 30V applied) while the other is essentially unaffected at low voltages. However, if high voltages (~100V/mil) are used, the scattering becomes independent of the direction of polarization due to the extreme turbulence introduced by the current flow.

The device structure is shown in cross-section in Figure 1-1. It consists of two pieces of In_2O_3 coated glass which serve as the electrodes with a liquid crystal sandwiched between. A mylar spacer is used to maintain uniform liquid crystal thickness. Optimum thickness, representing the best compromise between ease of fabrication, voltage requirements, and response speed is 0.0005 inch. The device is encapsulated after being filled with liquid crystal at a temperature above the nematic-isotropic

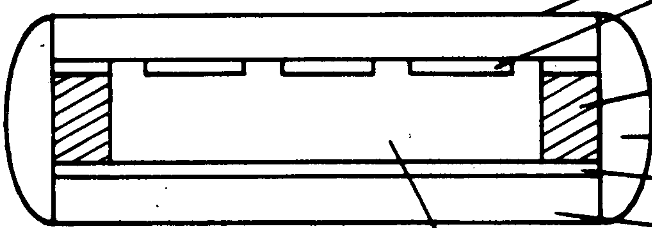

Figure 1-1 - Electrically Addressed Liquid Crystal Display transition. An epoxy which is completely non-reactive with the liquid crystal has been developed for this purpose. It has been found that this technique yields molecular alignment superior to the process of filling the liquid crystal cell after encapsulation.

The NASA FPF's were developed as low voltage devices (22V peak at 30 to 70Hz) specifically to permit use of standard FET switches for addressing. The structure consists of two separate filters as shown in Figure 3-1. The first part has forty 9 degree wedges extending over the active area, each connected to the terminal strip by a continuation of the indium oxide pattern. Each opposing pair of wedges is connected externally. In the active area the gaps between wedges are 0.002 inch. The small gap is advantageous since the scattering of an activated liquid crystal segment extends slightly more than one mil beyond the edge of the electrode. Hence, when two adjoining segments are activated there is no gap between them. The pattern of concentric rings is addressed by removing one 9^{o} segment from the rings and connecting each ring to a 0.002 inch lead also etched in the indium oxide which runs to the terminal strip. A complete ring/wedge filter consists of two devices, each filter having an electrode pattern as one electrode, and a common, uniformly coated indium oxide electrode. Due to this structure which physically separates the ring and wedge patterns, a relatively large depth of field is required, but an f/40 optical system satisfies this requirement. Figure 3-5 shows the completed device.

The device is operated at 22V peak, 30-70Hz A.C. A separate electronic box contains the voltage generator, addressing logic and switches. Addressing is performed by inserting a 7 bit binary code specifying on/off and any one of forty discrete elements. The input is directly computer compatible. The $\pm$ 32VDC and +5VDC power supplies for driving the addressing electronics and A.C. voltage generator are external to the addressing box so that they may be obtained from other voltage sources.

Operating the device under these conditions gives a rise time of approximately 20 msec and a decay time of approximately 80 msec. These times depend upon the ambient temperature. Temperature effects are minimized by using a mixture of methoxybenzylidene-p-n-butylanyline, and butoxybenzylidene-p-n-butylanyline which has a broad temperature range centered at room temperature. This material also has a rapid response time and scatters very efficiently.

1.2 History of Liquid Crystal Work at Itek

A program was initiated at Itek in the fall of 1970 to investigate the general properties of liquid crystals. Commercially available liquid crystal compounds were utilized as a source of material. At the beginning of 1971, this program became oriented toward electrically addressed flat panel displays, particularly the development of 1000 element matrix addressed displays for use in cockpits.

2. LIQUID CRYSTALS, THEORY OF OPERATION

Many organic materials exhibit mesomorphic behavior. In other words, they exhibit one or more stable phases in a temperature range between the melting point of the solid and the point at which the material becomes isotropic. In this range the material can be poured like a liquid but exhibits many of the properties of a crystalline solid, i.e., x-ray diffraction, birefringence, optical activity, etc.

One of the mesomorphic phases, the nematic phase, is of particular interest since it is well known that passage of current through a nematic layer causes scattering of light at voltages above a threshold, typically 5-8V.[1] Further at low voltages, below the scattering threshold, it has been reported that optical activity can be induced.[2] It has been shown in this laboratory that these effects can be combined at voltages above the scattering threshold, typically 25-30V, to give extremely high contrast, up to 1000 to 1.

The contrast of the device is altered in the following manner. Initially in the quiescent state the liquid crystal molecules are aligned along the surface of the electrodes. This is accomplished by stroking the electrode surfaces uniformly in one direction with a cotton swab, and filling the pre-encapsulated device by capillary action at a temperature above the nematic-isotropic transition temperature. On cooling the material returns to the nematic phase and aligns in the direction of stroking. This produces a uniaxial crystal-like layer.

Passage of a small current through the liquid crystal layer, typically 1.0-10.0 $\mu A/cm^2$ at 20-40V causes the liquid crystal to become scattering. At moderate voltages the scattering results from an ordered motion of the liquid crystal, which creates a phase diffraction grating. This effect has previously been observed only at voltages below the scattering threshold. Recent measurements made at Itek have shown that the latter effect becomes large at voltages above the scattering threshold permitting a large enhancement of the contrast if a polarizer is placed in the optical path after the device. The effect is strongly dependent upon the f-number of the optical system as is shown in Figure 5-2. For a contrast of 100:1 an f/20 (1.4° light cone half angle) system is more than adequate while a contrast of 1000:1 is possible using an f/60 optical system. Over the same range, contrast varies between 4.5:1 and 12:1 without the polarizer. These effects are different from the usual results described in the literature using reflective devices. There only scattered light is detected and contrast is determined through measurements of the surface brightness. In that case contrast never exceeds 40:1.

The possibility of using liquid crystals for optical processing was demonstrated recently[3] using a transmissive device but without a contrast enhancing polarizer. Interferometric measurements in this laboratory have shown that light passing through a quiescent liquid crystal remains coherent while the scattered light is incoherent. Hence a system utilizing the scattered light is not feasible even if the contrast requirements could be met. MacAnally's demonstration of matched filtering yielded a contrast ratio of 20:1, typical of transmissive devices operated without the use of polarizers.

To obtain high contrast in the liquid crystal device, the axes of the liquid crystal and of the polarizer are aligned parallel to the direction of polarization of the incoming beam. Thus, in the quiescent state, essentially the only losses are due to reflection at the various interfaces. Typically these would be 4% at each glass/air interface and

25% at the electrodes, yielding a theoretical maximum transmission of 52% ignoring effects of the polarizer. Tests on actual liquid crystal devices show a typical transmission of 30% including the polarizer, implying a transmission in the vicinity of 16% for two devices in tandem utilizing one polarizer.

These materials are advantageous for low power display and modulation applications since they require approximately 50 $\mu W/cm^2$ at 30 V. They do, however, require a certain amount of temperature control since they operate in a range limited by the solid-nematic and nematic-isotropic transition temperatures. Typical temperature ranges are 20-41°C for MBBA (N(p-methoxybenxylidene)-p-n-butylaniline), 80-110°C for APAPA (anasylidine paramino phenyl acetate) and 18-80°C for a compound material manufactured by Liquid Crystal Industries. Materials have been reported which will operate at virtually any temperature from 0°C to 200°C.

The lifetime of these liquid crystal samples is typically greater than 5000 operating hours and due to their low cost replacement at the end of that time is practical. Further, failure is not catastrophic but rather cosmetic. Certain areas cease to scatter and become dark and inactive. This effect can be largely avoided by a-c operation since failure is caused by electrolytic effects at the electrode/liquid crystal interface.

The response time of liquid crystals is currently in the millisecond range. Typical scattering rise times are 10-30 msec and decay times are approximately 100 msec at room temperature. The former is sensitive to temperature, voltage and thickness of the liquid layer, while the latter is dependent primarily upon temperature.

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[1] G. H. Heilmeier, L. A. Zanoni, and L. A. Banton, Proc. IEEE 56, 1162 (1968).
[2] M. Schadt and W. Helfrich, Appl. Phys. Lett. 18, 127 (1971).
[3] R. B. MacAnally, Appl. Phys. Lett. 18, 54 (1971).

3. DEVICE FABRICATION TECHNIQUES

3.1 Photomasks

The photomasks were prepared by Itek's Optical Systems Division using the equipment normally employed in the preparation of high resolution targets and reticles. Rubylith masters for each mask were cut using a precision coordinatograph and reduced 10X for the final photographic mask using a custom built camera system. Because of the large size of the image (2.5 inch by 2.0 inch) and the high resolution (0.002 inch) required some problems with field curvature and resolution were encountered in the outer periphery of the mask, particularly at the coarse alignment crosshairs. However, accuracy to $\pm$ 0.0002 inch was achieved at those points and accuracy better than $\pm$ 0.0001 inch was obtained in the active area of the device. Figure 3-1 shows the electrode patterns used.

3.2 Electrode Fabrication

Indium oxide coated float glass was obtained from PPG Industries and cut to size.

Photofabrication of the indium oxide electrodes was performed by Itek's Measurement Systems Division using standard photoresist techniques.* Initially, Kodak KOR negative working photoresist was used to produce the pattern but it was found that Shipley positive resist gave superior edge definition and resistance to the etching solutions so it was used in the later work. The etchant consisted of HCl and distilled water in the volume ratio of 1:3. To this solution a small amount of aluminum or zinc was added to produce hydrogen required to speed the etching process. The solution must be stirred to give uniform distribution of the hydrogen and provide uniform etching. It was observed that some nonuniformity in the etch developed occasionally despite this precaution. It is known that small variations in the crystal structure and stoichiometry of the indium oxide can cause variations in the etch rate. It is believed that this is the problem, but it was not possible to make any verification due to the very small crystallite size of the coating which made detection by x-ray or reflection electron diffraction impossible.

*An outside vendor was also employed to develop an improved technique for indium oxide electrode fabrication.

