

INVESTIGATION OF OPTICAL/INFRARED SENSOR TECHNIQUES
FOR APPLICATION SATELLITES

NASA Research Grant NGR 03-001-052

Final Report

18 May 1972



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COLLEGE OF ENGINEERING SCIENCES
ARIZONA STATE UNIVERSITY
Tempe, Arizona 85281

Prepared by


Irving Kaufman
Principal Investigator

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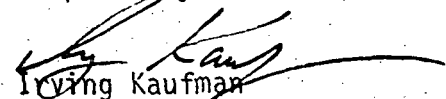
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The objective of the work performed under this grant was to investigate the method of scanning an optical sensor array by acoustic surface waves. This investigation was a continuation of work performed under Contracts NAS 12-2173 and F44620-69-C-0025. The latter, a contract between Arizona State University and the Department of Defense, falls under the category "Project THEMIS" and is being monitored by the U. S. Air Force Office of Scientific Research.

The major work accomplished included a detailed computer-based analysis of the operation of a multi-element acoustic-surface-wave-scanned optical sensor array, the development of design and optimization techniques that were used to show the feasibility of an integrated array to design several such arrays, and experimental verification of a number of the calculations, with discrete sensor devices.

This work is described in the attached report SSRL-131 entitled "Analysis and Performance of a Surface-Wave-Scanned Optical Sensor Array." A more detailed account is presented in the Ph.D. dissertation of Kenneth Alan Shaw, entitled "Optical Sensor Array Scanning by Acoustic Surface Waves." (Arizona State University, November 1971.)

In addition to this work, we initiated experimental work toward the fabrication of integrated sensor arrays by investigating the deposition of photoconducting films. Here, we found the literature full of partial descriptions of methods of depositing photoconducting films; it was difficult, however, to get complete information. Several industrial firms fabricate such films, of course, but often under a proprietary process. Ultimately, however, we were provided with some

information by Mr. D. Foria, of Sylvania, Precision Materials Division.

During the course of the investigation, the following films were deposited:

1. Poly-N-Vinyl Carbazole: Deposited by a dip-coating process.
2. Cadmium Sulfide: Deposited by vacuum evaporation of elemental cadmium and sulfur and followed by recrystallization.
3. Cadmium Sulfide/Cadmium Selenide: Deposited by a spray process, followed by recrystallization.

Of the three different processes, the "spray" method was found most desirable. While at the time that marked the end of the grant period we had not achieved the degree of competency that allowed us to duplicate films consistently from batch to batch, we had achieved films of up to 5000 in light-to-dark resistance ratio, of 7.5 milliseconds response time; and of 2060 ohm-centimeter resistivity in 700 μ watts/cm² light.

Personnel

This work was performed in the Solid State Research Laboratory of the College of Engineering Sciences of Arizona State University. Principal Investigator was Dr. Irving Kaufman. Graduate students active on the project were Mr. K. A. Shaw and Mr. R. M. Vasquez. Mr. Shaw has been awarded the Ph.D. degree; Mr. Vasquez has been awarded the M.S.E. degree.

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ANALYSIS AND PERFORMANCE
OF A SURFACE-WAVE-SCANNED
OPTICAL SENSOR ARRAY

K. A. Shaw
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18 May 1972

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I. INTRODUCTION

The electron beam scanned camera tube remains to date the most successful technique for conversion of an image pattern into an electrical signal. However, the great interest in all-solid-state systems has led to the investigation of several alternate techniques. These usually use photoconducting or photovoltaic elements for optical detection and one of a variety of ways for performing the scanning function. Among the methods used for performing such scanning are techniques employing acoustic (elastic) pulses. In one such technique, due to Yando,⁽¹⁾ an elastic pulse traveling through a sandwich structure composed of piezoelectric material, a photoconducting layer, and transparent optical contacts convert the spatial variation of optical intensity into a time-varying electric current. More recently, Kaufman and Foltz⁽²⁾ (K-F) described a technique that is similar but uses elastic surface waves.

This paper is a more detailed investigation of the method described in K-F. We start by describing the principle of operation and some basic considerations relating to performance. This is followed by an account of various configurations possible. Next we describe the various steps of a computer-based analysis of such elastic-wave-scanned sensor arrays that was carried out to determine the interdependence of the various parameters. This analysis utilizes the scattering matrix characterization of piezoelectric interdigital surface wave transducers (IDT's). Finally, by use of an optimization technique, we arrive at the design of an integrated one-dimensional sensor array.

A number of experiments were carried out with prototype systems. A description of some of these and their results are seen to substantiate some of the calculations.

II. PRINCIPLE OF OPERATION

The basic structure of the self-scanned optical sensor as proposed in K-F is shown in Figure 1. Here a photoconducting layer is deposited on top of an array of IDT's. The transducers are connected to a common pulsed voltage source through individual resistors. A single transducer at the right is used to convert the acoustic strain signals arriving from the left into electrical (voltage) output signals.

Since photoconducting material lies on top of each of the input transducer pairs, each pair is effectively shunted by a light-dependent resistance. As a result, when an image is projected on the array, those transducer pairs that are strongly illuminated are essentially electrically shorted; those that are in the dark are virtually unshunted. Since each pair has a resistor in series between it and the pulsed voltage source, the voltages appearing across the terminals of the various transducers vary in inverse proportion to the local illumination. If the voltage pulse used is a half-cycle pulse of the frequency at which the surface wave transducer spacing is half of the acoustic wavelength, the output signal received by the single pair output transducer will be an amplitude modulated wavetrain whose varying degree of modulation is the time analog of the spatial illumination pattern on the photoconductive surface.

While the concept of such a one-dimensional sensor array is easily acceptable, its use as a device will be determined by the sensitivity and resolution possible, as well as by the ability to construct it.

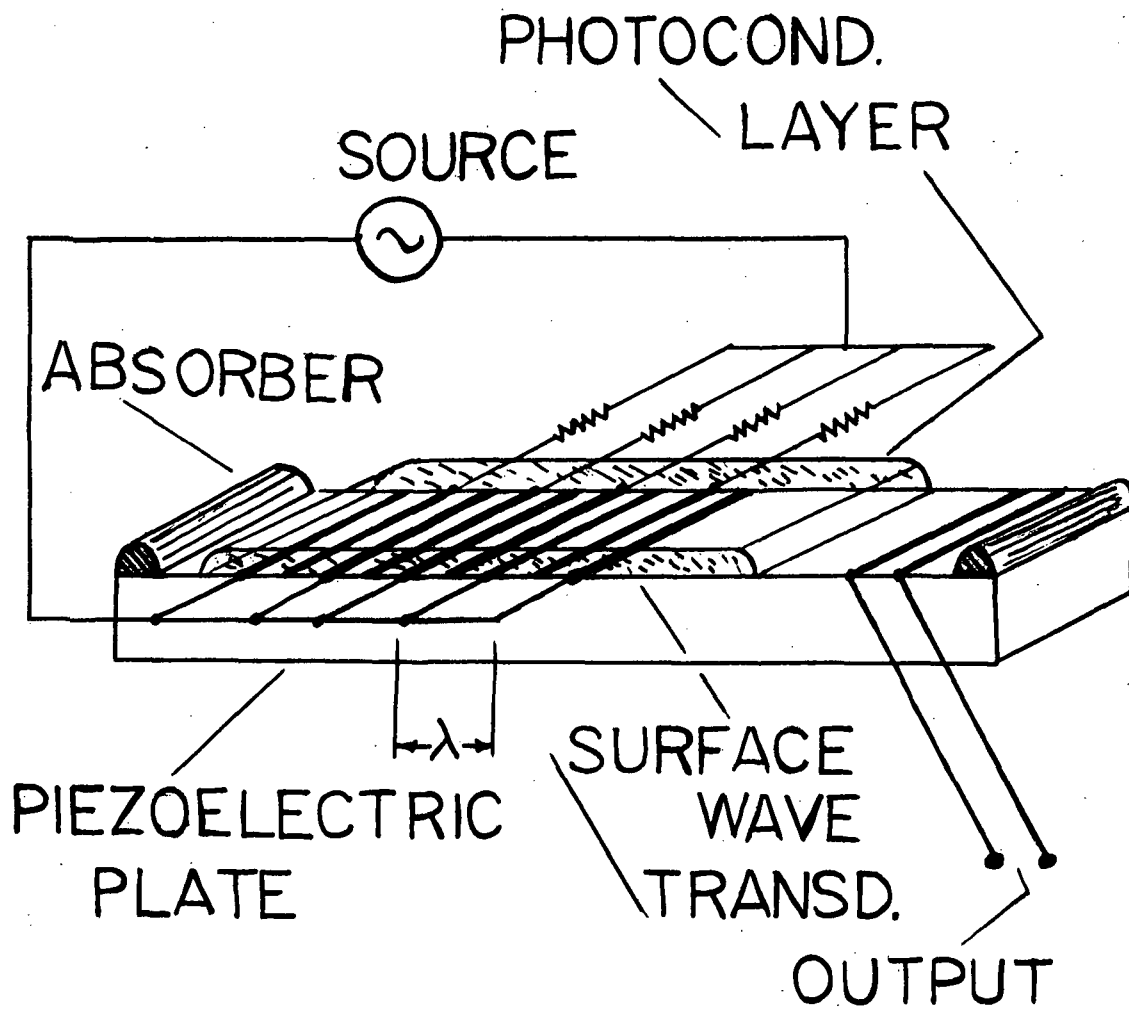


Figure 1

Self-scanning sensor array constructed of acoustic surface wave transducer elements overlaid by photoconducting material.

We will therefore briefly consider the interrelations between some of the variables.*

A simple equivalent circuit of an acoustic transducer pair covered with photoconducting material as in the circuit used here is given in Figure 2. Here it is seen immediately that if this circuit is to be responsive to light, then R' under full illumination should be of the order of the magnitude of the reactance of the capacitor that shunts it, or lower, i.e., the magnitude of C is a crucial factor. Approximating the transducer stripes by parallel wires, an estimate of the capacity per unit width for two adjacent stripes is $C_\ell = 27.8 \epsilon' (\ln b/a)^{-1} 10^{-12}$ farads/meter, where ϵ' is the dielectric constant of the medium in which these wires are imbedded and b/a is the ratio of transducer center-to-center spacing to wire radius. Letting $\epsilon' = 4$ (quartz) and $b/a = 4$, we find $C_\ell = (8) 10^{-11}$ f/m. To find the reactance, it is necessary to consider a frequency of operation. In the arrangement of Fig. 1, the linear resolution will be of the order of the acoustic wavelength λ , i.e., twice the spacing between adjacent stripes. For a resolution of, say, 100 elements per cm, and an acoustic wavelength therefore of $\lambda = 10^{-4}$ meters, the frequency of operation (of which a half-cycle pulse is impressed) for quartz is 32 MHz. At this frequency, the reactance of C_ℓ is $X = 62/W$, where W is the transducer width. If the resistance between contacts (under illumination) just equals X , then, for thickness t of photoconducting material, its resistivity is given, approximately,

*The material of this section is only an order-of-magnitude estimate. Results of more detailed calculations are given in Section VI.

