PROJECT INITIATION

Date: 6/7/71

Project Title: Design and fabrication of an experimental novel focusing light modulator

Project No.: A-1233

Project Director: Dr. R. E. Shepherd

Sponsor: NASA, Marshall Space Flight Center

Effective: July 23, 1971
Estimated to run until: February 23, 1972

Type Agreement: Contract No. NASA-17377
Amount: $55,016.00

Annexation of time for preparation and submission of the Final Report.


Sponsor Contact Person: Administrative Matters
At R. E. Shepherd, Chief
Administrative Controlling Officer
Room 413, L. E. Seed Building
Coppus

Technical Matters
(to be officially designated by future letter)

Assigned to: Electronics (Space Systems) Division

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PROJECT TERMINATION

Date: December 5, 1977

PROJECT TITLE: Design & Fabrication of an Experimental Image Forming Light Modulator

PROJECT NO: A-1335

PROJECT DIRECTOR: Mr. R. C. Shackelford

SPONSOR: NASA - Marshall Space Flight Center

TERMINATION EFFECTIVE: 3/1/72 (Contract Expiration)

CHARGES SHOULD CLEAR ACCOUNTING BY: 3/31/72

Contract Close-out Items Remaining: Final Invoice & Closing Documents
Final Report of Inventions
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Mr. J. H. Kerr  
S & E - ASTR - IRD  
NASA/Marshall Space Flight Center  
Marshall Space Flight Center, Alabama 35812  

Title: "Design and Fabrication of an Experimental Image Forming Light Modulator"  


Dear Sir:

Technical activities during the first month of the subject contract were concentrated on procurement of the electro-optic crystal assemblies, and on preparation of a high vacuum electron bombardment chamber suitable for the initial experiments on determining the modulator parameters.  

A survey of industrial firms with capabilities for growing and fabricating electro-optic crystal assemblies resulted in only one firm quotation which would meet the required specifications. The reluctance to submit quotations involves the requirement that the KD*P crystal be lapped and optically polished to a thickness of 0.010 inch. Both personal contact with representatives of the electro-optics industry at the CLEA meeting held on 2-4 June in Washington, D.C., and telephone conversations with several experts in the crystal industry have confirmed that polishing KD*P to a thickness less than 0.025 inch is a high risk affair which usually results in a low yield of acceptable units and a prohibitively high unit cost. The Isomet Corporation, the only company who returned a firm quotation, has had previous experience in fabricating electro-optic light valves utilizing thin KD*P crystals for the University of Illinois and the U.S. Air Force Rome Air Development Center. Both facilities have indicated their satisfaction with the Isomet units.
An order for one modulator crystal assembly utilizing a 2 x 2 x 0.010 inch KD\(^*\)P crystal with a CdO transparent electrode deposited on one side, a hard anti-reflective coating of SiO\(_{1.7}\) deposited on the other, and the crystal cemented to a 1 cm thick CaF substrate, has been placed with Isomet. This unit represents state-of-the-art fabrication techniques, and should be capable of a resolution of about 200 lines per inch when employed as the storage element in an image forming light modulator. Delivery of the Isomet unit is scheduled for 25 August 1971.

Before any further KD\(^*\)P crystal assemblies are ordered, the Isomet unit will undergo thorough testing in a high vacuum chamber which is currently being modified for measurement of the secondary emission characteristics, contrast, and resolution of the electro-optic crystal assemblies. This chamber, which will require only slight modification for the desired measurements, will permit evaluation of key parameters which will determine the electron beam operating point before the construction of the IFLM housing is completed. Technical specifications for an electron gun capable of being focussed to a 0.001 inch spot at the current required to cause half wave retardation of the laser beam have been discussed with the Superior Electronics Company, and an order for a gun meeting the desired specifications will be placed soon.

While construction of the modulator and testing of the Isomet KD\(^*\)P assembly is being carried out, experiments directed toward development of improved fabrication techniques will be initiated. Two of the preliminary fabrication concepts under consideration are ion plating of the transparent electrodes for improved thermal performance, and diffusion bonding of the KD\(^*\)P crystal to its substrate, which would eliminate the low thermal conductivity silicone cement currently employed as the bonding agent.

Current expenditures and man-hours effort covering the first reporting period are:

- **Technical Effort - 207 Man-Hours**: $3,214
- **Material and Supplies - KD\(^*\)P Crystal Assembly and PLZT Test Crystals**: $2,040
- **Total Expenditures to Date**: $5,254
Next month's technical efforts will involve modification of the high vacuum test chamber for the electron beam optics, design of a crystal holder for the Isomet KD*P assembly, and preliminary design of the modulator housing and high vacuum pumping system. Since the Isomet KD*P assembly is not scheduled for delivery until August 25, emphasis will be placed on initial deposition and testing of thin film electrodes on glass slides. Techniques for bonding the metal coated glass slides to CaF will also be investigated.

The projected expenditures and man-hours effort covering the second reporting period are:

- Technical Effort - 350 Man-Hours $5,450
- Materials and Supplies - High Vacuum Pumping Equipment and Vacuum Deposition Supplies 2,500

Total Projected Expenditures $7,950 for the Second Reporting Period

Respectfully submitted,

R. G. Shackelford
Project Director

Approved:

Head, Special Techniques Branch
Electronics Division
3 August 1971

Mr. J. H. Kerr
S & E - ASTR - IA
NASA/Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

Title: "Design and Fabrication of an Experimental Image Forming Light Modulator"


Dear Sir:

Technical activities during the second month of the subject contract included specification and procurement of vacuum and electron beam components for the IFLM, planning of the initial electron beam experiments on the KD\textsuperscript{P} crystals, and preliminary experiments on fabrication of electro-optic crystal assemblies.

The design of the high vacuum system has been finalized, and all components have been ordered. Delivery of the vacuum components is scheduled for mid-August; however, the preliminary electron beam tests on the KD\textsuperscript{P} crystals will not be affected since a high vacuum pumping station is available for use. The electron beam write and flood guns have also been ordered, and design of the deflection circuitry is in progress. Final design of the IFLM deflection circuitry will depend on the cross-over points on the KD\textsuperscript{P} secondary emission characteristic which will comprise the first measurement on the high vacuum test chamber.

Initial deposition of transparent electrodes on glass microscope slides has begun. Since the melting point of KD\textsuperscript{P} is only 253°C, a low temperature ion plating technique will be employed on both the glass slides and the KD\textsuperscript{P} for comparison. The thermal expansion of KD\textsuperscript{P} is closely matched by that of indium and aluminum, and these two metals will be employed in several fabrication techniques conceived to eliminate the bonding of the KD\textsuperscript{P} crystal to its substrate with silicone cement.

Expenditures and man-hours effort covering the first two reporting periods are:

<table>
<thead>
<tr>
<th>Description</th>
<th>Hours</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technical Effort</td>
<td>739</td>
<td>$7,930</td>
</tr>
<tr>
<td>Materials and Supplies</td>
<td></td>
<td>5,989</td>
</tr>
<tr>
<td><strong>Total Expenditures</strong></td>
<td></td>
<td><strong>$13,919</strong></td>
</tr>
</tbody>
</table>
Next month's technical effort will involve the measurement of secondary emission properties of KD\textsuperscript{P} and PLZT, the design of deflection circuitry for the electron beam optics, and continued design of the sample holder. Calculations of the equilibrium temperature of the KD\textsuperscript{P} assembly under operating conditions are being made for several sample holder configurations. Since much higher resolution and lower beam accelerating potentials can be employed with the sample cooled to its Curie temperature, careful consideration is being given to the problems involved in mounting a two-stage thermoelectric cooler in the modulator. Published specifications on a number of standard units indicate that the crystal assembly's temperature could be maintained within several degrees of the Curie temperature (-60°C) with a thermal input comparable to that which will be encountered in operation.

The projected expenditures and man-hours effort covering the third reporting period are:

- **Technical Effort** - 590 Man-hours $8,500
- **Materials and Supplies** - Miscellaneous $200
  - Vacuum Components and Crystal Materials

Total Projected Expenditures for the $8,700 Third Reporting Period

Respectfully submitted,

R. G. Shackelford
Project Director

Approved:

Head, Special Techniques Branch
Electronics Division
Mr. J. H. Kerr  
S & E - ASTR - IA  
NASA/Marshall Space Flight Center  
Marshall Space Flight Center, Alabama 35812

Title: "Design and Fabrication of an Experimental Image Forming Light Modulator"


Dear Sir:

Technical activities during the third month of the subject contract included fabrication of target holders and deposition masks for the secondary emission measurements, characteristic measurements on thin film electrodes, and breadboarding of the electron gun deflection circuitry for the initial electron beam writing measurements.

All vacuum components ordered for the test housing and modulator housing have been received, and fabrication of the test housing has been completed. Several target holders and deposition masks suitable for the KDP, KD³P, PLZT sample configurations have been machined, and tests to determine the cross over points on the secondary emission curve for these materials will begin within a week.

Thin film electrodes of chromium and indium oxide have been ion plated on glass slides in order that measurements can be made to determine the proper thickness of an electrode for the electro-optic crystals. Measurements thus far on the chromium films have shown that a transmission of about 80 percent at the wavelength of 5145 Angstroms requires a thickness of about 100 Angstroms with a resulting resistance of about 10⁵ ohms per square. While some difficulties have been experienced with obtaining uniform depositions with indium oxide, initial measurements have shown that a transmission of greater than 80 percent can be obtained with a thickness which results in a resistance of less than 500 ohms per square. While modifications are being made on the ion plating facility to improve the uniformity of the indium oxide films, it appears that an RF sputtering facility would greatly reduce the problems now being experienced with the oxide compounds. Although an RF sputtering facility is not presently available, there is a good chance that the proposed modifications to the existing facility will lead to acceptable oxide films. Cadmium oxide powder has also been obtained and will be tested along with the indium oxide.
A deflection yoke for the electron write gun has been obtained, and the electronic driving circuitry compatible with this yoke has been breadboarded and tested. Both the write and erase electron guns are scheduled for delivery during the first two weeks of September, and as soon as they are received tests to determine the operating points for deflection, focusing, and desired beam current will be initiated.

Expenditures and man-hours effort covering the first three reporting periods are:

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technical Effort</td>
<td>1,064 Mh</td>
</tr>
<tr>
<td>Materials and Supplies</td>
<td>6,539</td>
</tr>
<tr>
<td><strong>Total Expenditures</strong></td>
<td><strong>18,804</strong></td>
</tr>
</tbody>
</table>

Next month's technical efforts will involve the measurement of cross over points on the secondary emission characteristics of KD\(^x\)P, and PLZT, testing of the high vacuum pumping equipment in measuring the outgassing properties of the electro-optic crystals and the materials used in construction of the modulator, preliminary measurements to determine the electron beam operating points, and continued design of the sample holder for the KD\(^x\)P assembly. The use of a thermoelectric cooler is being investigated, and an attempt will be made to employ numerical techniques in solving the heat flow equation in the KD\(^x\)P assembly to approximate the temperature distribution under operating conditions.

The projected expenditures and man-hours effort covering the fourth reporting period are:

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technical Effort</td>
<td>639 Mh</td>
</tr>
<tr>
<td>Materials and Supplies</td>
<td>Miscellaneous</td>
</tr>
<tr>
<td>Vacuum Components and Crystal Materials</td>
<td></td>
</tr>
<tr>
<td><strong>Total Projected Expenditures for the Fourth Reporting Period</strong></td>
<td><strong>$9,680</strong></td>
</tr>
</tbody>
</table>

Respectfully submitted,

R. G. Shackelford
Project Director

Approved

Head, Special Techniques Branch
Electronics Division
Mr. J. H. Kerr  
S&E-ASTR-IA  
NASA/Marshall Space Flight Center  
Marshall Space Flight Center, Alabama 35812  

Title: "Design and Fabrication of an Experimental Image Forming Light Modulator"  


**Dear Sir:**

Technical activities during the fourth month of the subject contract included attempts at measuring the secondary emission characteristics of KD\textsuperscript{2}P, design and finalization of a two-stage thermoelectric cooler and sample mounting frame, and continued testing of the electron gun deflection breadboard.

A measurement procedure conceived to determine the upper and lower cross over points for KD\textsuperscript{2}P was implemented and analyzed. This method consisted of modulation of the electron beam potential and measurement of the current induced in the secondary of a transformer connected between the target electrode and connector ring. When the electron beam potential is between the cross over points, the crystal surface and the collector ring are at the same potential, and no current will be induced on the transformer. As the electron beam potential approaches the cross over point, the modulating voltage will cause the crystal to swing into that part of the secondary emission characteristic where the surface potential no longer follows the collector ring potential and an alternating current will be induced in the transformer secondary. It was found, however, that the magnitude of the induced current depends on the capacitance of the area on the crystal addressed by the electron beam, and for the crystal geometry available for these tests, a calculated current of about $10^{-14}$ amps resulted. Stray electrons collected on the aluminum crystal holder resulted in a background current which masked "signal" current, and several attempts at shielding the crystal were unsuccessful in establishing the signal-to-noise ratio necessary for determining the secondary cross over point.

An analysis of the measurement techniques and equipment available for determining the secondary emission characteristics has resulted in the following considerations:
(1) Measurement of cross over points by modulation of the electron beam potential would require a thin film target in order to increase the capacitance to a value that would result in the signal-to-noise ratio necessary for discriminating between the "signal" and background currents.

(2) A direct measurement of the primary and secondary electron currents would be possible with the present sample geometry if a Faraday cup were designed and fabricated for the electron beam test housing.

(3) An optical technique based on the electro-optic properties of KDP could be used to measure the potential of the crystal surface after equilibrium has been reached, and thus determine the upper cross over voltage.

Since the upper cross over point is really the only feature of the secondary emission characteristic that is essential to the specification of operating points for the IFLM, the optical technique has been chosen over the thin film sample or Faraday cup for this measurement.

