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BINARY/ANALOG CCD CORRELATOR DEVELOPMENT. (U)

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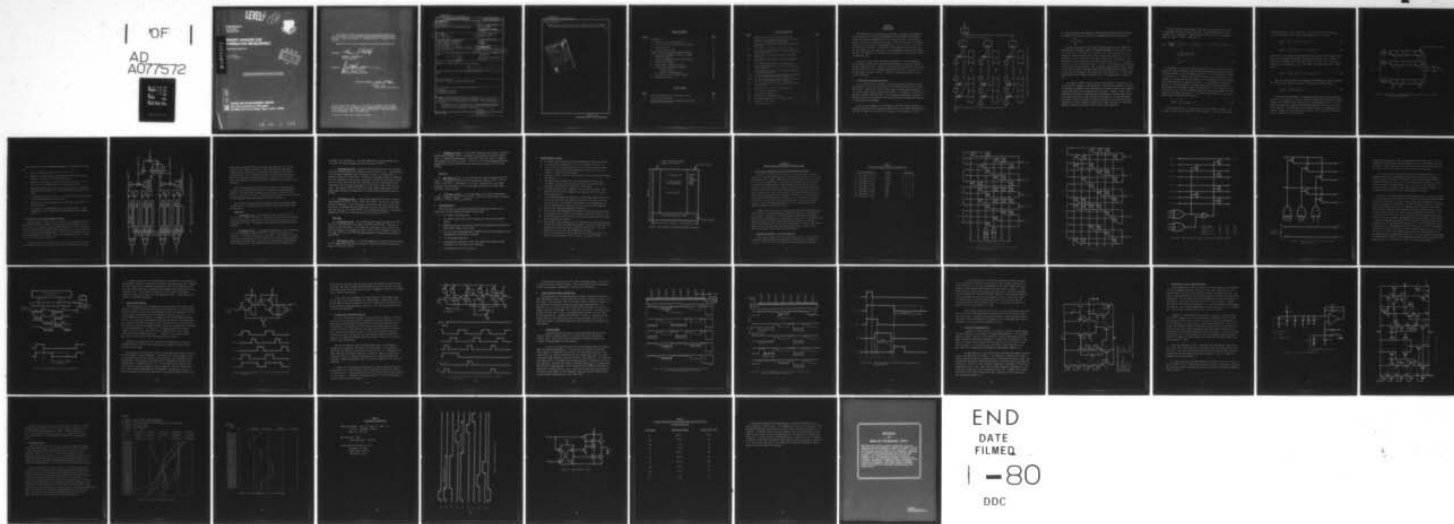
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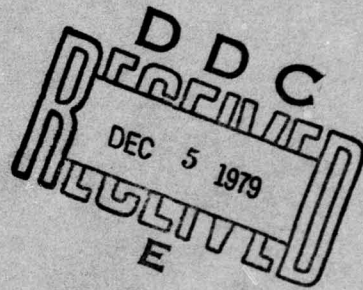
**RADC-TR-79-211**  
Interim Report  
September 1979



**BINARY/ANALOG CCD  
CORRELATOR DEVELOPMENT**

Texas Instruments, Inc.

R. A. Haken  
R. C. Pettengill



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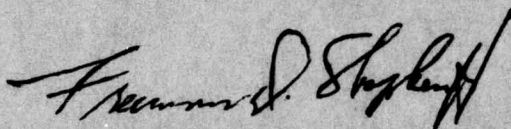
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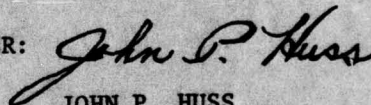
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TABLE OF CONTENTS

<u>SECTION</u>		<u>PAGE</u>
I	INTRODUCTION . . . . .	1
	A. Binary/Analog Correlator Operation. . . . .	1
	B. Architecture for a General-Purpose Correlator . . . . .	7
	C. Constituent Cells . . . . .	11
	D. Accomplishments to Date . . . . .	12
II	GENERAL PURPOSE BINARY/ANALOG CORRELATOR DESIGN. . . . .	14
	A. Filter Length, Weighting Accuracy, and Mode Selection Circuitry . . . . .	14
	B. Programmable Weighting Using a Four-Phase CCD . . . . .	14
	C. Digital Shift Register. . . . .	22
	D. Microprocessor Interface Circuitry. . . . .	24
	E. Charge Transfer Between CCD Registers . . . . .	26
	1. Clocking Scheme. . . . .	26
	2. Charge-to-Voltage Amplifier. . . . .	30
	F. Differential Current Integrator Design. . . . .	32
	G. Correlator Clocking . . . . .	35

LIST OF TABLES

<u>TABLE</u>		<u>PAGE</u>
1	Filter Configuration Versus Input Select Word. . . . .	15
2	DCI Amplifier Performance. . . . .	38
3	Loading Capacitances and Corresponding Clock Driver Areas for 20 ns Rise Time. . . . .	41

LIST OF ILLUSTRATIONS

<u>FIGURE</u>		<u>PAGE</u>
1	Block Diagram of the Binary/Analog Correlator. . . . .	2
2	Schematic of a Programmable CCD Correlator with M-bit Accuracy on the Weighting Coefficients . . . . .	6
3	Analog Signal Flowgraph of 1024-Stage Binary/Analog Correlator . . . . .	8
4	Chip Layout of the General-Purpose Correlator. . . . .	13
5	Circuitry for Selecting Filter Length and Weighting Coefficient Accuracy . . . . .	16
6(a)	Input Switches for Single, Double, and Quad Mode Selection. . . . .	18
6(b)	Output Switches for Single, Double, and Quad Mode Selection. . . . .	19
7	Programmable Weighting Using a Four-Phase CCD. . . . .	21
8	Digital Shift Register Circuit with Controlling and Output Waveforms . . . . .	23
9	Microprocessor Interface Circuitry Showing Generation of Load and Hold Pulses. . . . .	25
10(a)	CCD Output Stage Showing Surface Potential Variations During Charge Transfer Between CCD Registers . . . . .	27
10(b)	CCD Input Stage Showing Surface Potential Variations During Charge Transfer Between CCD Registers . . . . .	28
10(c)	Clocking Scheme for Transferring Charge Between CCD Shift Registers. . . . .	29
11	Charge Amplifier Circuit and Characteristics . . . . .	31
12	DCI Circuit with Parasitics. . . . .	33
13	DCI Amplifier Schematic. . . . .	34
14	DCI Open Loop Transfer Function. . . . .	36
15	DCI Step Response for +/- 4 V Output Swing . . . . .	37
16	Correlator Clock Timing. . . . .	39
17	Clock Driver Circuit . . . . .	40

SECTION I  
INTRODUCTION

The objectives of this program are to design, fabricate, and evaluate a general-purpose, electronically programmable, binary/analog CCD correlator. The device features programmability of the reference signal, the correlator length, and weighting coefficient accuracy. Off-chip circuitry is minimized by including all clock drivers, output-amplifiers, logic, and analog and digital shift registers, on-chip. This results in an integrated filter circuit that has the versatility to be operated in nine programmable configurations, thereby giving it the flexibility to be used in a wide variety of filtering and correlation applications.

Section I of this report describes the operation of the programmable binary/analog correlator and the architecture necessary to realize a general-purpose integrated filter. Section I concludes with a breakdown of the principal constituent cells of the general-purpose correlator and a summary of the accomplishments to date. Section II contains a technical discussion of the circuits designed.

A. Binary/Analog Correlator Operation

In a conventional CCD transversal filter the weighting coefficients are implemented by use of the well-known split electrode technique and are therefore fixed. Although such filters have a number of important applications in Air Force Systems, there are applications where it is necessary to electronically program the weighting coefficients. Of the present programmable techniques, the most attractive for matched filtering and correlation tracker applications is the binary/analog approach.

Electronic programmability is achieved in the binary/analog approach by decomposing each one of the weighting coefficients into a binary representation that can be loaded into a static shift register, as illustrated in Figure 1.

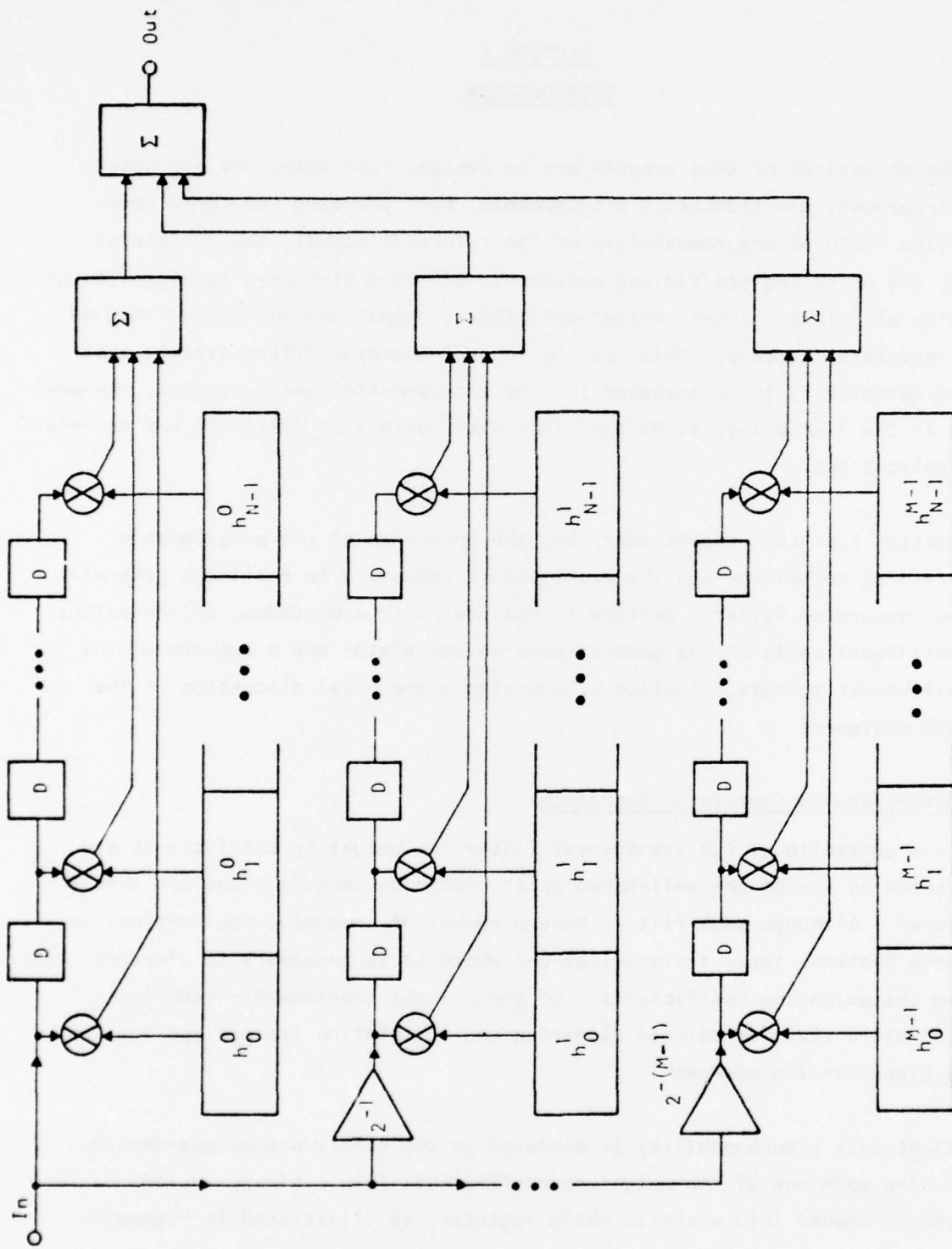


Figure 1 Block Diagram of the Binary/Analog Correlator

For M-bit accuracy of each weighting coefficient M parallel CCD binary/analog correlators are required, so that  $h_n$  is represented with M-bit accuracy by

$$h_n = \sum_{k=0}^{M-1} h_n^k 2^{-k} \quad . \quad (1)$$

The most significant bit  $h_n^0$  of each weighting coefficient is loaded into the static shift register, shown as elongated rectangles in the filter at the top of the figure. The second most significant bit  $h_n^1$  of each coefficient is loaded into the second coefficient store, and the least significant bit  $h_n^{M-1}$  is loaded into the coefficient store shown at the bottom of the figure. The analog signal must be weighted by the appropriate factor of  $2^{-(n-1)}$  at either the input or output of each correlator. In Figure 1 the weighting is performed at the input to the correlators, with the analog signal applied without attenuation to the top filter (most significant bit) and attenuated by a factor of two at the input of the second filter (second most significant bit). At the input to the bottom filter (least significant bit) it is attenuated by a factor of  $2^{M-1}$ .

The choice of whether input or output signal weighting is employed, or a mixture of both, depends on the application. Input signal weighting is simpler to implement as capacitor ratio techniques can be used, whereas output weighting requires amplifiers with accurately controlled gain. However, output signal weighting is desirable in some applications because of a dynamic range limitation associated with the input weighting configuration. For general-purpose correlators it may be desirable to perform a mixture of both input and output weighting to strike a balance between dynamic range, the number of integrators required, weighting coefficient accuracy, and logic simplicity.

The total weighting coefficient for any one of the M parallel CCD bits is determined by the sum of the coefficients in the M parallel static shift register bits. Consequently, when the outputs of each filter are summed together as shown in Figure 1, the result is

$$H(z) = \frac{V_{out}(z)}{V_{in}(z)} = \sum_{n=1}^N h_n^0 z^{-n} + 2^{-1} \sum_{n=1}^N h_n^1 z^{-n} + \dots + 2^{-(M-1)} \sum_{n=1}^N h_n^{M-1} z^{-n} \quad (2)$$

$$= \sum_{n=1}^N \left[ \sum_{k=0}^{M-1} (h_n^k 2^{-k}) \right] z^{-n} \quad (3)$$

$$= \sum_{n=1}^N h_n z^{-n} \quad (4)$$

Programmability of the CCD weighting coefficients is achieved by using the coefficient code in the static shift register to determine the relative timing of charge transfer in the four-phase CCD register. This is described in detail in Section II.B. In essence, the coefficient code in each of the static shift register cells determines when the charge in the corresponding CCD bit transfers to the electrode that is connected to the DCI. If the charge is transferred early at  $t_1$ , the charge packet is sampled underneath the sense electrode and contributes to the integrator output during that cycle. If the charge is transferred late at  $t_2$ , after the integrator sampling period has finished, the charge does not contribute to the output. In the time interval between  $t_1$  and  $t_2$  the output signal is available and given by:

$$Q_{out}(n) = \sum_{i=1}^N h_i Q_{sig}(n-i) \quad (5)$$

As described thus far, the device can only handle unipolar signals. For a signal of either sign to be used it must be added to a fat zero, which also

improves the charge transfer efficiency. The actual CCD input is then  $Q_{sig} + Q_{FZ}$  and the output from a single binary/analog filter is given by:

$$Q_{out}(n) = \sum_{i=1}^N h_i \left[ (Q_{FZ} + Q_{sig})(n - i) \right] \quad (6)$$

$$Q_{out}(n) = \sum_{i=1}^N h_i Q_{FZ} (n - i) + h_i Q_{sig} (n - i) \quad (7)$$

The first term represents a code-dependent offset and must be eliminated. The second term is the desired signal. To eliminate the first term, a parallel filter must be added in which the input signal is inverted, i.e., the input to the second CCD becomes  $Q_{FZ} - Q_{sig}$ . The output of the parallel filter is then given by:

$$Q_{out}(n) = \sum_{i=1}^N h_i Q_{FZ} (n - i) - h_i Q_{sig} (n - i) \quad (8)$$

When the two CCD outputs are connected to a differential current integrator, the undesired terms cancel, resulting in the DCI output being given by

$$Q_{out}(n) = \sum_{i=1}^N 2h_i Q_{sig} (n - i) \quad (9)$$

The differential approach for implementing coefficients with multiple-bit accuracy is illustrated in Figure 2, where the configuration correlates N analog samples with N digital words, each of which is represented by M-bits. In this scheme the weighting is applied to the analog signals at the input of the CCD shift registers. The summing of the M parallel channels is accomplished by a parallel connection of the  $\phi_4^+$  and  $\phi_4^-$  clock buses. Thus, only one differential current integrator (DCI) is required.