B

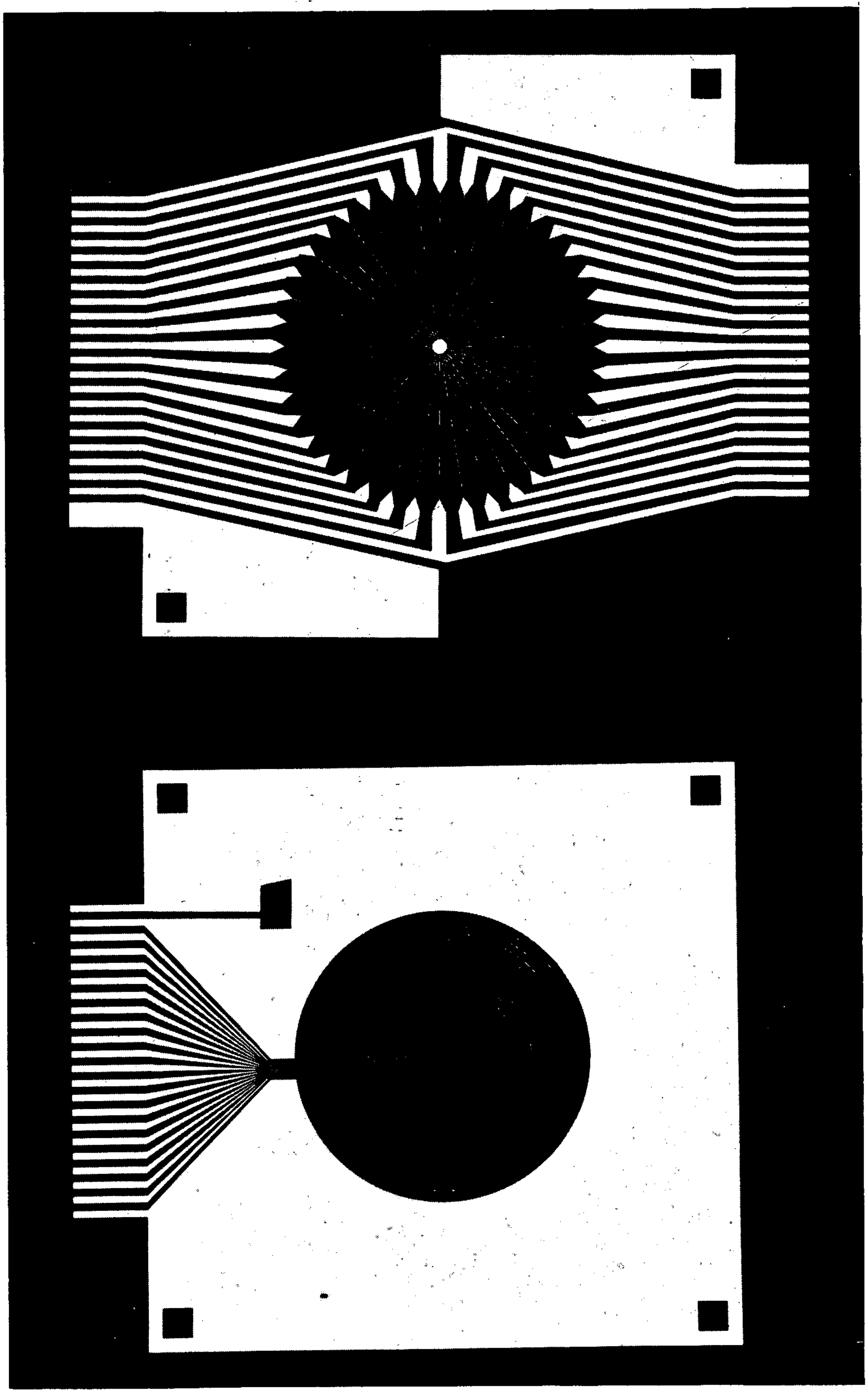

Figure 3-1 - FPF Electrode Patterns

The initial design called for 360 degree rings with a photoresist insulation pattern overcoated with an aluminum lead for connection to the initial rings. This required alignment of three masks to a precision of $\pm$ 0.0005 inch. A vacuum mask aligner was built for this purpose. Motion in two directions and angular rotation were provided by precision threaded screws. A worm gear drive was used for the rotational motion. The aligner casing was built completely of plexiglass to provide the light transmission required. Alignment was accomplished by means of four reference marks, one in each corner of each mask. It was found that a collimated, monochromatic light source produced a diffraction pattern which was highly sensitive to the position of the reference masks on the work plate and exposure mask facilitating the alignment.

Typical fabrication procedure is as follows. The initial electrode pattern is etched into the indium oxide. Only this step is required for the wedge pattern. The ring pattern is then coated with a thick (0.0005 inch) layer of photoresist and exposed to produce the ring blocking pattern. A layer of aluminum, typically 700 Å, is evaporated over the entire plate and the ring electrode leads are fabricated on the photoresist stripes. Two problems were encountered in this procedure. Although the resist adhered very well to the indium oxide, it had a tendency to peel off the clear glass areas in the cleaning bath required for adherence of the aluminum. In addition, crazing of the resist stripes was observed both before and after evaporation of the aluminum layer. These problems are discussed in more detail below. For these reasons, this approach was abandoned and a ring electrode pattern having a 351 degree active area with one nine degree segment removed for leads was used in the final device. Fabrication of this electrode pattern is a single step process identical with the wedge electrode pattern.

3.3 Liquid Crystal Compounds

Two liquid crystal materials have been used in the Fourier plane filters. One is methoxybenzylidene-p-n-butylanaline (MBBA) with a nematic temperature range of 21° - 45° C. The other is a mixture of 55 percent MBBA and 45 percent butoxy benzylidene-p-n-butylanaline (BBBA). The latter has a wider nematic range extending from below room temperature to approximately 58°C. There is no detectable difference between these materials in terms of scattering intensity, however, the pure MBBA is approximately ten percent faster in rise time at a given resistivity, e.g., $10^{10}\ \Omega$-cm. Both have comparable decay times typically 90 msec for a 0.5 mil sample and 150 - 200 msec for a 1.0 mil sample.

The liquid crystalline materials are prepared in-house in order to maintain control over their purity. Typically, in the case of MBBA, equimolar portions of butylanaline and anisaldehyde are mixed and refluxed with benzene in a Dean-Stark trap until the reaction is complete. The mixture is then placed in a vacuum distillation apparatus and distilled until the resistivity of the nematic fraction exceeds $5 \times 10^{10}\ \Omega$-cm. Normally, two distillations are sufficient. The resultant material is then transferred immediately to an evacuated container by means of a hypodermic syringe and stored until used.

Curves of the scattering rise time versus voltage are shown in Figure 3-2 . The scattering occurs in two stages. For a short time after the voltage is applied, there is no scattering observed (Figure 3-2 a) . This is the time in which the local space charge builds up to the threshold of hydrodynamic instability. Figure 3-2 b shows the rise time of the scattering as a function of voltage with the t = 0 point taken at the time the voltage is applied. The rise time is proportional to $1/E^2$ and depends upon the resistivity although not in a simple fashion (Figure 3-3) . The decay time depends somewhat on the applied voltage but these effects are rather small(Figure 3-4).

3.4 Cell Fabrication

Cell fabrication is the most critical step in building the device. The following is a work schedule detailing the step by step fabrication procedure:

1. Check all electrode elements for internal shorts. Occasionally, shorts can be opened with a brief wash in an etching bath without affecting the pattern.
2. Make a crude LC sandwich with the electrode pattern and a common electrode and check each element for continuity and uniformity. This test is normally performed at 22VDC.
3. Disassemble the sandwich and clean the electrodes preparatory to fabrication as follows:

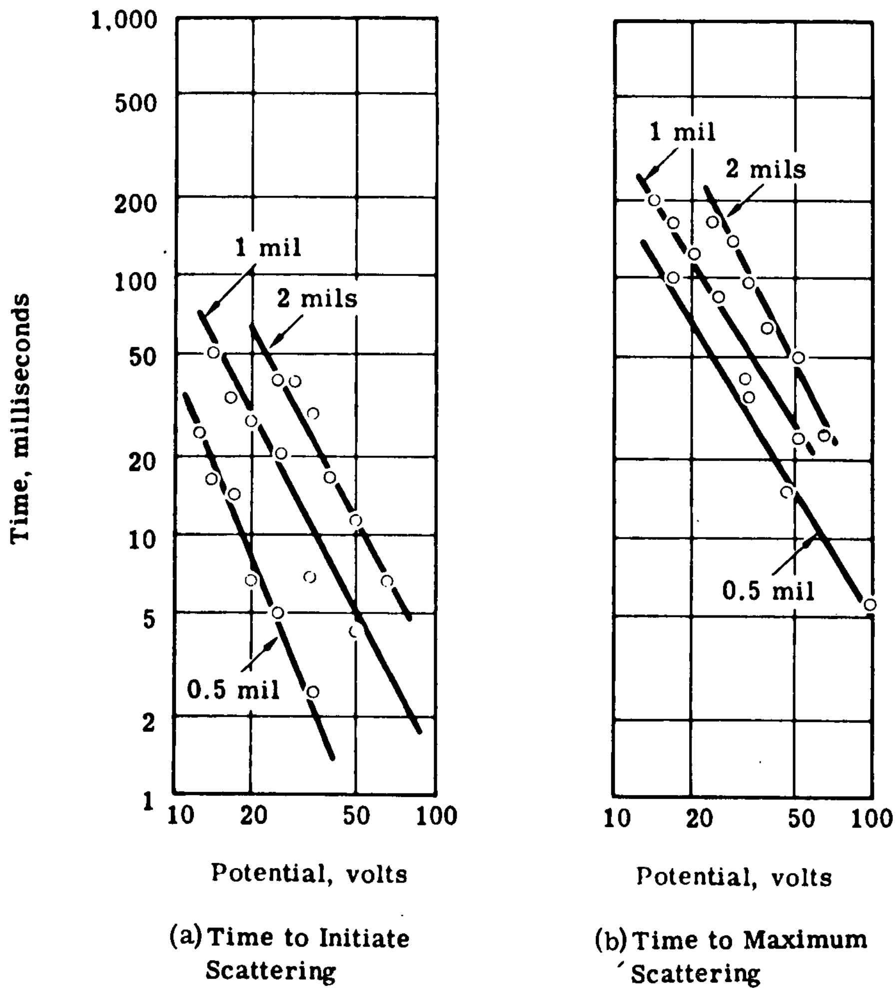

Figure 3-2 - Rise Time of MBBA at 25°C

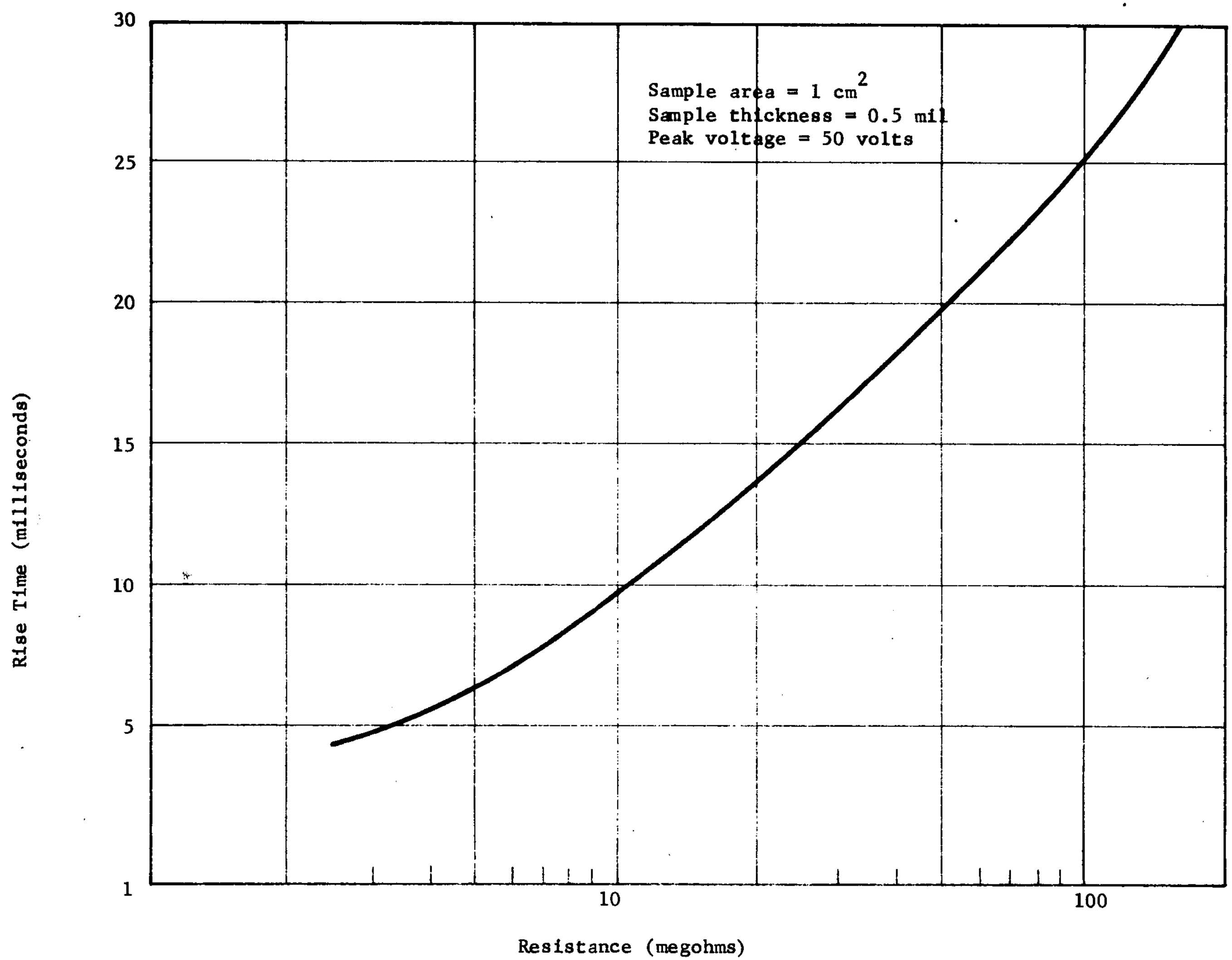

Figure 3-3 - Rise Time of MBBA Versus Resistance

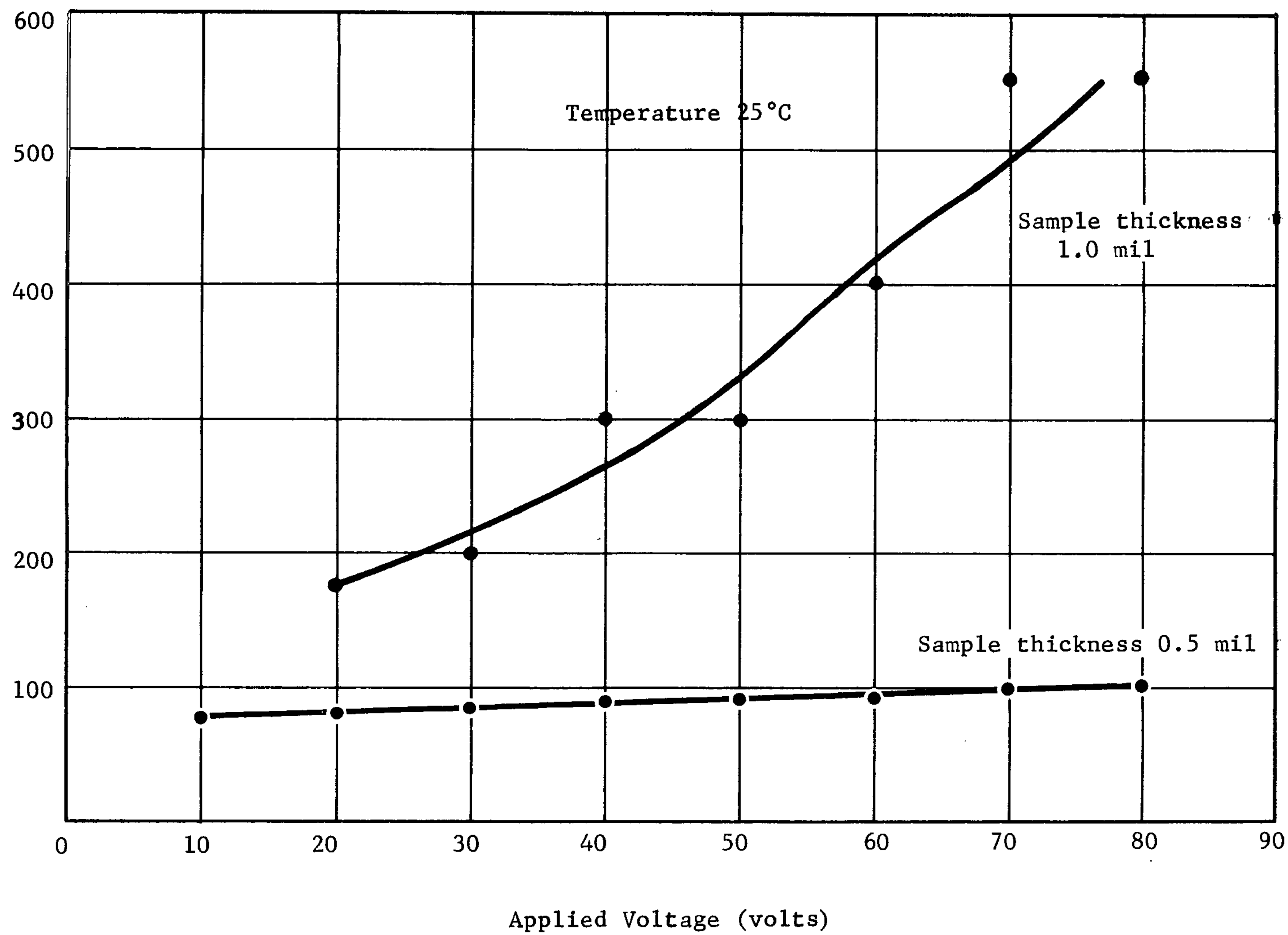

Figure 3-4 - Scattering Decay in MBBA Versus Applied Voltage

a. wash thoroughly in isopropyl alcohol to remove all traces of the L.C.

b. wash in chromic acid for fifteen seconds

c. rinse in deionized water. If the water does not wet the surface repeat steps b and c.

d. rinse in electronic grade isopropyl alcohol which has not been exposed to moisture contamination.

e. dry in a warm air stream.

4. Cut a mylar spacer to the appropriate dimensions, and rinse in isopropyl alcohol to remove dust and any static charge.

5. Place both glass plates and the liquid crystal on a hot stage and heat above the L.C. isotropic transition temperature.

6. Using a cotton swab, rub both electrodes uniformly in one direction to create the conditions required for parallel molecular alignment.

7. Position the mylar spacer on the electrode pattern.

8. Pour the isotropic liquid crystal on the electrode and complete the sandwich with the common electrode.

9. Clamp the device, remove the heat, and allow the sample to cool.

10. Clean off excess L.C. with a cotton swab damp with isopropyl alcohol.

11. Check device visually for uniform transparency in the active region.

12. Test each element at 22 VDC for uniform scattering and lack of shorts.

13. Encapsulate the unclamped edges of the device with Conap K-230 epoxy, move the clamps to the encapsulated edges and complete encapsulation of the four sides.

14. Do not remove the clamps until the epoxy is completely cured; at least twelve hours.

3.5 Mechanical Assembly

The ring filter and wedge filter are first cemented together. This is done using a slow drying cement and a spacer to avoid interference fringes from two glass surfaces in contact. The two devices are aligned approximately using the alignment marks in the corners of the glass. Then the device is placed in a 12X monocular vertical viewing microscope and viewed in transmitted yellow light from directly below. This makes the wedge and ring electrode patterns visible. Cement is now applied to the edges of the devices and the top device is positioned over the bottom using a micromanipulator so that the inner ends of the wedges match the gap between the first and second rings. This operation requires that the light source, microscope and centers of the filter all be colinear. The mated filter is now held in position until the cement is set.

Two mechanical mounts were used during this project. Both are based on the Kinematic 275-OB-O carrier*. The first filters were delivered in a demountable holder (Figure 3-5). Tykon+ 255-25-30-190 printed circuit edge connectors were used to make electrical contact to the device and to provide the mounting support. Later, filters were hard wired (Fig. 3-6) since it was felt that greater mechanical stability was desirable. In this case, the filter is cemented to an aluminum backing plate and electrical contact is made to a terminal strip with #36 enameled copper wire. The wires are led from the terminals to the device and cemented in place using a high resistance epoxy. Electrical contact is made by a dot of silver filled epoxy (Eccobond 56C or Technit 72-00008) joining the tip of the wire to the indium oxide electrode (Figure 3-6). A plastic cover plate is then placed over the outer portion of the filter to protect the wires.