Neither the electron write guns nor the 2" x 2" KDP assembly have been delivered, and are now one month overdue. Repeated inquiries to the electron gun vendor (Superior Electronics Co.) have produced only promises of new shipping dates and no action. Apparently the problem concerns meeting one of the design specifications, but several discussions with the engineering staff have not resulted in a definite answer as to which specification. Our efforts in resolving this problem will be intensified during the coming weeks. Our last contact with the KDP vendor (Isomet Corporation) revealed that the assembly was being coated and would be shipped soon. The delay in receiving the electron guns has resulted in a delay in fabrication of the modulator housing and electron beam deflection circuitry.

A design for an aluminum sample mounting frame and thermoelectric cooler has been completed, and the components, including a proportional controller, have been ordered. This assembly will provide for proportional control of the sample temperature within ±1°C from room temperature down to the Curie temperature for KDP (≈ -60°C), and will allow operation at reduced electron beam potentials with improved resolution and picture quality.

Expenditures and man-hours effort covering the first four reporting periods are:

Technical Effort - 1,497 Man-hours $19,390

Materials and Supplies 7,571

Total Expenditures to Date $26,961
Next month's technical efforts will include measurement of the upper cross over point using the optical technique, and if the electron write guns are received, fabrication of the modulator housing and electron gun electronics will be initiated.

The projected expenditures and man-hours effort covering the fourth reporting period are:

- Technical Effort - 591 Man-hours
- Materials and Supplies - Crystals and High Vacuum Components
- Total Projected Expenditures for the Fifth Reporting Period

Respectfully submitted,

R. G. Shackelford
Project Director

Approved:

J. W. Dees, Head
Special Techniques Branch
Mr. J. H. Kerr  
S&G-ASTR-IA  
NASA/Marshall Space Flight Center  
Marshall Space Flight Center, Alabama 35812

Title: "Design and Fabrication of an Experimental Image Forming Light Modulator"

Subject: Monthly Report No. 5 on Contract NAS8-27375  
for the Period 25 September 1971 through 24 October 1971

Dear Sir:

Technical activities during the 5th month of the subject contract were focused on implementation of an optical technique for measuring the upper secondary emission cross over point for KD*P, and fabrication of the IFM modulator housing.

The upper cross over point of an insulating target is easily calculated if the target surface potential can be measured during the electron bombardment. For reasons outlined in Monthly Report No. 4, direct measurement of the surface potential is very difficult, and hence an indirect optical scheme for determining the surface potential has been implemented. This technique utilizes the birefringence induced in the KD*P target by the surface charge, and involves measurement of the polarization rotation of a laser beam which passes through the KD*P target.

Since the supply of KD*P targets had been expended in earlier tests, a KDP target was employed in the optical tests. Tracking of the front surface potential with the collector ring potential was first confirmed, and the optical rotation was then measured as the potentials of the electron gun, target back surface electrode, and collector ring were varied over a range of about 3 kV. The half wave voltage of KDP is about 8.5 kV at the laser wavelength, and the test voltages employed should have resulted in a maximum rotation of about 30 degrees. When a maximum rotation of only 10 degrees was obtained, it was decided that a bench measurement of the KDP should be performed to determine the actual half wave voltage for our samples. A second sample of the same crystal was coated on both sides with a transparent conductive film, and the tests were repeated with a potential applied directly to the two surface electrodes. Characteristic rotation could not be obtained over the range of 0-7 kV, and the crystal was then carefully examined for proper
The orientation was found to be z-axis normal, and measurements with an electrometer showed that the impedances of the conductive films and the leakage current through the KDP sample were also well within the desired range. In the process of applying the indium oxide films, the crystals were baked at 150°C for several days, and there is the possibility that indium has diffused into the KDP, thereby lowering its resistivity and resulting in most of the voltage being dropped across the oxide surface film. Since this anomalous behavior is not understood, the tests have been set aside until a new batch of KDP crystals are received. These will be electroded with chromium films at room temperature, and the tests will be repeated.

The 2" x 2" KDP light valve and the write electron guns were received during the quarter, and a prototype modulator employing the final electron gun and window configurations has been assembled. The modulator was pumped down using the IFLM vacuum system and a pressure of 4 x 10^-8 mm Hg was achieved with the Orb-lon pump air cooled and the anode current at about 25 mA. While this pressure level is adequate for the proposed operating mode, further testing is planned so that the final modulator housing can be run at an anode current which will insure both long filament life and proper operating pressure. Both the write and erase guns have been mounted in flanged glass-to-metal seals, and machining of the final modulator housing components is nearing completion. Considerations are now being given to the option of mounting the deflection coils inside or outside of the modulator housing, and it is likely that both configurations will be tested.

Initial inspection of the 2" x 2" KDP crystal has been very favorable. The surface polish looks very good and no scratches are visible. Flaws or strains in the crystal will not be visible, however, until we begin writing on it with an electron beam. The orientation was checked and found to be proper, and the resistance of the CdO transparent electrode was found to be 3 x 10^4 ohms per square.

Fabrication of the two-stage thermoelectric cooler and heat sink has been completed, although the design is not as useful as was hoped. The 2" x 2" KDP crystal came mounted on a circular CaF substrate, and our plans for a target holder adapting to the thermoelectric cooler, which were based on a square substrate, will need to be modified somewhat. The proportional controller was received during the quarter, and the cooler will be tested soon.

Expenditures and man-hours effort covering the first five reporting periods are:
Total Expenditures to Date $39,477

Next month's technical efforts will center around fabrication of the final IFLM modulator housing and initial scanning operation with the electron write gun. Testing of the small KD\textsuperscript{3}P targets will continue until the proper electron beam operating points have been determined.

The projected expenditures and man-hours effort covering the sixth reporting period are:

- Technical effort - 506 Man-hours $6,845
- Materials and Supplies 0

Total Projected Expenditures for the Sixth Reporting Period $6,845

Respectfully submitted,

R. G. Shackelford
Project Director

Approved:

J. W. Dees, Head
Special Techniques Branch
Mr. J. H. Kerr  
S&E-ASTR-IA  
NASA/Marshall Space Flight Center  
Marshall Space Flight Center, Alabama 35812

Title:      "Design and Fabrication of an Experimental Image Forming Light Modulator"

Subject:   Monthly Report No. 6 on Contract NAS8-27375  
            for the Period 25 October 1971 through 24 November 1971

Dear Sir:

During the last reporting period, fabrication and testing of the final modulator housing was completed, and testing of the write gun was initiated. The one inch square crystals of KD*P have not been received, and thus the secondary emission measurements have been delayed.

Fabrication of the final modulator housing has been completed, and the housing has been pumped down to the 10^-9 mm Hg vacuum range. The IFLM is now in final form with only the crystal housing and mounting stage remaining to be finished. The modulator employs a two inch diameter window on the input flange along with the write and erase guns. The configuration chosen reduces the length of the modulator to about eight inches and provides for a 1.4" x 1.4" image scanning format.

The write gun has been mounted, and initial tests to determine its emission, spot size, and deflection characteristics have begun. A breadboard deflection circuit is being employed, and the results of the initial tests will furnish parameters for the final circuits.

Expenditures and man-hours effort covering the first six reporting periods are:

Technical Effort - 2,341 Man-Hours  $32,350
Materials and Supplies  13,414
Total Expenditures to Date  $45,764

Technical efforts during the coming month will emphasize testing of the electron beam optics and finalization of the electronic circuitry for electron beam deflection and video amplification. If initial tests on the write gun are successful, it is anticipated that tests utilizing the 2" x 2" KD*P crystal will begin during the month of December.
The projected expenditures and man-hours effort covering the seventh reporting period are:

<table>
<thead>
<tr>
<th>Description</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technical Effort - 415 Man-Hours</td>
<td>$5,800</td>
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<tr>
<td>Materials and Supplies</td>
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</tr>
<tr>
<td><strong>Total Projected Expenditures for the Seventh Reporting Period</strong></td>
<td><strong>$7,750</strong></td>
</tr>
</tbody>
</table>

New Technology Statement

A thorough review was conducted during the reporting period by the technical staff assigned to contract NAS8-27375 to determine if any reportable items of new technology as defined in NASA Form 1162 resulted from the above described technical efforts. The engineering techniques applied to fabrication of the IFLM were carefully reviewed, and no reportable items of new technology were uncovered.

Respectfully submitted,

R. G. Shackelford
Project Director

Approved:

J. W. Dees, Head
Special Techniques Branch

RGS:mdh
5 January 1971

Mr. J. H. Kerr
S&G-ASTR-IA
NASA/Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

Title: "Design and Fabrication of an Experimental Image Forming Light Modulator"


Dear Sir:

During the last reporting period, the secondary emission parameters of KD*P were measured, the IFLM was operated as a modulator in a non-scanning mode, and a substantial portion of the electronic circuitry was completed.

Testing of the electron write guns, which was begun on the last day of the previous reporting period, was completed, and it was found that internal shorts between the grid structures would not permit normal operation of either gun. In addition, a filament-to-cathode short in one of the guns resulted in complete loss of emission. Since the internal shorts developed during the cathode emission tests, it was not possible to measure the current of the extracted electron beam or its spot size at the target. Negotiations with the electron gun vendor, Superior Electronics Company, have resulted in our placing a second order for two electron guns of the original design with modified grid structures which will eliminate the internal shorting problem. The vendor will also manufacture a third gun which will be used to verify the proper operating parameters before the guns are shipped. The malfunction of these devices has caused a significant delay in our development schedule, and notice of a possible delay in delivery of the IFLM has been forwarded to Mrs. Saundra Hill. The new guns are scheduled for delivery on 15 January 1972, and every effort is being made to expedite their delivery.

The electron flood gun, which will be used for erasing the image charge pattern, has been tested and found to exceed the design specifications. A 2" x 2" phosphor target was employed to observe the intensity distribution of the electron beam, and it was found that a very uniform spot of about 2" diameter could easily be obtained with a total beam current exceeding 10 mA.
The 1" x 1" KD\(^{x}\)P crystals arrived during the quarter, and were employed to determine the electron beam parameters for full modulation in the IFLM. One sample was coated on both sides with a transparent chromium film, and bench tested using a high voltage supply to provide the electric field necessary for phase retardation of the polarized laser beam which was transmitted through it. A Pockel's cell arrangement with crossed polarizers was employed to measure the intensity of the transmitted laser beam as a function of the electric field across the crystal, and the half wave voltage was found to be about 4 kV for the wavelength of 6328 Angstroms.

The second sample was coated on only one side and placed in the IFLM, and the electron flood gun was employed to measure the intensity as a function of electron beam potential with the IFLM operating in the Pockel's cell arrangement. A grounded collector ring surrounding the KD\(^{x}\)P crystal provided a means of measuring the upper crossover point on the secondary emission characteristic. An analysis of the secondary emission characteristic shows that when the cathode of the electron gun is at a potential which is less than that of the upper crossover point, the secondary emission ratio is greater than one, and the surface of the crystal will charge to the potential of the collector ring. If for this condition, both the collector ring and the crystal electrode are placed at ground potential, no electric field will be present across the crystal and no change in intensity of the laser beam should be observed. As the potential of the cathode is increased beyond the upper crossover value, the surface will charge negatively to an equilibrium potential which is the difference between the cathode potential and the upper crossover potential. This behavior was observed as expected, and the upper crossover potential was measured to be 2 kV. While a thorough literature search has not revealed any published values for the upper crossover potential of KD\(^{x}\)P, the above measured value is consistent with published values of other insulators many of which lie in the range of 1.5 to 2.5 kV. It is likely that the upper crossover potential is a function of sample temperature, and these data should be repeated with a thermistor probe in contact with the crystal so that the temperature can be monitored. The above measured value is for a 90 percent deuterated KD\(^{x}\)P sample, and while no significant differences are expected, this measurement will be repeated on the 2" x 2" sample which is 99 percent deuterated. It is anticipated that a technical note containing the results of these measurements will be submitted for publication at a later date.

With the IFLM operating in the Pockel's cell mode, it was found that full modulation was obtained with a cathode potential of about 9.5 kV. This measurement suggests that the half wave voltage of the KD\(^{x}\)P sample was 7.5 kV, which differs significantly from the bench measured value of 4 kV. This difference is easily accounted for, however, if there was heating during the electron beam bombardment. The half wave voltage varies inversely with the dielectric constant which goes approximately as \(1/(T-T_c)\), where \(T_c\) is the Curie temperature. A calculation based on
a first order thermal model of the KD*P sample and its mounting configuration has shown that the temperature corresponding to a half wave voltage of 7.5 kV (∼ 100°C) would be reached after approximately 5 minutes operation with the electron flood gun. This condition is not expected to present a problem in the final operating mode since the current of the write gun is much smaller than that of the erase gun, and the 2" x 2" crystal will be mounted on a two stage thermoelectric cooler which can handle a continuous heat input of 200 mW.

A substantial part of the electronic circuitry was fabricated and tested during this reporting period. A high voltage video coupling and isolation link consisting of a light emitting diode transmitter and photodiode detector was constructed and its circuit parameters selected for a response of 5 MHz. The LED coupling link was employed to transmit the composite video signal from a TV camera to a TV monitor, and the details of a standard EIA test pattern were accurately reproduced on the monitor screen. The deflection circuitry was linearized, and the keystone correction and sweep failure protection circuits were added. A sync separator circuit was also constructed, and the sweep circuits were successfully locked to a standard TV sync signal.

Expenditures and man-hours effort covering the first seven reporting periods are:

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technical Effort</td>
<td>2,708 Man-hours $37,754</td>
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<td>Materials and Supplies</td>
<td>$14,034</td>
</tr>
<tr>
<td>Total Expenditures</td>
<td>$51,788</td>
</tr>
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</table>

Technical efforts during the next reporting period will involve completion of the electronic circuitry, and testing of the IFLM modulator with the 2" x 2" KD*P crystal. The half wave voltage of the 2" x 2" KD*P crystal will be measured as a function of temperature with operation near the Curie point as a goal. When the electron write guns are received, tests will be initiated to determine the resolution and contrast obtained in the scanning mode. A visit will be made by R. G. Shackelford and J. R. Walsh, Jr. to the Marshall Space Flight Center during the next reporting period for the purpose of interfacing our electronics and system operating cycle with optical data processing components which will be used to determine performance of the IFLM upon its delivery.