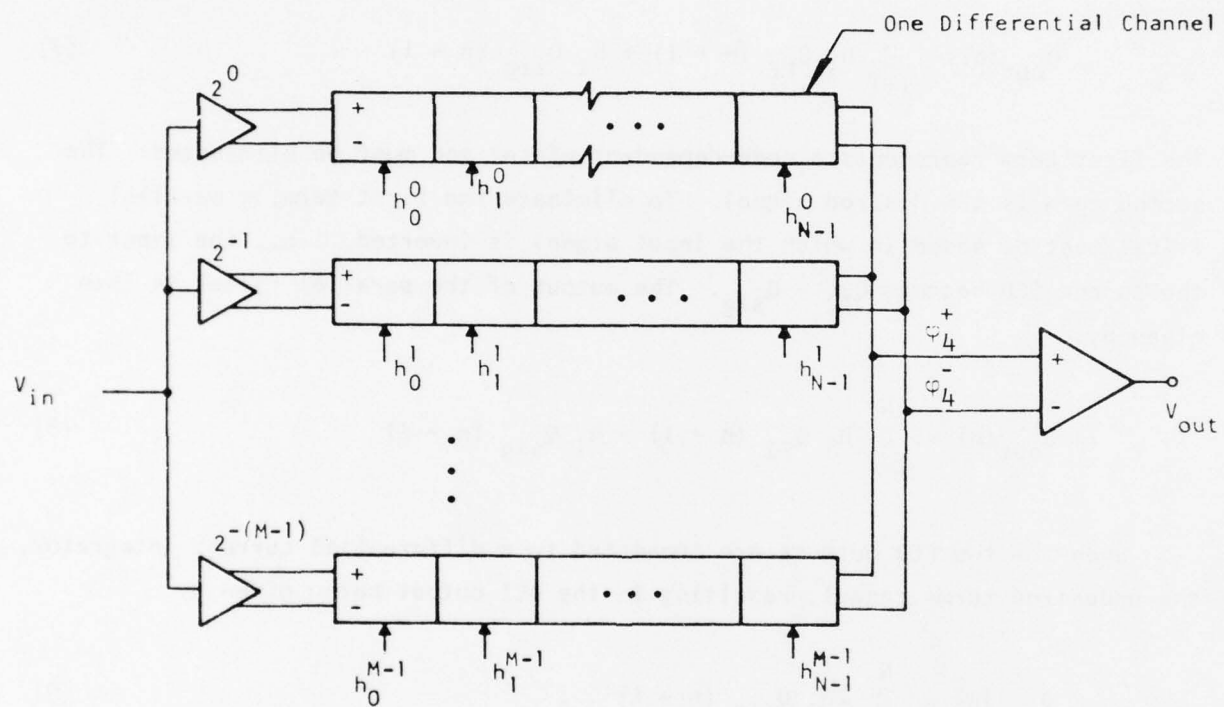


Figure 2 Schematic of a Programmable CCD Correlator with M-bit Accuracy on the Weighting Coefficients

The salient points of the binary/analog approach to programmable correlators are:

- One-bit programmable filters in which  $h_n$  can be 1 or 0.
- Capability to expand to M-bit accuracy by combining M binary/analog correlators in parallel with the appropriate gain.
- Capability to program the filters to the desired length ( $N = 32, 64, 128, \text{etc.}$ ) and to cascade filters to achieve longer filters.
- Weighting coefficient accuracy sufficient to give eight-bit resolution on weighting coefficients (i.e., weighting coefficient accuracy of 0.2%,  $\frac{1}{2}$  LSB).
- Minimization of off-chip circuitry. All clock drivers, output amplifiers, static shift registers, etc., are on-chip.
- Capability to utilize a microprocessor to read data out of memory into the code registers.
- Elimination of the code-dependent output dc level problem. A code-independent dc level is essential for spread spectrum and ECM applications.

#### B. Architecture for a General-Purpose Correlator

A general-purpose architecture for an electronically programmable 1024-stage binary/analog correlator is shown in the simplified block diagram of Figure 3. The architecture is arranged so that the 1024-stage device is folded into eight 128-stage sections with the output of each section fed via a unity gain amplifier to the input of the next 128-stage device. This provides a convenient point to insert an alternative input signal, together with the necessary logic for selecting the filter configuration desired.

To achieve multiple-bit accuracy, some of the signal weighting is performed at the input and some at the output, as this yields the optimum balance between

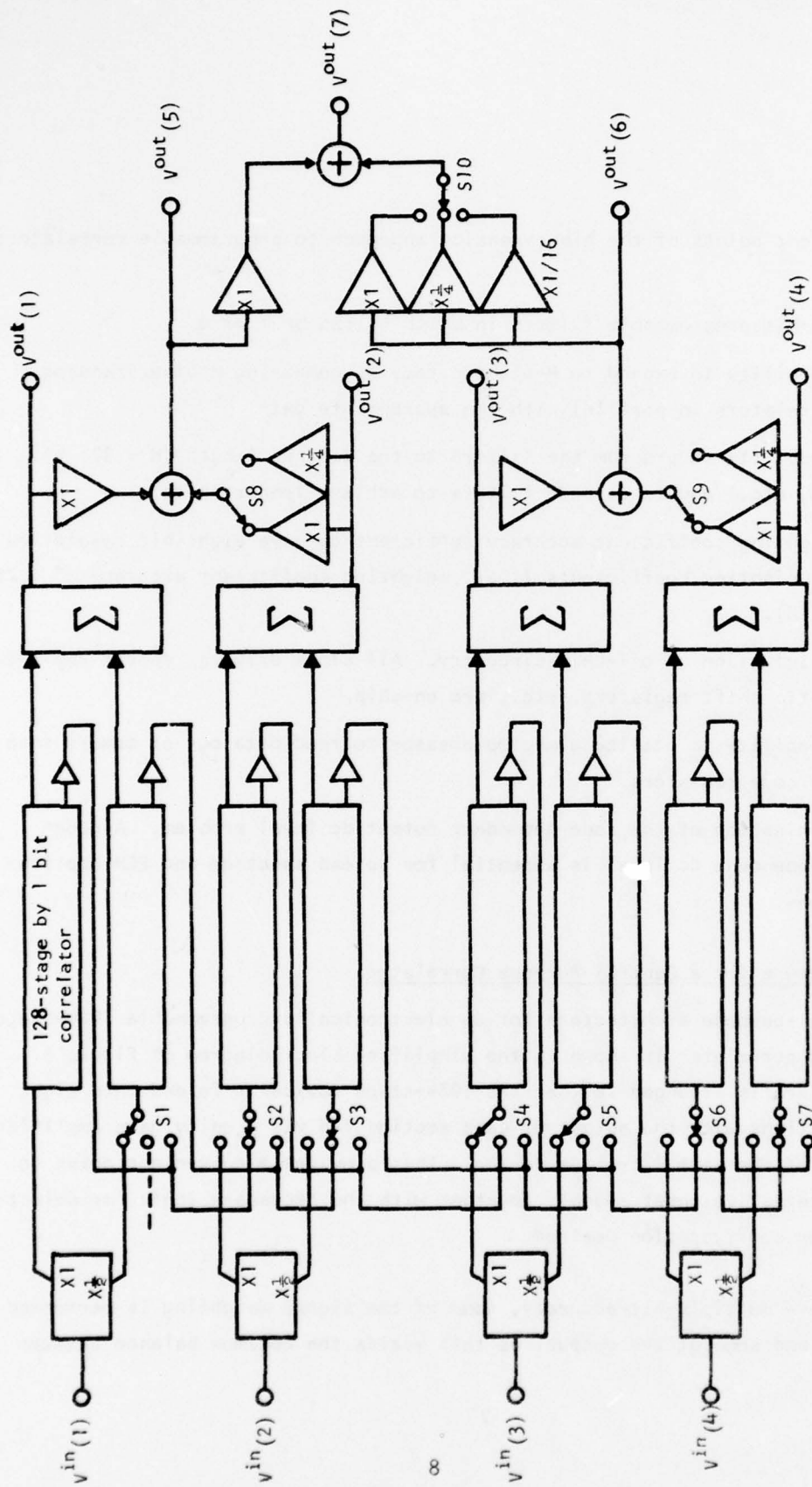


Figure 3 Analog Signal Flowgraph of 1024-Stage Binary/Analog Correlator (shown connected as a 256-stage by four-bit correlator)

dynamic range, weighting coefficient accuracy, the number of DCIs, and logic simplicity. The rectangles labeled  $X1$ ,  $X\frac{1}{2}$  through which the input passes indicate that the input signal is passed with unity gain ( $X1$ ) and with 50% attenuation ( $X\frac{1}{2}$ ). The input selection switches to the correlators determine whether the attenuated or unattenuated signal is applied to the correlator input. The remainder of the signal weighting is performed at the output of the correlators.

The correlation outputs of the correlators (output at the top of each correlator) go to the differential current integrators and summing amplifiers labeled  $\Sigma$ . By summing the correlation outputs in pairs, the number of DCI amplifiers required is only four. The DCI outputs are summed through two switched, weighted summation stages that determine the mode of operation.

The flexibility of the architecture chosen to realize the general-purpose correlator chip is illustrated by the nine possible operating configurations described below.

#### Single Mode

1. 1024-stage by 1 bit. In this mode the input is applied to  $V^{in}(1)$ , and the output is taken from  $V^{out}(7)$ . The inputs to each correlator are switched to the lower position so that the serial output from the preceding correlator is applied to the input. The switches on the outputs all select the unity gain amplifiers.

2. 512-stage by 2 bits. In this mode of operation the input is applied to  $V^{in}(1)$ , and the output is taken from  $V^{out}(7)$ . The  $X1$  input is applied to correlator 1, and  $X\frac{1}{2}$  input is applied to correlator 2. The inputs of all other correlators are switched to the central position such that the unattenuated ( $X1$ ) signal passes from correlator 1 to correlator 3 to correlator 5 to correlator 7, and the attenuated ( $X\frac{1}{2}$ ) signal passes from correlator 2 to correlator 4 to

correlator 6 to correlator 8. The output amplifiers are all switched to the unity gain setting and summed to provide the output at  $V^{\text{out}}(7)$ .

3. 256-stage by 4 bits. Four-bit and 8-bit operation are the only modes that utilize output amplifier settings at other than unity gain. The connections for this mode of operation are illustrated in Figure 3. The same input is applied to both  $V^{\text{in}}(1)$  and  $V^{\text{in}}(3)$ . The top four correlators perform a 256-stage by 2-bit correlation with the most significant bit (MSB) and the second significant bit (2SB), and the bottom four correlators perform a 256-stage by 2-bit correlation with the third significant bit (3SB) and the least significant bit (LSB). The outputs  $V^{\text{out}}(5)$  and  $V^{\text{out}}(6)$  are then summed together with  $V^{\text{out}}(6)$  being summed through the  $X\frac{1}{4}$  amplifier to provide the 4-bit weighted output at  $V^{\text{out}}(7)$ .

4. 128-stage by 8 bits. In this mode of operation the input is applied simultaneously to  $V^{\text{in}}(1)$ ,  $V^{\text{in}}(2)$ ,  $V^{\text{in}}(3)$ , and  $V^{\text{in}}(4)$ . The top four correlators perform a 128-stage by 4-bit correlation with the MSB, 2SB, 3SB, and 4SB; the bottom four correlators perform a 128-stage by 4-bit correlation with the 5SB, 6SB, 7SB, and LSB. The output  $V^{\text{out}}(6)$  is then summed through the  $X1/16$  amplifier, together with  $V^{\text{out}}(5)$ , to provide the 8-bit correlation at  $V^{\text{out}}(7)$ .

#### Dual Mode

5. 512-stage by 1 bit. In this mode the two inputs are applied to  $V^{\text{in}}(1)$  and  $V^{\text{in}}(3)$ , and the outputs are taken from  $V^{\text{out}}(5)$  and  $V^{\text{out}}(6)$ . Operation is similar to the 1024-stage by 1 bit except that the switch at the input to the fifth correlator is in the upper position so that  $V^{\text{in}}(3)$  is applied to the input. The outputs  $V^{\text{out}}(5)$  and  $V^{\text{out}}(6)$  are taken separately instead of being summed to give  $V^{\text{out}}(7)$ .

6. 256-stage by 2 bits. In this mode operation is similar to the 512-stage by 2-bit mode except that inputs are made at  $V^{\text{in}}(1)$  and  $V^{\text{in}}(3)$ , and outputs are taken at  $V^{\text{out}}(5)$  and  $V^{\text{out}}(6)$ .

7. 128-stage by 4 bits. In this mode of operation the top four correlators perform one 128-stage by 4-bit correlation and the bottom four perform another. Input 1 is applied simultaneously to  $V^{in}(1)$  and  $V^{in}(2)$ , and input 2 is applied simultaneously to  $V^{in}(3)$  and  $V^{in}(4)$ .  $V^{out}(2)$  and  $V^{out}(4)$  are summed through the  $X\frac{1}{4}$  amplifier, to  $V^{out}(1)$  and  $V^{out}(3)$  to provide the two outputs at  $V^{out}(5)$  and  $V^{out}(6)$ .

#### Quad Mode

8. 256-stage by 1 bit. In this mode the four inputs are applied to  $V^{in}(1)$ ,  $V^{in}(2)$ ,  $V^{in}(3)$ , and  $V^{in}(4)$ ; and the four outputs are taken at  $V^{out}(1)$ ,  $V^{out}(2)$ ,  $V^{out}(3)$ , and  $V^{out}(4)$ . Correlators 1, 3, 5, and 7 select the  $X1$  input (upper position); and correlators 2, 4, 6, and 8 select the output from the previous correlator (lower position).