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*Ardel Instrument Company

+Cinch Manufacturing Company

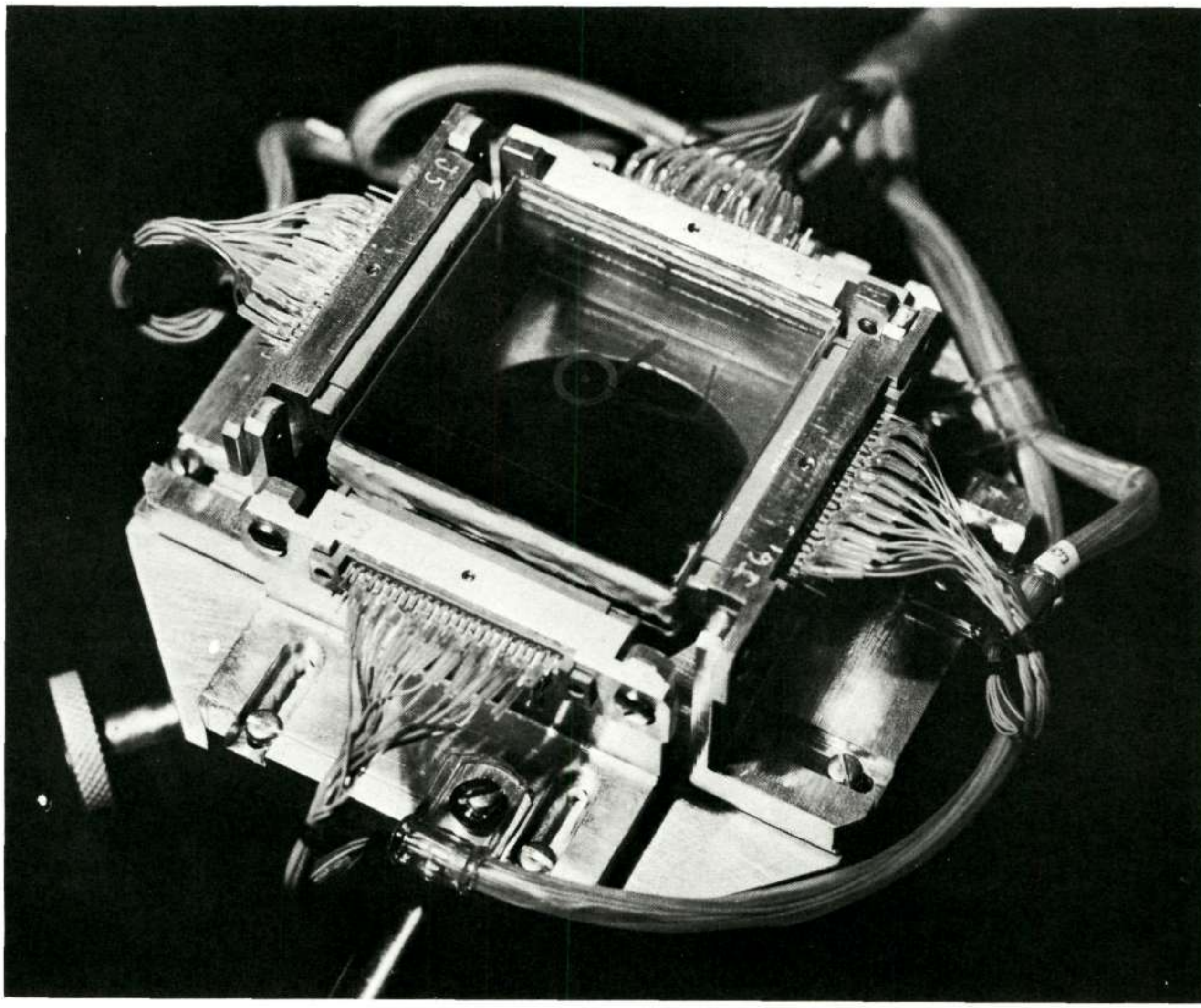

Figure 3-5 - Fourier Plane Filter in Demountable Holder

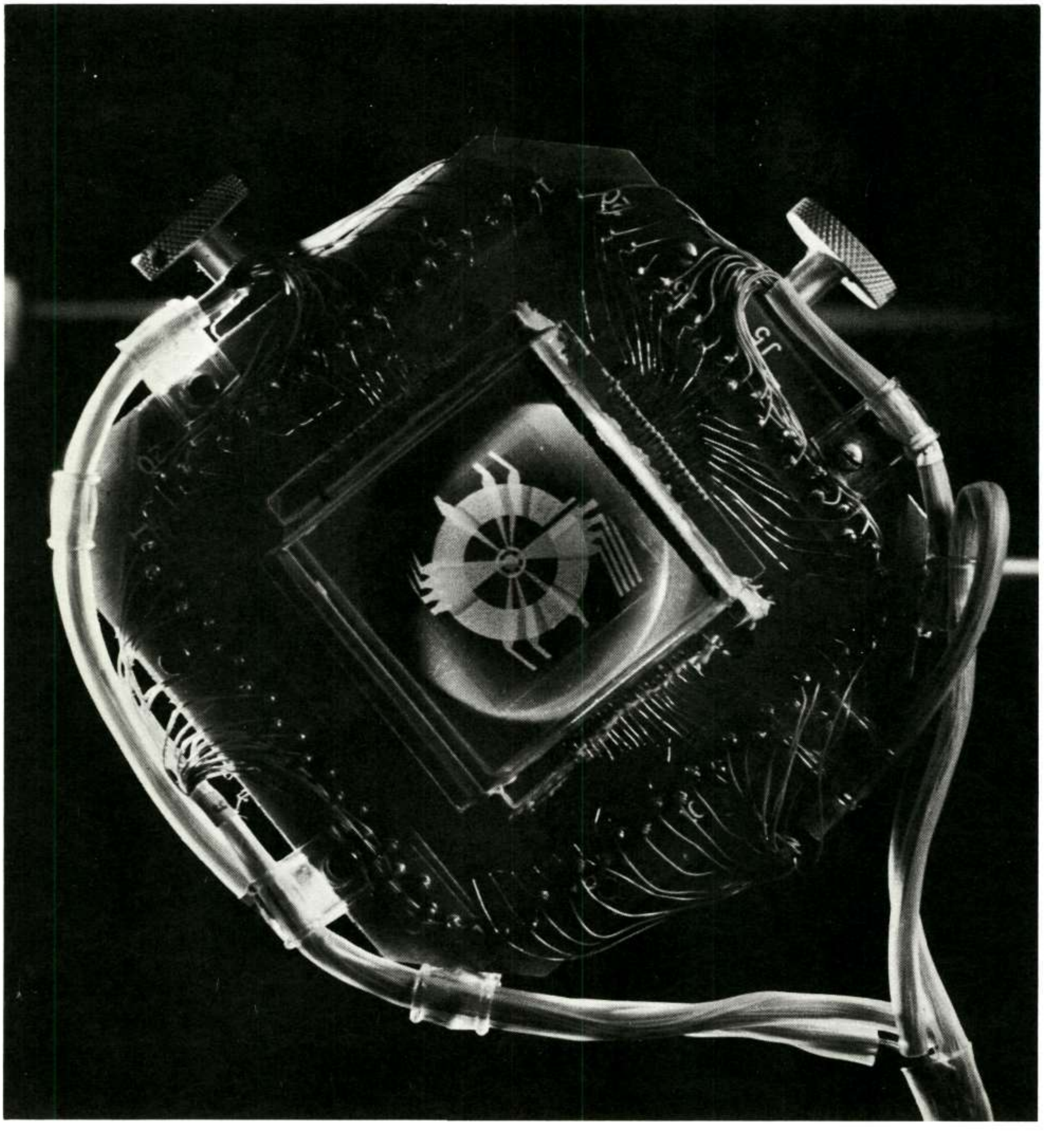

Figure 3-6 - Hard Wired Fourier Plane Filter

3.6 Device Testing

As described above, initial device testing is carried out during fabrication. That is to crudely evaluate the device before proceeding with encapsulation and assembly. Once the device is complete the following tests are performed:

1. The resistance of each element is tested to be certain that it exceeds 10^6 ohms.

2. All elements are operated at $\pm$ 60V, 60 Hz for at least one hour.

3. Contrast greater than 100 and transmission uniformity are measured by moving the active device mechanically across a laser beam and measuring the light output.

4. Simple filtering operations (activating various rings and wedges) are performed at f/40 on a triangle and a 200 mesh screen to test for cross talk and contrast.

Total operating time for the filter in this test program is in excess of twenty hours. If no problems, e.g., shorts or opens, appear in that time and the filter passes the tests outlined above, the device is deemed acceptable.

4. SELECTION LOGIC AND BUFFER MEMORY

The selection and driving functions for the liquid crystal elements were accomplished on two custom designed printed circuit boards. Board #1, "LIC SEL" Itek Number 9656-112 contains the decoding and memory portions of the digital logic. Board type #2, "LIC SW" Itek Number 9656-111, contains the switching circuitry turn "on" or "off" the liquid crystal. A sinusoidal signal, +25 volts to -25 volts (peak to peak) at 60HZ is applied to induce scattering in the liquid crystal element.

Input data lines and power supply lines are brought in on J2-(Winchester Connector, Type MRAC, 20 pin). Output leads are brought out on J1-(Winchester Connector, Type MRAC, 66 pin). Information flow is designated on Itek drawing (SK112877-2E) "Fourier Plane Filter Wire Routing" (Figure 4-1).

4.1 "LIC SEL" Board Description (Reference Drawing Element Select SK112877-3E) "Figure 4-2)

Input data lines are negative true logic, that is "1" = ground level, "0" = +5 volt level. Bits 0 thru 5 are address bits for a total of 64 possible selections, although only 40 are used in the Fourier Plane Filter application. All data inputs should be DTL-TTL compatible. Each input represents one TTL load to the driving source.

Memory is achieved by using Fairchild's 9334. The 9334 is an 8-bit addressable latch with active high outputs. There are four possible modes of operating the addressable latch.

1. With the "strobe" line (J2-pin K) at ground, the addressed element will follow the "Data Bit, Bit 6 (J2-pin H)" while all non-addressed elements remain in their previous states.

2. With the "strobe" line up at +5.0 volts, and the "C" input (J2-pin J) up at +5.0 volts, all elements remain in their previous state and are unaffected by the address inputs.

FOLDOUT FRAME

FOLDOUT FRAME

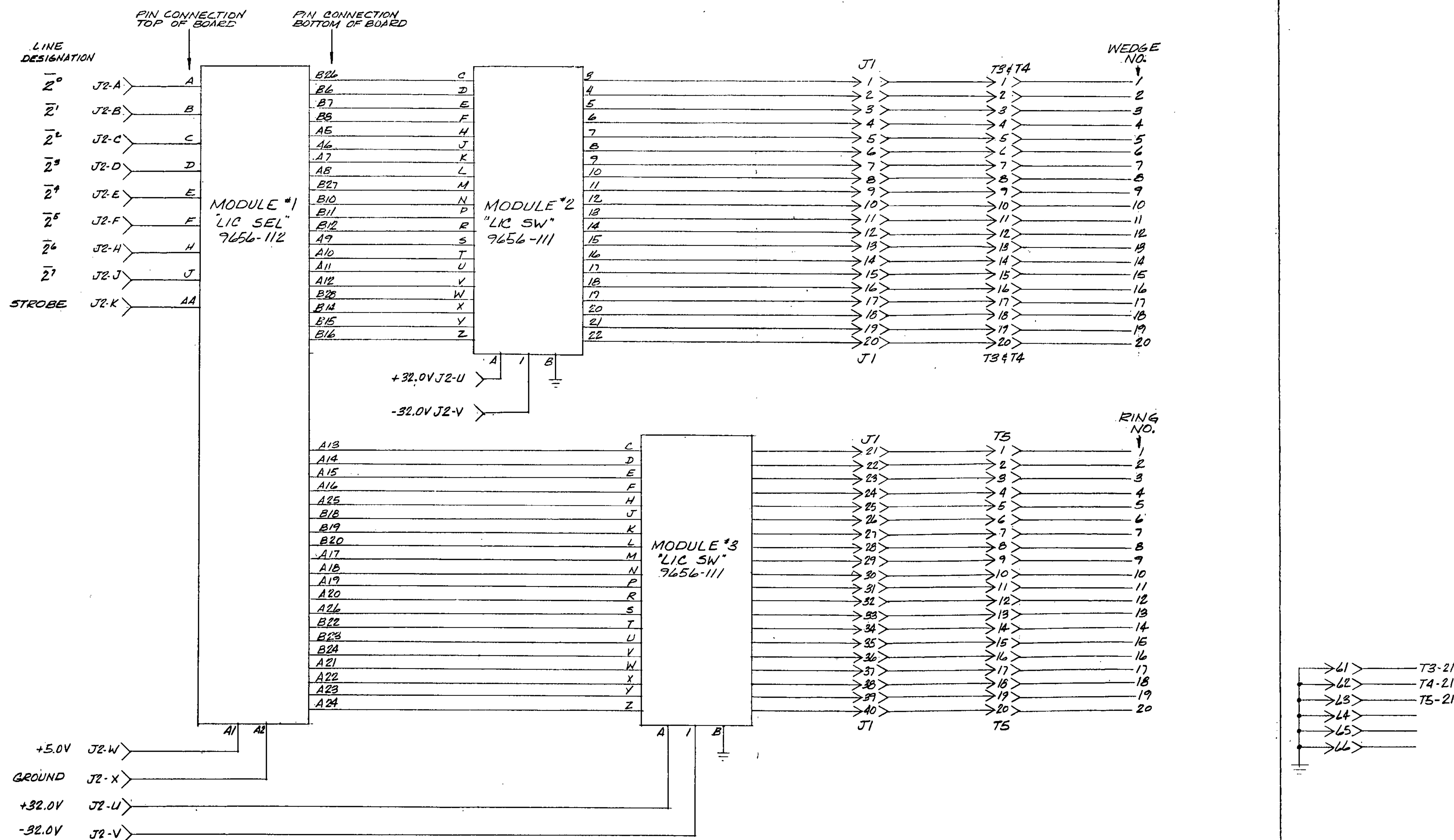

Figure 4-1 - Fourier Plane Filter Wire Routing

C

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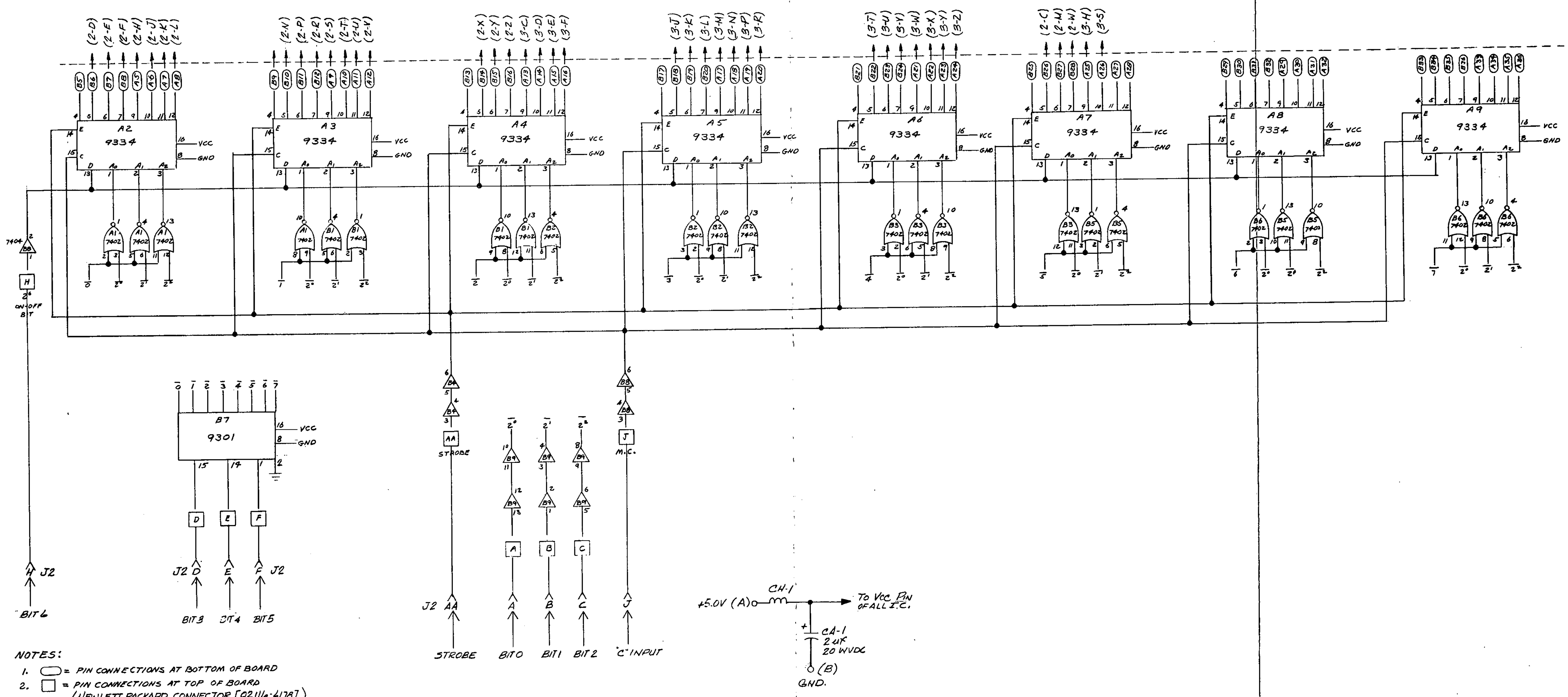

Figure 4-2 - Element Selection Logic

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FOLDOUT FRAME 1

FOLDOUT FRAME 2

3. When the strobe line is grounded and the "C" line is grounded, the selected output will follow the state of the "Data Bit", with all other outputs in the logical zero state. (The logical zero state, at this level, causes the liquid crystals to scatter.)

4. If the "C" line is held at a ground level and the strobe line is at +5.0 volts, all outputs are forced to the logical zero state and are unaffected by the address inputs.