The projected expenditures and man-hours effort covering the eighth reporting period are:
Technical Effort - 367 Man-hours  $5,400
Materials and Supplies       500
Total Projected Expenditures  $5,900
for the Seventh Reporting Period

New Technology Statement

A thorough review was conducted during the reporting period by the technical staff assigned to contract NAS8-27375 to determine if any reportable items of new technology as defined in NASA Form 1162 resulted from the above described technical efforts. The engineering techniques applied to fabrication of the IFLM were carefully reviewed, and no reportable items of new technology were uncovered.

Respectfully submitted,

R. G. Shackelford
Project Director

Approved:

W. Dees, Head
Special Techniques Branch
Title: "Design and Fabrication of an Experimental Image Forming Light Modulator"


Dear Sir:

During the last reporting period, the thermoelectric cooler was tested in the IFLM housing, fabrication of the mounting base was completed, and the video and deflection electronics were finalized.

The two stage thermoelectric cooler was mounted on a four-inch flange along with six electrical feed-throughs and two tubing feed-throughs for water cooling of its heat exchanger. The sample holder base and a dummy thermal load representing the 2" x 2" KD*P modulator unit was attached to the cold stage of the cooler and the unit was tested in the IFLM housing under high vacuum conditions for rate of cooling and low temperature limit. The initial cooling rate was found to be about 6°C/min. from room temperature down to -10°C with the rate gradually decreasing to about 0.3°C/min. at -40°C and then rapidly decreasing from -40°C to the low temperature limit of -56.5°C. It takes approximately one hour to go from room temperature to the low temperature limit, and although the initial cooling rate is faster than might be desired, the cooling rate is very low over a 10°C range approaching the Curie temperature (≈ -50°C for 99% deuterated KD*P). Since the components of the modulator assembly have been carefully matched for thermal expansion, the measured cool-down rate should not present a problem.

A kinematic mounting base providing variable yaw, pitch and roll orientation along with precision translation in a plane perpendicular to the optic axis has been completed. This base will provide for adjustments of ±5 degrees in yaw, ±1 degree in pitch and roll, and ±0.5 inch in translation.

The video and deflection circuits have been finalized and tested. The alternate frame blanking concept has been implemented, and found to be compatible with the standard EIA synchronization.
The 2" x 2" KD*P modulator mounting frame has been fabricated, and will be mounted in the thermoelectric cooler within one week. Plans have been completed for the final testing phase, and these tests will also begin within one week.

Expenditures and man-hours effort covering the first eight reporting periods are:

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<tr>
<th>Technical Effort - 3194 Man-hours</th>
<th>$43,724</th>
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<tr>
<td>Materials and Supplies</td>
<td>$15,171</td>
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<tr>
<td>Total Expenditures to Date</td>
<td>$58,895</td>
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Technical efforts during the final reporting period will be concentrated on final testing and delivery of the engineering model IFLM. These tests will involve determination of resolution and contrast of the IFLM with a standard EIA test chart image providing the input video signal. Since instrumentation is not available to perform a shrinking raster resolution test, the results of the performance tests will be subjective in that they will involve visual determination of the resolution of merging lines on the resolution chart. Image quality will thus be judged relative to a commercial TV image whose resolution is about 260 line pairs.

The projected expenditures and man-hours effort covering the ninth reporting period are:

<table>
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<th>Technical Effort - 362 Man-hours</th>
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<tr>
<td>Materials and Supplies</td>
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<td>Total Projected Expenditures for Ninth Reporting Period</td>
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New Technology Statement

A thorough review was conducted during the reporting period by the technical staff assigned to contract NAS8-27375 to determine if any reportable items of new technology as defined in NASA Form 1162 resulted from the above described technical efforts. The engineering techniques applied to fabrication of the IFLM were carefully reviewed, and no reportable items of new technology were uncovered.

Respectfully submitted,

R. G. Shackelford
Project Director

Approved:

J. W. Dees, Head
Special Techniques Branch
15 June 1972

Mr. J. H. Kerr
S&G-ASTR-IA
NASA/ Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

Title: "Design and Fabrication of an Experimental Image Forming Light Modulator"

Subject: Combined Monthly Reports Nos. 9-12 on Contract NAS8-27375

Dear Sir:

Final Assembly and Testing of the IFLM

During the ninth reporting period, final assembly of the IFLM system was accomplished and tests to determine image quality were performed.

A phosphor screen was mounted in the crystal support bracket, and a remote TV camera and the IFLM electronics were employed to form an image on the screen. Observation of the image in this manner provides a reliable means for adjusting the sweep linearity and size, and the video contrast and brightness controls. The Keystone correction electronics were found to provide sufficient compensation for the off-axis location of the write gun. A rectangular raster could be formed and varied in width and height from about 3/4 inch to 2 inch by adjustment of the sweep magnitude and position of the focusing coil along the neck of the write gun. The sweep was observed to have vertical distortion which results in a slight elongation of the upper half of the field, and a slight compression of the lower half of the field. The current waveform supplying the vertical deflection yoke was examined, and was not found to have a non-linearity of magnitude comparable to the observed distortion in the image. It is possible that the deflection yoke, which was intended for a large deflection TV application, is the major contributor to the observed distortion. This yoke has been modified to provide a low inductance to the deflection drive circuits, and its linearity and mutual coupling characteristics could have been affected by altering its geometry. A linear, low inductance yoke wound on a stator type form would improve or completely eliminate this problem.

The image quality was observed to be sharp, and exhibited a gray scale comparable to the TV camera's monitor. Four shades of a standard EIA gray scale were easily resolved, and the measured grid transfer characteristics of the electron gun predict a much longer gray scale on the appropriate phosphor. Although the video bandwidth decreases from 5 MHz to about 3.5 MHz in the alternate frame mode, no degradation in picture quality was observed. With the write gun operating just below saturation (an all white picture), the horizontal lines in a 1.5 inch raster can be resolved. The electron beam spot
is, therefore, less than six mils in diameter. It was not possible to measure
the electron beam current during the initial tests because the extra feed-
throughs in the thermoelectric cooler flange were allotted to a thermistor
which was used to monitor the cooling rate of the KD*P modulator.

A major concern associated with operation of the modulator crystal near
the Curie point was the possibility of cracking the crystal. Although the
components of the crystal assembly were carefully matched for thermal expansion
coefficients, large internal forces could result from cooling the crystal too
fast. Using the heat pumping characteristics of the thermoelectric cooler and
the mass of the KD*P assembly, the temperature of the KD*P crystal was cal-
culated as a function of time. These calculations, which represent a worst
case since heat exchange with the surroundings has been neglected, predicted
that a temperature of -45°C would be reached after an elapsed time of about
1.5 hours. Thus, in the worst case, one would expect a cool down rate of
about 1°C per minute.

The first 2" x 2" x 0.010" KD*P unit received from Isomet Corporation was
epoxied to the crystal mount, and run through a complete cooling cycle to
determine its cooling rate and terminal temperature. The cooling rates were
measured and found to be 1.25°C/min. for the first half hour, 0.25°C/min. for
the next half hour, and the terminal temperature was found to be -43°C after
sixteen hours of pumping. Heat losses associated with radiation exchange with
the IFM housing, and a thermal conduction path along the modulator ground lead
were responsible for the extra long time required to reach -43°C. After nine-
teen hours the crystal was returned to room temperature and removed from the
IFLM for inspection. No damage to the crystal could be seen as a result of
the first cooling cycle.

Prior to the initial IFLM imaging tests, KD*P-1 was cooled down again,
and no changes were observed in the cooling rate. The thermoelectric cooler
was shut off, and when the thermistor on the mounting plate indicated 10°C
(50°F), the crystal assembly was removed from the modulator housing. Water
vapor immediately condensed on the surface, and was quickly removed by blotting
with lens tissue followed by flushing with methyl alcohol. Microscopic exam-
ination of the surface coating, however, revealed substantial damage. The
damage layer appeared to be confined to the SiO1.7 coating and the near surface
layer of the KD*P. No pits or scratches were observed, but many pinholes were
found to exist in the coating. In areas of high pinhole density the crystal
appeared dull to the unaided eye.

KD*P-1 was remounted in the IFM, and tests were initiated to determine
the contrast and resolution of an image formed on a laser beam. A 5mW HeNe
laser equipped with a spatial filter and beam expander was employed to project
the image formed by the IFLM. Using this system, a projection contrast of 130
and a transmission of 57 percent including losses in the polarizer, spatial
filter, and beam expander was measured. The projection contrast was limited
by the polaroid polarizer employed to form the image, and a contrast of 400-
500 could be expected with a prism type polarizer.
The image quality was observed to be poor with low resolution and contrast. It was found that maximum image contrast was obtained with the laser beam polarized along the diagonal of the modulator crystal. It had been assumed though not specified that the crystal would be supplied with the crystallographic axes parallel to the edges of the square modulator plate, since this is the standard geometry for modulator crystals.

The second 2" x 2" KD*P crystal unit (KD*P-2) was mounted and installed in the IFLM, and tests were repeated to determine its image quality and cooling rate. The results of these tests were similar to those obtained with KD*P-1. The overall image quality was poor, and microscopic examination of the surface of KD*P-2 showed the same type of pinhole deterioration found in KD*P-1. During the imaging tests, the orientation of KD*P-2 was observed to be normal; that is, the maximum contrast was obtained with the laser beam polarized parallel to the sides of the modulator plate.

With one sweep axis disabled, and the beam defocused, a line of charge about 6 mm wide was written on the modulator, and the electro-optic effect was measured on an unexpanded, polarized laser beam which was directed through the line charge location. The threshold potential for the electro-optic effect was found to be about 10kV, and the half-wave potential was found to be about 17.5kV. Since the threshold potential should have indicated the upper secondary emission cross-over point, which had been previously measured to be about 2kV, the results obtained were unexpected, and have not as yet been satisfactorily explained. The original design concept was based on the modulator housing acting as a collector for the secondary electrons, and as a reference for the potential of the KD*P surface. To determine the validity of this concept, a collector ring positioned about 0.5 in. from the surface of the KD*P was installed, and the electro-optic effect remeasured as a function of electron beam potential. Since similar results were obtained, the surface potential is probably not floating without reference as was originally suspected.

The measured electron beam potentials for threshold and half-wave modulation effect could possibly result from the surface coating; however, the coating specified for the KD*P should match the secondary emission characteristics of the KD*P very closely. Upper secondary cross-over potentials go as high as 7-10kV for some insulators, although data for SiO$_2$ were not available. This discrepancy will have to be explained if operation of the KD*P in a secondary emission mode is attempted.

Since the image quality obtained with both KD*P-1 and KD*P-2 was observed to be poor, an analysis of the beam quality of the electron write gun was undertaken. A small hole was drilled in the phosphor screen, and a Faraday cup was attached to the back of the screen over the position of the hole. The maximum current which could be obtained from the electron gun below the saturation point was 4.5 µamp, and the video drive necessary for cut-off was -50 volts. For a beam current of 4.5 µamp, and a beam spot size of 1.5 mils, and a laser wave length of 6328A, the calculated resolution is 35 line pairs/inch. The low value of beam current obtained for this gun was a result of cathode deterioration which was caused by repeated cycling of the operating pressure between atmospheric and high vacuum.
A new write gun was obtained, and electron beam tests repeated. The maximum measured current for the new gun was found to be 15 μamps, which would predict a resolution of 120 line pairs/inch for a beam spot size of 1.5 mils. The beam spot size is, however, only an estimate since an accurate technique for its measurement has not been devised. The phosphor is too grainy to allow an optical determination of beam size from a shrinking raster measurement, and several attempts to measure the beam profile by deflecting the spot across the entrance hole of the Faraday cup were unsuccessful.

Imaging tests were performed on the IFLM using the newly installed write gun, and the results showed significant improvements over the previous tests. A standard EIA test chart was used to form the image, and the resolution of the projected image was sufficient to resolve the 100-200 line/inch bars and lettering. The contrast showed considerable variation across the surface of KD*P-2 with a low contrast-low intensity band present in the center of the crystal. Although inspection of the crystal prior to these tests had revealed a slight discoloration in this area, no pinhole effect or clouding had been observed. It was noted that the band in the center had a time constant to changes in the image which was much longer than that of the rest of the crystal. This interesting observation led to speculation that the resistivity of the coating in the band area was significantly higher than that over the rest of the surface. A contrary indication was obtained, however, when the centering controls on the sweep were used to move the edge of the raster in and out of the band area. With the raster off to one side of the crystal and out of the band area, a normal image was observed. As the raster was moved into the edge of the band and stopped, the entire area of the band would slowly become bright. This observation would indicate a lateral spreading of charge across the surface of the crystal, and hence lower resistivity in the band area. The resistivity could be measured by depositing a series of conducting strips across the crystal surface, but this procedure would ruin the crystal as a modulator. Since the current density in the band area was much higher in the electro-optic tests than it will ever be in the imaging mode, no further attempts were made to obtain an answer to the observed behavior.

The third 2" x 2" KD*P modulator (KD*P-3) was installed in the IFLM and the imaging tests were once again performed. A high quality image with smooth contrast and resolution was obtained across the entire modulator surface. The IFLM system was then dismantled for shipment to MSFC with the IFLM housing under vacuum.

Delivery of the IFLM to MSFC (10-11 Reporting Periods)

The IFLM was transported by Messrs. R. G. Shackelford and J. R. Walsh to MSFC on 13 March 1972. The equipment arrived in good condition and was operational by noon of the following day. Initial alignment of the optical system revealed several undesirable features which resulted in degradation of the IFLM's image quality. These features resulted from spatial variations in the polarization of the expanded laser beam employed to project the image, and "optical noise" produced by transmission through the polarization analyzer. These problems were undoubtedly present to some extent in the optical system.
used at Georgia Tech, but were much more apparent in MSFC's optical system because of the higher power HeNe laser employed. Since the spatial variations in the polarization were confined to the outer area of the expanded laser beam, some improvement was obtained by expanding the beam to a size considerably larger than required, and masking off the undesired beam area. A Nicol prism polarizer placed between the laser and the spatial filter also resulted in a slight improvement; however, a substantial amount of optical noise remains.