9. 128-stage by 2 bits. In this mode the pairs of filters operate separately. Inputs are made at  $V^{in}(1)$ ,  $V^{in}(2)$ ,  $V^{in}(3)$ , and  $V^{in}(4)$ ; outputs are taken at  $V^{out}(1)$ ,  $V^{out}(2)$ ,  $V^{out}(3)$ , and  $V^{out}(4)$ .

#### C. Constituent Cells

The architecture of the general-purpose binary/analog correlator can be broken down into the following principal on-chip cells.

- 16 x 128-bit four-phase CCDs
- 16 x 64-bit static binary shift registers for storing the reference signal
- Switching circuitry for selecting the filter configuration and operating mode; either single, dual or quad
- 16 x unity gain charge amplifiers (CVAMPs) for linking the output of one 128-stage CCD to the input of the next
- 7 x DCIs/summing amplifiers
- Microprocessor interface circuitry for loading the reference signal from memory into the static shift registers
- Clock generation and drive circuits.

D. Accomplishments to Date

- An overall layout scheme has been developed (see Figure 4) resulting in a chip size of approximately  $7.1 \times 6.2 \text{ mm}^2$  ( $280 \times 245 \text{ mils}^2$ ).
- A bus line structure has been devised that strikes a balance between length of routing (and hence resistance and capacitance) with the number of crossovers and crossunders.
- The input, output, and filter mode selection circuitry has been designed and laid out.
- The digital shift-register cell has been designed, laid out, and simulated. The cell has also been included on a TI-funded test bar and should be available for evaluation during March.
- The CVAMP design has been completed, laid out, and simulated. This amplifier has also been included on the same test bar as the digital shift-register cell.
- A clocking scheme has been devised for shifting the charge from the output of one CCD through the CVAMP to the input of the next CCD during one clock cycle. This scheme allows charge to move through only one CCD bit and therefore prevents the loss of any correlation samples.
- The CCD cells have been designed and laid out.
- Circuitry has been designed and simulated to allow the reference signal to be loaded into the static shift-register under microprocessor control.
- The differential current integrators and output-summing amplifiers have been designed and simulated.
- The complete clocking requirements of the device have been evaluated and the various loading capacitances calculated. The clock drivers have been designed and simulated and are currently being laid out. The clock generation circuitry has been designed and simulated.
- Accuracy considerations require that the  $X_1$  and  $X_{\frac{1}{2}}$  signal amplifiers, which are located ahead of the correlators, be placed off-chip.

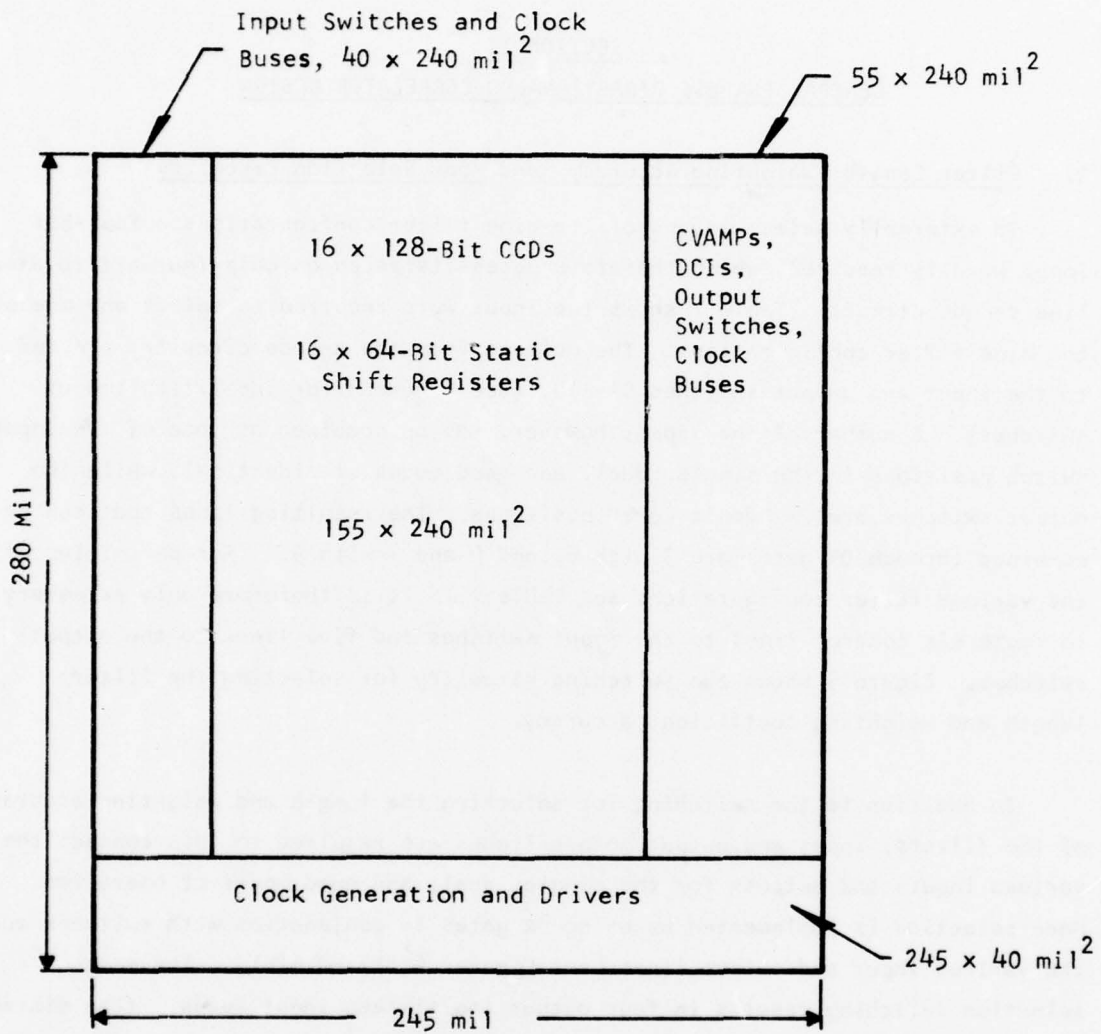


Figure 4 Chip Layout of the General-Purpose Correlator

SECTION II  
GENERAL PURPOSE BINARY/ANALOG CORRELATOR DESIGN

A. Filter Length, Weighting Accuracy, and Mode Selection Circuitry

To externally select anyone of the nine filter configurations a four-bit input word is required, which therefore necessitates an on-chip four-bit to nine-line decode circuit. Table 1 shows the input word required to select any one of the nine filter configurations. The outputs from the decode circuitry are fed to the input and output switches S1-S10, (see Figure 3 for identification of switches). A number of the lines, however, may be combined as some of the input switch positions in the single, dual, and quad modes are identical, while the output switches are in "don't care" positions. The resulting lines that can be combined through OR gates are 3 with 6, and 4 and 7 with 9. (For definition of the various filter configurations see Table 1.) It is therefore only necessary to route six control lines to the input switches and five lines to the output switches. Figure 5 shows the switching circuitry for selecting the filter length and weighting coefficient accuracy.

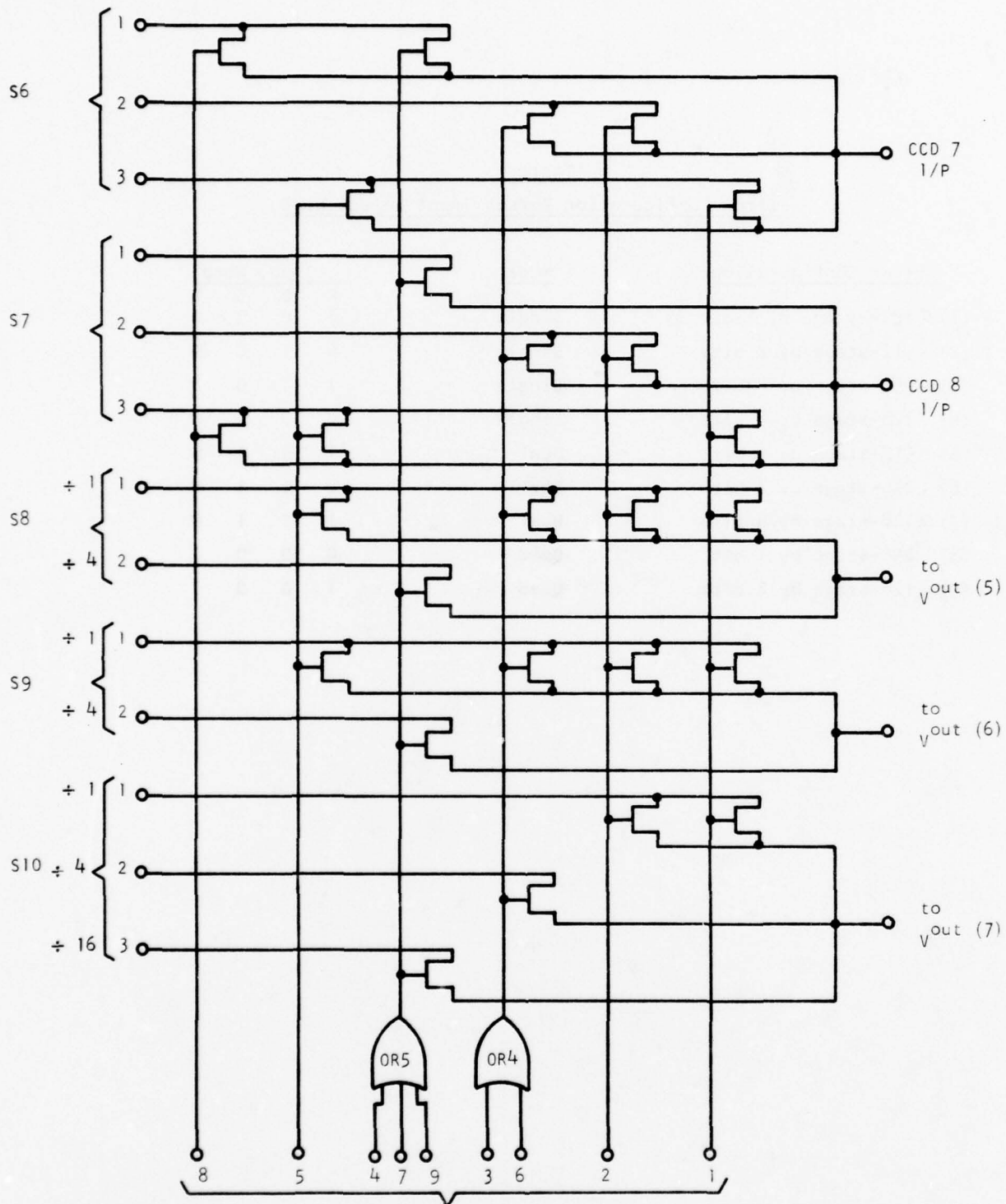
In addition to the switching for selecting the length and weighting accuracy of the filters, input and output mode switches are required to interconnect the various inputs and outputs for the single, dual, and quad modes of operation. Mode selection is implemented by using OR gates in conjunction with switches across the various input and output lines [see Figures 6(a) and 6(b)]. The mode selection switching results in four output and sixteen input leads. (The sixteen inputs are due to the  $X_1$  and  $X_{\frac{1}{2}}$  functions being off-chip; in Figure 3 each 128-stage correlator incorporates a differential pair.)

B. Programmable Weighting Using a Four-Phase CCD

In the original proposal for the binary/analog correlator, No. 23-R77, the programmable weighting scheme was discussed with reference to a two-phase CCD structure. Since that time a four-phase CCD technology has been developed,

Table 1  
Filter Configuration Versus Input Select Word

<u>Filter Configuration</u>	<u>Mode</u>	<u>Input Word</u>			
		<u>A</u>	<u>B</u>	<u>C</u>	<u>D</u>
(1) 1024-stage by 1-bit	Single	1	0	0	0
(2) 512-stage by 2 bits	Single	0	1	0	0
(3) 256-stage by 4 bits	Single	1	1	0	0
(4) 128-stage by 8 bits	Single	0	0	1	0
(5) 512-stage by 1 bit	Dual	1	0	1	0
(6) 256-stage by 2 bits	Dual	0	1	1	0
(7) 128-stage by 4 bits	Dual	1	1	1	0
(8) 256-stage by 1 bit	Quad	0	0	0	1
(9) 128-stage by 2 bits	Quad	1	0	0	1



From 4-bit to 9-line decode circuit

Figure 5 Circuitry for Selecting Filter Length and Weighting Coefficient Accuracy

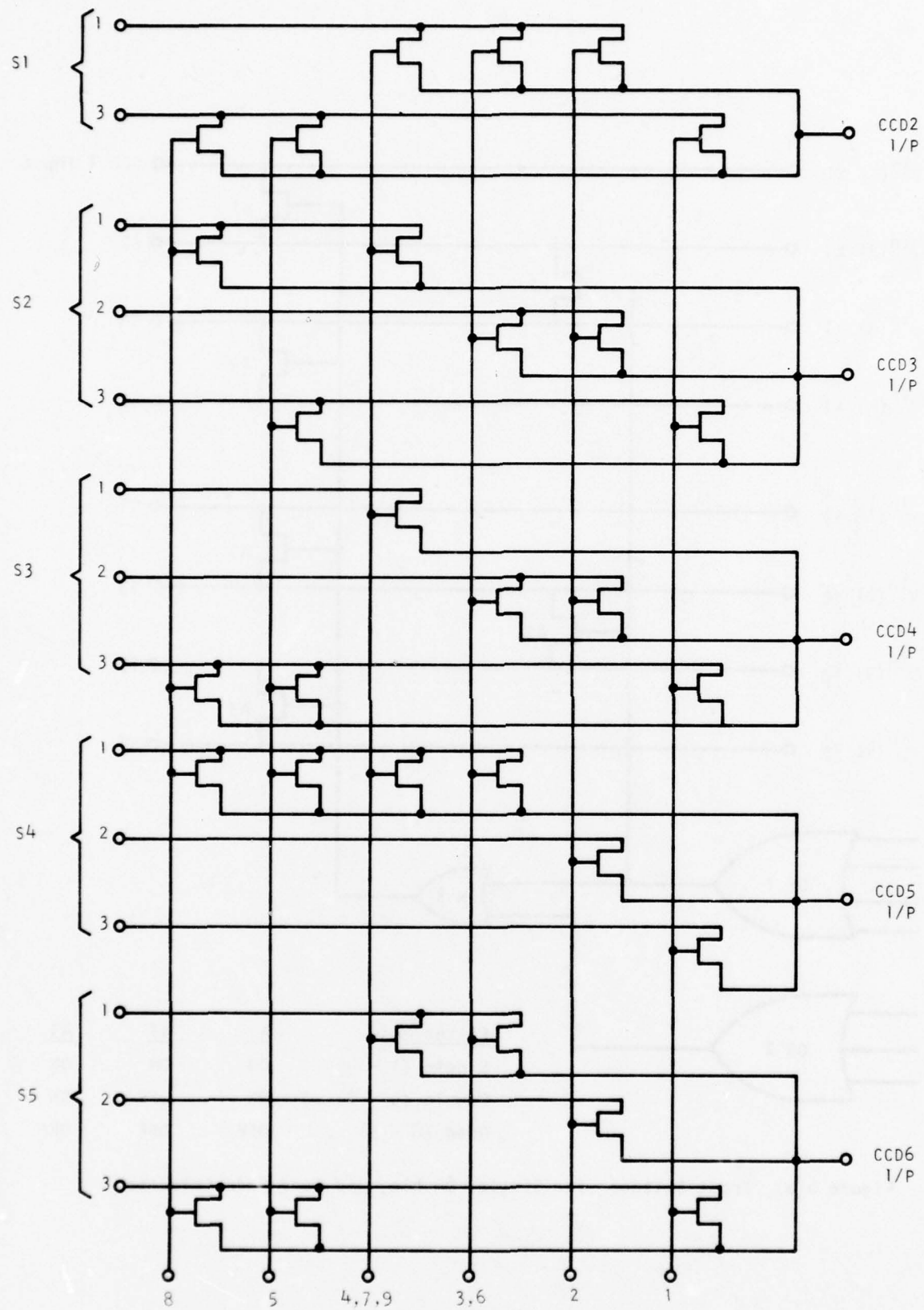


Figure 5 (continued)