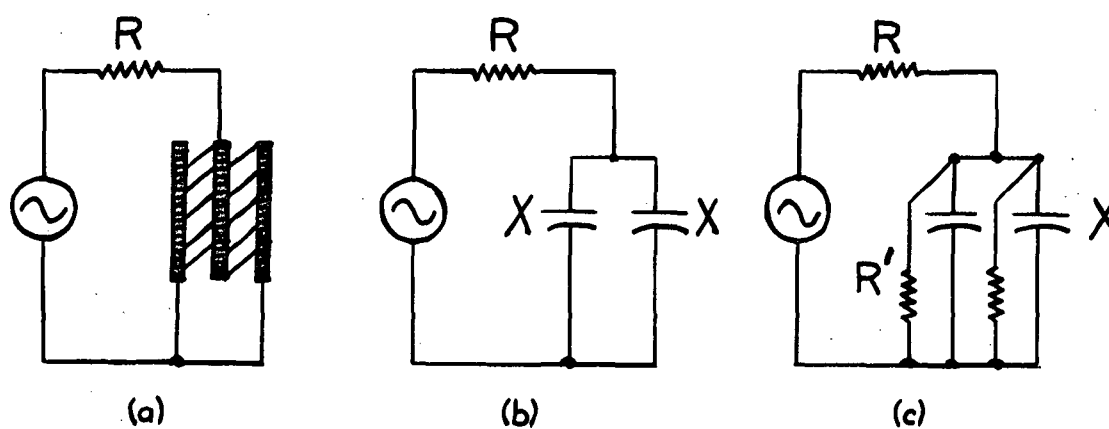


Figure 2

Elemental circuit of scanning sensor array.

- (a) Elemental circuit of source, resistor, and acoustic transducer with photoconducting material overlay.
- (b) Equivalent circuit in the dark.
- (c) Equivalent circuit under illumination.

by $\rho \approx (2.5)(10^6)(t)$ ohm-meters. Corresponding to a mobility $\mu=10^{-2}$ m²/volt-sec (100 cm²-volt-sec), this represents a light generated carrier density per unit area of

$$n_s = (\rho\mu q)^{-1} t = (2.5)(10^{14}) \text{ electrons/m}^2. \quad *$$

(Here q is the electronic charge.)

To create these carriers with light, assuming a quantum efficiency of 10 percent, requires an energy of $(n_s h\nu)/0.1 = (8.3)(10^{-4})$ joules/m². Here h is Planck's constant; ν is the optical frequency, taken here to be the frequency of 6000 Å light.

For a carrier effective lifetime of 10^{-2} seconds, commensurate with TV frame rates, the optical power density required is therefore $(8.3)(10^{-2})$ watts/m², or $(8.3)(10^{-6})$ watts/cm².

To see how this compares to ordinary light levels, we consider an image focused through a lens of f-number F . From Fink⁽³⁾, and after some manipulations, we find $E' \approx (4)(10^{-7}) B/F^2$, where

E' = power density at the image plane, in watts per square cm;

B = luminance of the image surface, in foot lamberts. **

According to Fink⁽³⁾, the luminance measured for, say, an overcast sky is 900 to 2000 foot lamberts. Using the relation for E' , above, for an $f/2$ lens this corresponds at an image plane to a light intensity of from 10^{-4} to $(2)(10^{-4})$ watts/cm². Since this is an order

* We note that here n_s is independent of thickness t . Practical thicknesses of the order of 1 to 100 microns correspond to acceptable carrier densities here.

**This relation is based on the use of the conversion factor 1 watt = 680 lumens, which is true only for 5550 Å light. The power density corresponding to a given luminance of white light is considerably higher, as determined by the curve of visual sensitivity.

of magnitude greater than the power intensity required for the shunting resistance to equal the reactance of the transducer capacitance, we conclude that the proposed method of scanning a sensor array can have sufficient light/dark discrimination for Vidicon-type of operation. The results of this estimate are strengthened by the results of Section VI.

III. ALTERNATE CONFIGURATIONS

During the course of work on this problem, several alternate possible configurations evolved. These are:

1. Interchange of Input and Output Connections

In K-F, the input pulse is applied to the transducers that are shunted by photoconducting material; output is from a single transducer pair "downstream". The system is perfectly reciprocal, however, so that the input pulse can thus be applied to the single transducer pair, while the output appears across the photoresistor-shunted multi-transducer section. The latter configuration has the advantages that the pulse generator sees a constant load and that there is no danger here of exceeding the breakdown voltage of the photoresistors. This method was used in most experimental investigations of this study.

2. Off-Substrate Array.

While the completely integrated array, i.e., the configuration that has either a piezoelectric material that is also photoconducting, or a photoconducting material deposited on a piezoelectric substrate, is very appealing, this intimate contact is not necessary. The technique will function equally well with the photoconducting elements located in an area physically removed from the piezoelectric materials. This "off-substrate" array technique allows more flexibility, as seen below. It permitted us to test for experimental verification of calculated results without requiring the complete development of photoconductor material and transparent ohmic contact deposition. A schematic for such an "off-substrate" array is given in Figure 3.

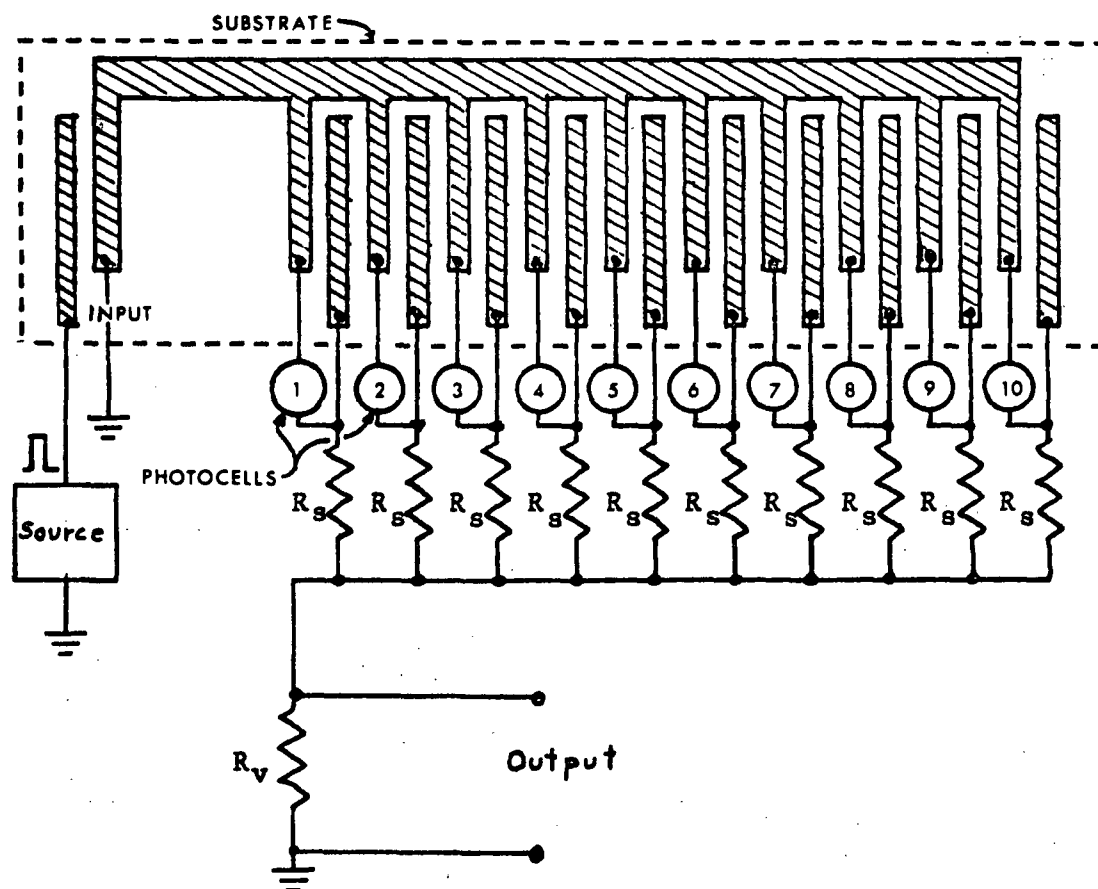


Figure 3

Off-substrate Array. The configuration shown here has a single transducer pair connected to the input; output appears across the photoresistor-shunted multi-transducer section. This circuit, with Clairex Type CL904 photocells, with $R_s = R_v = 10^4$ ohms, and with the transducers on Y-cut alpha quartz and of center frequency 5MHz, was used for experiments described in Section VII.

3. Series Connection.

In K-F, and in Figures 2 and 3, the photoconducting material is in shunt with the transducer elements. The off-substrate array allows also a series connection, where the photoconducting element is in series with the transducer. Now the illuminated element permits maximum voltage to appear across the transducer pair; the element in the dark allows minimum signal. This is seen in Figure 5, which gives the response to spatially varying illumination in an experiment using the prototype series circuit of Figure 4.

4. Two-dimensional Arrays

(a) Acoustic Waveguide. A completely integrated two-dimensional array would be composed of very narrow adjacently placed piezoelectric surface waveguides,⁴ with each waveguide containing the photoconducting material as well as the surface wave transducer element. Each waveguide would be excited in turn, to accomplish line by line scan of a two-dimensional raster. In experiments performed in our laboratory, D. J. Geist was easily able to excite and receive pulsed 10 MHz waves with IDT's deposited on a ridge produced by cutting slots in Y-cut alpha quartz, for a beam width of only 0.375 mm. In these experiments each IDT had 5 pairs. Even when reduced to one pair, signal transmission was possible, although at reduced efficiency. Use of materials of higher coupling factors than quartz, with efficient acoustic waveguiding, could quite possibly yield a two-dimensional sensor array.