The initial image tests were encouraging, but the overall optical quality was much worse than that obtained in the tests at Georgia Tech. After an analysis of the electronic video waveform was performed, the major source of the problem was found. The silicon target vidicon cameras employed with the IFLM are very sensitive to light level and appear to have a low dynamic range. Each camera-monitor system has a full range of adjustments for image quality, and it was found that the setting of the sync pulse level was not optimum for use with the IFLM electronics. The camera readjustments were made, and a significant improvement in image quality resulted. Although the gray scale was still somewhat compressed, the images were sharp and the resolution appeared to be very good. It was the consensus of opinion that the optical noise and camera-IFLM incompatibility problem was limiting the performance of the IFLM. It was decided that an image orthicon camera and a large area Nicol prism polarizer should be obtained for further testing. The IFLM system was accepted and certified to meet the specifications which were set out in the original contract and its modifications.

Additional tests were performed by Messrs. Shackelford and Walsh during 27-29 March 1972, after two weeks operation by MSFC personnel. The system was found to be in good shape with the exception of some optical damage in a crescent shaped area in the center of the crystal. The damage was first noted on 24 March, but there was no indication as to how it may have occurred. Some lateral charge spread was observed when images were formed in this area resulting in reduced resolution and contrast. While the optical damage was not severe, it did detract from the overall image quality, and we decided to mask the illuminating laser beam so that only a square area located in the lower right quadrant of the crystal was illuminated. With this arrangement, it was possible to clearly resolve an image consisting of thirty six presstype letters and symbols. The image was optically magnified to an area of about four square inches and viewed on a ground glass screen. From a measurement of the space between adjacent letters, the resolution was estimated to be 160 line pairs per inch.

Once again, considerable difficulty was encountered in interfacing with the TV equipment. The video input signal for the IFLM was initially in parallel with a monitor, and on several occasions electronic circuitry associated with the monitor coupled into the IFLM video signal causing a loss in sweep synchronization. An image orthicon camera was obtained for use with the IFLM, and no further difficulty was experienced.

Modification of the IFLM (12 Reporting Period)

Redesign of certain components of the IFLM as set forth in Amendment No. 7 to the existing contract have begun. The modulator housing has been modified
to accept a four inch ground and polished input window. A new thermoelectric heat exchanger and mounting flange have also been fabricated. The new design will provide more efficient heat exchange for the thermoelectric cooler, and four additional electrical feed-throughs. A retractable fluorescent screen has also been installed in the modulator.

Redesign and breadboarding of the LED video isolation link has been completed, and a bandwidth of 10 MHz has been obtained. Redesign of the deflection drive circuits to reduce coupling and improve linearity has been initiated, and initial testing of the Celco linear deflection yoke has been performed.

Expenditures and man-hours effort covering the first twelve reporting periods are:

- Technical Effort - 4,114 Man-hours $56,315
- Materials and Supplies 16,204
- Total Expenditures to Date $72,519

During the remaining work period, all redesign efforts and testing of the modified IFLM system will be completed. Techniques for measuring image quality will be established, and the modified IFLM will be delivered to MSFC at the end of the contracting period.

The projected expenditures and man-hours effort for the last reporting period are:

- Technical Effort - 491 Man-hours $6,716
- Materials and Supplies 832
- Total Projected Expenditures $7,548

New Technology Statement

A thorough review was conducted during the reporting period by the technical staff assigned to contract NAS8-27375 to determine if any reportable items of new technology as defined in NASA form 1162 resulted from the above described technical efforts. The engineering techniques applied to fabrication of the IFLM were carefully reviewed, and no reportable items of new technology were uncovered.

Respectfully submitted,

R. G. Shackelford
Project Director

Approved:

W. Dees, Head
Special Techniques Branch
ENGINEERING EXPERIMENT STATION
Georgia Institute of Technology
Atlanta, Georgia 30332

FINAL REPORT
PROJECT NO. A-1335

DESIGN AND FABRICATION OF AN EXPERIMENTAL IMAGE FORMING LIGHT MODULATOR

by

R. G. SHACKELFORD
and
J. R. WALSH, JR.

RESEARCH CONTRACT NAS8-27375

25 May 1971 to 25 June 1972

Performed for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812
ABSTRACT

This report describes the design and development of an image conversion device called an image forming light modulator (IFLM). The IFLM was designed to generate an optical transparency from an EIA TV video signal representation of a two-dimensional image. The operating mode was specified to include image formation with complete erasure at a 30 cycle per second rate or storage of the optical transparency for at least 1 minute. The image quality was designated to be comparable to that of a commercial TV display with a minimum resolution of 300 lines/inch over an image plane of 2" x 2".

These specifications were achieved in a device whose design will permit its use as a test vehicle for advanced concepts in image conversion. The electro-optic Pockel's effect was employed in an optical transmission mode device utilizing an electron-beam-addressed KD*P modulation medium. A maximum resolution of 320 lines/inch was measured with a contrast of about 95 for linear conversion of the TV video signal. Image retention of several minutes was provided by cooling the KD*P crystal to a temperature near its Curie point.

All major assemblies including the modulator were designed to be easily demountable for convenience in adapting the IFLM to other operating modes with different modulation media. A high speed Orb-Ion vacuum pump was also incorporated into the modulator housing to facilitate establishment of the required operating pressure.
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I. INTRODUCTION

Information processing by means of optical Fourier transform techniques has a long history of successes in the fields of microscopy, photography, character recognition, and holography to name a few. The advent of the laser has, however, resulted in a renewed interest in the development of new and innovative applications of coherent optical processing. One such application is real time spatial processing of optical images.

In many optical processing techniques, the input information takes the form of an optical transparency on photographic film. While an input format employing photographic film has the advantages of high resolution and availability over a wide range of exposure and spectral response characteristics, it is not suitable for real time processing because of the length of time required for development of the film. The extension of coherent optical processing to real time applications has resulted in the realization of a class of imaging devices which generate time varying optical transparencies [1-16]. In general, these devices transform an incoherent image into a coherent one by means of a modulation medium whose optical transmission characteristics are caused to conform to some feature of the input image. In some of these devices, the total image is generated essentially at one time while in others it is developed point by point over a short time interval.

The physical basis for the spatial modulation of an optical wave is a localized amplitude or phase change in the modulation medium. Amplitude changes are accomplished directly by absorption and scattering, or indirectly by polarization changes, while phase changes are in general a
result of either electrically or mechanically induced changes in the index of refraction. Some examples of modulation mechanisms and medias are scattering in liquid crystals, the electro-optic effect in solid crystals or in fine grain ferroelectrics, and mechanical deformation of plastic films. Descriptions of the operating characteristics and physical mechanisms in the above examples and others are contained in References 4, 11, 13, and 16.

The design, development and operation of an imaging device called an image forming light modulator (IFLM) is the subject of this report. The IFLM, which employs an operating mode similar to the one developed by Casassent [6], was designed to transform an electrical signal representation of an image into an optical transparency. The electrical image representation was specified to conform to the standard EIA composite TV video signal. Each point on the image is developed sequentially from an electron beam which scans an electro-optic crystal situated in the modulator plane. A charge pattern proportional to the image intensity is deposited on the crystal surface, and modulation of a light beam passing through the crystal results from the longitudinal electro-optic effect. The modulator may be envisioned as a two-dimensional array of Pockel's cells which completely cover the image plane. The size of a resolution cell and the contrast of two adjacent cells are determined by the physical properties of the electro-optic crystal and the diameter of the electron beam spot.

The goal of the IFLM development was to build an engineering model device which could be used for investigating system concepts in optical data processing, and which would also serve as a basic breadboard for testing advanced concepts in optical imaging. These goals were successfully
fulfilled in the IFLM system which was delivered to MSFC on 13 March 1972.
The modulator housing was constructed in such a manner that all of the major components can be easily removed for modification or replacement with different components. The electro-optic crystal is attached to a demountable assembly which can be conveniently adapted to other modulation media, and whose temperature can be controlled over the range $-50^\circ \leq T \leq 27^\circ C$.

A detailed exposition of the design and fabrication of the IFLM containing theory of operation, calculation of design parameters, and a description of construction techniques is presented in this report. The operation and performance of the IFLM are also discussed, and recommendations for improving the performance and packaging of the device are included.
II. DESIGN OF THE IFLM

A. Image Forming Techniques

Spatial modulation of the polarization of a light beam can result in the formation of an image if the polarization change is proportional to the image intensity at each point, and the modulated beam is projected through a polarization analyzer. When the polarization modulation is induced by an applied electric field in a medium whose optical properties are such that the modulation is a linear function of the applied field, the process is called the linear electro-optic or Pockel's effect.

The IFLM employs an electron-beam-addressed modulator to transform a standard EIA TV video signal into a two dimensional image transparency which can be erased and reformed on each succeeding TV frame. The modulator crystal is cut in the basal plane with its optic axis (z-axis) perpendicular to the plane of the cut, and then ground and polished to a thin plate. A transparent conducting film is deposited on one surface of the plate, and during operation the film is grounded to provide a reference potential plane. Charge deposited by the scanning electron beam establishes a spatially varying electric field along the z-axis between the electron-beam-addressed surface and the grounded conducting film on the opposite surface. In this manner, a point-by-point polarization modulation is impressed on the wavefront of a linearly polarized light beam which is projected through the crystal plate along a direction parallel to the z-axis. The charge distribution is removed at the end of each picture frame by illuminating the surface with a uniform flux of low energy
electrons. During this operation, secondary emission results in the establishment of a uniform charge distribution on the crystal's surface whose magnitude is determined by the potential of a collector ring which surrounds the modulator crystal assembly. The collector ring is normally fixed at several volts above ground to assure complete erasure of the image features.

The physical mechanism responsible for modulation of the light beam is the linear electro-optical or Pockel's effect. The general theory of this effect has been treated in detail by Yariv [17], and thus will only be summarized below. In addition, Billings [18], Carpenter [19], and others [20-22] have thoroughly discussed the electro-optic effect in uniaxial crystals of the dihydrogen phosphate type.

The dielectric constant tensor of an anisotropic crystal has in general three independent elements, $\varepsilon_{11}$, $\varepsilon_{22}$, and $\varepsilon_{33}$, where the subscripts 1, 2, and 3 represent orthogonal directions along three crystal axes. For uniaxial crystals, $\varepsilon_{11} = \varepsilon_{22} \neq \varepsilon_{33}$, and the direction assigned to subscript 3 is designated the optic axis of the crystal. If a linearly polarized plane wave is incident on a uniaxial crystal in a direction parallel to the optic axis, the phase velocity will not depend on the orientation of the polarization vector, and no changes will be observed in the emerging wave.

In crystals of the noncentrosymmetric class, the application of an electric field will cause a change in the dielectric tensor. In some crystals, the induced dielectric change is proportional to the first power of the applied field, and in others, the change is proportional to the
square of the applied field. Specifically, when an electric field is applied
along the optic axis of certain uniaxial crystals, the crystal becomes
biaxial with a $45^\circ$ rotation of the principal axes in the plane perpendicular
to the optic axis. A linearly polarized wave incident along the optic
axis of such a crystal will be resolved into two orthogonal components
along the induced principal axes which have associated dielectric constants
with different magnitudes. Thus, one orthogonal component of the incident
wave will have a different phase velocity than the other orthogonal com-
ponent, and the retardation is given by

$$\delta = \frac{n_0^3 r_{63} V_{33}}{\lambda_o}, \quad (1)$$

where $\delta$ is the number of wavelengths retarded, $n_0$ is the ordinary index of
refraction, $r_{63}$ is the electro-optical constant ($\mu m/V$), $V_{33}$ is the applied
voltage along the optic axis (V), and $\lambda_o$ is the vacuum wavelength of the
light wave ($\mu m$).

If the polarization vector of the incident wave bisects the induced
principal axes, and the projected wave is passed through a polarization
analyzer, the intensity of the transmitted wave, $I_T$, is related to the
intensity of the incident wave, $I_o$, by

$$I_T = I_o \sin^2(\pi \delta). \quad (2)$$

Minimum transmission occurs for $V_{33} = 0$ (polarization analyzer rotated
90° with respect to the laser field), and maximum transmission occurs for
$V_{33} = V_{1/2}$ as defined by
\[ v_{1/2} = \frac{\lambda_0}{2n_o^3 r_{63}} \quad (3) \]

where \( r_{63} = A(e_{33} - e_o) \), and A is a constant. The modulation described in Equations 1 through 3 is known as the longitudinal Pockel's effect.

B. Selection of an Electro-Optic Crystal

Although there are a number of candidate crystals exhibiting the longitudinal Pockel's effect, only KDP and its isomorphs have the proper combination of electro-optical and mechanical properties required to satisfy the specifications set forth for performance of the IFLM. The three primary considerations in selecting an electro-optic crystal for imaging applications are the crystal's optical quality, its mechanical properties, and its electro-optic coefficient.

To be useful, the crystal plate must be practically free of growth imperfections, natural birefringence, optical activity, and impurities. Its mechanical properties must be such that it can be fabricated in the form and with the dimensions required for a high resolution modulator. For good handling and stability, it should not be exceptionally brittle, hygroscopic, or possess a large piezoelectric coefficient. It is desirable that the electro-optic coefficient be large so that a voltage compatible with the crystal's dielectric strength is required for full modulation.

It will be shown in Section II-C that at room temperature, the minimum spacing between two resolvable charge spots on the crystal surface is about equal to the thickness of the crystal plate. The specified resolution of 300 lines on a 2" x 2" plate, for example, requires a thickness of about
13 mils. The requirement of a large plate of good optical quality eliminates all candidate crystals but KDP and its isomorphs KD*P and ADP. The electro-optical coefficient for KD*P is about 2.5 times greater than that of KDP, and about 3 times greater than that of ADP. The required potential for $V_{13}$ across a 13 mil plate results in electric field strengths of $0.82 \times 10^7$ V/m, $2.14 \times 10^7$ V/m, and $2.63 \times 10^7$ V/m for KD*P, KDP, and ADP respectively. These required fields for full modulation exceed the dielectric strengths of KDP and ADP, and prevent them from performing reliably in high resolution imaging configurations.