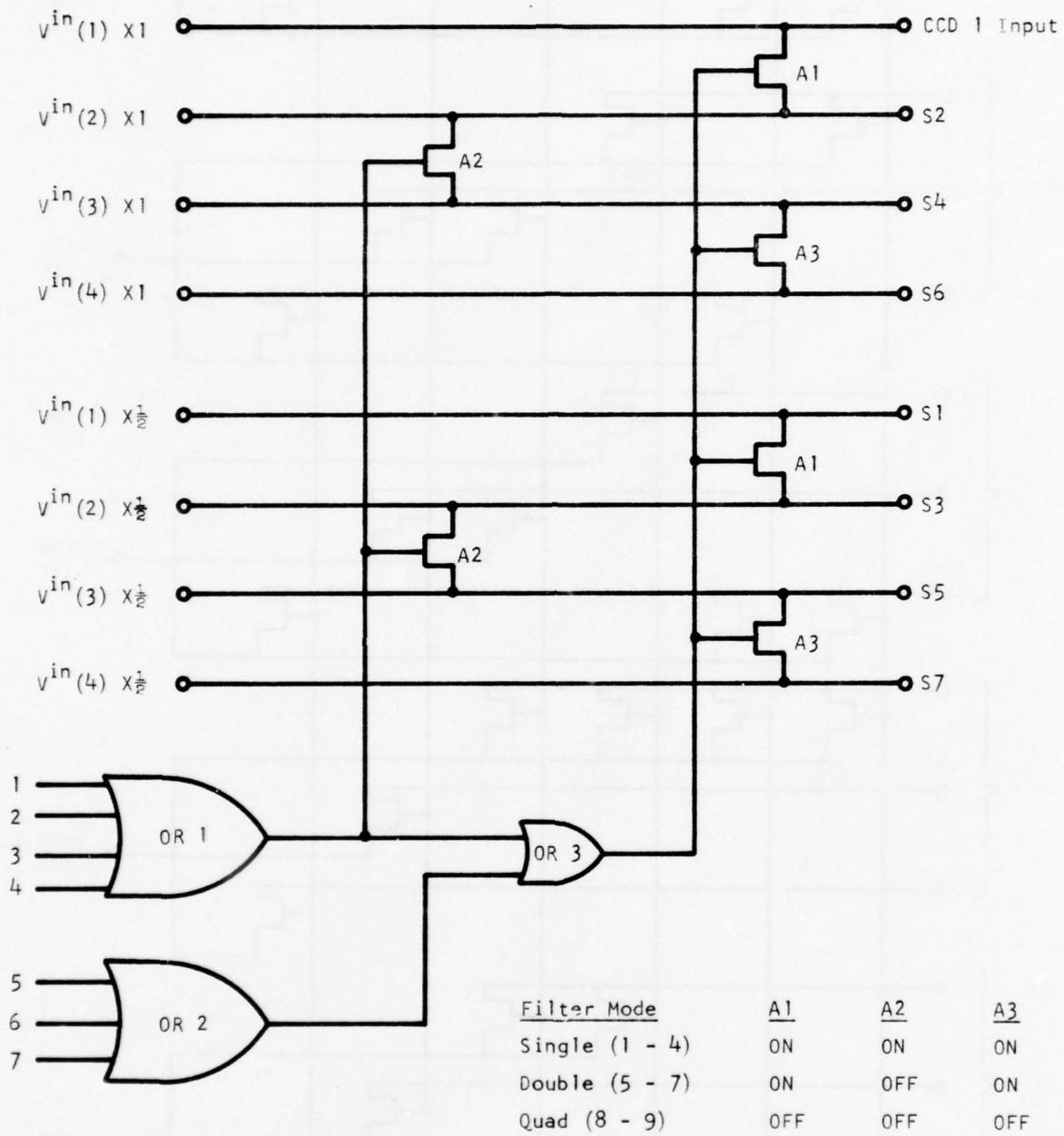


Figure 6(a) Input Switches for Single, Double, and Quad Mode Selection

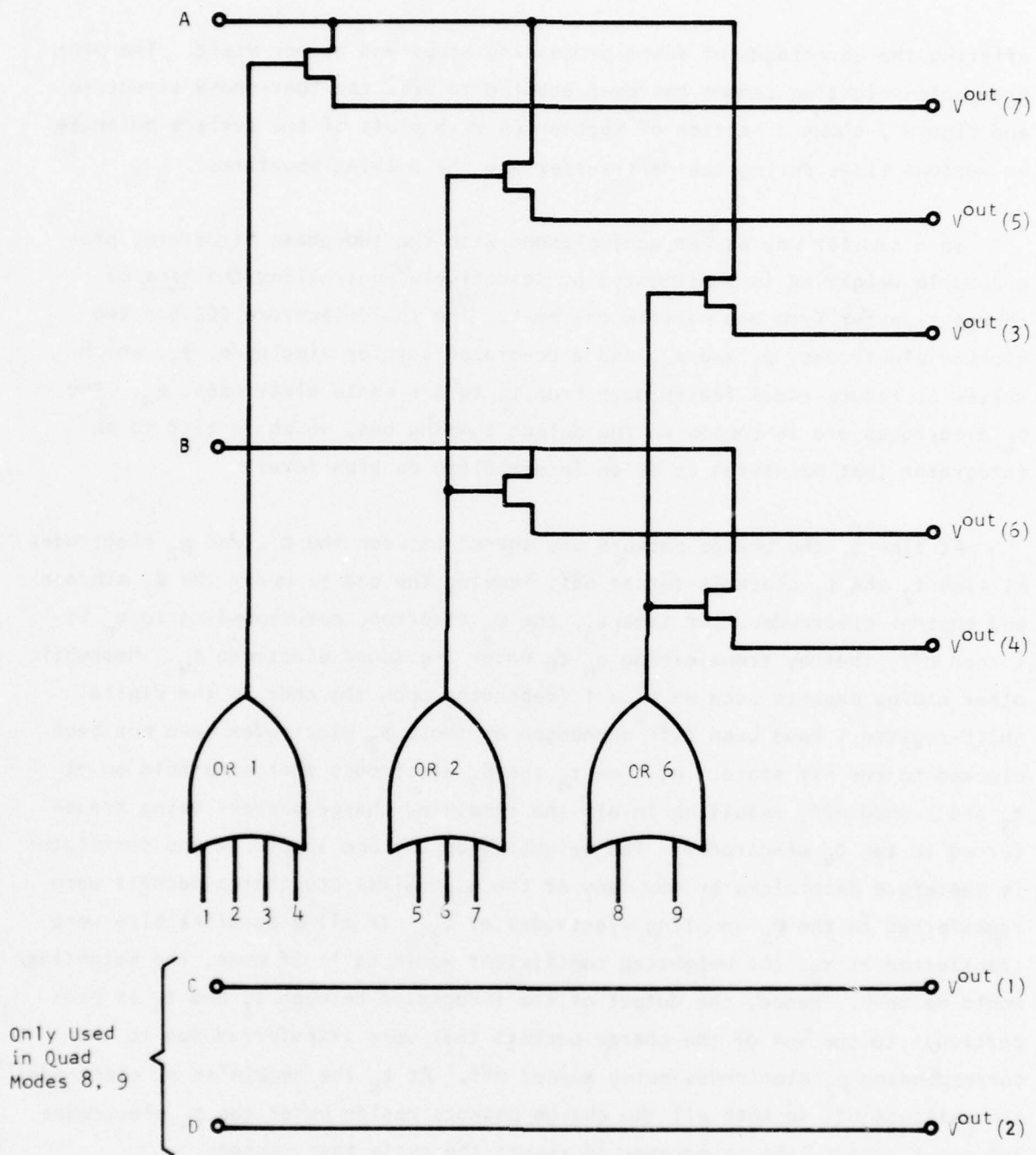


Figure 5(b) Output Switches for Single, Double, and Quad Mode Selection

offering the advantages of fewer processing steps and higher yield. The programmable weighting scheme has been adapted to suit the four-phase structure, and Figure 7 shows a section of such a CCD with plots of the surface potential at various times during charge transfer and the driving waveforms.

In a similar way as was accomplished with the two-phase structure, programmable weighting is implemented by selectively controlling the time of charge transfer from one well to the next. The four-electrode CCD has two clocked electrodes,  $\phi_1$  and  $\phi_2$ , and a dc-biased barrier electrode,  $\phi_3$ , which serves to reduce clock feedthrough from  $\phi_2$  to the sense electrodes,  $\phi_4$ . The  $\phi_4$  electrodes are in common on the output summing bus, which is tied to an integrator that maintains it at an intermediate dc bias level.

At time  $t_1$  the charge packets are shared between the  $\phi_1$ , and  $\phi_2$  electrodes. At time  $t_2$  the  $\phi_1$  clock is turned off, leaving the charge under the  $\phi_2$  storage and control electrodes. At time  $t_3$ , the  $\phi_2$  electrode corresponding to  $q_n$  is turned off, thereby transferring  $q_n$  to under the sense electrode  $\phi_4$ . Meanwhile, other charge packets such as  $q_n + 1$  (depending upon the code in the digital shift-register) have been left unchanged as those  $\phi_2$  electrodes have not been clocked to the off state. At time  $t_4$  the  $\phi_2$  electrodes that were held on at  $t_3$  are turned off, resulting in all the remaining charge packets being transferred to the  $\phi_4$  electrodes. The weighting on any one sample in the correlator is therefore determined by how many of the  $M$  parallel CCD charge packets were transferred to the  $\phi_4$  sampling electrodes at  $t_3$ . If all  $M$  parallel bits were transferred at  $t_3$ , the weighting coefficient would be 1; if none, the weighting would be zero. Hence, the output of the integrator between  $t_3$  and  $t_4$  is proportional to the sum of the charge packets that were transferred due to the corresponding  $\phi_2$  electrodes being turned off. At  $t_4$  the remaining  $\phi_2$  electrodes are switched off so that all the charge packets reside under the  $\phi_4$  electrodes. Between  $t_4$  and  $t_1$  the integrator is reset; the cycle then repeats.

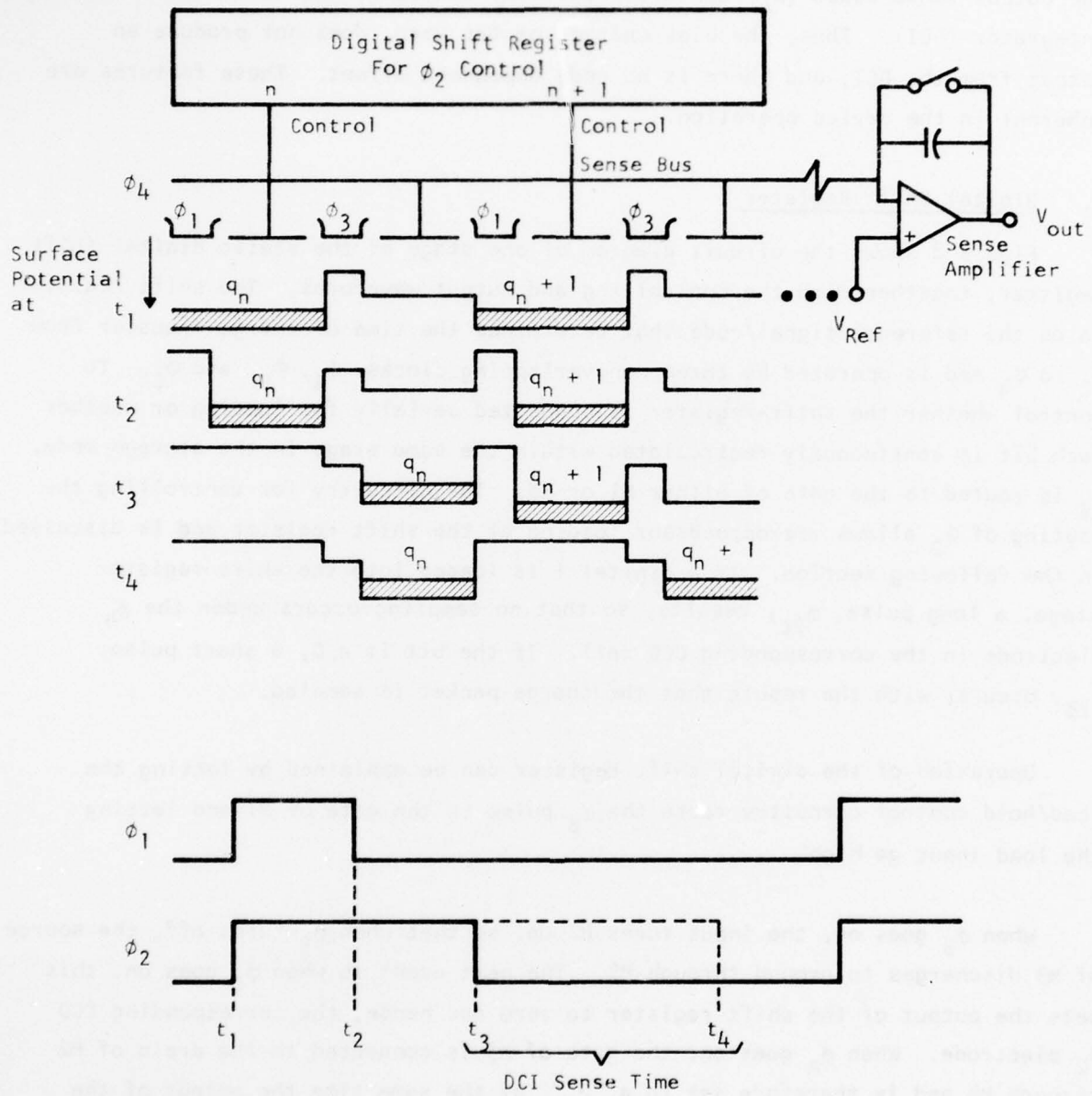


Figure 7 Programmable Weighting Using a Four-Phase CCD

As noted in Section I.A, for each section of the correlator two CCD channels are operated in parallel, both being controlled by the same digital shift-register. The input signal and its complement are applied to the two CCD channels, while the output sense buses ( $\phi_4$ ) are differentially summed by the differential current integrator (DCI). Thus, the bias charge, or fat zero, does not produce an output from the DCI; and there is no code dependent offset. These features are inherent in the device operation.