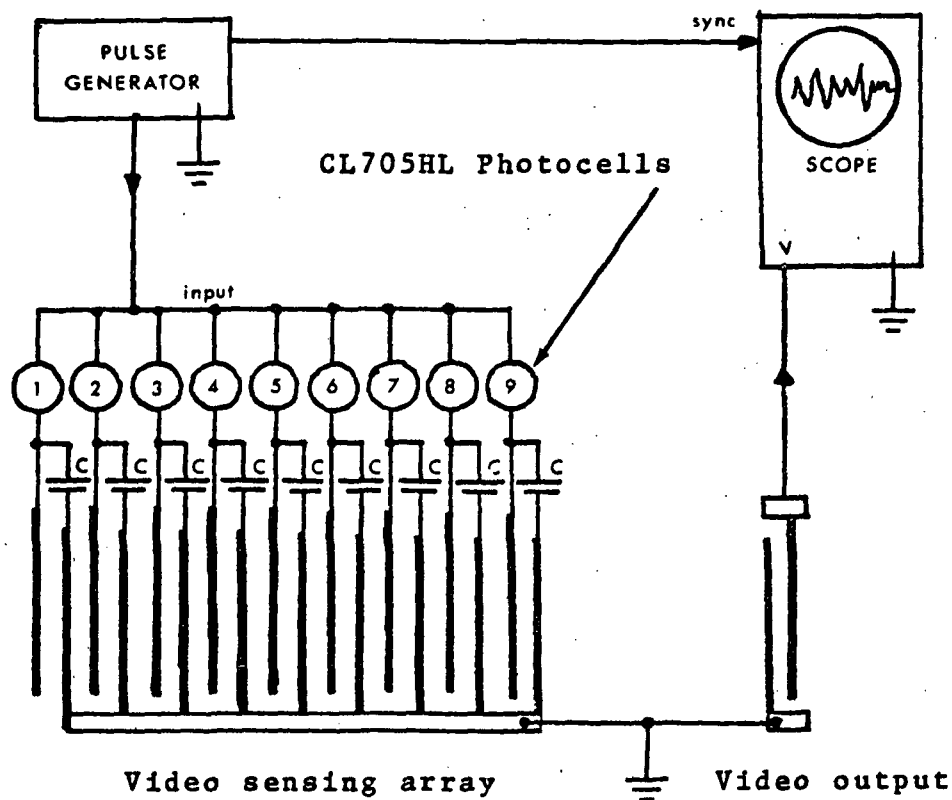
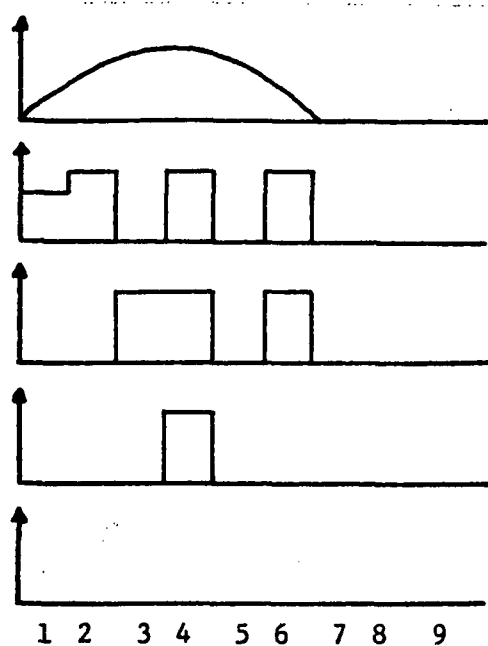
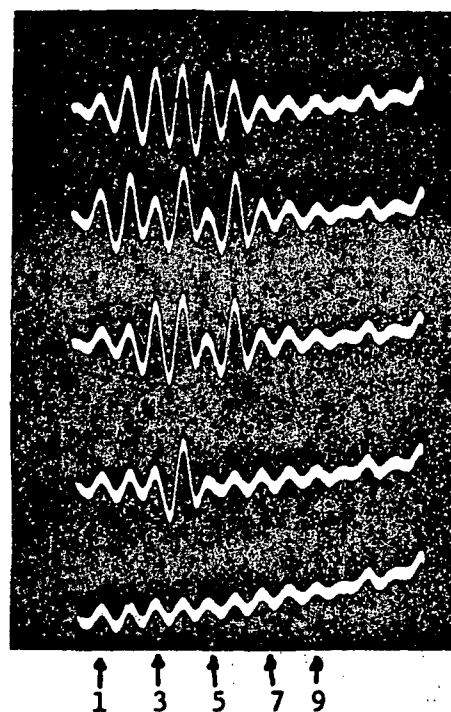


Figure 4

Series connection of photoresistors and transducers. This circuit with 3 MHz transducers on Y-cut alpha quartz, and with Clairex Type CL705HL photocells, was used in an early experiment. The capacitances **C** were added to improve sensitivity. The response is shown in Figure 5.



-a-



-b-

Figure 5

Oscilloscope output traces for varying amounts of illumination on the array of Figure 4.

- a) Light intensity distribution over array of sensors. Peak light level was 300 foot-candles.
- b) Output signal for light intensity distribution of (a). Horizontal scale: 0.4 microseconds/division; vertical scale: 500 microvolts/division. Input pulse here was 60 volts, 0.16 microseconds duration.

(b) X-Y Lines. An alternate technique is the use of a system of X and Y lines, as shown in Figure 6. This configuration is similar to the array of Weimer et al,⁵ except that an acoustic line has been substituted for the fast shift register. The use of a line of IDT's, which are easily and reliably fabricated, could have advantages in cost and reliability over other fast shift registers. The diodes shown in Figure 6 are needed to prevent crosstalk. As in the array of Weimer et al,⁵ such diodes can be fabricated by choice of the proper contact material to the photoconductor.

5. Phototransistors.

The acoustic scanning technique readily lends itself to the use of active elements, such as phototransistors. We have, in fact, performed experiments in which discrete phototransistors were connected to an array of IDT's on a piezoelectric line and scanned by an acoustic pulse.* Because the photocurrent of each transistor was multiplied by that transistor's beta, light levels below 1 foot-candle were easily sensed. One difficulty with this arrangement, however, was that the sensitivities of the various phototransistors were different, so that constant light level intensities produced varying signals from the different elements of the line. This difficulty, however, does not appear insurmountable, since a technique recently proposed in our laboratory could equalize these sensitivities. On the other hand, the scheme does have the drawback of requiring the introduction of semiconductors--even for a one-dimensional array.

* See Section VII

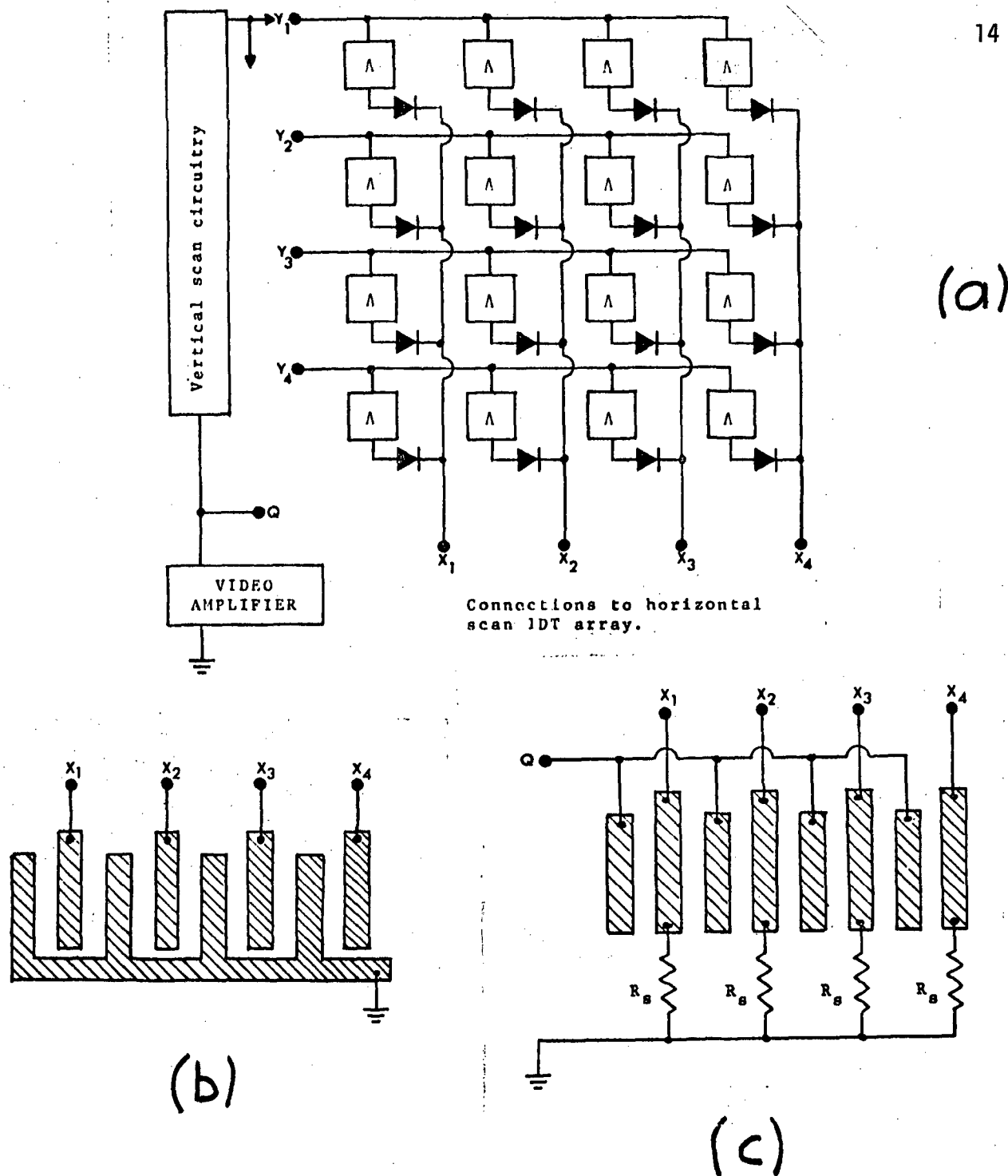


Figure 6

Two-dimensional sensor array using X-Y lines.
 The function of the box labeled "Vertical Scan Circuitry" is to connect point Y_i to point Q.
 Input IDT not shown.

- a) General two-dimensional array, with diodes to minimize cross-talk.
- b) Array IDT connections for series sensor element circuit operation.
- c) Array IDT connections for shunt sensor element operation.

IV. GENERAL DESIGN CONSIDERATIONS

Because of the many interactions among the various elements of a sensing array, a computer-based analysis was developed, to predict the behavior of proposed designs. This section deals with the components of the system and some general design considerations.

The system chosen for the analysis was the off-substrate photoconducting array, because of its greater flexibility. Only one-dimensional arrays were examined because: (1) There are applications for such single-line scanners; (2) the one-dimensional array is a building block of the two-dimensional system. It was felt that if feasibility of design for this single-line system could be demonstrated, the two-dimensional system could also readily be constructed.

The configuration examined was that of Figure 3, in which a single-pair IDT is the input transducer; output is the mixed signal from an IDT line. Initially, both series and shunt-connected photoconductors were considered. After a number of computer runs it was found, however, that the series connection did not appear to be useful for a many-element line. Our attention was therefore focused on the shunt-connected array of Figure 3.

1. Acoustic Line.

The design of the acoustic surface wave line is dependent upon the number N_v of optical sensors to be scanned, the piezoelectric material used for the substrate, and the linear density of the IDT output pairs. The parameters are similar to those for a sonic delay line with N_v output taps, with one important exception: Unlike normal

delay line design, a degree of mismatch is desired between each output tap and its associated load. This is a necessary criterion, for if the number of IDT's first excited or "scanned" by the acoustic pulse were to absorb most of the acoustic energy, there would be insufficient excitation for the last IDT in the array. An acceptable design rule is that the acoustic pulse amplitude should not be attenuated more than $(6/N_v)$ db by any single output IDT.

It will be possible to compensate for such a small gradual decrease in acoustic pulse amplitude by slight tapering of the length of the IDT fingers, or by the introduction of some resistance in the interconnection.