Although KD*P becomes the choice for high resolution electro-optic imaging by default, it is by no means an ideal material. While its optical properties are satisfactory for most applications, some residual birefringence can be found in most large area samples. In addition, variations in bulk resistivity across the basal plane result in image intensity variations for room temperature operation because of associated variations in the charge leakage rate. Fabrication of a modulator plate is difficult because KD*P is very brittle. Even when the KD*P crystal is bonded to a thick substrate before grinding and polishing operations are undertaken, the chance of breakage remains high for large area plates of 10 mils thickness. The plate must also remain bonded to the substrate in operation because of the high probability of thermal fracture or breakage due to piezoelectric strain. Handling and operation of the modulator are also complicated by the fact that the KD*P is water soluble and has a low melting point. In summary, KD*P has excellent electro-optical properties, can be grown and fabricated into large, thin plates of good optical quality, but
lacks the mechanical properties needed to provide good flexibility in adapting the modulator to an optimum operating mode.

C. Factors Affecting Resolution and Contrast

The maximum resolution of the optically projected image is limited by the diameter of the electron beam and the electric field distribution of the deposited charge spot between the front and back surfaces of the crystal. If the diameter of the electron beam is \( d \), and the thickness of the crystal is \( t \), Peterson [23] has shown that for an isotropic crystal, the potential falls to approximately half maximum at a radius of \( \frac{d + 0.44t}{2} \) in a plane parallel to the crystal surface. Two charge spots are said to be barely resolved when they are separated by the half maximum diameter. Thus, the maximum resolution, \( R \), in an isotropic medium is given by

\[
R = \frac{1}{d + 0.44t} .
\]  

In an anisotropic medium, where the three principle components of the dielectric constant tensor are not equal, the dependence of the half maximum potential diameter on the electron beam diameter and crystal thickness is quantitatively altered. For a longitudinal electro-optic crystal of the \( \text{KD}^* \text{P} \) symmetry class, the two principle dielectric components \( (\varepsilon_{11} \text{ and } \varepsilon_{22}) \) in a plane perpendicular to the applied electric field are equal to each other, and are not equal to the dielectric component \( (\varepsilon_{33}) \) along the direction of the applied field. Sand [24] has shown for this case that the resolution as defined by two spots separated by the diameter of the half maximum potential is functionally the same as that for the isotropic case, namely,
\[ R = \frac{1}{d + 0.44t'} \tag{5} \]

where the effective crystal thickness \( t' \) is given by
\[ t' = t\sqrt{\frac{\varepsilon_{11}}{\varepsilon_{33}}} \tag{6} \]

In general, \( d \) can be made smaller than \( t' \), so that the maximum resolution obtainable depends primarily on the mechanical and dielectric properties of the electro-optic crystal. The minimum thickness to which the crystal can be ground for this application depends on its brittleness and whether its dielectric strength will permit the half wave voltage to be established along the thickness direction without breakdown. For \( KDP \) crystals larger than about 1" x 1", the limit on thickness established by the crystal's mechanical properties is about 10 mils, and dielectric breakdown does not occur at this thickness.

Although the physical thickness of a \( KDP \) crystal of useable size is currently limited to about 10 mils, the behavior of its dielectric component \( \varepsilon_{33} \) as a function of temperature can be exploited to significantly reduce the effective crystal thickness \( t' \). As the temperature of a crystal of the \( KDP \) point group is reduced, the dielectric component \( \varepsilon_{33} \) increases to a maximum at the Curie temperature, whereas the dielectric component \( \varepsilon_{11} \) remains relatively unchanged. The behavior of \( \varepsilon_{33} \) as a function of temperature is approximately given by
\[ \varepsilon_{33} = 4.5 + \frac{3100}{T - T_c} \tag{7} \]

where the Curie temperature, \( T_c \), is about -55°C for 95% deuterated \( KDP \). The expression for resolution given in Equation 5 may by inclusion of Equation 6 and 7 be written as
\begin{equation}
R(T) = \frac{1}{d + 0.44t \sqrt{\frac{\varepsilon_{11}(T-T_c)}{4.5(T-T_c) + 3100}}}. \tag{8}
\end{equation}

The temperature dependence of \( \varepsilon_{33} \) also results in the reduction of the voltage required across the KD\(^*\)P crystal for 100\% modulation in the Pockel's configuration. Employing Equations 3 and 7, the expression for \( V_{\frac{1}{2}} \) in KD\(^*\)P may be written in the form

\begin{equation}
V_{\frac{1}{2}}(T) \approx \frac{26(T-T_c) \lambda_o}{3.5(T-T_c) + 3100}. \tag{9}
\end{equation}

\( R(T) \) and \( V_{\frac{1}{2}}(T) \) for KD\(^*\)P have been calculated and plotted in Figure 1 as a function of \( T \) for \( \lambda_o = 0.5145 \, \mu m \), \( d = 0.001 \) inch, \( t = 0.010 \) inch, and \( \varepsilon_{11} = 56. \)

The full advantage of operating the crystal at a temperature near the Curie point is not evident from Figure 1. In addition to higher resolution, the potential difference between points of adjacent charge at full contrast is greatly reduced. The reduced surface charge would result in smaller beam landing errors and hence a sharper image. Still another advantage of low temperature operation is the storage capability provided by increased charge leakage time constants. Charge stored on the crystal's surface tends to migrate laterally between adjacent points of high potential, and leaks through the crystal to the grounded electrode with a time constant which is proportional to the product of \( \varepsilon_{33} \) and the resistivity along the axial direction. Calculations by Marie [4] have shown that the axial and lateral time constants increase from 0.17 sec. and 0.08 sec. at 20\degree C to 33 min. and about 8 min. at -50\degree C, respectively for 95\% deuterated KD\(^*\)P.
Figure 1. Dependence of Resolution and Half-Wave Potential on Temperature in a KD\textsuperscript{P} Modulator.
For storage applications, Marie has shown that KDP which has a time constant of about $8 \times 10^4$ years at $-145^\circ C$ would be a better choice than KD*P.

Curie point operation of KD*P can be economically implemented with thermoelectric cooling; however, it will be shown in Section II-E that high resolution operation in the cooled mode requires higher electron beam currents than room temperature operation. One could also obtain a higher resolution image with the same electron beam current by operating at the Curie point with a thicker crystal so that $t=0.010$ in. The resulting increase in thickness (~0.030 in. at $T=-50^\circ C$) would permit fabrication of a crystal assembly with larger surface area and hence a higher number of resolution cells.

D. Modulator Housing

The housing of the IFLM consists of a stainless steel vacuum chamber provided with ports for attachment of the roughing and high vacuum pumps, optical windows, electron guns, and the electro-optic crystal assembly. An additional port has also been provided for manual control of a flip-down fluorescent screen which is employed in setting the electron gun operating points and optimizing the video circuitry. A photograph of the IFLM housing is shown in Figure 2, and a drawing showing details of the electro-optic crystal assembly is presented in Figure 3.

1. Geometrical Considerations

The geometrical arrangement of the system components was limited by several design constraints. In a transmission mode IFLM, it is desirable...
Figure 2. Photograph of IFLM Modulator Housing.
Figure 3. Drawing of IFLM Showing Details of Modulator Assembly.
for the incident optical beam to pass through the crystal surface at normal incidence, and for the crystal surface to be approximately parallel with both incident and exit windows. Surface reflections at each boundary should, in addition, be minimized by the use of appropriate dielectric coatings. It is also desirable, but not necessary, to have the electron beam impinge upon the crystal surface at normal incidence. In the transmission mode IFLM, off-axis location of the electron gun must be employed to prevent shadowing of the optical beam by the electron beam lens. The resulting Keystone distortion can be removed by appropriate current waveforms in the magnetic deflection electronics. Finally, to improve the resolution of the electron beam spot, it is necessary to locate the electron gun as close to the surface of the electro-optic crystal as possible. Distortions resulting from the off-axis geometry and the speed of the electron beam lens establishes the minimum gun-to-target distance.

These highly interacting and somewhat conflicting requirements were satisfactorily met in the configuration adopted for the IFLM housing. The entrance and exit windows were located in line and parallel to the crystal with a clear 3 inch diameter optical corridor through the system. The electron guns were located off-axis with an inclination of 30 degrees, and the gun-to-target distance was fixed at 10.5 inches. A ground and polished window mounted on a house keeper seal was used for the entrance window, and a standard vacuum window mounted on a Conflat flange was employed as an exit window. Because of the close time schedule encountered during fabrication of the IFLM, neither window was antireflection coated.
The IFLM housing was mounted on a kinematic base providing variable
yaw, pitch, and roll orientation. Two screw adjustments riding in a
curved track provide ± 1 degree changes in pitch and roll, while a ball
bearing pivot in conjunction with the curved track allows a ± 5 degree
adjustment in yaw. A ± 0.5 inch ball bearing translation stage has also
been provided to facilitate mounting of the IFLM to an optical rail or
magnetic base.

2. Vacuum System

In order to provide a suitable environment for operation of the
electron guns, and to prevent surface contamination of the electro-optic
crystal, the system operating pressure was specified to be < 10⁻⁷ Torr.
For reliable vacuum performance, the stainless components of the system
were heli-arc welded, and all flanged connections were fitted with Conflat
metal gasket assemblies. The pumping system employed with the IFLM has
the advantages of low bulk and weight while preserving the performance
characteristics of ion-type vacuum pumping. A Varian Vac-Sorb pump was
employed to rough pump the system, and the final operating pressure was
achieved with a Varian Orb-Ion pump. The maximum pumping rate of 100 ℓ/s
provided by the Orb-Ion pump was found to be more than adequate for the
outgassing load presented by the electron beam addressed KD*P crystal.
System pressure measurements were made with a Vecco RG-75 ion gauge and
controller over the range 10⁻⁹ < P < 10⁻² Torr.

The evacuation procedure is initiated by chilling the Vac-Sorb pump
with liquid nitrogen for about 30 minutes. The roughing valve is then
opened, and the system pressure is monitored as it decreases. When the system pressure reaches $10^{-3}$ Torr, the Orb-Ion pump can be started. After turn-on the emission current is slowly increased, and the roughing valve is closed when the pressure begins to decrease. A pressure of $10^{-7}$ Torr can be achieved after one hour of pumping, and an ultimate pressure of about $2 \times 10^{-8}$ Torr can be reached without baking.

3. **Optical Windows**

A 4-inch diameter Pyrex window was employed on the exit end of the IFLM housing to allow changing of the electro-optic crystal without removal of the thermoelectric cooler and crystal support flange assembly. The window was mounted in a Conflat flange so that dismounting from the IFLM housing could be easily accomplished. Initially, a 2½ inch diameter entrance window was mounted on a house-keeper seal and welded directly to the electron gun support flange. In subsequent optical tests, the window was found to produce unacceptable edge distortions with a 1.5 inch square viewing format. This window was replaced with a 4-inch diameter window which was mounted on the electron gun flange by means of a stainless tubing transition. Satisfactory optical performance was assured by grinding and polishing both sides of the window to 40-30 scratch and dig with a flatness of better than 10 bands. Because of the pressing time schedule on fabrication and testing of the IFLM, the windows were not antireflection coated; however, application of such coatings would improve optical performance by eliminating interference patterns which are projected on the image plane.
4. Crystal Mount

The electro-optic crystal assembly was fabricated by Isomet to specifications established at the outset of this program. To obtain as much image resolution as possible, a 2" x 2" x 0.010" KD\(^+$\) P crystal was specified. A thick substrate was employed for mechanical rigidity, and all components were thermally matched to minimize stresses over the operating temperature range. A Z-cut 99% deuterated KD\(^+$\) P crystal blank was polished on one side and coated with a semitransparent conductive coating of CdO doped with Cd. The coating was specified to be 80% transmissive with a surface resistance of less than 10\(^5\) ohm/square. The coated side of the crystal blank was then cemented to a 1 cm thick CaF substrate with a bubble-free silicon cement and the other surface of the KD\(^+$\) P blank was ground and polished to a thickness of 0.010". The fabrication processes were developed by Isomet, and all crystal units were found to be within the desired specifications when received. A photograph of the crystal assembly is shown in Figure 4.

To achieve operation near the Curie temperature, the crystal mounting plate was attached to the cold plate of a Borg Warner Model 932-1 two-stage thermoelectric cooler. To facilitate installation and replacement of the crystal assembly in the IFLM housing, the CaF substrate was bonded to an aluminum plate which was attached to the cold plate by means of a beryllium copper spring clip. An epoxy staking compound with close thermal expansion matching was employed to bond the crystal assembly to the aluminum plate.

A water cooled cooper heat sink was soldered to the hot plate of the thermoelectric cooler to hold its temperature to approximately 30\(^\circ\)C. The
Figure 4. Photograph of KD*P Assembly.
water cooling tubes were then passed through the support flange and welded to insure vacuum integrity. An eight pin feed-thru was also mounted in the support flange to accomodate power and thermistor monitoring leads for the cooler.

The performance of the thermoelectric cooler was satisfactory even though the lowest temperature obtainable with tap water flowing through the heat sink was about 7 degrees above the Curie point of the clamped crystal. A plot of the temperature of the crystal assembly as a function of cooling time is shown in Figure 5. This data was taken with a thermistor which was bonded to the crystal support bracket. Although the rate of cooling was somewhat higher than that which was desired, no strains or cracks were observed in the crystal after several cycles between room temperature and -43°C. Some deterioration was observed, however, in the transparent conducting coating on one of the crystal assemblies. It has not been conclusively determined whether this effect was associated with the cooling cycle or with some other operating characteristic.