Bits 3, 4, and 5 are decoded by Fairchild I. C. Chip 9301. The A_3 input is held low so the device serves as a one of eight decoder.

Maximum propagation delay for information transfer to the driving logic is 65 nanoseconds. Information is transferred on the fall of the strobe line and on the fall of the "C" line.

4.2 "LIC SW" Board Description

(Reference Drawing "Liquid Crystal Drive Circuit" #SK112877-4E) (Figure 4-3)

Analog Devices operational amplifier AD 741K (part number OA-1) is used in a Wein Bridge configuration for the 60HZ sinusoidal signal and operational amplifier OA-2 shifts the phase by 180 degrees. A one stage transistor amplifier increases the peak to peak to 50 volts for each signal. Transistors Q84 and Q85 are used as common emitter amplifiers to drive a maximum 20 FET's. Provisions are made by means of standoffs to apply a 60Hz sine wave or its 180° counterpart to the source terminal of the FET (2N464).

There are 20 analog FET swtiches on each board. Input logic levels are ground and +3.5 volts. When the input is +3.5 volts transistor Q1 is turned on, transistor Q21 is turned on allowing +32V to be applied to the gate of the FET. Positive 32 volts applied will pinch off the FET shutting off the sinusoidal to the liquid crystal. If the input signal is at ground transistor Q41 and Q61 are turned on applying a -32v level to the FET gate allowing the full oscillator signal to be applied to the liquid crystal element. Tables follow which designate the interface connector pin usage and the Fourier Plane Filter element address codes.

Pin	Function
J2-A	Bit 0
J2-B	Bit 1
J2-C	Bit 2
J2-D	Bit 3
J2-E	Bit 4
J2-F	Bit 5
J2-H	Bit 6 - Data Bit
J2-J	"C" Input
J2-K	Strobe
J2-L	N.C.
J2-M	N.C.
J2-N	N.C.
J2-P	N.C.
J2-R	N.C.
J2-5	N.C.
J2-T	N.C.
J2-U	+32V D.C.
J2-V	-32V D.C.
J2-W	+5V D.C.
J2-X	Ground

Table 4-1 Computer Interface Connector Use Designation

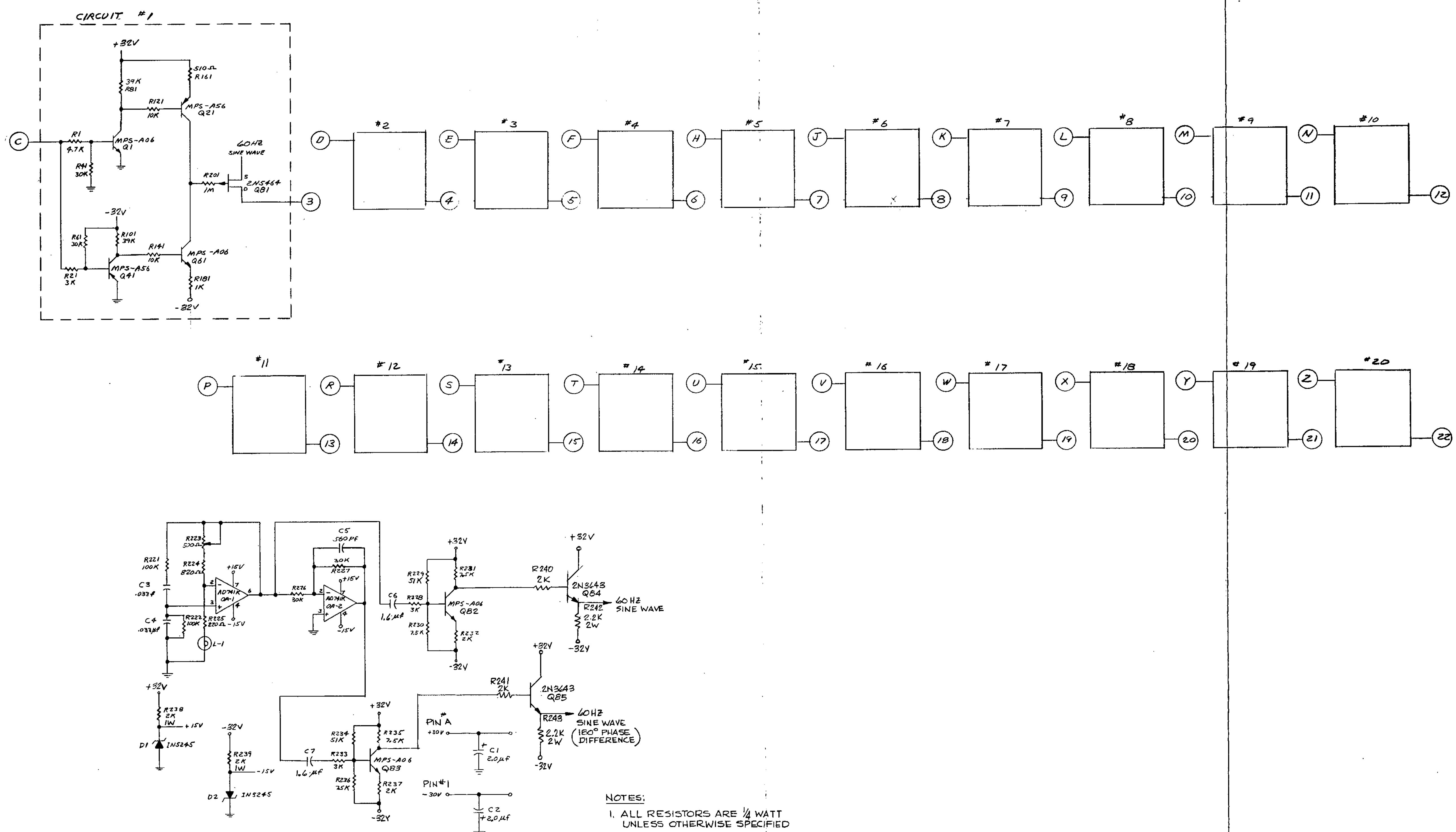


Figure 4-3 - Liquid Crystal Drive Circuit

FOLDOUT FRAME 1

FOLDOUT FRAME 2

Bits						
5	4	3	2	1	0	Element
1	0	1	1	0	0	Ring #1
1	0	1	1	0	1	Ring #2
1	0	1	1	1	0	Ring #3
1	0	1	1	1	1	Ring #4
0	1	0	1	0	0	Ring #5
1	0	0	0	0	1	Ring #6
1	0	0	0	1	0	Ring #7
1	0	0	0	1	1	Ring #8
1	0	0	1	0	0	Ring #9
1	0	0	1	0	1	Ring #10
1	0	0	1	1	0	Ring #11
1	0	0	1	1	1	Ring #12
0	1	0	1	0	1	Ring #13
0	1	1	0	0	1	Ring #14
0	1	1	0	1	0	Ring #15
0	1	1	0	1	1	Ring #16
0	1	1	1	0	0	Ring #17
0	1	1	1	0	1	Ring #18
0	1	1	1	1	0	Ring #19
0	1	1	1	1	1	Ring #20

"1" - Ground Level

"0" - +5 volt Level

Table 4-2 FPF Ring Element Designation Codes

		Bits				
5	4	3	2	1	0	Element
0	1	0	0	0	1	Wedge #1
1	1	1	0	0	1	Wedge #2
1	1	1	0	1	0	Wedge #3
1	1	1	0	1	1	Wedge #4
1	1	1	1	0	0	Wedge #5
1	1	1	1	0	1	Wedge #6
1	1	1	1	1	0	Wedge #7
1	1	1	1	1	1	Wedge #8
0	1	0	0	1	0	Wedge #9
1	1	0	0	0	1	Wedge #10
1	1	0	0	1	0	Wedge #11
1	1	0	0	1	1	Wedge #12
1	1	0	1	0	0	Wedge #13
1	1	0	1	0	1	Wedge #14
1	1	0	1	1	0	Wedge #15
1	1	0	1	1	1	Wedge #16
0	1	0	0	1	1	Wedge #17
1	0	1	0	0	1	Wedge #18
1	0	1	0	1	0	Wedge #19
1	0	1	0	1	1	Wedge #20

"1" - Ground Level

"0" - +5 volt Level

Table 4-3 FPF Wedge Element Designation Codes

J1 - 66 Pin MRAC Winchester Connector - Logic/Filter Interface

J2 - 20 Pin MRAC Winchester Connector - Computer/Logic Interface (Table 4-1)

P.C. Conn. #1 - 72 Pin Elco - Itek P.C. Board "LIC SEL" (Figure 4-2)

P.C. Conn. #2 - 44 Pin Hirose - Itek P.C. Board "LIC SW" (Figure 4-3)

P.C. Conn. #3 - 44 Pin Hirose - Itek P.C. Board "LIC SW" (Figure 4-3)

P.C. Conn. #4 - 44 Pin Hirose - Spare

Note: On P.C. Conn. # 2, 3, and 4, every fifth pin on the numbered side is marked in red (i.e., 5, 10, 15, 20)

Table 4-4 - Connector Type and Use Designation

5. FOURIER PLANE FILTER SYSTEM

5.1 System Requirements

The following are the specifications of the original RFP.

1. The filter consists of two elements, a ring filter having twenty concentric rings on a one inch diameter and a wedge filter having forty 9° wedges on the same diameter. The inner 0.050 inch diameter of the wedge filter is clear. It is desirable that the filters be mounted as closely as possible.

2. Any area within the one inch diameter active area which is not capable of activation must be opaque.

3. The off-state transmission of the filters in combination must exceed 12.5 percent.

4. The off-state transmission must be uniform to ± 8 percent over the active area.

5. The on-state transmission must be less than 0.01 of the off-state transmission at each point on the device.

6. Cycle time of the filter must be less than 0.5 second.

7. The mean optical path difference between any two areas of the filter must be less than 19μm.

8. Lifetime is unspecified.

9. A memory is desirable, i.e., elements should be able to be set in the "on" or "off" state and remain in that state indefinitely.

10. Power and voltage should be minimized.

The system specifications were met in the following fashion.

1. The filter consists of electrodes etched into indium oxide coated glass plates, each wedge and ring pattern having its own common electrode. Separation of the active liquid crystal portions of the mated filters is approximately 6.2 mm.

2. Since the resolution of the liquid crystal in a scattering mode is somewhat less than 0.001 inch, it is possible to dispense with blocking patterns in the active area with the 0.002 inch interelectrode gaps used. If two adjoining elements are excited the effect is identical to exciting a single element having twice the extent. This effect was discovered during the project and provided a great simplification to the fabrication procedure.

3. The transmission of each liquid crystal filter is approximately 0.7. In addition, a sheet polarizer having a maximum transmission of roughly 0.5 is required. Thus, transmission of a complete filter in the off-state is 0.25 $\pm$ 0.1.

4. The critical factor in off-state transmission uniformity is production of uniform orientation of the liquid crystal molecules. This is accomplished by stroking the electrodes uniformly in one direction. When this is carefully done, transmission uniformity of $\pm$ 5 percent can be achieved. The primary cause for variation in transmission is variation in the thickness of the indium oxide and the small increase in transmission in passing over an interelectrode gap.

5. The on-state transmission is determined by the applied voltage and the collection aperture of the optical system since the LC is a light scatterer. The original system operated at $\pm$ 22V, 60Hz with an f/40 optical system. A contrast of 100:1 can be achieved in this way as is shown by Figures 5-1 and 5-2. However, due to the brightness of the central spot, even higher contrast is desirable. This can be achieved by using higher voltages and the last two filter sets were built to accommodate this requirement. Liquid crystal thickness was increased from 0.5 mil to 1.0 mil and the devices were tested at $\pm$ 60V, 60Hz. It is probable that these devices could be operated at $\pm$ 100V although with sharply reduced lifetime.

6. Cycle time of the filter is determined by the scattering rise and decay times. The rise time varies as E^{-2} and is typically 20 msec at the voltages used. The decay time is primarily a function of viscosity and thickness provided the voltage is applied for a time long compared to the rise time. Typical values are 80 - 100 msec for a 0.5 mil device and 150 - 200 msec for a 1.0 mil device.

7. Typical nonuniformity in the optical path difference is summarized below:

a. glass thickness $\pm$ 3 µm (4 layers)
b. liquid crystal thickness $\pm$ 1µm (2 layers)
c. gap between filters $\pm$ 1µm

This gives a maximum nonuniformity of $\pm$ 15µm. In actuality, the nonuniformities are not additive and typical results indicate a nonuniformity of 10 to 12 µm.