Care must also be exercised in selecting parameters so that the acoustic power that is reflected from an IDT as an acoustic pulse encounters it will be negligible. Otherwise, spurious responses will occur from reflected interactions among the IDT's. We have considered an arrangement as acceptable if the portion of the acoustic pulse reflected from any IDT is at least 30 db below the incident acoustic power.

For the array in which photoconducting material is deposited directly over the piezoelectric line the resonant frequency of each IDT is determined directly by spatial density of the sensitive element. Thus, for example, for a linear array density of 50 elements per centimeter, and a piezoelectric substrate of Y-cut alpha quartz, the IDT resonant frequency would be 15.77 MHz for propagation in the x-direction. Other piezoelectric material, with different acoustic wave velocities, would determine different frequencies.

The dimensions of an off-substrate array are, of course, not tied to the IDT frequency quite so rigorously. Based on spacing considerations, however, they do determine that frequency within at least a factor of five.

2. Optical Sensors

In Section II it was shown that when used in the input circuit, the resistance of R' of the photo-resistive element shunting an IDT should vary from a "dark" resistance much higher than the IDT reactance to an "in light" resistance much lower than this reactance. The same consideration holds when the photosensors are used in the output end of the acoustic line. The actual curve is shown in Figure 7. Here, V_{TAP} and Z_{TAP} are the Thevenin-equivalent parameters for an IDT receiving a stress-strain excitation arriving from one direction of its piezoelectric line. Because of the requirement of low power transfer from an IDT to its load circuit, Z_{TAP} turns out to be principally the reactance of the IDT capacitance and associated connecting lines. While a range of R_λ/Z_{TAP} from 0.1 to 10 is seen to result in the maximum range of V_{VIDEO} , considerably more liberty is allowed for useful output. The range of photoresistance values actually available from a photoconductive cell is a function of its geometry, the photosensitive material, the available light excitation, and the spatial density of the video elements.

3. Video Circuitry

Each sensor circuit comprised of an output IDT and its respective optical sensor and other circuit elements is to be connected in parallel

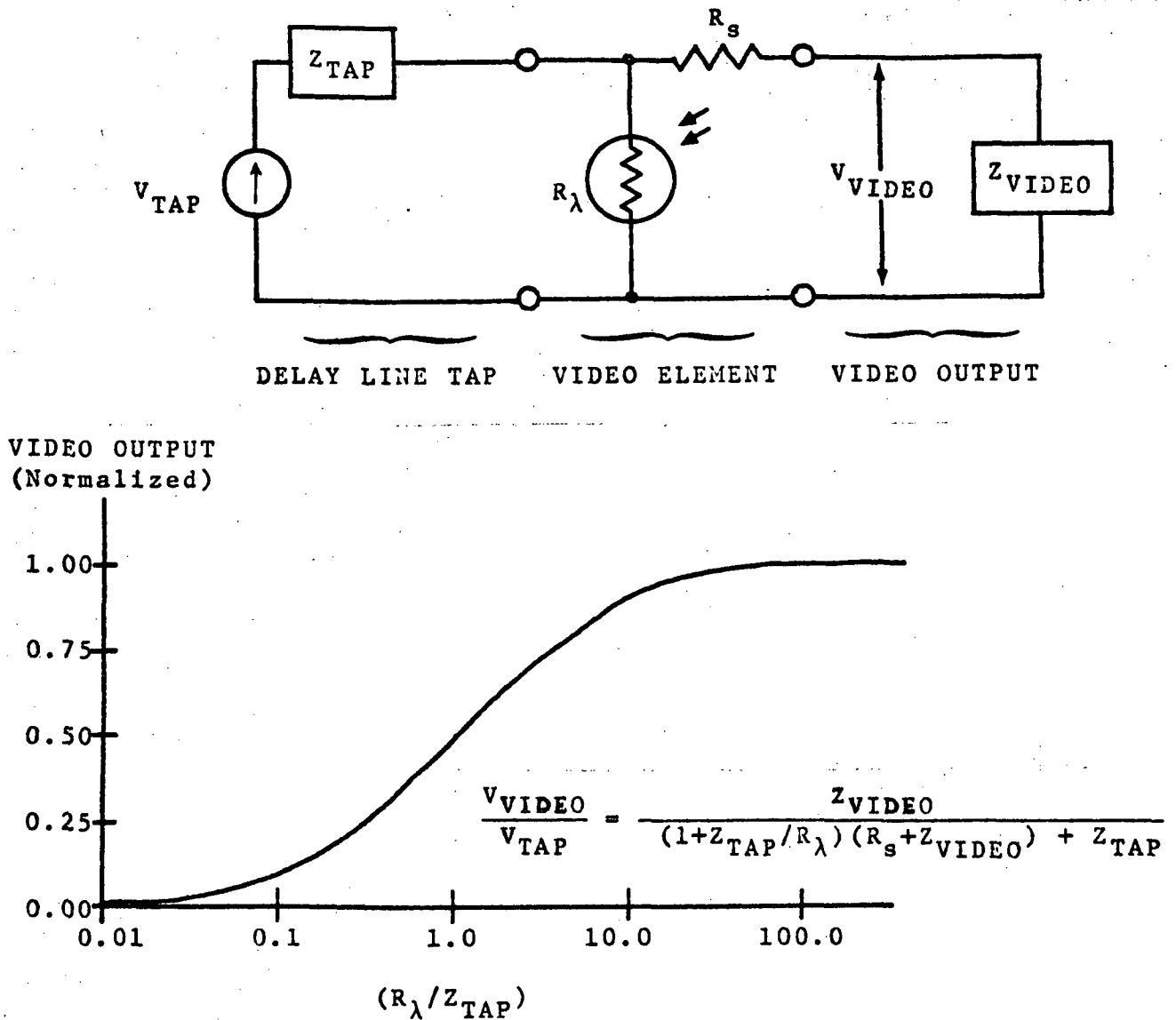


Figure 7

Simple circuit model for IDT-photoresistive sensor combination, with associated output characteristic curve. V_{TAP} and Z_{TAP} are the Thevenin-equivalent voltage source and source impedance associated with the IDT acoustic "tap." R_λ is the resistance of the light-sensitive element; R_s is the element that isolates each IDT-sensor combination, therefore allowing connection to a common output load Z_{VIDEO} . This common load is the parallel combination of a load resistor and a parasitic (cable, etc.) capacitance. To obtain this response curve, single frequency operation was assumed.

with the other sensor circuits to the video signal bus. An important consideration here is the effect of loading on one IDT-sensor circuit by the other sensor elements at a given instant. Ideally, the output of a given IDT-sensor combination (IDTSC) should be independent of the states of the other elements. In practice, this is not completely possible. Loading variations^{*} can be minimized by increasing the value of the series isolation resistor (R_s) for each sensor element and decreasing the common load impedance. (See Figure 3.) However, the output signal amplitude is also decreased by this approach; thus, a design compromise is required between the need for minimum loading effects and the need for sufficient signal levels.

4. Optical Excitation

As already stated in Section II, the available range of light excitation is a function of the imaging lens. The optical attenuation A_λ due to a focusing lens is given by³

$$A_\lambda = \{T\pi\cos^4\theta\} \cdot \{4F^2(1+m)^2\}^{-1}, \quad (1)$$

where T is a transmission factor for the lens material, θ is the angle from the optic axis, F is the f number for the lens diaphragm opening, and m is the image magnification. Normally, $m \gg 1$ and can be neglected.

Thus, for an $f/4$ lens, with a transmission factor of 95%, and an object illuminance of 250 foot-lamberts, the image illumination at the array on the optic axis would be 11.5 foot-candles.

^{*} Also called "crosstalk"

V. SCANNING SYSTEM ANALYSIS

This section discusses the procedure used to predict the detailed behavior of an acoustic wave optical scanner, some results, and a method of system optimization.

The operation of the array sensor is based on the use of short pulses. A rigorous analysis of the system is therefore a pulse analysis in which the frequency-dependent transfer function of each block of Figure 8 is taken into account. However, since the single pair transducer and the other components used here are broadband, it was acceptable to perform a single frequency analysis.*

To analyze the scanning system, we considered the behavior of a single video element excited by the acoustic scan pulse and then applied superposition to find the response of the entire array. A block diagram of the various components that enter into the discussion of the self-scanned sensor array, reduced to the operation of one sensing element, is given in Figure 8. The analysis of the system consisted of devising an equivalent circuit model for each block, obtaining the admittance parameters, transforming these into a set of scattering coefficients, then finding the system response by combining the various scattering coefficients into one and computing the response to an input signal.

1. Admittance Matrices

(a) IDT Admittance. The methods developed by Smith et al^{6,7} were used to find the admittance parameters of the interdigital transducer section. As developed there, there are at least two different

* A brief discussion of the relation of output to input waveform is given in Appendix A.

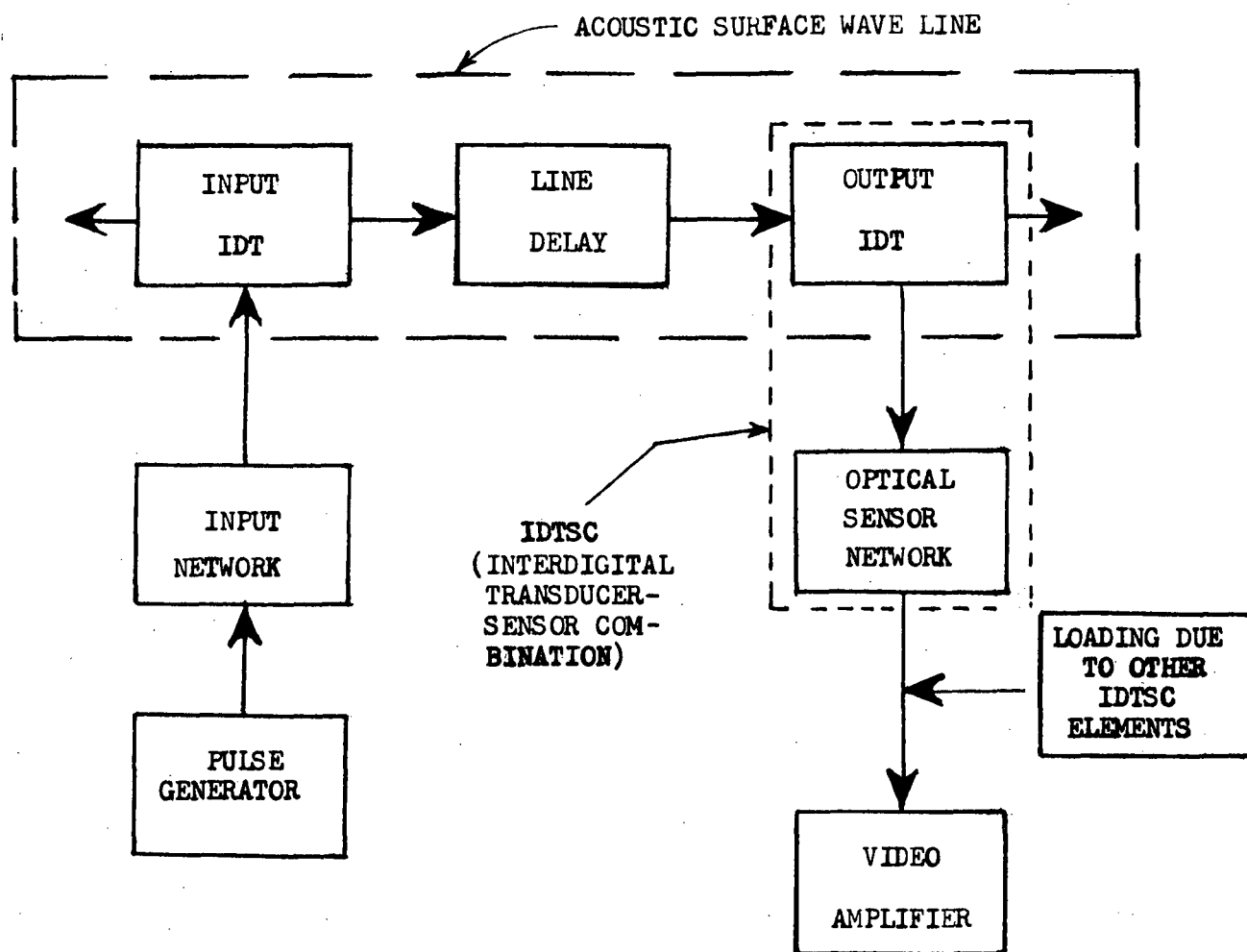


Figure 8

Block diagram of scanning system for one interdigital transducer-sensor combination (IDTSC).