The thermoelectric cooler is programmed with a proportional controller with dial settings between -37.5 and -67.5°C and control range of ± 1°C. The load capacity of the cooler was chosen to provide a heat pumping capacity of about three times the maximum heat input of the electron beam (0.2 W) at the Curie point. It was found, however, that the lowest temperature obtainable with this unit is approximately limited by radiation heating of the crystal assembly. The calculated heat input from radiation exchange with the IFILM housing is plotted on the characteristic cooling curve of the thermoelectric cooler in Figure 6. The radiation exchange curve was calculated from the expression
Figure 5. Modulator Cooling Characteristic.
Figure 6. Thermal Load Characteristics of the Two-Stage Thermoelectric Cooler.
\[ Q = e \sigma A_c (T_0^4 - T_c^4), \]

where

- \( Q \) = heat input to the crystal assembly (watts),
- \( e \) = average emissivity of the crystal surfaces (~0.5),
- \( \sigma \) = Stephan Boltzman Constant \( (0.567 \times 10^{-11} \text{ wattscm}^{-2}\text{deg}^{-4}) \),
- \( A_c \) = area of the crystal assembly (~70 cm\(^2\)),
- \( T_0 \) = ambient temperature (~300°K), and
- \( T_c \) = temperature of the crystal assembly (~K).

The intersection of the two curves, which predicts the lowest temperature obtainable, occurs at about -41°C, while the lowest temperature measured at the sample support bracket was -43°C. The difference in the calculated and measured values for crystal temperature are not significant, and could result from conduction loss between the support bracket and the crystal or an incorrect estimation of the average emissivity of the crystal surface. If a lower operating temperature is desired in any future application of this device, an additional 20 degrees decrease in cold plate temperature can be easily obtained by pumping chilled water at about 5°C through the copper heat sink.

E. Electron Beam Optics

1. Write Gun

The IFLM was designed to generate an optical transparency from a TV video representation of the image. A beam current modulated, high resolution electron gun was employed to deposit a charge pattern proportional to the intensity of the image on the electro-optic crystal. The minimum
electron beam current and maximum spot size required from the electron gun were determined by the resolution and contrast specifications for the optical transparency, which are in turn functionally dependent on the thickness and dielectric properties of the electro-optic crystal.

Expressions for the resolution and contrast developed in Section II-C show the dependence of these image parameters on the electron beam diameter and temperature of the crystal. The electron beam current is also a function of temperature for a given contrast and crystal thickness, and is a quadratic function of beam diameter for maximum contrast.

An approximate expression for the maximum electron beam current can be written for the case where the electron beam addresses the crystal at normal incidence, and is assumed to reside on one resolution cell during the time interval $\tau/R$, where $\tau$ is the horizontal line time of the EIA TV sweep, and $R$ is the resolution. The potential maximum between the front surface of the crystal and the grounded conducting film on the back surface of the crystal results from charging an equivalent parallel plate capacitor whose area is $\pi d^2/4$, and whose thickness is $t$. Thus, the effective capacitance is given by

$$C = \frac{\varepsilon_0 \varepsilon_{33} \pi d^2}{4t},$$

where $\varepsilon_{33}$ is the principal dielectric component of the crystal perpendicular to the crystal plane. The quantity of charge, $|\Delta Q|$, stored in time $\Delta t = \tau/R$ is

$$|\Delta Q| = \frac{\tau}{R} (1 - \delta) I_o,$$
where $I_o$ is the electron beam current and $\delta$ is the secondary emission ratio. For electron beam potentials $> 10$ kV, $\delta \approx 0$, and using Equations 11 and 12 in $\Delta Q = C\Delta V$ leads to the expression

$$I_o \approx \frac{e_0 e_{33} \pi d^2 R \Delta V}{4 \pi t}.$$  \hspace{1cm} (13)

For full contrast, $\Delta V = V_\frac{1}{2}$, and employing Equations 7 and 9, the electron beam current becomes

$$I_o \approx \frac{2656 \rho d^2 \lambda_o}{4 \pi t} \left[ \frac{4.5(T-T_c) + 3100}{(T-T_c) e_{11}} \right] \left[ \frac{4.5(T+55) + 3100}{3.5(T+55) + 3100} \right].$$ \hspace{1cm} (14)

Over the temperature range of interest ($-55^\circ C < T < 27^\circ C$), the quantity $\left[ \frac{4.5(T+55) + 3100}{3.5(T+55) + 3100} \right]$ is approximately equal to one, and hence

$$I_o \approx \frac{2656 \rho d^2 \lambda_o}{4 \pi t} \left[ \frac{4.5(T-T_c) + 3100}{e_{11}(T-T_c)} \right].$$ \hspace{1cm} (15)

The beam current required for full contrast was calculated as a function of beam diameter and wavelength over the temperature range $-50^\circ C < T < 27^\circ C$. Figure 7 shows the results of three sets of these calculations for the wavelength 0.5145 µm and the temperatures $-50^\circ C$, $-25^\circ C$, and $27^\circ C$. To achieve the design specification of 150 line pairs/inch, design goals of a one mil diameter beam and a beam current of 10 µA were chosen for the electron gun. The calculations above predict a maximum resolution of 216 line pairs/inch at full contrast for a gun with a one mil beam at 10 µA and a crystal temperature of $-16^\circ C$. In terms of electron beam current density, operation with full contrast at the temperatures $27^\circ$, $-25^\circ$, and $-50^\circ C$ requires current densities of approximately 1.6, 2.4, and 4.0 amps/cm$^2$ respectively.
Figure 7. Electron Beam Current Required for Maximum Contrast and Resolution with $\lambda = 0.5145 \text{ \( \mu \)m}$, Modulator Temperatures of $27^\circ\text{C}$, $-25^\circ\text{C}$, and $-50^\circ\text{C}$.
The design goals for the gun were also determined in part by the availability of off-the-shelf commercial guns. A thorough survey of industrial suppliers of high resolution CRT and electron microscope devices was conducted, and it was found that an electron gun with published operating parameters approaching the design goals was available from Superior Electronics Company. The gun chosen was a modified model SE-5Z which was originally intended for application in a flying spot scanner.

The modified electron gun, which was designated the SE-469, was designed to focus to a beam diameter of 1.0 mils at the target with a beam current of 10 μA, with guaranteed specifications of 1.5 mils at 10 μA. Two guns were initially ordered to provide one back-up unit for installation before delivery of the IFLM to MSFC. The guns were mounted on hard glass stems, and a glass blower was employed to fuse the gun mounts onto 1.5 inch diameter glass tubes which were attached to Conflat flanges with glass-to-metal seals. During initial tests with the first gun, it was found that shorting occurred between grids $G_1$ and $G_2$ when the filament was brought up to the specified operating temperature. The second gun was also found to be shorted after conditioning of the cathode, but its short was found to occur between the cathode and $G_1$.

Three replacement guns were obtained with increased intergrid spacing, but intermittent shorting continued to be experienced during the operating tests. It was also found that the cathode of the gun was being poisoned by cycling the IFLM housing between high vacuum and atmospheric pressure during changes of the target configuration. This problem was improved by obtaining new units with the standard oxide cathode replaced by a Phillips
Metallonics type BP-1B cathode which can usually be reactivated after atmospheric exposure.

To determine the electron gun's performance, two tests were performed. The total beam current was measured by deflecting the focused beam into a Faraday cup, and recording the current indicated by an electrometer for various settings of the $G_1$ and $G_2$ voltages. The spot size was estimated by performing a shrinking raster measurement on a fine grain phosphor target with the aid of an optical magnification inspection system.

The $G_1$-cathode transfer characteristic was found to vary significantly between different guns of the same type. A typical measured characteristic is shown in Figure 8. Variation in the $G_1$ cut-off was found to cover the range -10V to -75V; however, the maximum beam current obtained on any of the units tested did not exceed 5 µA with the recommended filament power input.

The spot size of the gun was investigated by examining a TV raster produced by the focused gun on a fine grain fluorescent screen situated at the electro-optic crystal plane. An estimate of the spot size was made by measuring the height of the shrinking raster for which the horizontal lines appeared to merge when viewed through an optical inspection system of about 10 power magnification. The best units were estimated to have a spot diameter of about 3 mils. Although the individual lines were easily resolved with the optical inspection system, it is felt that the true spot diameter might have been less than the spot diameter estimated by the method described above. The grain size of the phosphor was an order of magnitude less than the specified 1 mil spot; however, diffraction effects were
Write Gun

Anode Voltage = 15 kV
Beam Focused into Faraday Cup Aperture

Figure 8. Grid Transfer Characteristics of the Electron Write Gun.
observed to be a strong function of the beam current, and the size of a stationary spot was observed to decrease with decreasing beam current until it was no longer visible in the scanning mode. A more precise and much more sophisticated experiment for measuring the beam spot size would be to calibrate the deflection system in terms of angular deviation versus deflection coil current, and to steer the beam across a small hole in front of a Faraday cup. In this manner, both the beam profile and its half power spot diameter could be measured with greater accuracy than that possible with an optical technique. Such an experiment was not attempted because of the short time schedule involved with development of the IFLM.

Because of the problems experienced with the electron gun, a thorough analysis of the gun design and an assessment of its potential for satisfactory performance in the IFLM were made. It was found that the gun was fabricated from standard components which are commonly employed in guns designed for use in TV picture tubes where the requirements on spot size are significantly relaxed from those of the IFLM application. The intergrid spacings were found to range from about 4 to 6 mils, and the cathode to G₁ spacing was measured to be about 12 mils. The G₁ aperture is about 4 mils, and hence alignment of the various lens elements is quite critical. Microscopic examination of the apertures show that they are not circular and have rough edges. This condition results in high diffraction losses, and limits the beam current obtainable from the gun.

The shorting of one grid element to another is a result of poor grid alignment and thermal expansion of G₁ experienced when the cathode is heated to operating temperature. The grid cups are stamped and thus the
mechanical strains which are relieved when the cathode is heated result in buckling and deformation. The cathode also tends to grow "whiskers" normal to its surface during operation, and when these "whiskers" touch the $G_1$ surface shorting occurs. This type of short can usually be opened by discharging a Tesla coil between $G_1$ and the cathode.

The low beam current obtained with this design is partially due to poor axial alignment of the elements, but is more fundamentally limited by the gun design. The magnification of the electron beam lens is about 7, and thus the cathode area contributing to the extracted beam is about $35 \times 10^{-6}$ cm$^2$. Maximum emission from the BP-1B cathode is about $2A/cm^2$, and thus the maximum cathode emission contributing to the beam is about 70 $\mu$A.

The two lens used in the gun have estimated scattering and diffraction losses of about 10 dB, so that the expected beam current in a 1 mil diameter spot would, therefore, be about 7 $\mu$A.

Several improvements are possible for the SE-469, but would be of questionable value in view of the marginal design of the gun. For example, the elements of the gun could be machined instead of stamped, thereby reducing the possibility of deformation from cathode heating. A tungsten ribbon filament-cathode assembly could also be substituted for the BP-1B cathode and would provide the same beam current with less heating of the surrounding structures. It is apparent, however, that the desired operating conditions of a 1 mil diameter beam spot at a current of 10 $\mu$A can only be obtained from a gun of the SE-469 design by pushing the gun to its operating limits. Operation in this mode will continue to result in poor reliability, and it is recommended that the design and development of a new gun with adequate reserve capacity be initiated.
2. Erase Gun

The erase gun was also purchased from Superior Electronics Company, and consisted of a standard diode emission stage combined with a single anode for control of the beam diameter at the target. The specifications called for a uniform beam of about 3 inches in diameter with a minimum total beam current of 1 mA. Although it was eventually necessary to replace the standard oxide cathode with the BP-1B cathode, no serious difficulties were encountered with the erase gun.

Tests using a fluorescent screen and Faraday cup configuration confirmed that a uniform beam of approximately 3 inches in diameter could be obtained with beam currents up to about 4 mA. The anode voltage for these tests was set at 1 to 1.5 kV corresponding to the peak secondary emission potential range for KD*P. A set of measured characteristics showing the beam current as a function of $V_{G_1}$ for various values of $V_{G_2}$ is shown in Figure 9.

F. Electronics

1. Introduction

The electronics portion of the Image Forming Light Modulator (IFLM) provides the electronic interface between an Electronic Industries Association (EIA) standard composite television input signal and the video drive, deflection, and timing requirements of the IFLM. The IFLM uses two electron guns, which were described in Section II-E, to operate the electro-optic crystal. This image is written on the crystal at the standard television rates and with the standard television format. The other electron gun
Flood Gun

Anode Voltage = 1.5 kV
Beam Collected on Phosphor Coated Aluminum Plate

Figure 9. Grid Transfer Characteristics of the Electron Flood Gun.
provides an erase function which removes images written on the crystal. Erasure is accomplished by flooding the crystal with a high current, uniform beam during a vertical blanking interval in the television signal. To properly position the write beam on the face of the crystal with the proper intensity, and to provide for energizing the erase gun at the proper time, the various electronic circuits must provide several synchronized waveforms. The deflection circuits must provide the drive signals for the magnetic deflection system along with keystone correction to compensate for the off-axis location of the electron gun. The video drive circuits must present the proper amplitude video waveform at the grid of the write gun so that the charge pattern deposited by the modulated electron beam results in the formation of a proper image on the optical beam. The low level video drive circuits must also be isolated from the final drive stage since the grid operating point is close to the cathode potential which is depressed below the grounded target by 15-20 kV. The required isolation is accomplished by using an amplitude modulated infrared light link for transmission of the video signal to the final grid drive stage. The timing circuits are required to generate the proper timing signals in synchronization with the input television waveform. A block diagram of the IFLM electronics is shown in Figure 10. The operating characteristics of each circuitry block shown in Figure 10 will be discussed in the following paragraphs. Circuit details are given in the schematic diagrams contained in Appendix A. The figures in Appendix A are arranged in the general order of overall signal flow from the video input to the deflection circuits and the write gun.
Figure 10. Block Diagram of IFLM Electronics.
2. Synchronizing Circuits

A television signal conforming to the EIA standards is applied in parallel to synchronization circuits, video amplifier, and gating circuits. The television signal required for operation with the IFLM has a peak-to-peak amplitude of one volt, with the sync tips negative, and is at an impedance level of 75 ohms. The sync signals occupy the negative most 0.29 volts of the EIA signal. The synchronization circuits remove the synchronization signals, both horizontal and vertical, from the composite video waveform.