1-MIL MBBA, f/40

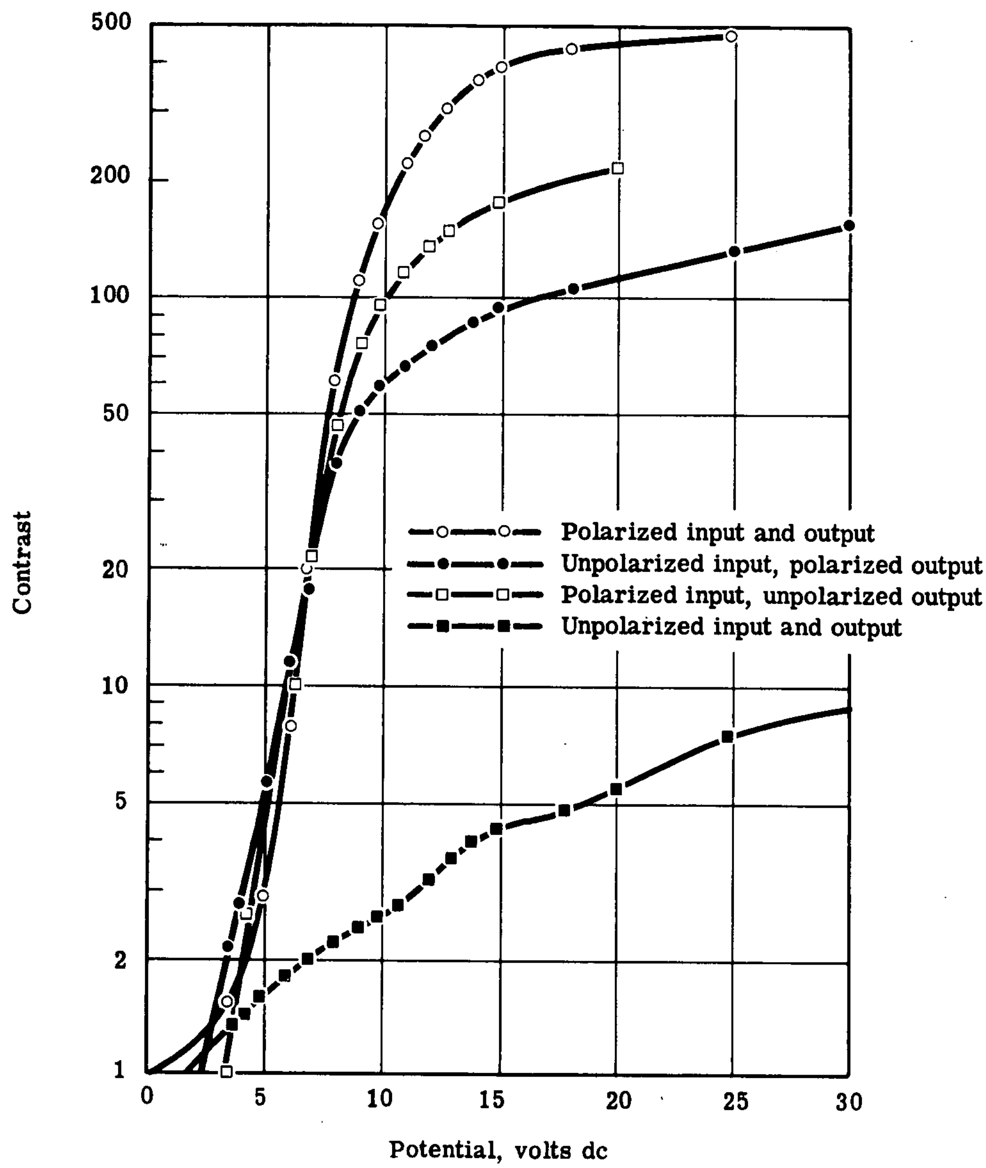


Figure 5-1 - Contrast Versus Voltage - Light on Axis

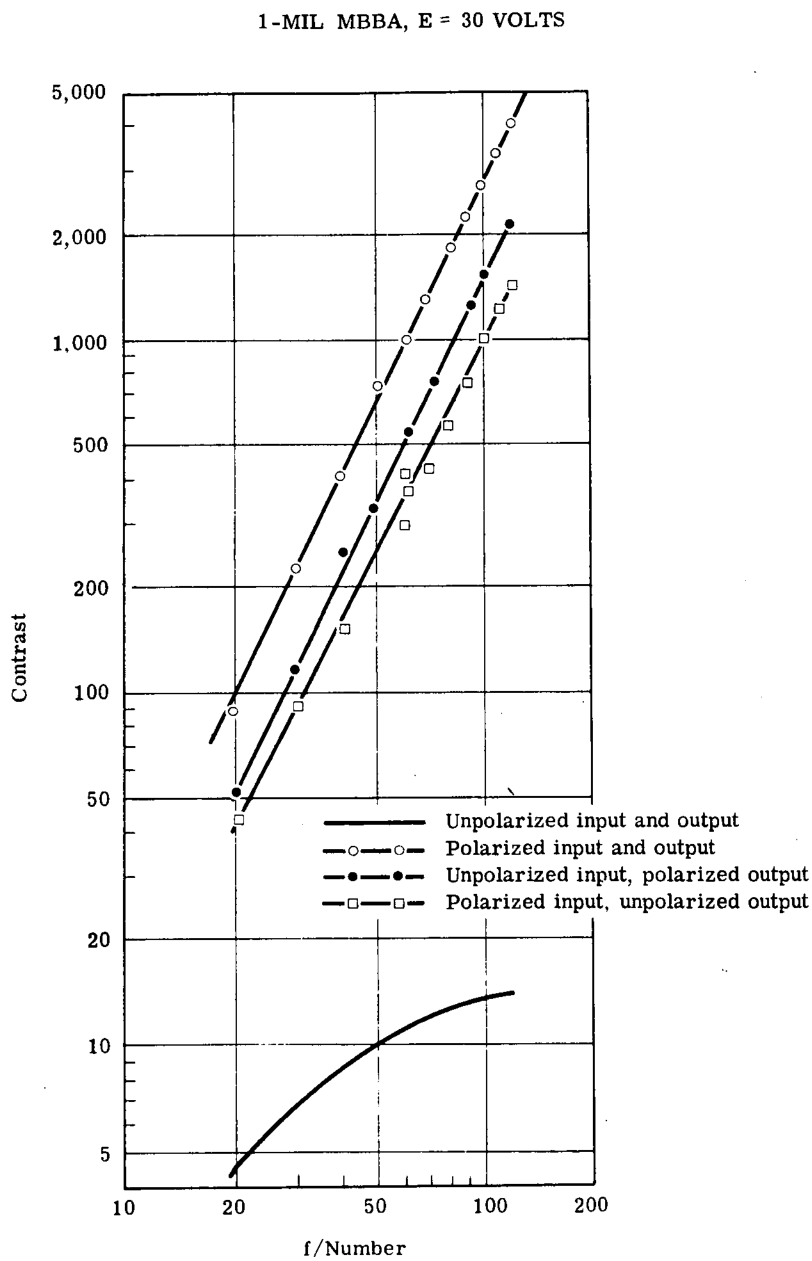


Figure 5-2 - Contrast Versus f/number

8. Lifetime of the device depends critically on the operating voltage. In general, D.C. operation will cause device degradation in 50 - 300 hours depending on the voltage applied. However, use of an A.C. voltage gives vastly improved life and is the driving voltage used. Operating times of encapsulated A.C. operated devices exceed 1000 hours. of continuous operation. It should also be pointed out that a determination of lifetime is largely subjective. The primary effect is that the device responds more slowly and exhibits reduced contrast. A secondary effect is the appearance of nonscattering blemishes in the active area but this occurs much later. Exactly where one chooses to fix a point for determining lifetime is thus indeterminate. The normal point chosen in this laboratory is the initial appearance of blemishes.

9. Memory is achieved electronically in the device addressing. Once an element is activated or deactivated, the electronics latch in that state until a change-of-state command is received.

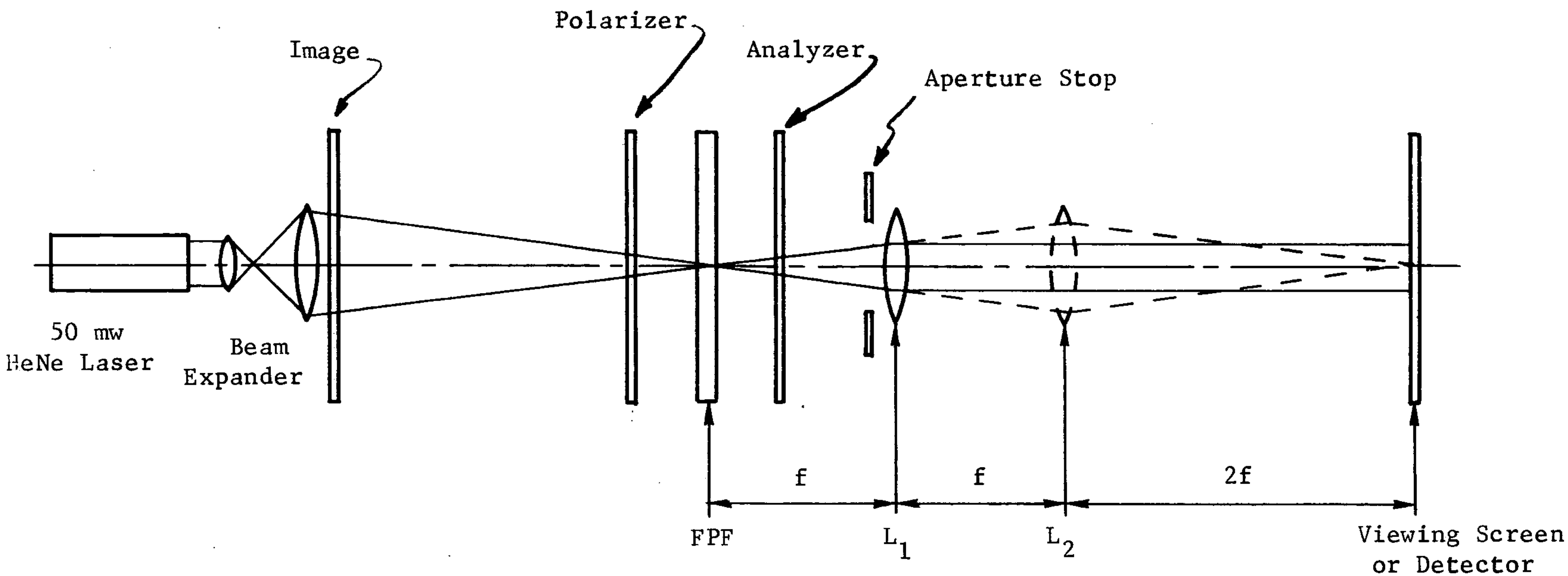
10. The electronic system is discussed elsewhere.

5.2 Optical Apparatus (Figure 5-3).

The optical apparatus used for testing the filter is composed of a He-Ne laser, a beam expander which gives a one inch diameter beam, polarizer, analyzer, photodetector and various lenses which permit reimaging of the Fourier plane or the image plane. The photodetector, an EG&G radiometer, is used only to test contrast and uniformity. During filtering tests, a viewing screen or polaroid camera back is placed at either the Fourier plane, the image plane, or frequently a general Fresnel plane. The latter is useful since the various diffraction orders of the image are visible as multiple images and one can thereby test the efficiency of the ring filter while viewing an image rather than its Fourier transform. The FPF is located in the Fourier plane between the polarizer and analyzer. The position of the polarizers in the system is not significant.

5.3 Filtering Performance Tests

Initially, the polarizer and analyzer are aligned to give maximum transmission through the optical system. The filter is then inserted with the liquid crystal molecular axis (the long dimension of the wedge filter) parallel to the direction of light polarization. The filter and/or polarizers are then fine adjusted to give maximum contrast determined by switching the entire array on and off.