equivalent circuits that can be used to represent acoustic surface wave transducers. The choice of which of the two models to use becomes critical only when the number of pairs of transducer elements is considerably larger than one. Since in our configuration each transducer is only a single pair, the choice of models is then arbitrary. Consequently, we chose to use the 3-port admittance matrix that characterizes the in-line, or series resonance model, since it has no infinities at resonance (where the center-to-center spacing of adjacent conductors is half of an acoustic wavelength.) This admittance matrix is

$$[Y] = (j\omega_0 C_S / 16) \cdot \begin{bmatrix} -1/N & 1/N & 4 \\ 1/N & -1/N & -4 \\ 4 & -4 & 0 \end{bmatrix} \quad (2)$$

Here, ω_0 = the resonant angular frequency,

C_S = the transducer capacitance.

N = number of transducer pairs--taken here to be one.

In this matrix, and as shown in Figure 9, port 3 is the electrical port, while ports 1 and 2 are the acoustic ports, with all units couched in electrical terms. This procedure, as indicated by Smith et al,⁶ follows that of Berlincourt.⁸ The electrical unit equivalent for the acoustic terminal force F_i and particle velocity U_i in this equivalent network is given by $E_i = F_i/\Phi$ and $I_i = U_i/\Phi$, with Φ as the "turns ratio of an acoustic-to-electric circuit transformer." The quantity R_0 , the electrical circuit equivalent

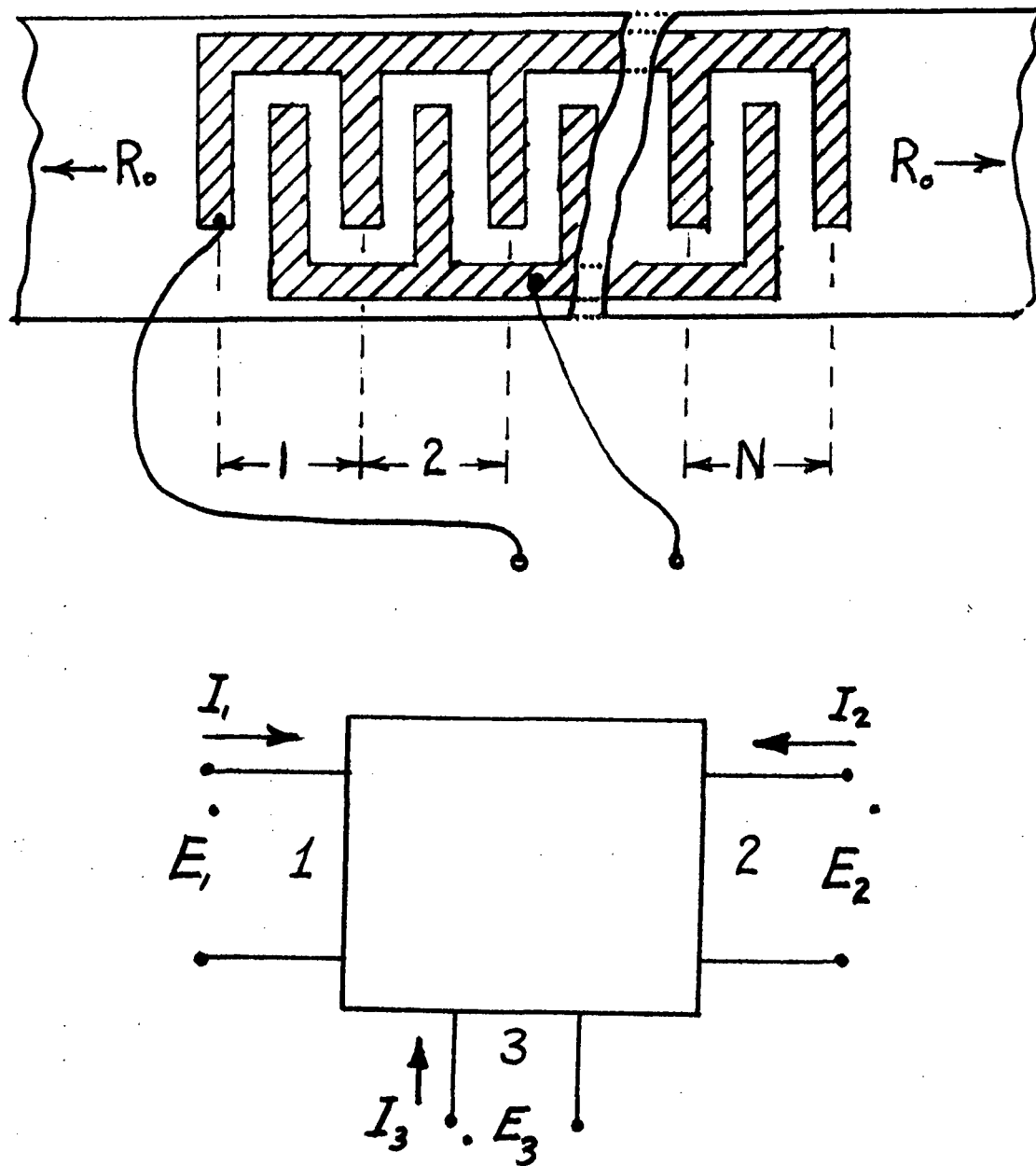


Figure 9.

Figures used for obtaining admittance matrix for IDT.

Top: IDT on piezoelectric substrate.

Bottom: Three-port system for this IDT.

characteristic impedance of the acoustic surface wave line, is related to the mechanical impedance Z_0 by $R_0 = Z_0/\phi^2 = 2\pi/\omega_0 C_s k^2$, where k is the effective electromechanical coupling constant.

b. Optical Sensor Network. The shunt optical sensor circuit, as it pertains to one element, is shown in Figure 10. This circuit includes the loading elements C_V and Y_L . Of these, C_V is just the shunt capacity portion of the input impedance of the video amplifier that connects to the sensing bus. (The shunt resistance was considered as a load.) The component Y_L , on the other hand, is the element that determines the crosstalk, i.e., the changes in output of a particular sensing circuit that are due to the changing conditions of the other sensors, since the other sensor circuits are all in parallel with a representative one shown in Figure 10. For an array of N_V sensors, if each sensor circuit had equal output impedance Z_{out} , then Y_L would be $(N_V - 1)/Z_{out}$. One aspect of our calculations was to determine the change in output voltage as Z_{out} was allowed to vary from minimum to maximum values.

Since the admittance matrix for Figure 10 is straightforward, we shall not dwell on it here.

c. Input Network. The input network represents the input cable shunt capacitance (C_I) and the series lead inductance. The admittance parameters were obtained in the conventional manner.

d. Video Amplifier. The input impedance of the video amplifier was considered to be a parallel RC combination. Since a

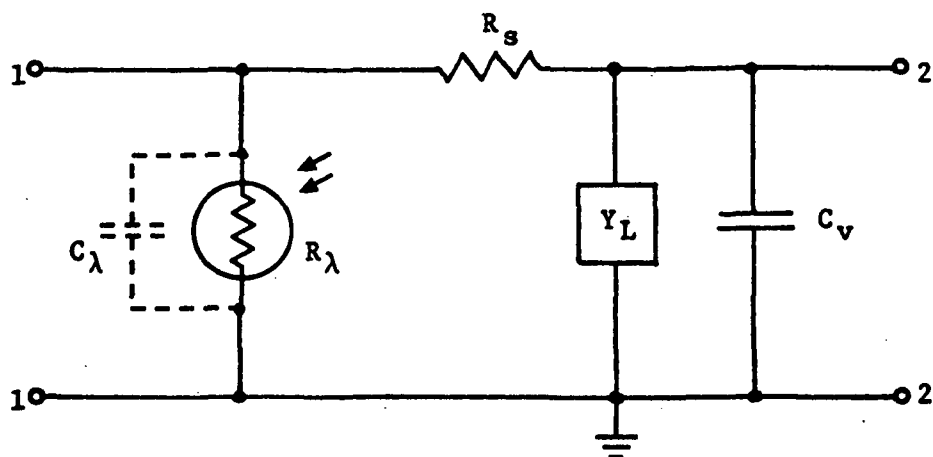


Figure 10

Optical sensor circuit for sensor-in-shunt connection. Terminals 1-1 connect to the IDT. C_λ and R_λ are the shunt capacitance and resistance associated with the sensor element. R_s is the series isolating resistor.

scattering matrix analysis was performed, it was found convenient to keep the reference impedances real. The video amplifier capacitance C_v was therefore included as part of the optical sensor network of Figure 10. The shunt R-component of the video amplifier was then considered as the load of the entire array.

2. Scattering Matrix Analysis.

If the admittance parameters are available for a network, then the normalized scattering matrix for the network can be obtained.⁽⁹⁾

The resulting matrix equation is

$$\begin{aligned} S &= [\sqrt{g}] \left([Y] + [y] \right)^{-1} \left([Y]^* - [Y] \right) [\sqrt{g}] \\ &= -[1] + 2[\sqrt{g}] \left([Y] + [y] \right)^{-1} [\sqrt{g}] \end{aligned} \quad (3)$$

where $[1]$ is the unit matrix, $[\sqrt{g}]$ is the square root of the real part of the reference admittance matrix, $[y]$ is the reference admittance matrix for the ports, and $[Y]$ is the admittance matrix for the network. Details of the use of this method for an IDT are given in Appendix B. The result for the series resonant IDT network is:

$$[ST] = \begin{bmatrix} ST_{11} & ST_{12} & ST_{13} \\ ST_{12} & ST_{11} & -ST_{13} \\ ST_{13} & -ST_{13} & ST_{33} \end{bmatrix} \quad (4)$$

where, with $T = \omega_0 C_s / 8 G_0$, and with $G_0 = 1/R_0$, for a one-pair IDT we have

$$ST_{11} = \{1 - j(T/N) + 8T^2\}^{-1};$$

$$ST_{12} = ST_{11} \cdot \{8T^2 - j(T/N)\};$$

$$ST_{13} = ST_{11} \cdot -(j4T);$$

$$ST_{33} = ST_{11} \cdot \{1 - j(T/N) - 8T^2\}.$$

The scattering matrix for the delay section between input and output IDT is:

$$[SD] = \begin{bmatrix} 0 & \exp(-\beta_g L) \\ \exp(-\beta_g L) & 0 \end{bmatrix}, \quad (5)$$

where L is the physical spacing between the input and output IDT's and β_g is the ratio ω_0 / v_s , with v_s the velocity of the acoustic wave.