### C. Digital Shift Register

Figure 8 shows the circuit diagram of one stage of the static digital shift register, together with the controlling and output waveforms. The shift register holds the reference signal/code that determines the time of charge transfer from  $\phi_2$  to  $\phi_4$  and is operated by three nonoverlapping clocks,  $\phi_A$ ,  $\phi_B$ , and  $\phi_C$ . To control whether the shift-register is connected serially for loading or whether each bit is continuously recirculated within the same stage in the storage mode,  $\phi_B$  is routed to the gate of either M1 or M8. The circuitry for controlling the routing of  $\phi_B$  allows microprocessor loading of the shift register and is discussed in the following section. If a digital 1 is loaded into the shift register stage, a long pulse,  $\phi_{2L}$ , results, so that no sampling occurs under the  $\phi_4$  electrode in the corresponding CCD cell. If the bit is a 0, a short pulse,  $\phi_{2S}$ , occurs, with the result that the charge packet is sampled.

Operation of the digital shift register can be explained by letting the load/hold control circuitry route the  $\phi_B$  pulse to the gate of M1 and letting the load input go high.

When  $\phi_B$  goes on, the input turns M2 on, so that when  $\phi_B$  turns off, the source of M3 discharges to ground through M2. The next event is when  $\phi_C$  goes on, this sets the output of the shift register to zero and hence, the corresponding CCD  $\phi_2$  electrode. When  $\phi_A$  goes on, the gate of M5 is connected to the drain of M2 through M4 and is therefore set to a "0." At the same time the output of the shift register tracks  $\phi_A$  through M6. When  $\phi_A$  goes off, the shift register output is left floating high because M5 is turned off. Consequently, a long  $\phi_2$  pulse is generated; only when  $\phi_C$  comes on will the output be reset to zero. Now

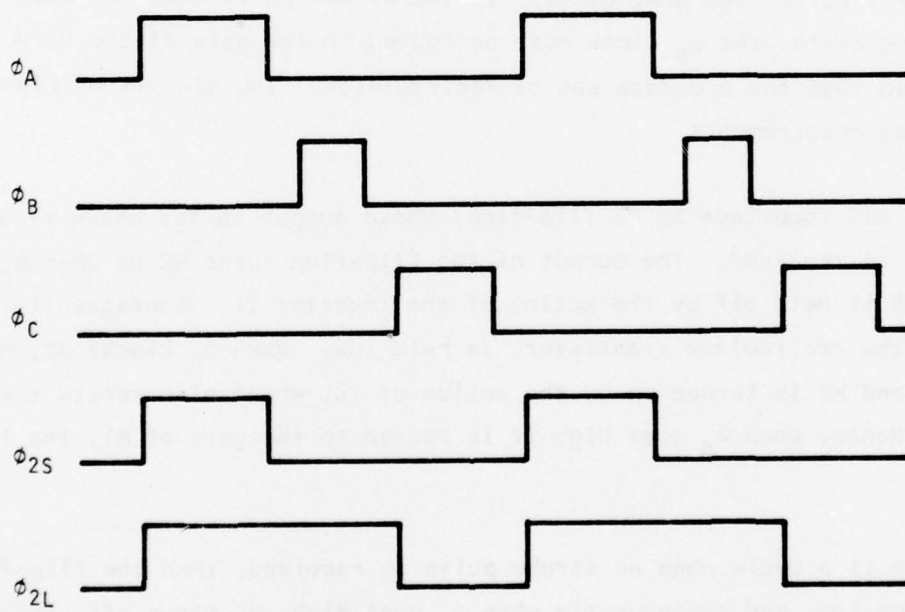
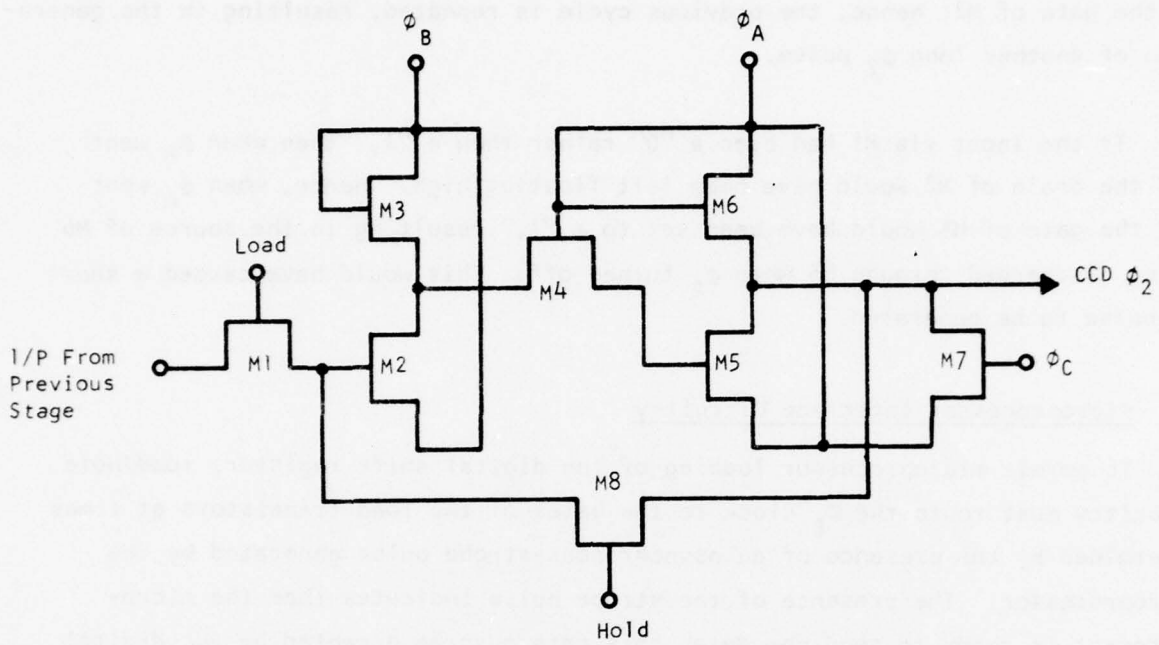


Figure 8 Digital Shift Register Circuit with Controlling and Output Waveforms

let the control circuitry route the next  $\phi_B$  pulse to the gate of the hold transistor M8. When M8 is clocked, the high output of the shift register is routed to the gate of M2; hence, the previous cycle is repeated, resulting in the generation of another long  $\phi_2$  pulse.

If the input via M1 had been a "0" rather than a "1," then when  $\phi_B$  went off the drain of M2 would have been left floating high. Hence, when  $\phi_A$  went on, the gate of M5 would have been set to a "1," resulting in the source of M6 being discharged through M5 when  $\phi_A$  turned off. This would have caused a short  $\phi_2$  pulse to be generated.

#### D. Microprocessor Interface Circuitry

To permit microprocessor loading of the digital shift register, load/hold circuitry must route the  $\phi_B$  clock to the gates of the load transistors at times determined by the presence of an asynchronous strobe pulse generated by the microprocessor. The presence of the strobe pulse indicates that the microprocessor is ready to send new data; this data must be accepted by the digital shift registers during the next cycle. If the strobe pulse does not occur during any one cycle, the  $\phi_B$  clock must be routed to the gate of the hold transistor, so that the old data can be recirculated. The circuit of Figure 9 fulfills these requirements.

The circuit comprises an RS flip-flop, whose output is set whenever a strobe pulse is received. The output of the flip-flop turns MC on when  $\phi_C$  clocks MA; MB is held off by the action of the inverter I1. Consequently, the gate of M8, the recirculate transistor, is held low. When  $\phi_A$  clocks MD, MF is held off and ME is turned on by the action of I2, which also resets the flip-flop. Hence, when  $\phi_B$  goes high it is routed to the gate of M1, the load transistor.

If there is a cycle when no strobe pulse is received, then the flip-flop output remains low, and consequently when  $\phi_C$  goes high, MC stays off, and MB is turned on by I1. When  $\phi_A$  goes high, MF is turned on and ME, by the action of I2, is turned off. Consequently when  $\phi_B$  goes high, it is routed through MB to the gate of M8, the hold transistor.

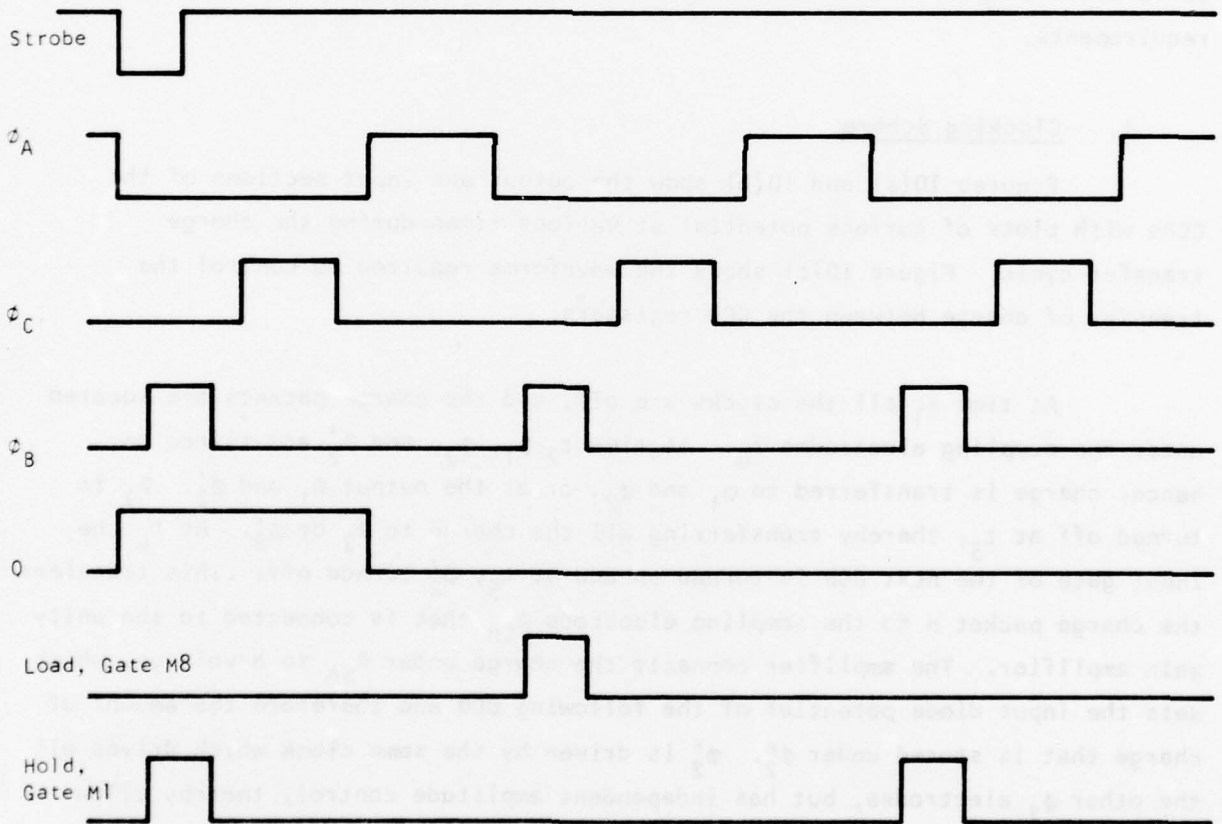
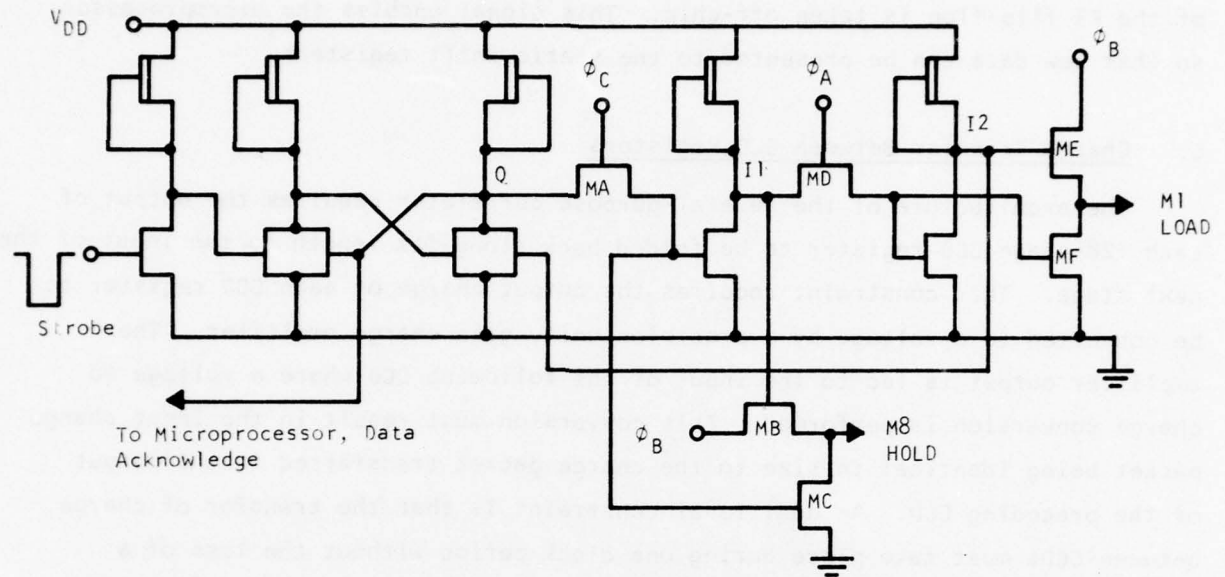


Figure 9 Microprocessor Interface Circuitry Showing Generation of Load and Hold Pulses

To provide the microprocessor with a data acknowledge signal, the Q output of the RS flip-flop is taken off-chip. This signal enables the microprocessor, so that new data can be presented to the static shift registers.