Separation of the sync pulses contained in the composite video signal is accomplished in the sync separator portion of the synchronization circuits. The composite input signal is ac coupled to the input of a μA710 integrated circuit comparator (IC1 in Figure A1 in Appendix A). The negative tips of the input signal are clamped at a negative potential established by a forward biased silicon diode with its anode grounded. The other input to the comparator is connected to a negative voltage approximately one half that at which the sync tips are clamped. This comparator input voltage is also obtained from a forward biased silicon diode and a two to one voltage divider. The level at which the comparator output voltage changes state is set by this reference voltage. As the sync pulses in the composite signal pass through this voltage level, the output of the comparator changes state. The output of the sync separator provides pulses which represent only the synchronizing information in the composite input signal since the sync separator is insensitive to the video content of the waveform. The amplitude of the output is approximately three volts. This output is differentiated to provide the input sync pulse for the horizontal sweep oscillator and
integrated to obtain synchronization pulses for the vertical sweep oscillator. Astable multivibrators which generate reset pulses for the horizontal and vertical sweep generators are synchronized by the recovered synchronizing pulses. The synchronization circuits are shown in Figure A1 of Appendix A.

3. Timing Circuits

The synchronization circuitry provides the input to the timing circuitry which controls the blanking of alternate television frames by use of a video gating system and which also generates the erase pulse for the erase gun. This erase pulse is used to turn on the erase gun anode supply thereby energizing the erase gun which removes the previous image written on the crystal in preparation for writing another image on the crystal. Blanking is accomplished in the gating circuits and video amplifier to which the composite video signal is also applied as shown in the block diagram of Figure 10. A timing diagram for the sequence of operations for the IFLM is shown in Figure 11. Figure 11(a) shows an abbreviated time waveform of the input television signal. Only the vertical blanking intervals are displayed in the television time waveform of Figure 11(a)—the horizontal blanking intervals have been omitted for clarity. The first two fields shown make up one television frame which comprises the complete image to be written on the electro-optical crystal. Figure 11(b) shows the video gate waveform in relation to the other signals. The video gate provides for passing of the input video signal to the write gun for two consecutive fields. Next in the timing sequence is the laser beam shutter pulse shown in Figure 11(c). This pulse provides the capability of gating
Figure 11. Timing Diagram of IFLM System.
the laser beam into the optical system for the next two consecutive television fields (one frame) following the two fields that were written on the crystal. Next the timing of the erase pulse is shown in Figure 11(d). The erase pulse occurs during the vertical blanking interval just before the next image is to be written on the crystal. The erase pulse duration is controllable over a range of 500 to 800 microseconds.

The timing circuitry is made up of an integrated circuit dual flip flop and an integrated circuit one shot multivibrator (Motorola MC853P and MC851P respectively, IC3 and IC4 in Figure A1 of Appendix A). The two flip flops are connected in series to obtain the trigger for the one-shot which is the erase pulse generator. The timing of this pulse is obtained by dividing the television vertical sweep rate by four which results in this pulse occurring at a 15 Hz rate. Outputs are also derived at the two flip-flops to provide the switching signals to the two shunt gates in the video blanking system.

4. Gates and Video Amplifiers

As shown in Figure 10, the composite video input signal also provides the input to a gate in the signal path (transistor Q7 in Figure A1). This gate is driven by the timing circuitry and passes video signals only when the input video signal is to be written on the crystal. A similar gate which is off when the video signal gate is on (transistor Q15 in Figure A1), passes only synchronizing pulses derived from the sync separator, to the write gun video amplifier during the time that no video signal is applied to the write gun. The purpose of this gating function is to minimize changes in d-c level at the write gun grid during alternate frame
times by furnishing a continuous string of sync pulses to the dc restorer in the high level video amplifier which drives the write gun. An output video amplifier (IC2 and its associated circuitry in Figure Al) is provided to re-establish standard output impedance and amplitude of the television signal furnished to the light emitting diode driver in the video isolation link which is contained in the electronics mounted on the IFLM housing.

5. Sweep Generators

The sweep generators for the deflection circuits use sure starting astable multivibrators which are synchronized by the pulses derived from the sync separator circuitry. The multivibrators provide reset pulses to constant current charging circuits which charge capacitors to produce linear sawtooth sweep voltage outputs. The voltage across the capacitors are reset by the pulse from an astable sweep multivibrator which is synchronized with the input video signal. One of the sweep generators operates at the television horizontal line rate and the other at the vertical sweep rate. The sweep generators provide additional outputs for the keystone correction circuits.

The sweep timing capacitors are shown in Figure Al as C10 for the horizontal sweep and C30 for the vertical sweep. These capacitors are charged by constant current generators made up of Q8 and Q31 for the horizontal and vertical sweep systems respectively. Provision is made in the constant current generators to modulate the amplitude of the current generated and, therefore, the amplitude of the sweep waveform produced. This is accomplished by transistors Q9 and Q32 which provides a means of charging the voltage in the emitter circuit of the constant current generators and therefore the current produced by them.
6. Keystone Correction Circuits

Because of the off-axis placement of the electron gun in the IFLM, the deflection produced on the crystal by linearly sweeping the two deflection currents is distorted. This distortion on one axis produces what is known as keystoning. If the gun is off both deflection axes, the image produced suffers additional distortion. It has been determined mathematically and confirmed experimentally that rotation of the deflection yoke to the proper orientation produces a point of minimum keystoning distortion along one sweep axis. This fortuitous position was exploited so that the keystone correction was applied only to the horizontal sweep generator. Control of both the starting current of the horizontal sweep and the current amplitude is provided by the insertion of some of the vertical sweep waveform into the horizontal deflection amplifier.

7. Deflection Drivers

The deflection driver amplifiers are feedback control systems in which a sample of the current in the deflection yoke is compared with the input deflection voltage thereby driving a current in the deflection coil which is a replica of the input deflection voltage. The deflection drivers provide a drive signal for a precision CELCO deflection yoke which has a nominal horizontal winding inductance of 75 microhenries and a nominal vertical inductance of 400 microhenries. The deflection driver is made up of a wideband operational amplifier (μA715 ICl in Figure A2) followed by a complementary symmetry emitter follower. Sweep correction signals are summed into one of the inputs of the deflection driver to provide an offset in the starting current at the sweep. Centering of the sweep on
the crystal is also provided by application of a variable dc voltage to the noninverting input of the operation amplifier. Both the horizontal and vertical amplifiers use the same design. The circuit diagram of the deflection drivers is shown in Figure A2 of Appendix A.

8. Sweep Protection Circuits

Sweep protection circuits are provided for both the horizontal and vertical deflection circuits. These circuits prevent the electron beam from coming to rest on the electro-optic crystal in case of the loss of either sweep. Protection is accomplished by removing the accelerating voltage from the write gun. Both the horizontal and vertical sweep protection circuits sample the current in the deflection coil by sampling the voltage across the one ohm current sampling resistor in the deflection drivers (R14 in Figure A2). This voltage is then amplified, rectified, and filtered to provide the current necessary to turn on a transistor switch in the protection circuit for each sweep. These switches are in series and are also in series with a relay in the Spellman 0 to 20 kV accelerating potential power supply. This relay is powered from the 17.5 volt power supply for the electronic circuits. A second relay powered from the 117 volts ac is controlled by the first and is used to interrupt the primary power to the Spellman power supply in the event of loss of sweep.

9. Video Isolation Coupling Link

A video isolation coupling link is provided to isolate the write gun video circuitry from the write gun accelerating potential. This link is required because the electro-optic crystal is operated at ground potential.
thus necessitating the operation of the write gun cathode at a negative potential corresponding to the accelerating potential required by the electron beam.

The coupling link constructed was an infrared light link using a light emitting diode (GE SSL34-D1 in Figure A3) and a semiconductor diode photo detector (HP 4207-D1 in Figure A4). The light emitting diode is driven with an average current of 100 ma and the video signal swings the current amplitude about this value. The photo detector is followed by an integrated circuit video amplifier (Motorola MC1552G-IC1 Figure A4), and a high level amplifier made up of discrete components. Both brightness (dc level) and contrast (video gain) control are provided in the high level amplifier. A diode dc restorer is used to re-establish the dc reference level lost in the ac coupled amplifiers. The output of the video amplifier is coupled to the write gun grid. The brightness and contrast controls have sufficient range to operate the write gun with a grid base of 60 volts.

10. Isolated Video Amplifier Power Supply

An isolated power supply is provided to furnish power to the isolated video amplifier. This power supply is operated from the 117 volt line and is powered by a one-to-one turns ratio 20 kV dc isolation transformer. The secondary voltage is rectified, choke input filtered, and regulated by a series pass transistor. Voltages supplied to the video amplifier are +75 for the output video amplifier and +30 for the remainder of the amplifier. The +30 volt output is further reduced in the video amplifier by a resistive divider and zener diode network to provide the
remaining voltages as required by the video amplifier. A schematic dia-
gram of the isolated video amplifier power supply is shown in Figure A5 
of Appendix A.

11. Commercial Power Supplies and Modifications

Several commercial power supplies are used to power the IFLM. The electronic circuitry, with the exception of the isolated video amplifier, is powered by a Lambda Model LPD-421-FM set to furnish ± 17.5 volts. This voltage is further reduced to ± 12 volts by zener diodes for all circuits but the deflection amplifiers.

The main anode supply for the IFLM is a Spellman Model UHR20N10, which is variable from 0 to 20 kV. This supply has been modified to pro-
vide for anode voltage cutoff by the sweep protection circuitry in case of sweep failure by inserting a relay contact in the 117V ac input.

The other required voltages for the IFLM write gun are furnished by a special supply constructed by Spellman High Voltage Co. and denoted by the title "Depressed Cathode CRT Supply". This supply furnishes isolated filament voltage for the write gun (settable from 0 to approximately 20V dc). The power supply was modified in accordance with the schematic drawing of Figure A7, Appendix A, to provide the variable dc filament supply. Also provided by this supply are the G₂ and focus voltages for the write gun.

An erase supply to furnish dc power to the erase gun is a Spellman Model RHR5N30. This supply has a variable output voltage of from 0 to 2 kV. This supply was modified as shown in Figure A6 of Appendix A, so that it could be pulsed on during the period of the erase pulse.
III. PERFORMANCE OF THE IFLM

Optical performance of the IFLM can be discussed in terms of the quality of the coherent optical image projected by the illuminating laser beam. Resolution, number of gray scale steps, and contrast are important parameters for evaluation of image quality. As the preceding discussion has shown, these parameters depend on the electron beam spot size and current density, and the thickness, operating temperature, and quality of the electro-optic crystal.

Since the evaluation of image quality by visual inspection is somewhat subjective, several supplemental tests were performed with the IFLM operating as a low resolution intensity modulator. Both the contrast and gray scale capability were investigated in the supplemental tests, and the electron gun operating parameters were established from measurements of the secondary emission characteristics of KD*P which were performed in the IFLM. The above measurements along with the results of imaging experiments performed at MSFC are discussed below.

A. Secondary Emission Characteristics of KD*P

Knowledge of certain key features of the secondary emission characteristics of KD*P was required for determination of both the electron write and flood gun operating points. The most common representation of secondary emission behavior for an insulator is a plot of the secondary emission ratio, $\delta$, as a function of the potential, $V_{pr}$, of the incident electron beam. The secondary emission ratio is usually defined as the number of secondary electrons emitted from a surface per primary electron incident
on the surface. The key features in this representation are the two values of electron potential (cross-over potential) for which the characteristic curve crosses through \( \delta = 1 \), and the value of electron potential which results in the maximum value of \( \delta \).

A typical secondary emission characteristic is shown in Figure 12(a). The two cross-over potentials are designated as \( V_{cr1} \) and \( V_{cr2} \), and the potential for which \( \delta \) is maximum is designated as \( V_{\max} \). Direct measurement of the secondary emission current from an insulator is difficult because of charging and discharging of the capacitor formed by the insulator and its grounded back surface conducting plate. To circumvent the charging problem, a dynamic pulse technique or two-gun steady state technique may be employed. Both techniques, however, require the construction of sophisticated test apparatus, and since measurement of the upper cross-over potential alone is sufficient for the establishment of IFLM operating points, a simpler experimental arrangement was devised.

In the technique devised for measuring the upper cross-over potential, the surface potential was indirectly determined from measurements of the electro-optic effect on a laser beam propagating through the electron beam addressed KD\( ^* \)P crystal. The experimental arrangement shown in Figure 13 was implemented in the IFLM with the electron flood gun providing the incident electron beam.

Interpretation of the results of measurements performed with this arrangement is aided by a study of the secondary emission characteristic of Figure 12(b). This characteristic shows the equilibrium target potential, \( V_{T} \), of a floating target under bombardment by electrons
Figure 12. Two Representations for the Secondary Emission Characteristics of a Floating Target.
Figure 13. Experimental Arrangement for Measuring the Equilibrium Target Potential of Electron-Beam-Addressed KD$^+$ P.
emitted from a gun whose cathode potential is $V_k$ relative to the collector grid. Note that the secondary emission characteristic of Figure 12(a) is plotted as a function of the potential, $V_{pr}$, of the incident electron beam, relative to the crystal surface, i.e., $V_{pr} = V_k - V_T$. While the details of the secondary emission characteristic are, in most cases, a complex function of the material's bulk properties and its surface state, the angle of the incident electron beam, and the efficiency of secondary electron collection, the general features are similar for all insulating materials. For values of cathode potential in the range $V_{cr1} < V_k < V_{cr2}$, the secondary emission ratio is $> 1$, and the target will assume a potential which is a few volts positive with respect to the collector potential.

As the cathode potential is increased so that $V_k > V_{cr2}$, $\delta < 1$, and the target will assume a negative potential so that $V_{pr} \approx V_{cr2}$ and $V_T \approx V_k - V_{cr2}$. It has been noted, however, that in most materials, $V_{cr2}$ increases as $V_T$ decreases so that the equilibrium target potential has a slope less than 45°. A thorough discussion of secondary emission from floating targets has been given by Kazan and Knoll [25].