Similar scattering matrices were found for the remaining components. To permit the mathematical manipulations associated with interconnections of the component matrices, the reference impedances for all three ports of the IDT's, as well as for the port of the electrical circuits connected to these IDT's, were chosen as R_0 .

With individual scattering matrices found, the components could now be joined mathematically into subsystem matrices and, by

additional combinations, into one matrix for the entire system. These subsystem matrices then provide information of the fraction of available power converted by the input transducer to acoustic power and the fractions of the acoustic power in the delay line reflected by and converted to electrical power at the output, in the manner illustrated in Appendix B. The method of joining individual scattering matrices is illustrated by the block diagram of Figure 11. The "voltage gain" of the system is then found from this final 4-port matrix by

$$V_o/V_i = \left[S_{43} \cdot S_{43}^* \cdot R_V/Z_i \right], \text{ for} \quad (6)$$

Z_i real.

Here V_o = output voltage;

V_i = input voltage;

S_{43}, S_{43}^* = element 4-3 of the scattering matrix and its complex conjugate, respectively;

R_V = reference impedance of output, chosen as video amplifier shunt-equivalent input resistance;

Z_i = reference impedance of input.

In addition to voltage gain and power absorbed and reflected by an IDT-sensor circuit, an important design consideration is the effect on the output of one sensor element exercised by the condition of the other sensor elements. This loading varies with the amount of illumination present on the other sensor elements. Thus, the

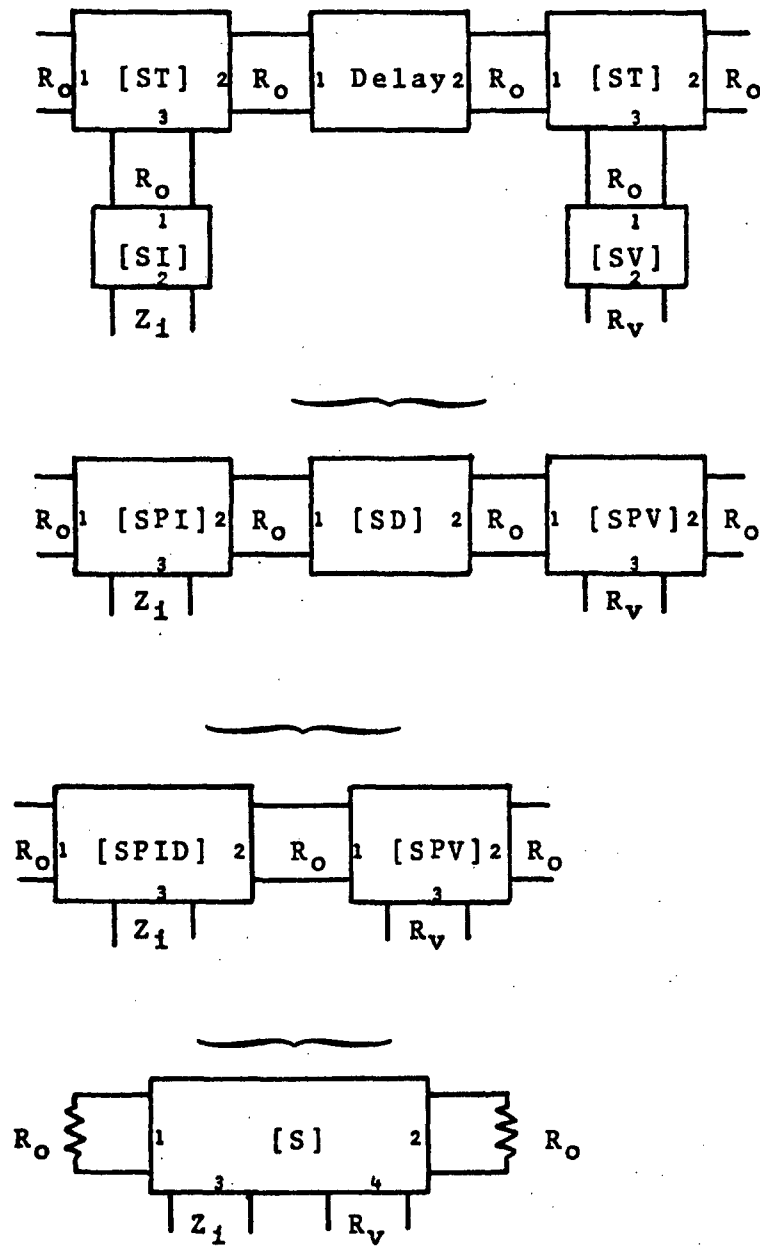


Figure 11

Outline of the derivation of the complete scattering matrix for the scanning device.

output of one element may be greatly dependent upon the light excitation prevailing over the rest of the array. This loading can be calculated by assuming an average illumination level over the array and determining the output impedance of one video element circuit for that light level, then dividing this impedance by the number of elements in the array minus one:

$$Y_L = (N_v - 1)/Z_{out} , \quad (7)$$

where the output impedance Z_{out} of the IDTSC's can be found by

$$Z_{out} = R_v \cdot (1 - SPV_{33}) \cdot (1 + SPV_{33})^{-1} \quad (8)$$

Here SPV_{33} is the 3-3 matrix element of the SPV scattering matrix, as in Figure 11. Although this expression is valid only when the other ports of [SPV] are terminated in their respective reference impedances, it is a valid assumption if the reflection loss is greater than 20 db and the acoustic line is terminated by absorbing material--the condition existing here.

Ideally, the output of one sensor element should be independent of the light condition prevailing over the others. This can be easily obtained by making $R_v \ll Z_{out}/(N_v - 1)$. Doing so, however, also reduces the voltage gain, so that a compromise is necessary between minimum loading variations due to average light fluctuations and the need for a reasonable output level.

To study these variations in output voltage for an IDT sensor combination because of fluctuation in average illumination on other

sensors, three curves of output parameters were calculated for each set of parameters. These were for :

- (1) The resistance of each of the other sensor elements has a value ten times that of the sensor element of our IDT-sensor test combination.
- (2) All sensor elements have the same resistance as the sensor of the test combination.
- (3) All sensor elements have a resistance 1/10th that of the resistance of the sensor of the test combination.

These three conditions correspond to the sensor of the "test IDTSC" being a brightly illuminated point surrounded by other points in the dark, an element surrounded by others equally illuminated, and a dark point on a bright background, respectively.

A typical computer printout that reveals the desired output parameters is given in Figure 12. In this computer output, the output parameters are printed out for a particular structure as the sensor resistance is allowed to vary from 10 ohms to 10^6 ohms. The points labelled as "T" show the fraction of power loss by an acoustic wave as it passes by the IDTSC-output combination. R is the fraction of acoustic power reflected; points D, A, and L are the point of voltage gain, with D, A and L corresponding to the test-combination sensor surrounded by dark, average, and strong illumination, respectively.

3. Optimization

In view of the many design variable combinations possible, and the amount of time required to calculate and plot the video response for each combination, computer optimization methods were applied to

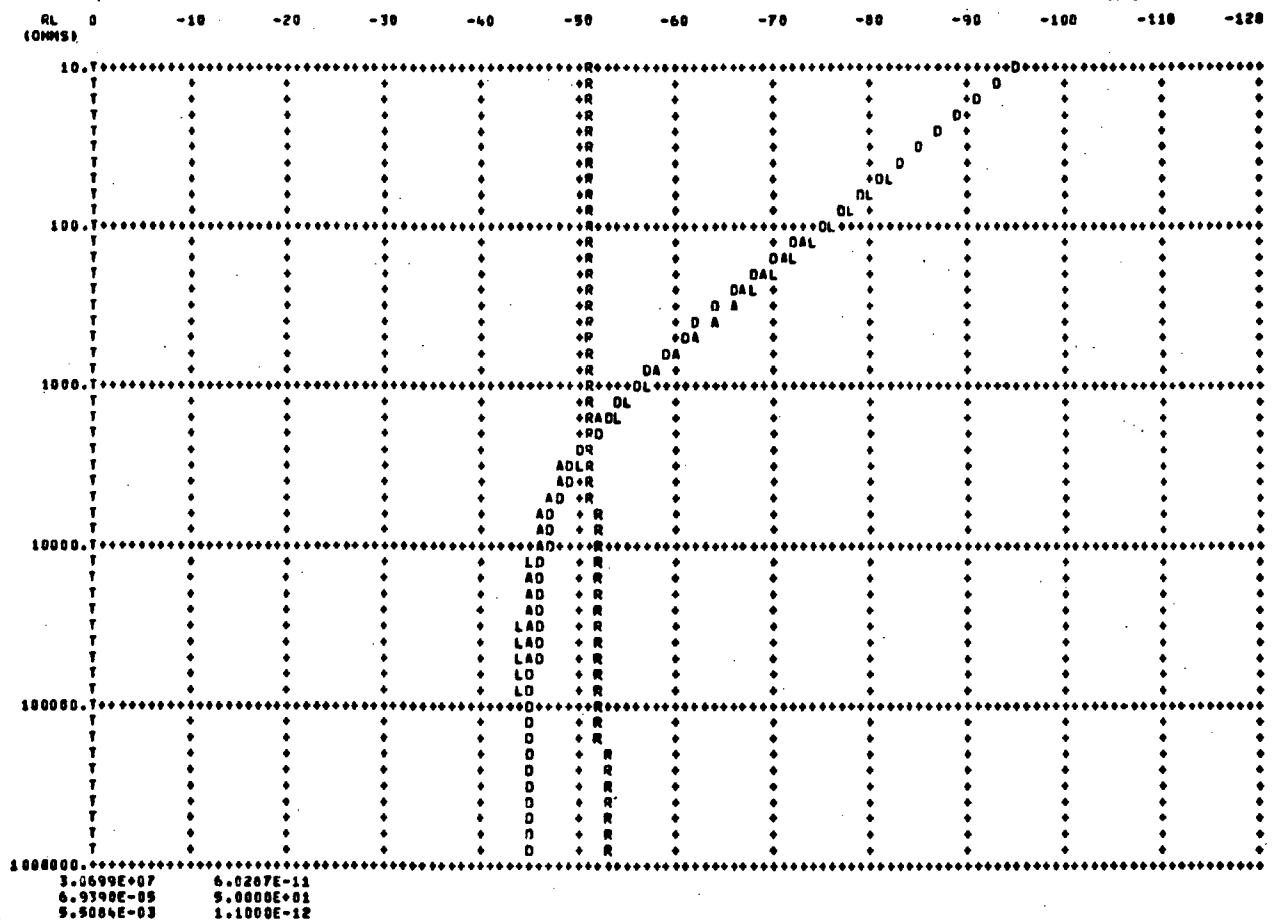


Figure 12

Reflection loss (R) in DB and transmission loss (T) in 100ths of a DB for the acoustic wave incident on a video element voltage gain for a video element (in DB) when the rest of the video elements are in relative darkness (D), have the same illumination (A), or are in a bright field (L).

scanning system design. The method that was used was a variation of the pattern search technique as outlined by Hooke and Jeeves¹⁰.