#### E. Charge Transfer Between CCD Registers

The architecture of the general-purpose correlator requires the output of each 128-stage CCD register to be folded back along its length to the input of the next stage. This constraint requires the output charge of each CCD register to be converted to a voltage by a precision unity gain charge amplifier. The amplifier output is fed to the input of the following CCD where a voltage to charge conversion is performed. This conversion must result in the input charge packet being identical in size to the charge packet transferred to the output of the preceding CCD. An additional constraint is that the transfer of charge between CCDs must take place during one clock period without the loss of a correlation sample. The scheme described in the following sections meets these requirements.

##### 1. Clocking Scheme

Figures 10(a) and 10(b) show the output and input sections of the CCDs with plots of surface potential at various times during the charge transfer cycle. Figure 10(c) shows the waveforms required to control the transfer of charge between the CCD registers.

At time  $t_1$  all the clocks are off, and the charge packets are located under the sampling electrodes  $\phi_4$ . At time  $t_2$   $\phi_1$ ,  $\phi_2$ , and  $\phi_2'$  are turned on; hence, charge is transferred to  $\phi_1$  and  $\phi_2$ , or at the output  $\phi_1$  and  $\phi_2'$ .  $\phi_1$  is turned off at  $t_3$ , thereby transferring all the charge to  $\phi_2$  or  $\phi_2'$ . At  $t_4$  the input gate of the next CCD is turned on and at  $t_5$ ,  $\phi_2'$  turned off. This transfers the charge packet  $n$  to the sampling electrode  $\phi_{SA}$  that is connected to the unity gain amplifier. The amplifier converts the charge under  $\phi_{SA}$  to a voltage, which sets the input diode potential of the following CCD and therefore the amount of charge that is stored under  $\phi_2''$ .  $\phi_2''$  is driven by the same clock which drives all the other  $\phi_2$  electrodes, but has independent amplitude control, thereby allowing the zero reference level to be "fine tuned."

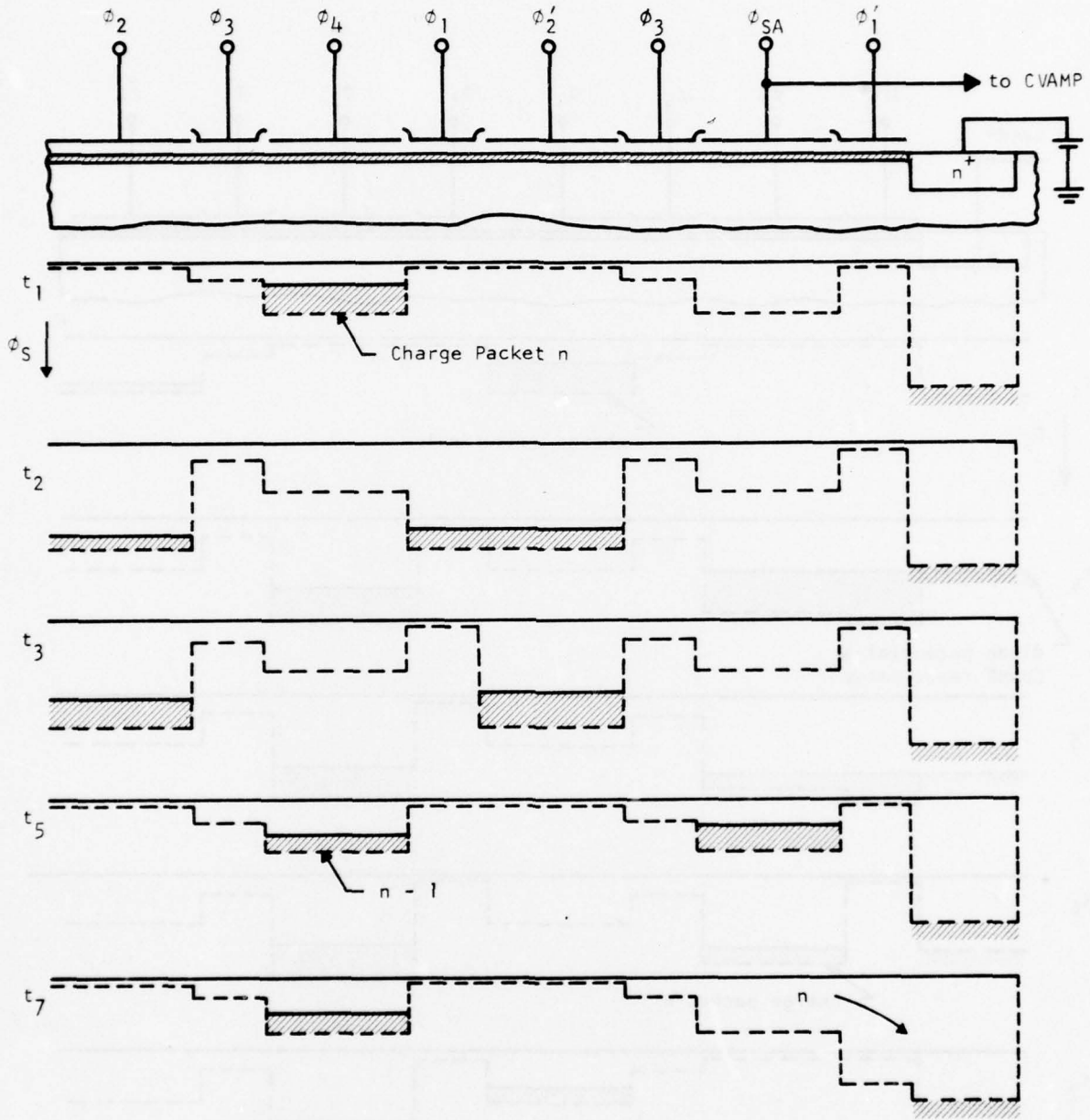


Figure 10(a) CCD Output Stage Showing Surface Potential Variations During Charge Transfer Between CCD Registers

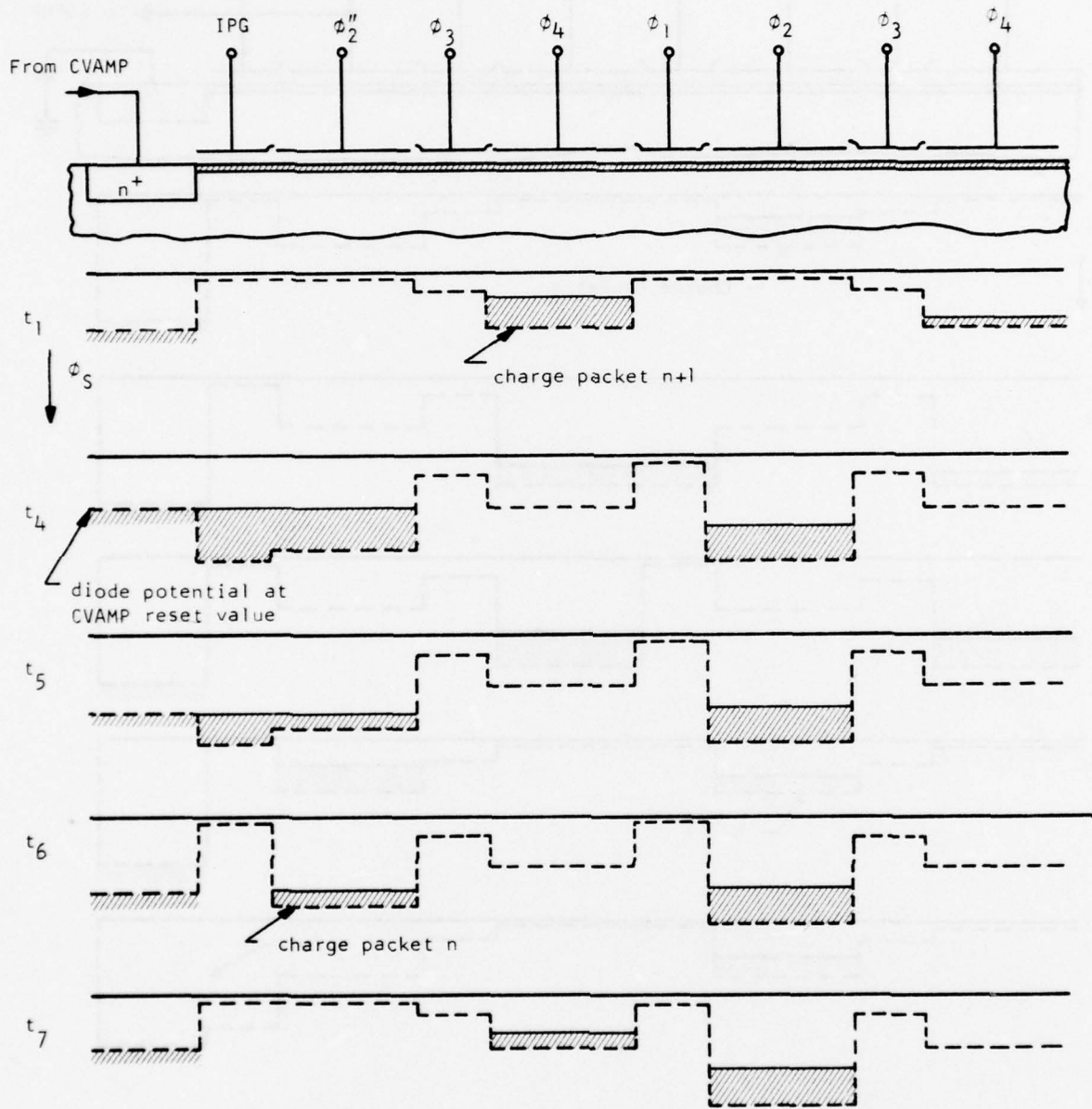


Figure 10(b) CCD Input Stage Showing Surface Potential Variations During Charge Transfer Between CCD Registers