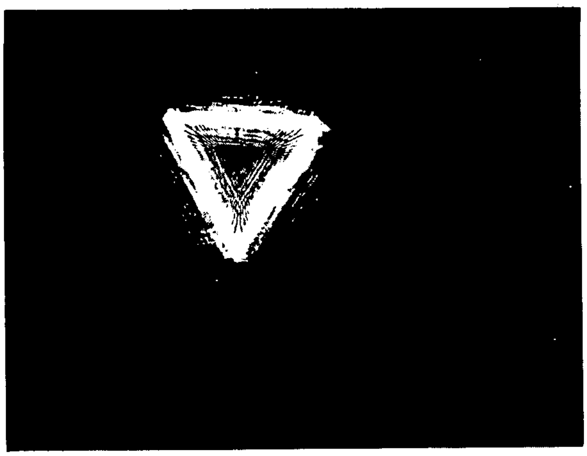


Lens L_1 produces reconstructed image on viewing screen

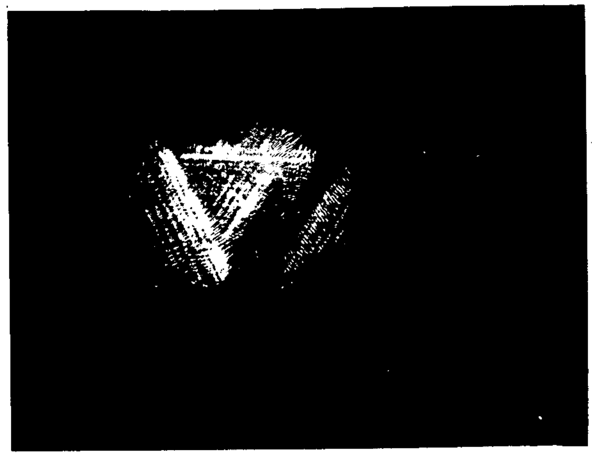
Lens L_2 produces Fourier transform of image on viewing screen

Figure 5-3 - Optical Apparatus for Performance Testing FPF

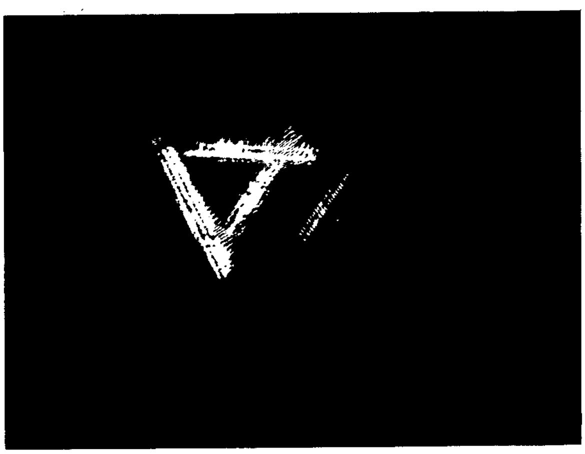
Typical filtering tests involve operations on square grids, triangles, bar targets at varying angles, and grids containing several different sets of lines having different spacings and orientations. Figures 5-4 and 5-5 show typical results of the filtering operations. The first shows the effect of a series of operations on a triangle viewed in a fresnel plane, and the second the effect of filtering a 10 l/mm square grid as seen in the image of the Fourier plane. The former demonstrates the desirability of higher contrast in the central spot. Final contrast testing is accomplished by looking at various orders of the Fourier transform of a square grid. If the photodetector records an intensity change of 100:1 when either the ring or wedge blocking that spot is activated, the device is considered acceptable.



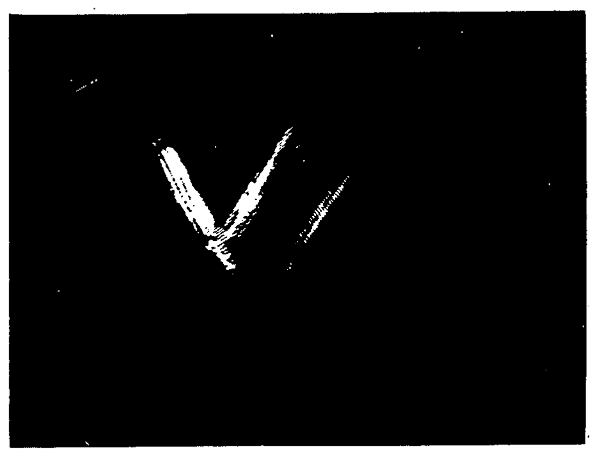
a. Triangle unfiltered



b. Triangle with zero diffraction order removed

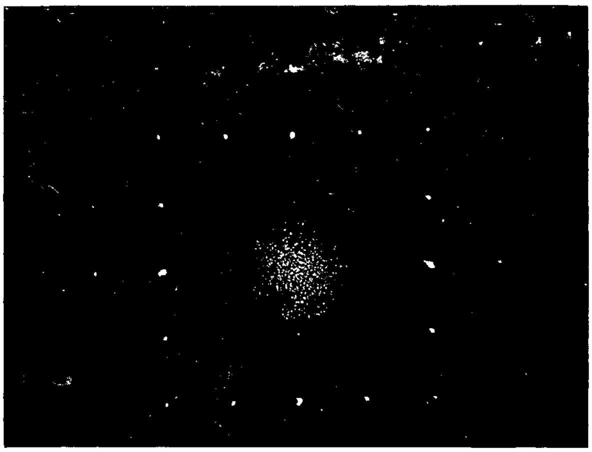


c. Triangle with higher diffraction orders removed



d. Triangle with vertical axis of Fourier transform blocked

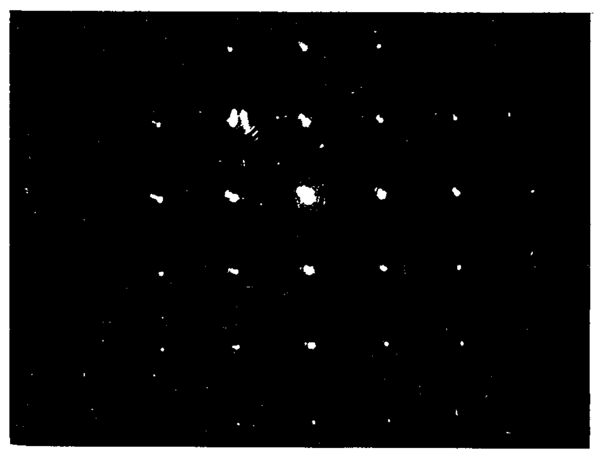
Figure 5-4 - Filtering of Low Resolution Triangle, Fresnel Plane Image



a. 200 mesh grid

b. 200 mesh grid with zero order removed

c. 200 mesh grid with 1st orders removed



d. 200 mesh grid with zero and 1st orders removed

Figure 5-5 - Filtering of 10-Line-per-Millimeter Rectangular Grid, Fourier Plane Image

6. PROBLEMS ENCOUNTERED

6.1 Photofabrication Problems

A major photofabrication problem was encountered which caused a significant change in the device design. That was the inability (with our current apparatus) to obtain electrically insulating photoresist layers. The original device concept called for a 360° ring pattern to be etched into the transparent indium oxide coating on the glass slide. Then a group of forty radial bars of photoresist 0.003 in. wide was to be fabricated on the rings, the bars corresponding to the gaps in the wedge filter electrode. Finally, aluminum was to be evaporated over the entire sample and etched into a 0.002 inch wide lead pattern on top of the photoresist bars. Gaps in the bars were to provide electrical contact to the appropriate rings. Calculations of the capacitative coupling showed that effect to be too small to cause crosstalk.

Two serious problems developed in this scheme. First, it was discovered that the negative photoresist used for the bars adhered well to the indium oxide, but very poorly to the glass. Hence, where the bars crossed the glass, they tended to break and fold over during the cleaning cycle required for an adherent aluminum deposition. The normal cleaning cycle, a wash in an ultrasonic cleaner followed by a thirty second rinse in chromic acid, attacked the photoresist strongly. An attempt was made to use chrome instead of aluminum since it is inherently more adherent, but it was found that the intense heat generated by the chrome evaporation melted the photoresist. Two cleaning processes were finally discovered, but neither gave repeatable results. One was a three second wash in cold chromic acid, the maximum immersion permitted with no observable attack of the photoresist. The second was to soak the sample in a solution of a mild detergent and water for sixteen hours. In both cases, the samples were then rinsed in deionized water, dried in a warm air stream and baked briefly at 80°C to remove any moisture in the photoresist. The prepared substrates were then placed immediately in a vacuum system and the evaporation performed. It was found that approximately half the samples suffered photoresist failure in the wash and one in three had poorly adherent aluminum layers after evaporation due to inadequate cleaning.

The problem which finally forced the abandonment of this scheme, however, was pinholes and crazing in the photoresist. A statistical analysis of the pinhole problem indicated that five pinholes or less per square centimeter would give greater than 50 percent chance of success and the photofabrication people felt this number was probably high for their coatings. However, to this difficulty was added the difficulty that the photoresist almost invariably crazed to some degree either during the aluminum evaporation or during one of the cleaning or fabrication steps. No method for overcoming this problem was developed despite a heavy effort in this area. Hence, this fabrication scheme was abandoned and a 351° ring pattern was prepared with the electrical contact being made via 0.002 inch leads etched in the area of the nine degree gap.

A final problem in photofabrication which was annoying but not disasterous was shorting between elements. Each pattern was checked prior to fabrication for isolation between each electrode pair and it was found that approximately eight in ten had some problem. A brief wash in a solution of HCl and zinc served to rectify the problem in roughly half the patterns without causing problems with the electrodes. It is believed that nonuniform etching of the indium oxide due to variations in the microcrystal structure is the most important factor involved here.

6.2 Liquid Crystal Materials Problems

The two major difficulties encountered with the liquid crystal cell were nonuniform molecular orientation and shorts. Uniform molecular orientation parallel to the surface of the glass plates is required for operation in the low voltage polarization mode. Any nonuniformity in this orientation gives a blotched appearance to the unactivated device due to scattering which results. Uniformity is achieved by stroking the electrodes in one direction with a cotton swab. It is presently believed that this has the effect of aligning water molecules trapped at the electrode surface. These then produce conditions favorable to the alignment. It is found that the efficiency of the aligning procedure was strongly humidity dependent; in very high humidity, good alignment could not be achieved. Since no humidity controlled environment was available, the problem was solved simply by fabricating only when the relative humidity was less than forty percent.

Shorts in the device take two forms, one due to dust specks in the material, the other due to nonflatness in the glass. The former problem is minimized by keeping the liquid crystal in a sealed container until it is applied to the device. However, during the time when actual fabrication is performed, the liquid crystal is exposed and may pick up dust from the area. Shorts of this type can usually be detected microscopically as small specks. Shorts due to nonflatness in the glass are avoided as much as possible by checking the glass surface with a Sloan Dektak surface profiler. It is not possible to scan the entire surface but gross features can be detected and those pieces having flatness worse than 0.1 mil per inch rejected. Unfortunately, the heating and compression used in fabrication occasionally produce sufficient deformation to cause a short. These shorts appear as small bubbles at the point of the short which grows and shrinks as the voltage is turned on and off.

Another problem with the materials has to do with the liquid crystal mixture. A mixture of MBBA and BBBA was used in the first device to give a broad temperature range and a lower scattering threshold. This device has operated successfully for several months. However, a problem has developed in later batches apparently due to changes in the liquid crystal synthesis which give improved purity. It is observed that after a period of time the BBBA solidifies out of the supposedly eutectic mixture. The solidification takes the form of long, narrow rectangular crystallites of BBBA emanating radially from a point, presumably the nucleation site. These crystallites are very thin, not over 0.1 mil thick, and are attached to one or the other electrode face. In no case was a crystallite observed floating free in the liquid crystal or extending from one electrode to the other. That the crystallization was indeed separation of the components was shown by heating tests. It was observed that the nematic/isotropic transition occurred at 42° - 45° C in the region immediately adjacent to the crystallites, yet when the crystallites were melted and heated isotropic, the transition occurred at 65° - 70° C in those regions. These are precisely the transition ranges of pure MBBA and BBBA respectively. No clear reason for this separation has been determined. The most recent devices were fabricated using pure MBBA to overcome this problem.