To use any optimization technique, the desired characteristics must be defined by a mathematical function that has a maximum, minimum or specified value for the optimum condition desired. A suitable figure of merit function for our case, defined with the aid of Figure 13, is

$$M = \left[V_o(R_{\lambda\max}) - V_o(R_{\lambda\min}) \right] - \sum_{i=1}^I \left| V_o(i, 10R_{\lambda}) - V_o(i, R_{\lambda}/10) \right| \quad (9)$$

Here M is our figure of merit. The range of photoresistances possible for light conditions corresponding to the desired range of operation

has been divided into I equal intervals. $V_o(R_{\lambda\max})$ is the output voltage from the IDTSC when the resistance of the test sensor as well

as that of each of that of all the other sensors is the maximum value;

$V_o(R_{\lambda\min})$ is the output voltage when the resistance of the test sensor as well as that of each of the other sensors is the minimum value.

Maximum value of the quantity $[V_o(R_{\lambda\max}) - V_o(R_{\lambda\min})]$ therefore maximizes the overall signal amplitude. The quantities $V_o(i, 10R_{\lambda})$ and $V_o(i, R_{\lambda}/10)$

are the output voltages from the test IDTSC when that sensor has a

resistance given by $R = R_{\lambda\min} + i [R_{\lambda\max} - R_{\lambda\min}] / I$ while each of the other sensors has resistance $10R_{\lambda}$ and $R_{\lambda}/10$, respectively. Minimization

of this set of terms therefore minimizes crosstalk. The type of

information provided by the computer is illustrated in Table 1.

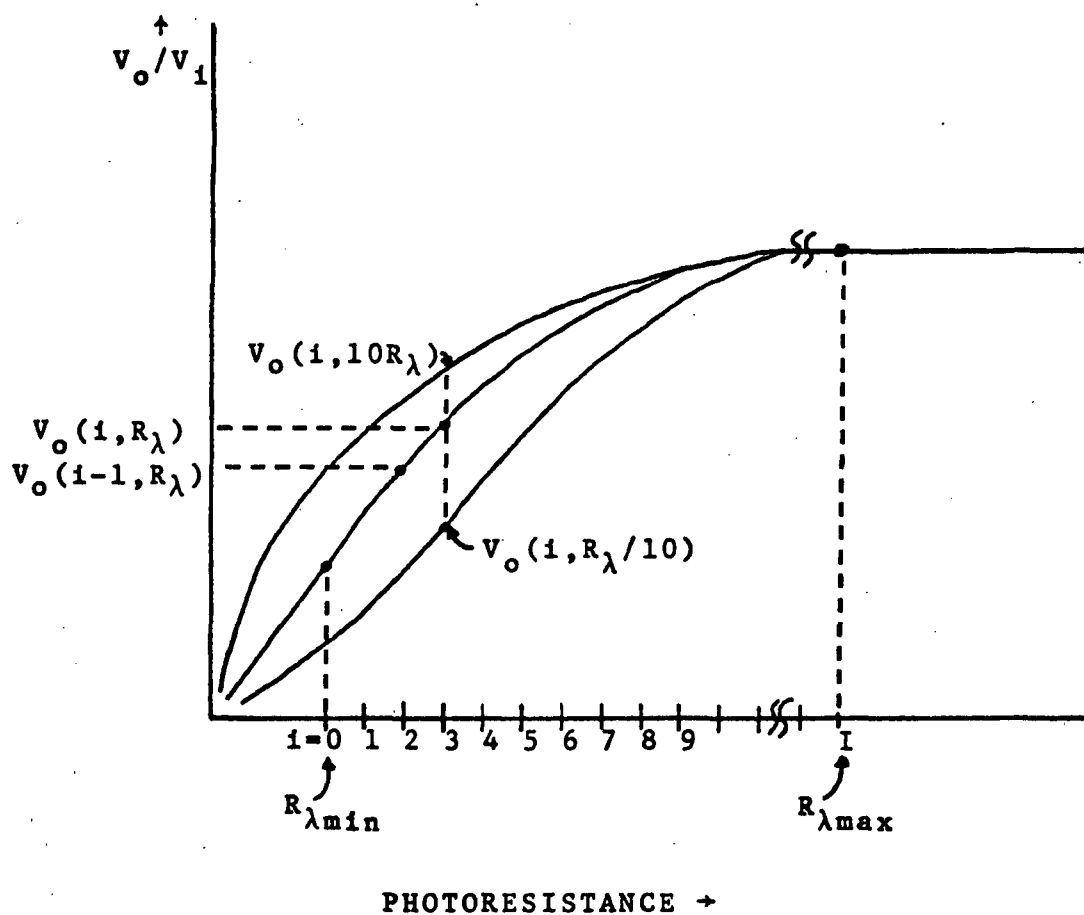


Figure 13

Illustration of terms used in the merit function. The three curves shown are typical responses for a given IDTSC for the three array conditions described in the text. $R_{\lambda \min}$ and $R_{\lambda \max}$ are selected for the range of photoresistance variation available for the light excitation involved.

Table 1

Typical computer printout for optimization program

Response characteristics of an optical sensing array using acoustic surface waves for scanning. Series resonant models are used for the surface wave transducers and photoconductors for the optical sensors.

Mode is array excited by an acoustic pulse, with the photoconductor in a shunt video circuit.

Device parameters are as follows:

ARRAY PARAMETERS

NUMBER OF VIDEO ELEMENTS IS 40.

SEPARATION BETWEEN INPUT AND OUTPUT STAGES IS .0055 METERS

WIDTH OF THE TRANSDUCERS IS .0100 METERS

SINGLE IDT HAS 1. PAIRS AND VIDEO IDT HAS 1. PAIRS PER
VIDEO ELEMENT

RESONANT FREQUENCY IS 30699000. HZ

ACOUSTIC IMPEDANCE IS 38162885. OHMS

LENGTH OF ARRAY IS .0400 METERS

PIEZOELECTRIC SUBSTRATE IS Y-CUT ALPHA QUARTZ.

SINGLE IDT NETWORK

REFERENCE IMPEDANCE IS 50. OHMS

SERIES INDUCTANCE IS 6.939E-05 HENRIES

SHUNT CAPACITANCE IS 6.029E-11 FARADS

VIDEO IDT NETWORK

REFERENCE IMPEDANCE IS 1000000. OHMS

LOAD CAPACITANCE IS 5.000E-12 FARADS

PHOTOCONDUCTOR SHUNT CAPACITANCE IS 1.100E-12 FARADS

PARASITIC CAPACITANCE IS 1.000E-14 FARADS

SERIES ISOLATION RESISTANCE IS 7113. OHMS

ARRAY FIGURE OF MERIT IS 1.2603E-01

VI. DESIGN OF INTEGRATED ARRAY

The design technique outlined above can now be used to examine the feasibility of integrated arrays, including the consideration of optimum piezoelectric material, resistivity and resistivity change with light of the photoconducting material, and the most suitable geometric configuration for photoconducting elements. We have performed analyses applicable to three such arrays consisting respectively of the number of elements per line N_v of 125, 250 and 500--all designed to fit into a 5 cm length. Although our calculations refer to a one-dimensional off-substrate array, we chose photoconducting elements to be of square shape, so that 125, 250 and 500 lines, respectively, could be combined into square two-dimensional arrays.

1. Design Considerations

(a) Photoconducting sensor element structure. Since there are N_v elements per line, the width d of each complete element, including contact lines, was chosen to be $(5/N_v)$ cm. Three configurations were considered, as shown in Figure 14. The values of resistance R_λ and capacitance C_λ that form the parallel equivalent circuit for such photosensor elements were calculated according to the expression of Table 2. Here the formula for resistance is straightforward; that for capacitance uses the approximation substantiated by Farnell et al,¹¹ takes into account the contribution of the substrate in the manner following Tseng,¹² and adds capacitance due to the insulator, where applicable. Numerical values of R_λ for the three arrays, for thicknesses of photoconducting layers of 1 and 10 microns and for a thickness t_i of the insulating material (here