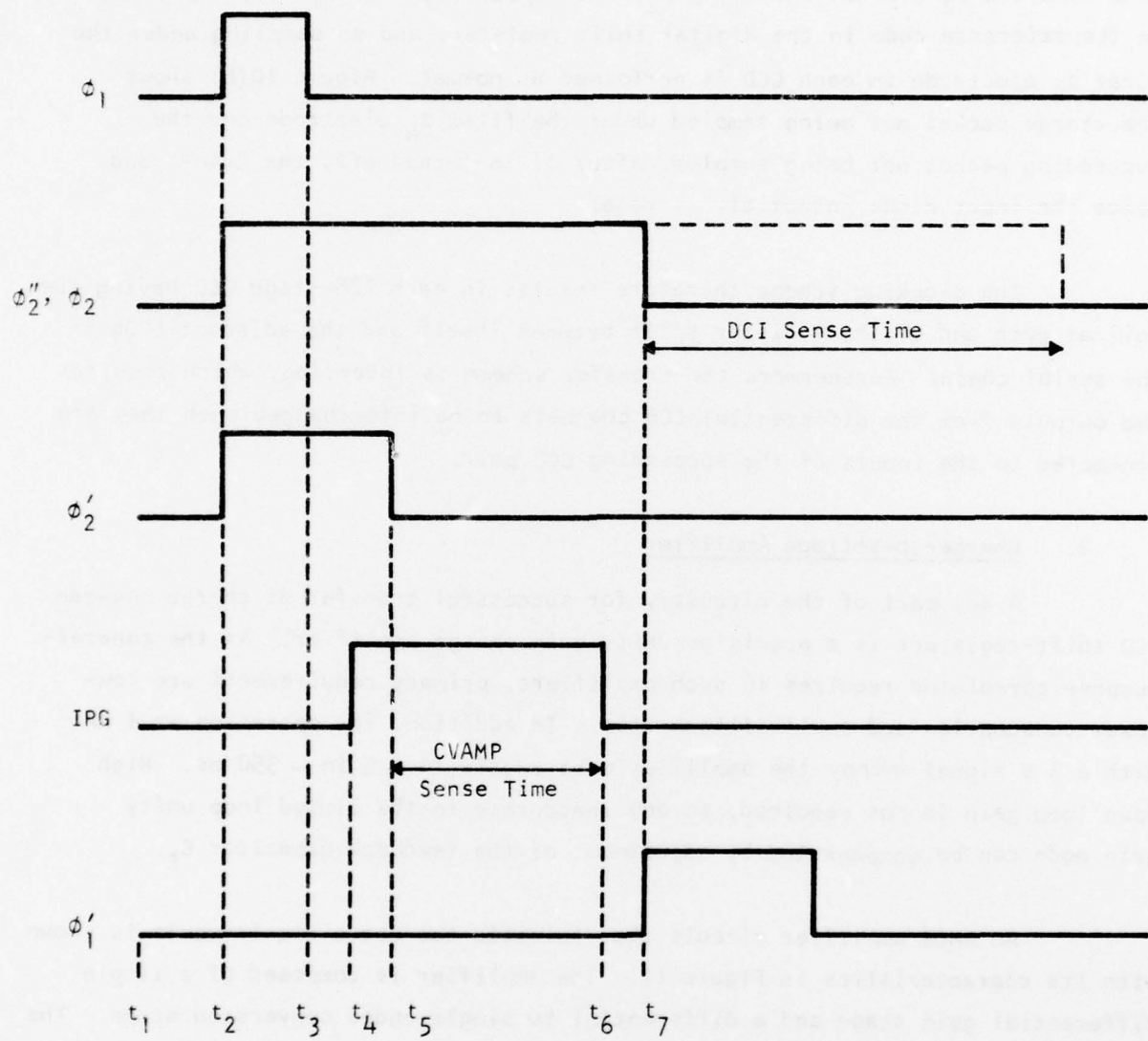


Figure 10(c) Clocking Scheme for Transferring Charge Between CCD Shift Registers

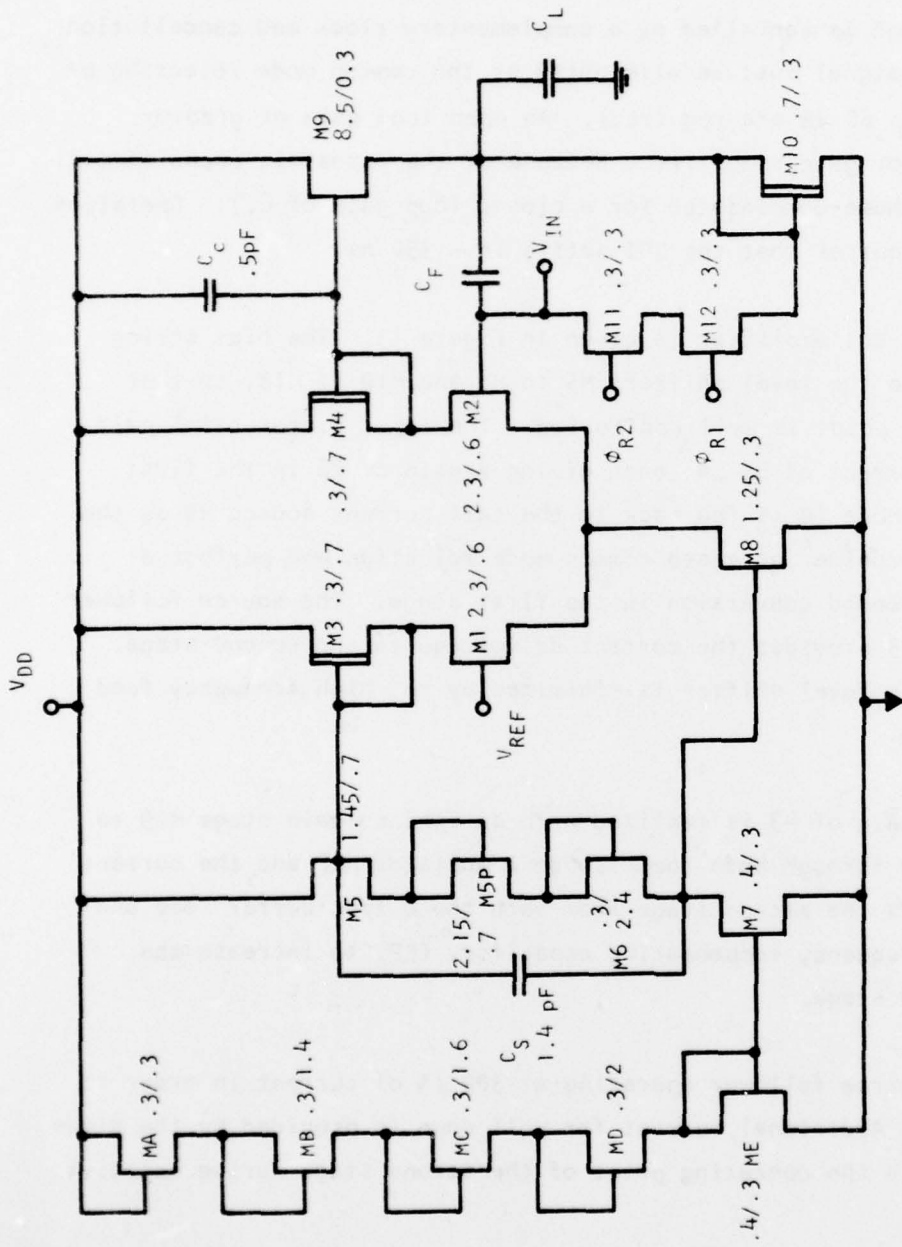
At  $t_6$  the input gate is turned off and hence the CVAMP has between  $t_5$  and  $t_6$  to settle, which at a clock rate of 1 MHz is approximately 370 ns.  $\phi'_1$  is turned on at  $t_7$  so that the charge packet that was located under  $\phi_{SA}$  is dumped into the reverse-biased diode at the end of the CCD register. At the same time the  $\phi_2$  clocks, including  $\phi''_2$ , are selectively turned off, depending on the reference code in the digital shift register, and so sampling under the first  $\phi_4$  electrode in each CCD is performed as normal. Figure 10(b) shows the charge packet not being sampled under the first  $\phi_4$  electrode and the succeeding packet not being sampled. After  $\phi'_1$  is turned off, the CVAMP, and hence the input diode potential, is reset.

The clocking scheme therefore results in each 128-stage CCD having the cell at each end of the register split between itself and the adjacent CCDs in the serial chain. Furthermore the transfer scheme is inverting, which requires the outputs from the differential CCD channels to be interchanged when they are connected to the inputs of the succeeding CCD pair.

## 2. Charge-to-Voltage Amplifier

A key part of the circuitry for successful transfer of charge between CCD shift-registers is a precision unity gain charge amplifier. As the general-purpose correlator requires 16 such amplifiers, primary requirements are low-power consumption and small-silicon area. In addition, for operation at 1 MHz with a 3 V signal swing, the amplifier must settle to 1% in  $\sim 350$  ns. High open loop gain is not required, as any inaccuracy in the closed loop unity gain mode can be compensated by adjustment of the feedback capacitor  $C_F$ .

An NMOS amplifier circuit that fulfills the above requirements is shown with its characteristics in Figure 11. The amplifier is composed of a single differential gain stage and a differential to single-ended conversion stage. The feedback path between M1 and M8 also provides for improved common mode rejection. The output is taken via a source-follower stage that is designed to drive a load capacitance of up to 5 pF. Open loop unity gain frequency compensation is provided by  $C_C$ , which also limits the amplifier slew rate. The amplifier occupies an area of  $0.5 \text{ mm}^2$  that includes both reset transistors and the closed loop gain adjustment capacitor  $C_F$ .



Charge Amplifier Characteristics

Power	6 mW
Open Loop Gain	40
Unity Gain Bandwidth	11 MHz
Slew Rate	20 v/ $\mu$ s
Phase Margin	50°
Load	5 pF
Silicon Area	0.05 mm <sup>2</sup>

Figure 11 Charge Amplifier Circuit and Characteristics

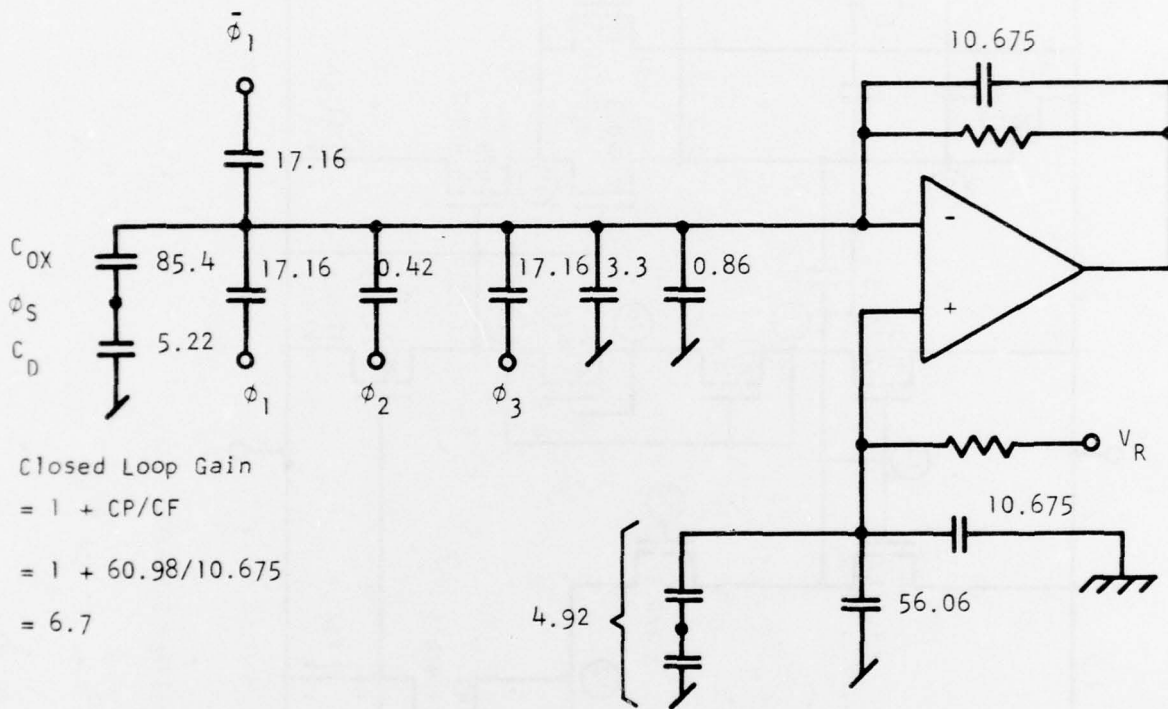
#### F. Differential Current Integrator Design

The DCI amplifier is shown in Figure 12 with the related circuit elements. The 10.7 pF feedback capacitor allows a full 8 V output swing when a filter processing gain of 0.25 is used and maximum signal is present in the CCD. The Phase 1 clock feedthrough is cancelled by a complementary clock and cancellation capacitance. Fat zero signal must be eliminated by the common mode rejection of the amplifier (more than 60 dB are required). An open loop gain of greater than 1000 is required for gain stability. Because of the parasitic capacitances, the amplifier must be phase-compensated for a closed loop gain of 6.7. Operation at a 1 MHz data rate requires that the DCI settle in  $\sim 350$  ns.

A schematic of the DCI amplifier is given in Figure 13. The bias string M14 to M18 is matched to the level shifters M5 to M8 and M10 to M13, so that the quiescent operating point is well controlled. The input differential pair M1 - M2 operate at a current of 65  $\mu$ A, each giving a gain of 26 in the first stage. The voltage at node 10 is fed back to the tail current source M9 by the source follower M5 to provide increased common mode rejection and perform a differential to single-ended conversion in the first stage. The source follower level shifter M10 to M13 provides the correct dc voltage to the second stage. Phase shift through this level shifter is minimized by the high frequency feed forward capacitor, CLS0.

The second stage gain of 43 is realized with an enhance gain stage M19 to M22. About 130  $\mu$ A flow through both the cascode transistor M20 and the current source M21. M27 buffers the second stage from both the output buffer load and a portion of the low frequency compensating capacitor, CCF, to increase the bandwidth of the second stage.

The output is a source follower operating at 300  $\mu$ A of current in order to drive a load of 15 pF. Additional current for pull down is provided by the diode MLS, which also controls the operating point of the second stage during negative output slewing.



Closed Loop Gain  
 $= 1 + C_P/C_F$   
 $= 1 + 60.98/10.675$   
 $= 6.7$

All Capacitance Values in pF

Figure 12 DCI Circuit with Parasitics

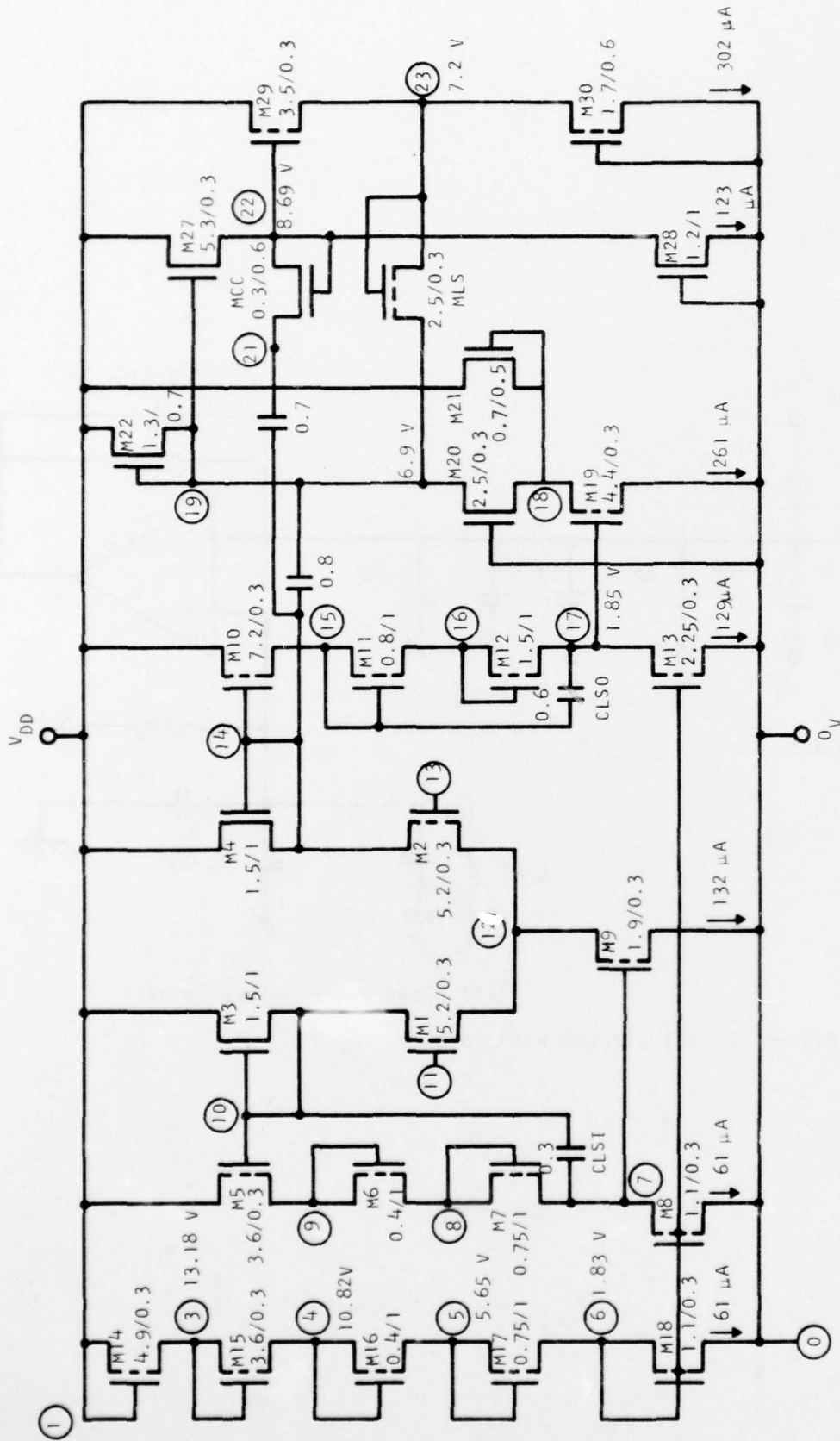


Figure 13 DCI Amplifier Schematic

The open loop transfer function of the DCI amplifier is given in the SPICE simulation output of Figure 14. The unity gain crossover frequency is 31 MHz, and the zero phase margin frequency is 18 MHz. A transient simulation for  $\pm 4$  V output steps is illustrated in Figure 15. All steps settle to eight bits in less than 300 ns. The performance of the amplifier is summarized in Table 2.

#### G. Correlator Clocking

Figure 16 shows the relative timing of the ten clocks required to operate the binary/analog correlator.  $\phi_A$ ,  $\phi_B$ , and  $\phi_C$  are used to control the operation of the digital shift register, which in turn controls the  $\phi_2$  CCD clock, as discussed in Section II.C.  $\phi'_1$ ,  $\phi'_2$ , and IPG control the transfer of charge between CCD registers (see Section II.E).  $\phi_1$  is the remaining CCD clock,  $\phi_{R1}$  and  $\phi_{R2}$  are the DCI reset clocks;  $\phi_B$  and  $\phi_C$  are also used to reset the CVAMPs. The clock timing has been designed to allow the maximum possible settling time for the DCIs and charge amplifiers. At a clock rate of 1 MHz these times are  $\sim 375$  ns.