7. PROJECT RESULTS

Three Fourier Plane Filters were designed, built, tested and delivered to NASA Goddard during the course of this work as described in the previous sections. One of the delivered devices utilized a liquid crystal mixture of MBBA and BBBA in 0.5 mil thick cells and employed printed circuit connectors in a demountable holder (Figure 3-5). The remaining two devices utilized MBBA in 1.0 mil thick cells and were hard wired into their holders for greater mechanical stability (Figure 3-6). All of the filters performed in accordance with the work statement and Figures 5-4 and 5-5 give photographic evidence of the ability of these devices to perform real time Fourier plane filtering of coherent images.

8. RECOMMENDATIONS

As presently configured the FPF has several drawbacks which could be alleviated by incorporating various techniques currently under development at Itek. These include the following:

1. Resolution is not adequate for fine discrimination in the filtering operation. This is particularly true in the case of the ring filters.
2. A higher contrast in the zero order spot is desirable to minimize scattering into other regions of the device.
3. The required depth of field is inordinately large.
4. The required f/number of the optical system results in a rather bulky package.
5. Speed should be improved, perhaps to a cycle time of 10 - 20 msec.
6. One 9 degree segment is completely lost where the electrical leads for the ring are brought out.
7. The device has a limited operating temperature range. The device should be thermostated for operation in a cold environment.

Most of these difficulties could be alleviated by new techniques which are being developed at Itek. The vendor who developed the indium oxide photofabrication process used to prepare the electrodes can now work with gaps less than 0.001 inch, hence the wedges and rings can be more closely spaced. It seems reasonable to consider doubling the number of wedges to 80 (40 addressable locations) and doubling or perhaps tripling the number of rings (60 addressable locations). Higher contrast and a concomitant reduction in the f/number could be achieved by using higher driving voltages, up to 100V, giving a field of 200V/mil. The higher driving voltage further has the effect of reducing the response time significantly. We have demonstrated turn on times as little as 2 msec at these fields using simpler devices. The decay time can be reduced by applying a high frequency AC signal (1 - 10kHz). Decay times less than 10 msec can be achieved with voltages of 50V peak. These voltages make it impossible to use FETs as switches on the electronic output but two methods have been developed to achieve the required voltage capacity. A bipolar all transistor addressing scheme can be used, or preferably switching can be performed at low voltages and the signals subsequently amplified. This requires one amplifying transistor per addressable element but reduces the number of high voltage components and system complexity.

The depth of field problem can be eliminated by applying a different addressing scheme which utilizes the fact that liquid crystals do not have a sharp scattering threshold. The principle is as follows. The device is fabricated with the wedge electrode on one side and the ring electrode on the other. There are no common electrodes. Low impedance addressing is used throughout. Selected rings and wedges are addressed with out of phase sine wave voltages; i.e., $\pm V$ on the rings and $\mp V$ on the wedges. Thus, all the addressed intersections see a voltage of 2V and all areas where only one side is addressed see a voltage equal to V. All other areas are held at zero potential. V is made large enough to produce the required contrast. Thus, the required depth of field is merely the thickness of the liquid crystal layer, 0.0005 inch. Such an addressing scheme has already been demonstrated in the laboratory.

The loss of one segment to ring element leads becomes even more critical when device resolution is increased. However, there now appears to be a feasible technique for reducing this problem to reasonable proportions. It is possible to obtain (Burroughs Research Company, Concord, Mass.) glass plates having metallized fibers imbedded in them which may be as small as 10µm in diameter, yet have adequate current carrying capacity to activate one segment of a device. A glass plate having one of these fibers for each element, all located along a single radial line could be prepared and coated on both sides with In_2O_3. Then the ring pattern could be fabricated on one side of the plate, one fiber making contact to each ring. An interconnection pattern could be fabricated on the other side of the plate to which the electrical leads would be attached, one lead for each ring, outside the active areas of the device. During fabrication, this line of opaque dots could be aligned with a gap in the wedge filter, and hence would not affect the device performance.

The completed device would then have 100 addressable elements, 40 wedges and 60 rings, a cycle time less than 20msec., contrast in excess of 100:1 at a reasonable f/number ($>$ f/20), and be essentially completely transparent. No attempt would be needed at this time to increase the operating temperature range.

9. NEW TECHNOLOGY

No new technology was developed during the duration of this contract.

APPENDIX

Model for the Polarization Enhancement Effect

Deutsch and Keating[1] have published an analysis of the scattering of polarized coherent light from liquid crystals. Using Fresnel diffraction theory, they were able to obtain a typical dimension of the size of the scattering center in the turbulent liquid crystal and observed that the scattering for a particular orientation of the polarizer and analyzer (both perpendicular to the optic axis of the liquid crystal) had a much wider angular distribution than other cases. However, for a device application a simpler, phenomenological model has more practicality.

Consider the liquid crystal layer in the quiescent state. All the molecules are aligned parallel and in the plane of the electrode but have no positional order. In addition, the material has a positive conductivity anisotropy and a negative dielectric anisotropy. The former tends to orient the molecules perpendicular to the electrodes when a current passes through the layer while the latter tends to hold the molecules in their original orientation. It is observed that when sufficient voltage is applied these competing forces result in an electrohydrodynamic instability and scattering appears as a result of the varying orientation of the birefringent molecules.

If one measures contrast as a function of various parameters the following data result. Figure A-1 shows a curve of contrast versus orientation for fixed voltage and f/number (the ratio of the separation between the detector and the device to the detector aperture).

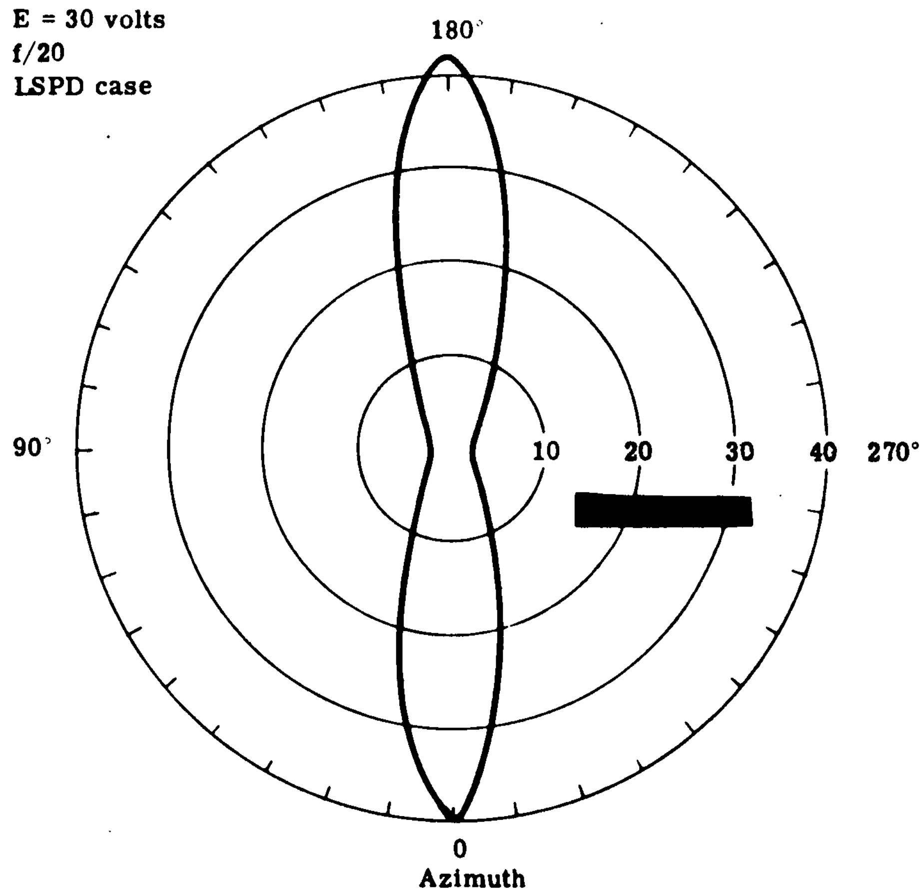


Figure A-1 - Angular Dependencae of Contrast

E

A strong angular dependence is observed in which light polarized in one direction is strongly scattered while light polarized at right angles is essentially unaffected.

Figure 5-1 shows the scattering as a function of voltage at the optimum orientation and constant f/number. Four polarization cases are shown: unpolarized light, unpolarized light with an analyzer placed between the device and the detector, polarized light with no analyzer, and polarized light with an analyzer in place. Note that in the last case the contrast rises rapidly and saturates while the dependence of contrast on voltage increases more gradually in the other three. It is worth mentioning that these curves meet at voltages of approximately 100 V/mil, hence the polarization scheme is essentially a technique of achieving high contrast at low voltage.

Finally, Figure 5-2 shows the contrast as a function of f/number. Within the experimental accuracy the slopes of all the polarizer curves is 2.0.

Consider the data in view of what is known about the liquid crystal layer. When the molecules move they will tend to travel and rotate such that they describe a circular path. If the initial orientation is uniform, they will then form a series of parallel cylinders of rotating material which will act as a polarization dependent diffraction grating. If the voltage is sufficiently high ($\sim$100 V/mil) this regular cylindrical structure breaks up yielding the polarization independent contrast observed at those fields.

Since the slope of the contrast versus f/number curves is 2.0 a simplified calculation of an "average" scattering angle can be made assuming a model which contains an inverse d^2 dependence. The simplest one, Rayleigh scattering, predicts a much too rapid increase in contrast, so the model chosen specifies that the light is scattered into a cone of apex angle θ. For simplicity, it is assumed that within the cone the intensity distribution is uniform, and is zero outside it. In addition, it is assumed that four possible cones can exist, one for each combination of input and output polarization. The base of each cone subtends a solid angle.

$$A_{ij} = 2\pi(1-\cos\theta_{ij})$$

where i = 1, 2 indicates incident polarization parallel or perpendicular to the direction of maximum contrast, and 7 = 1, 2 represents output polarization under the same conditions. Further, the detector aperture subtends a solid angle

$$A_D = 2\pi(1 - \cos\theta_D)$$

where

$$\tan\theta_D = \frac{1}{2\,(f/\#)}.$$

In addition, let f_i represent the amount of light retaining its initial polarization.

Considering the four polarizer options, one can write the following contrast equations:

1) Unpolarized input and output

$$C_1 = \frac{2}{A_D\left(\frac{f_1}{A_{11}} + \frac{1-f_1}{A_{12}} + \frac{f_2}{A_{22}} + \frac{1-f_2}{A_{22}}\right)}$$

2) Polarized input, no analyzer

$$C_2 = \frac{1}{A_D \left(\frac{f_1}{A_{11}} + \frac{1 - f_1}{A_{12}} \right)}$$

3) Unpolarized input, analyzer in place

$$C_3 = \frac{1}{A_D \left(\frac{f_1}{A_{11}} + \frac{1-f_2}{A_{21}} \right)}$$

4) Polarized input, analyzer in place

$$C_4 = \frac{A_{11}}{f_1 \; A_D}$$

From these equations and the contrast data one can then calculate the A_{ij} (or θ_{ij}) and f_i if one further approximation is made.

Case A. Aʒsume all light incident in one plane of polarization is scattered into the same cone irrespective of its output polarization. Then $A_{11} = A_{12}$ and $A_{21} = A_{22}$. This yields the values:

$$f_1 = 0.42 \pm \theta.1, \quad \theta_{11} = 0_{12} = 9°$$

$$f_2 = 0.98 \pm 0.1, \quad \theta_{21} = \theta_{22} = 2°$$

at 30V. Hence the light polarized in the direction of maximum contrast is scattered into a cone of angle 9° and completely depolarized while the other polarization is essentially unaffected.

Case B. Consider that all light scattered into one plane of polarization is scattered into the same cone irrespective of its incident polarization. Hence $A_{11} = A_{21}$, $A_{12} = A_{22}$ and one obtains

$$f_1 = f_2 \approx 1.0$$

$$\theta_{11} = \theta_{21} = 14°$$

$$\theta_{12} = \theta_{22} = 0.5°$$

In other words, incident light is scattered with no change in polarization but that scattered parallel to the direction of maximum contrast is scattered into a large cone while that scattered perpendicular to the maximum contrast direction is unaffected.

Case B is unphysical for two reasons. First, it is unrealistic to have no change in polarization on scattering. Further, θ_{22} is less than the subtended angle of the detector so the contrast should be 1:1 in that case rather than 2:1 as is observed. On the other hand, Case A predicts the correct contrast in that case.

[1]Ch. Deutsch and P. N. Keating, J. Appl. Phys. 40, 4049 (1969).