The significance of the equilibrium potential characteristic is that for writing an image on the crystal with maximum contrast, the cathode of the write gun must be set at a potential which is approximately equal to $V_{cr2} + \frac{V_1}{2m}$, where $V_1$ is the half wave potential associated with the Pockel's effect, and $m$ is the slope of the equilibrium characteristic for $V_k > V_{cr2}$.

It can also be seen from a careful study of the secondary emission characteristics that erasure of the crystal surface may be accomplished by grounding the collector grid and operating the flood gun cathode at a potential for which $V_{pr}$ falls within the range $V_{cr1} < V_{pr} < V_{cr2}$.
The initial tests to determine the secondary emission characteristic of KD*P were performed on a Z-cut, 90% deuterated sample of 0.125 inch thickness with an optically polished and uncoated surface facing the electron beam, and a conductive coating applied to the opposite surface. In these tests, the cathode potential, \( V_k \), of the electron gun was varied while the electro-optic effect was measured on a laser beam which was projected through the KD*P crystal and a polarizer. Figure 14 shows the data points obtained by measuring the projected intensity of a laser beam polarized along one of the principal axes of the crystal as a function of the cathode potential of the electron gun. A \( \sin^2 \) curve characteristic of the Pockel's effect was fitted to the data, and the upper cross-over potential, \( V_{cr2} \), was determined to be about 2 kV while the maximum modulation was obtained for a cathode potential of about 10 kV.

In order to determine the equilibrium slope, \( m \), for this sample of KD*P, it was necessary to measure \( V_{1/2} \) for the laser wavelength used in the secondary emission test. This measurement was performed at atmospheric pressure by coating both sides of an identical sample of KD*P (cut from the same boule) with a transparent conductive coating for the purpose of establishing an electric field along the Z direction, and employing an optical geometry identical to that shown in Figure 13 for observing the Pockel's effect. The transmitted laser beam intensity is plotted as a function of voltage applied to the crystal's electrodes in Figure 15, and a \( \sin^2 \) curve fitted to the data points indicates that the half wave potential, \( V_{1/2} \), for \( \lambda = 0.633 \) \( \mu \)m is about 3800 volts.
The normalized intensity, \( \frac{I}{I_0} \), is plotted against the flood gun cathode voltage, \( V_k \) (kV), in the diagram. The relationship is given by the equation:

\[
\sin^2 \left( \frac{V_k (kV) - 2}{8} \right) \frac{\pi}{2}
\]

The graph shows measured data points along with a fitted curve. Figure 14. Longitudinal Pockel's Effect in Electron-Beam-Addressed KD'P. (52)
Figure 15. Longitudinal Modulation Characteristics of 90% Deuterated KD*$P$. 

\[ \sin^2 \left( \frac{\pi V_A (kV)}{3.8} \right) \]
Results of the two measurements above were employed in the calculation of an equilibrium potential characteristic for the electron beam bombarded KD\textsuperscript{*}P sample which is presented in Figure 16. Investigation of the lower cross-over potential, \( V_{cr1} \), was not possible because of the resolution limitation imposed by the optical method employed in the measurements. It was found that the optical detection system could not respond to intensity changes about the null corresponding to less than 150 volt changes across the crystals electrodes. The value of \( V_{cr1} \) is, therefore, less than 150 volts if the equilibrium characteristic is assumed to follow the general features of Figure 12(b). The slope of the characteristic for \( V_k > V_{cr2} \) is 0.48, and the dependence of \( V_{cr2} \) on \( V_T \) was found to follow the relation \( \frac{V_{cr2}}{V_T} = 1.63 \) for \( V_k > V_{cr2} \).

Similar measurements were performed on the modulator assembly which was fabricated from a 99% deuterated, Z-cut KD\textsuperscript{*}P plate of 10 mils thickness. The surface of the modulator crystal facing the electron gun was coated with an SiO\textsubscript{1.7} film of about 0.13 \( \mu \)m thickness to protect the KD\textsuperscript{*}P surface from water vapor and the eroding effects of the electron beam. The half wave potential for the 99% deuterated KD\textsuperscript{*}P is 3400 volts at 0.6328 \( \mu \)m and the equilibrium potential characteristic for this sample plotted in Figure 17 surprisingly revealed a much higher upper cross over potential (-7.5 kV) than that obtained with the uncoated 90% deuterated sample. The slope of the curve for \( V_k > V_{cr2} \) was, however, found to be -0.49 compared with -0.48 for the 90% deuterated sample. The difference in the measured values of \( V_{cr2} \) for the two samples could be caused by the SiO\textsubscript{1.7} coating on the 99% deuterated modulator crystal, although the published values of \( V_{cr2} \) for most insulators seem to lie between 1.5 and 4 kV.
Equilibrium Target Potential of 90\% Deuterated KD$^+$P with No Surface Coating.

Figure 16.
Equilibrium Target Potential of 99% Deuterated KD P Coated with SiO1.7

Figure 17.

Electron Gun Cathode Potential, $V_k$ (kV)

Target Potential, $V_t$ (kV)

$m = 0.49$
The data in Figure 17 indicate that the proper potential for erasure of images formed on the modulator crystal would lie in the range \(-7.5 \text{ kV} < V_k < -3.4 \text{ kV}\). Tests with the modulator held at about \(-40^\circ\text{C}\) where the discharge time constant is of the order of several minutes revealed that the range of potential for the fastest erase times was about \(-4 \text{ kV} < V_k < -3.4 \text{ kV}\).

Based on the above tests performed on the modulator crystal, the potential of the write gun cathode was set at \(-15 \text{ kV}\), and the potential of the erase gun cathode at \(-3.4 \text{ kV}\).

**B. Contrast and Linearity**

The maximum contrast obtained with the IFLM was measured with the IFLM in its imaging configuration. A 2-inch diameter collimated laser beam was projected through the IFLM and an external Polaroid analyzer, and its intensity measured by a calibrated photocell as a function of the write gun \(G_1\)-to-cathode potential for \(V_k = -15 \text{ kV}\) and full raster scan. The maximum contrast obtained was 130, and the contrast for a maximum of \(\pm 5\%\) deviation in linearity between the measured change in intensity of the laser beam and the electron gun grid-to-cathode voltage was found to be about 95. A transmission coefficient of 0.57 including losses in the polarizer, spatial filter, and beam expander was also measured for the IFLM system.

It should be noted that the above contrast figures were measured in the center of the modulator pattern because of the polarization distortion which was present near the periphery of the collimated laser beam. The
distortion was caused by interaction between the pinhole filter and collimating optics of the laser beam expander, and improvements could not be obtained without reduction of the transmission coefficient to an unacceptable value.

With operation over the ± 5% deviation range, approximately 13 gray scale steps of 0.15 optical density change are possible. Assuming good quality optical windows are employed, the maximum number of gray scale steps that can be obtained depends on the quality of the laser beam expander and polarization analyzer, and also on the number of strains which are present in the KD\textsuperscript{P} crystal assembly. For example, the measured contrast ratio of the Polaroid analyzer employed in these measurements was 500 as compared with about 900 which is possible with a small Glan-Thompson prism; however, the contrast ratio is degraded to about 200 when the KD\textsuperscript{P} modulator assembly is inserted between the laser and either polarizer. Thus, it would appear that even if the laser beam expander could be significantly improved, an ultimate contrast of only 200 is possible with the present modulator crystal. This improvement would allow only one additional gray scale step. The major benefit that would be provided by an improved laser beam expander would be the realization of maximum contrast over the entire image.

C. Imaging Performance

Tests performed before delivery of the IFLM to MSFC showed that good quality images of an EIA test chart viewed with a TV camera could be reproduced by the IFLM. With the same KD\textsuperscript{P} unit employed in the previous test installed in the IFLM, the 200 line/inch bars could easily be resolved
near the center of the modulator; however, the projected image showed considerable variation in contrast across the crystal surface. Adjacent areas near the center of the crystal, for example, showed significant differences in contrast. The flood gun was not operative during these tests, and erasure of the image occurred by charge decay through the crystal to the grounded conducting film. Microscopic examination of the crystal surface revealed non-uniform discoloration in the SiO$_{1.7}$ film over the area addressed by the laser beam, and it was postulated that the higher resistivity which occurs in the discolored areas would result in variations in discharge time constant across the image. This condition, if true, would explain the variation in contrast observed over the projected image.

A new KD*P modulator unit was installed in the IFLM and the imaging tests using the EIA chart were repeated. A high quality image with visually uniform contrast and resolution across the entire modulator surface was obtained. As soon as these tests were concluded, the IFLM system was dismantled for shipment to MSFC with the modulator housing under vacuum.

Imaging tests were continued after arrival of the IFLM system at MSFC. It was found once again that spatial variations in the polarization of the illuminating laser beam and "optical noise" produced by transmission through the polarizer detracted from the performance of the IFLM. These effects were more noticeable at MSFC because the 1.4 x 1.4 inch projected image was picked up by a TV camera and displayed on a 12-inch monitor screen. The image quality was somewhat improved by prepolarization and aperturing of the laser beam; however, a substantial amount of the noise background remained. A typical image projected by the IFLM is shown in Figure 18.
Figure 18. Photograph of a Projected IFLM Image Covering One Quadrant of the Modulator Plate.
Considerable difficulty was initially encountered in interfacing the silicon target vidicon cameras employed at MSFC with the IFLM electronics. Each camera-monitor system has a limited range of adjustments for image quality, and the initial video signals provided by the camera units were not compatible with the IFLM's video circuitry. Loss of picture synchronization and compression of gray scale were observed in the IFLM's projected images while using these camera units. Adjustments were made, and a steady image with good resolution and somewhat compressed gray scale was obtained.

When a standard image orthicon camera was substituted for the silicon target vidicon camera, a significant improvement in image quality was observed. The resolution of the best images obtained was about 320 lines per inch although only 4 or 5 gray scale steps could be resolved on the EIA test chart.
An engineering model IFLM with good imaging properties and with the operational flexibility required for investigating advanced techniques in image conversion has been constructed and delivered to the MSFC. Performance tests have demonstrated that images comparable in resolution to those of commercial TV can be generated by this device.

Although the image quality of the IFLM was initially acceptable, degradation of the surface coating on the modulator crystal was observed during the tests. The observed damage is thought to result from surface etching caused by the scanning electron beam even though the disturbed areas were inexplicably confined to a region near the center of the crystal. Pinholes were also observed in the adhesive layer between the KD\textsuperscript{*}P plate and its substrate after several operating cycles between room temperature and the Curie point.

Operation of the IFLM in the optical transmission mode requires both high beam energy and current density. The electron gun design employed in this device is marginal in its ability to supply the required current density. A new electron gun design should be undertaken rather than any further attempts to modify off-the-shelf production line devices for this application. A more rugged protective film will be required for satisfactory performance of the modulator crystal. In addition, a thorough review of crystal fabrication techniques should be performed to ensure reliable operation of the modulator near the Curie temperature.
Strong consideration should be given in the next developmental program to operation of the IFLM in the optical reflex mode where the probability of crystal damage is greatly reduced. This mode, which has been described by Marie [4] and Pritchard [7], involves a geometry where the laser beam enters the crystal from the surface opposite the electron gun, and is reflected by a multilayer dielectric coated applied to the surface facing the electron gun. In this manner, the laser beam makes a double pass through the crystal thereby reducing $V_{1/2}$ by a factor of 2. The reduction in the required electron beam energy, however, occurs because charging of the crystal surface is based on secondary emission. In this scheme, the electron beam potential is set between the upper and lower cross-over points, and the modulating voltage is applied between the collector grid and the crystal’s conducting film. For operation near the Curie temperature, about 125 volts are required for full modulation, and the potential of the electron beam would be less than 2 kV for an uncoated KD* P modulator. During tests on two KD* P samples using the flood gun with a 2 kV beam potential, no surface damage was noted at beam currents which were a factor of 10 larger than required for reflex mode operation.

Improvements in packaging and operational simplicity would also result from operation in the reflex mode. Since erasure by a separate flood gun is not required for secondary emission modulation, the write gun can be located on-axis with respect to the laser beam. Electronic circuitry associated with the flood gun and write gun sweep correction would, therefore, be eliminated. Since the video information would be applied relative to the grounded crystal plane, the LED video isolation link would also be unnecessary.
Location of the electron gun on-axis would result in a significant reduction in the size of the modulator housing. The dimensional requirements for the reflex mode IFLM would be approximately 4 inches in diameter by 15 inches in length. Further reductions in size could, at a later stage in development, be obtained for designs excluding demountable components. Such a device could operate sealed off at low pressure with a small sublimation pump included to offset the outgassing load.

For long term development of image conversion devices, other modulation techniques and media should be investigated to determine their potential for operation at TV scan rates. The superior mechanical properties and significantly lower costs of ferroelectric and thermoplastic materials should be exploited if techniques for improving their response times can be developed. Liquid crystal media, though less useful for coherent optical processing applications, should also be kept under surveillance for possible application in generation of optical transparencies.
V. ACKNOWLEDGEMENTS

Successful completion of this program was a result of the combined efforts of several key personnel in the Systems and Techniques and Applied Sciences Department of the Engineering Experiment Station. Dr. L. N. Tharp and Mr. C. E. Wagner of the Applied Sciences Department should be cited for their contributions to the design of the modulator housing and testing of the electron guns. Mr. J. R. Walsh, Jr., of the Systems and Techniques Department was responsible for design of the electric circuitry, and was assisted in packaging of the components by Mr. J. D. Carr. Finally, the Mechanical Services Group should be acknowledged for their role in fabricating the modulator housing.
VI. REFERENCES


VII. APPENDIX A

Schematic Diagrams
Figure A1. Video Processor and Sweep Generator.
Figure A2. Deflection Amplifier and Sweep Protection Circuits.
Figure A3. LED Driver.
Figure A4. Isolated Video Amplifier.
Figure A5. Isolated Video Amplifier Power Supply.
Figure A6. Erase Power Supply Control Circuitry.
Figure A7. Write Gun Filament Modification to Spellman Depressed Cathode CRT Supply.