The clock driver circuit is shown in Figure 17. The six devices driven by the input lines act as buffers between the large gates of the output devices and the input signal drivers. They also provide an appropriate delay so that the bottom of the bootstrap capacitor MB is held at ground as an ON signal is applied. After a short delay, M2 is turned off. The source of M1 is bootstrapped to  $\sim 1.5 V_{DD}$ , and the load voltage can rise to within a threshold of  $V_{DD}$ . The device aspect ratios are determined by the required risetime and load capacitance. From the layout of the CCD and digital shift register cells, the various clock loading capacitances have been calculated and are given in Table 3. The high load capacitances result in the drive circuits occupying a considerable portion of the bar area,  $\sim 20\%$ . The area of the drive circuits, designed to drive the various load capacitances with a 20 ns rise time, are also included in Table 3.

LEGEND:

A: VM(14) FIRST STAGE OUTPUT MAGNITUDE  
 B: VM(19) SECOND STAGE OUTPUT MAGNITUDE  
 C: VM(23) DCI OPEN LOOP XFER FUNCTION MAGNITUDE (LOAD=15PF)  
 D: VP(14) 1ST STAGE PHASE  
 E: VP(19) 2ND STAGE PHASE  
 F: VP(23) OUTPUT PHASE  
 FREQ

(A)-----	1.000D-02	1.000D-01	1.000D+00	1.000D+01	1.000D+02
(BC)-----	1.000D-01	1.000D+00	1.000D+01	1.000D+02	1.000D+03
(DEF)-----	-1.900D+02	-9.000D+01	0.0	9.000D+01	1.800D+02
1.000D+05	.	. D	.	A 2	CB
1.259D+05	.	. D	.	A . 2	CB
1.585D+05	.	. D	.	A . 2	CB
1.995D+05	.	. D	.	A . 22	
2.512D+05	.	. D	.	A	C3
3.162D+05	.	. D	.	A	CB2
3.981D+05	.	. D	.	A	2 FE
5.012D+05	.	. D	.	A	CB FE
6.310D+05	.	. D	.	A	CB FE
7.943D+05	.	. D	.	A	CB FE
1.000D+06	.	. D	.	A	CB FE
1.259D+06	.	. D	.	A 2	FE
1.585D+06	.	. D	.	A CB	FE
1.995D+06	.	. D	.	A CB	FE
2.512D+06	.	. D	.	A CB	F.E
3.162D+06	.	. D	.	A 2	F.E
3.981D+06	.	. D	.	A 3	F.E
5.012D+06	.	. D	.	A 3	F.E
6.310D+06	.	. D	.	A 3	F.E
7.943D+06	.	. D	.	A 3	F.E
1.000D+07	.	. D	.	A 3	F.E
1.259D+07	.	. D	.	A 3	F.E
1.585D+07	.	. D	.	A 3	F.E
1.995D+07	.	. D	.	A 3	F.E
2.512D+07	.	. D	.	A 3	F.E
3.162D+07	.	. D	.	A 3	F.E
3.981D+07	.	. D	.	A 3	F.E
5.012D+07	.	. D	.	A 3	F.E
6.310D+07	.	. D	.	A 3	F.E
7.943D+07	.	. D	.	A 3	F.E
1.000D+08	.	. D	.	A 3	F.E

Figure 14 DCI Open Loop Transfer Function

LEGEND:  
 A: V(23)  
 TIME

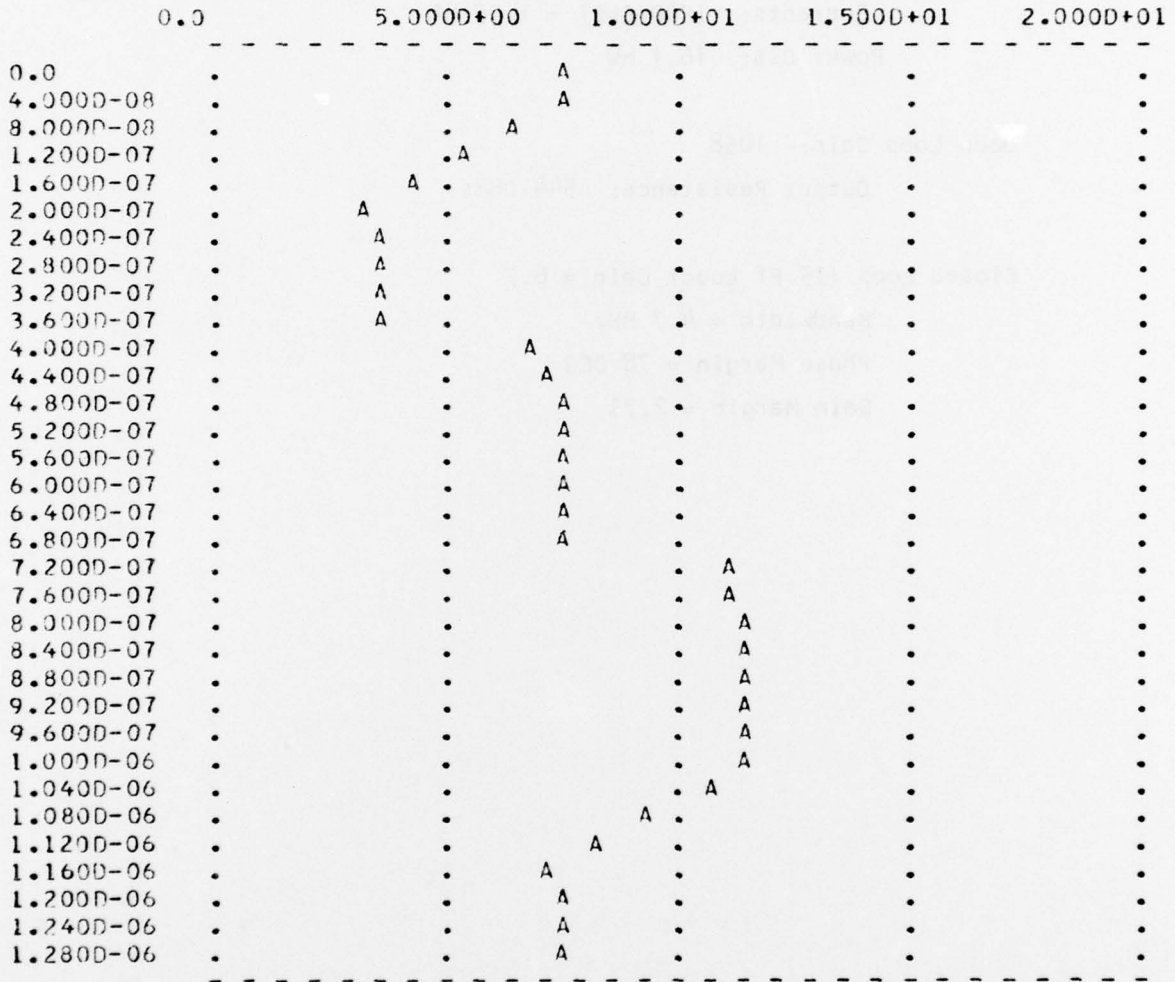


Figure 15 DCI Step Response for +/- 4 V Output Swing

Table 2  
DCI Amplifier Performance

Operating Voltages:  $V_{DD} = 15 \text{ V}$ ,  $GND = 0 \text{ V}$ ,  $V_{BB} = -5 \text{ V}$

Currents: (FDD/GND) = 1.07 MA

Power Dis: 16.1 MW

Open Loop Gain: 1058

Output Resistance: 544 Ohms

Closed Loop (15 Pf Load) Gain = 6.7

Bandwidth = 4.7 MHz

Phase Margin = 78 DEG

Gain Margin = 2.73

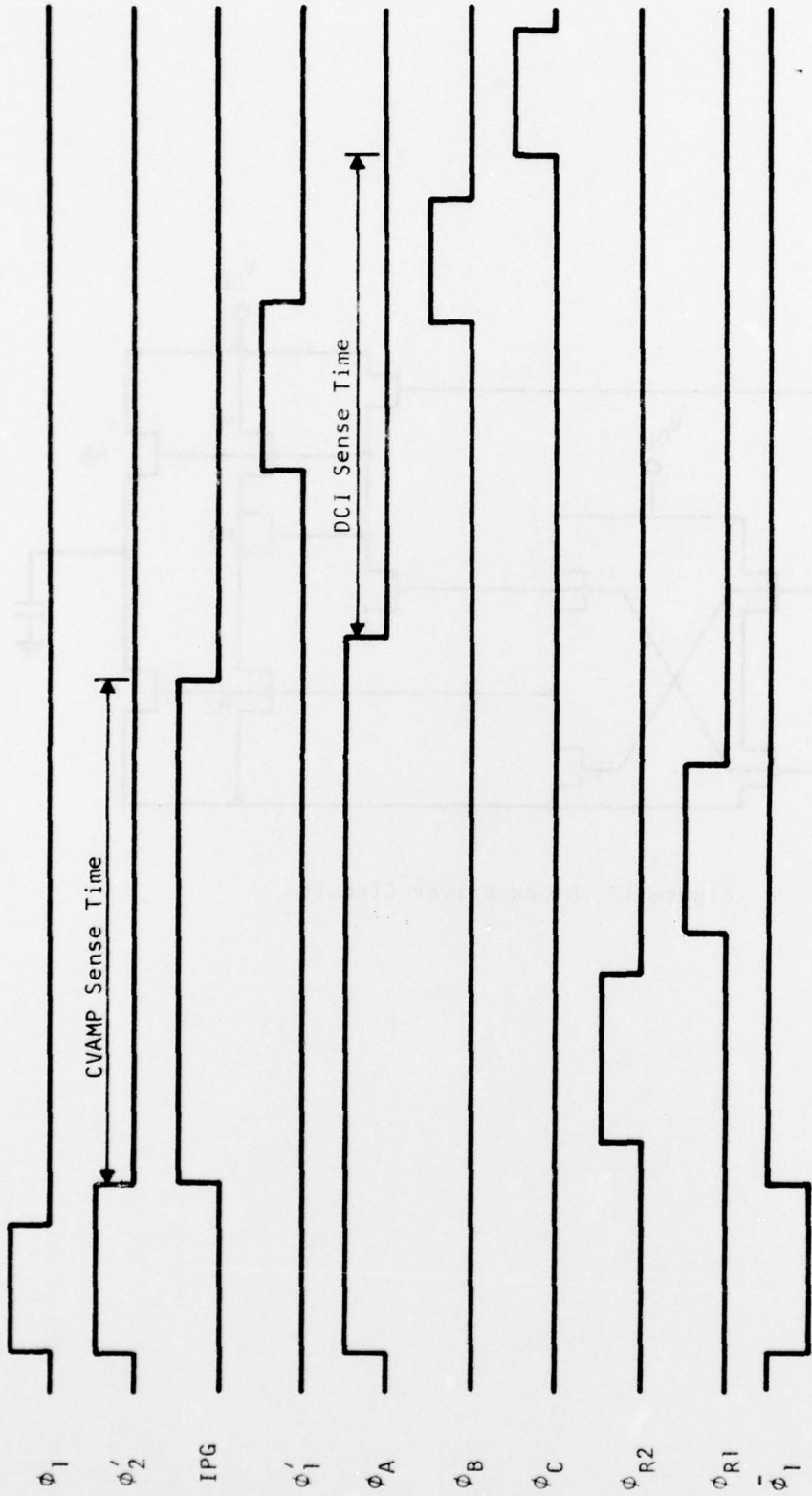


Figure 16 Correlator Clock Timing

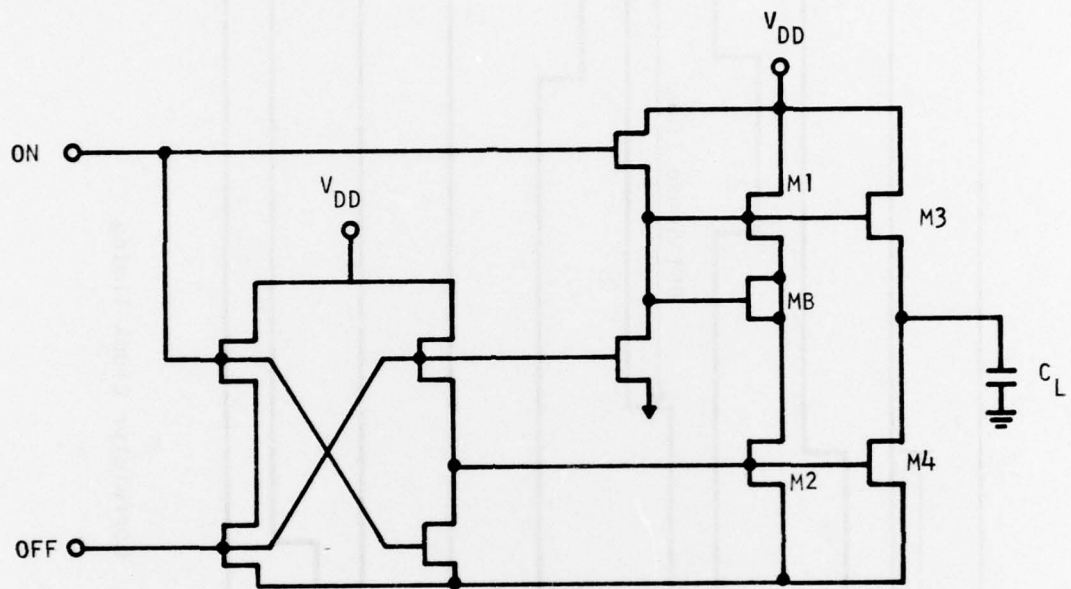


Figure 17 Clock Driver Circuit

Table 3  
Loading Capacitances and Corresponding Clock Driver Areas  
for 20 ns Rise Time

<u>Clock Phase</u>	<u>Capacitive Loading</u>	<u>Driver Area, mils<sup>2</sup></u>
$\phi_1$	425 pF	400
$\phi'_2$	10 pF	57
IPG	7 pF	57
$\phi'_1$	7 pF	57
$\phi_A$	720 pF	840
$\phi_B$	140 pF	213
$\phi_C$	60 pF	127
$\phi_{R2}$	10 pF	57
$\phi_{R1}$	10 pF	57
- $\phi_1$	10 pF	57

The maximum frequency of device operation is primarily determined by the power dissipation of the drivers. The frequency limit turns out to be about 1 MHz, as with 80% efficient drivers and a 15 V clock swing, the power dissipation is  $\sim 400$  mW. To estimate the total chip dissipation, the driver dissipation must be added to that of the circuitry for generating the clock waveforms,  $\sim 150$  mW; the seven DCIs,  $\sim 140$  mW; and the 16 charge amplifiers,  $\sim 100$  mW; a total of  $\sim 800$  mW. In addition to the power dissipation restricting the maximum frequency of operation to  $\sim 1$  MHz, neither the DCIs nor the CVAMPS will settle quickly enough to permit operation at much beyond this frequency.



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