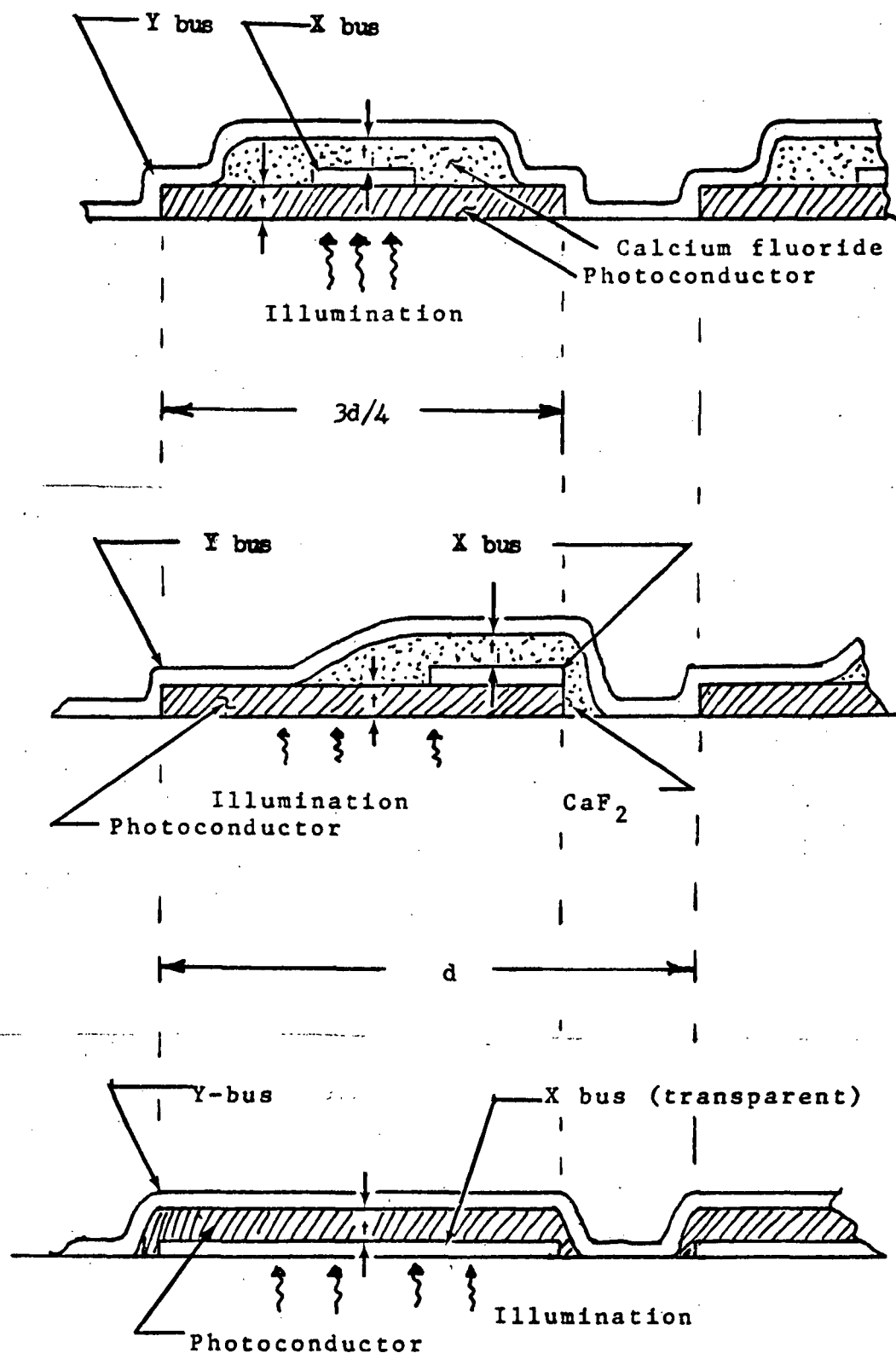


Figure 14

Sensor element geometries (cross-sectional views). Top: Geometry described by Weimer et al⁵. Center: Modified Weimer model. Bottom: Parallel plate model. In each case, the length of sensor and contacts is $3d/4$.

Table 2

Shunt resistance and capacitance for the three sensor structures of Figure 14. Values for dielectric constants used here are $\epsilon_\lambda = 9.53$, $\epsilon_s = 4.5$, $\epsilon_i = 7.36$.

Weimer model:

$$R_\lambda = (1/2) \cdot (3d/16) / (\sigma t \cdot 3d/4) = 1/8\sigma t$$

$$C_\lambda = C_{\text{substrate}} + C_{\text{photoconductor}} + C_{\text{insulator}} \\ = d\epsilon_0 \{ (0.2934\epsilon_s) + (4\epsilon_\lambda t/d) + (0.1406\epsilon_i d/t_i) \}$$

Modified Weimer model:

$$R_\lambda = (d/4) / (\sigma t \cdot 3d/4) = 1/3\sigma t$$

$$C_\lambda = C_{\text{substrate}} + C_{\text{photoconductor}} + C_{\text{insulator}} \\ = d\epsilon_0 \{ (0.2934\epsilon_s) + (3\epsilon_\lambda t/d) + (0.1875\epsilon_i d/t_i) \}$$

Parallel plate model:

$$R_\lambda = t / \{ \sigma (3d/4)^2 \} = 16t / 9\sigma d^2$$

$$C_\lambda = \epsilon_0 \epsilon_\lambda \cdot (3d/4)^2 / t = 9\epsilon_0 \epsilon_\lambda d^2 / 16t$$

taken to be calcium fluoride of 2 microns), and for a mid-range resistivity of the photoconducting material of 10^4 ohm centimeters* are given in Table 3. In view of the fact that operation of the sensor device requires the shunt resistance to be of the same order of magnitude, or lower than the shunt reactance, it is clear that the parallel plate model is the only configuration that is useful here. Since the capacitance of this configuration can easily be larger than that of the IDT, it is the ratio of shunt reactance to resistance of the sensor that now determines the output response to varying amounts of illumination. Therefore, all designs hereafter will be assumed to be using sensor elements of this type of construction.

(b) Sensor Element Material Parameters. As indicated in Section II, it is not only necessary for the sensor to be of sufficiently low resistance, it must also reach this resistance for light levels of practical interest. To establish design criteria, we therefore turn again to Fink⁽¹³⁾, who states that the luminance of the earth in daylight can vary from 10 foot-lamberts (very dull day) to 5000 foot-lamberts (sunny day on snow). When focused through an f/2.8 lens, by Eq. (1) this becomes an image intensity of from 1 to 500 foot-candles.

An equally important consideration for the imaging of moving objects is the requirement that a material be used that can respond rapidly to changes of light.

* This is an easily obtained value for cadmium sulfide--probably the most popular photoconducting material.

Table 3. COMPARISON OF RESISTANCE AND CAPACITANCE VALUES OBTAINED FOR THE VARIOUS VIDEO ELEMENT GEOMETRIES.

	t = 1 micron			t = 10 microns		
	$R_{\lambda}(\Omega)$	$C_{\lambda}(\text{pF})$	$X_{\lambda}(\Omega)$	$R_{\lambda}(\Omega)$	$C_{\lambda}(\text{pF})$	$X_{\lambda}(\Omega)$
<u>Weimer Model</u>						
125x125 array: d = 0.4 mm.	10^8	0.736	$2.2 \cdot 10^4$	10^7	0.749	$2.1 \cdot 10^4$
250x250 array: d = 0.2 mm.	10^8	0.187	$8.5 \cdot 10^4$	10^7	0.199	$8.0 \cdot 10^4$
500x500 array: d = 0.1 mm.	10^8	0.048	$3.3 \cdot 10^5$	10^7	0.060	$2.6 \cdot 10^5$
<u>Modified Weimer Model</u>						
125x125 array: d = 0.4 mm.	$2.6 \cdot 10^8$	0.981	$1.6 \cdot 10^4$	$2.6 \cdot 10^7$	0.991	$1.6 \cdot 10^4$
250x250 array: d = 0.2 mm.	$2.6 \cdot 10^8$	0.248	$6.4 \cdot 10^4$	$2.6 \cdot 10^7$	0.257	$6.2 \cdot 10^4$
500x500 array: d = 0.1 mm.	$2.6 \cdot 10^8$	0.063	$2.5 \cdot 10^5$	$2.6 \cdot 10^7$	0.073	$2.2 \cdot 10^5$
<u>Parallel Plate Model</u>						
125x125 array: d = 0.4 mm.	1110	7.59	2100	11,110	0.759	21,000
250x250 array: d = 0.2 mm.	4440	1.90	8380	44,440	0.190	83,000
500x500 array: d = 0.1 mm.	17,800	0.47	33,900	178,000	0.047	339,000

The above values are for a photoconductivity of 10^{-4} mhos per centimeter, an insulating layer of calcium fluoride that is 2 microns thick, and cadmium sulfide for the photoconducting material.

Accordingly, a good set of criteria for the choice of photoconducting material is (1) photoresistivity range greater than 10 to 1, centered around 1000 ohm-centimeter resistivity, for light intensity striking the sensor of from 1 to 50 foot-candles; (2) response time less than 30 milliseconds, to conform with the standard TV frame rate.

To determine if such materials are available, an extensive literature search was undertaken. The results, listed in Table 4, are seen to be very encouraging.

(c) Contacts to photoconducting material. The parallel plate model for the sensor element requires a transparent conductor for one of the contacts. Promising materials here are thin metallic films of such materials as indium or gold, or reactively sputtered films of indium oxide/tin oxide. Recent reports of $\text{In}_2\text{O}_3/\text{SnO}$ deposition, for example, describe a film 1500 Å thick, with optical transmission of 90% and a surface resistivity of 200 ohm-centimeters.¹⁴ Another conducting film of 75% transparency, and a resistivity of 14 ohms per square, has also been reported.¹⁵ These films, together with metallic films for interconnections, should be satisfactory for the sensing array.

As indicated in Section III, a two-dimensional array will require special techniques, i.e., diodes, for preventing line-to-line crosstalk. These can be blocking Schottky barrier diodes, incorporated in the manner used by Weimer et al.⁵

Table 4

Reported values of photoresistivity and response time for photoconductor materials.

Photoconductive Material	Photoresistivity Range in $\Omega\text{-cm}$		Response Time (msec.)	Ref.
	Min.	Max.		
CdSe	3×10^2	2×10^4	----	[65]
CdS	50:1*		0.1	[61]
CdSe	10	3×10^6	----	[59]
CdSe	$10^6:1^*$		1.0	[72]
CdS	2.75	850	----	[46]
CdS	20	2×10^5	150	[35]
CdS-CdSe	6.92	692†	----	[15,81]
CdSe-CL903L	750	$2.4 \times 10^3 \Pi$	5 to 20	[86]
CdS-CL905L	2200	$4.9 \times 10^3 \Pi$	35	[86]
Type A	1000	$3 \times 10^5 \S$	25	[90]
Type B	2100	$3 \times 10^6 \S$	10	[90]
Type C	330	$3 \times 10^5 \S$	20	[90]

* Insufficient data in reference for accurate determination of photoresistivity values. Range listed here for further study.

† Calculated from information in references for the 180x180 array design by Weimer, et al⁵.

$\Pi, \S$ Calculated from data given by Clairex [16] and Allen-Bradley [17], respectively, for their photocells. A photoconductive layer thickness of 100 microns was assumed for each of their device geometries. The other physical dimensions were either measured or taken from their data sheets.

(d) Piezoelectric material for IDT substrate. The properties of different materials considered for use as IDT substrates in the design for each of the three arrays are listed in Table 5. As stated in Section IV, two critical design restraints that the IDT substrate material must satisfy are the maximum limits for acoustic transmission loss (less than $6/N_v$) and reflection loss (greater than 30 db) per IDT pair.

(e) Computer routine modification - photoresistivity. To determine the sensor response for the integrated array, the parallel plate model of the photoresistive element and the photoresistivity (rather than photoresistance) were entered into the computer analysis. Photoresistivity limits allowed for the 125 and 250-element unit ranged from 10^2 to 10^6 ohm-cm; for the 500-element unit from 10^3 to 10^5 ohm-cm. The optimization routine was then used to select the photoconducting material thickness that would give the optimum $R_\lambda C_\lambda$ combination.

2. Computer Results

Plots of computed optimum sensor overall output/input response characteristics for the arrays of 125, 250 and 500 elements (in 5 cm length) are given in Figures 15, 16 and 17. These curves would seem to indicate lithium niobate to be the optimum material, from the viewpoint of voltage gain. To use this criterion alone is misleading, however, for high transmission reflection losses will prevent the use of this material. This is seen from Figures 18 and 19, which show transmission and reflection loss curves for the 250 element array. As seen there for

Table 5

Piezoelectric materials and their surface wave properties.

<u>Piezoelectric Material</u>	<u>Surface Wave Velocity (m/sec)</u>	<u>Coupling Constant (k^2)</u>	<u>Relative Permittivity (ϵ_r)</u>
α -quartz (Y-cut)	3154	0.0022	4.5
PZT-8A (Normal-poled)	2198	0.0430	1000
ZnO (X-cut)	2675	0.0112	8.84
LiNbO ₃ (Y-cut)	3470	0.0246	38.5
Li ₂ GeO ₃ (Y-cut)	3350	0.0094	9.5
CdS (X-cut)	1720	0.0062	9.53
Bi ₁₂ GeO ₂₀ (110-cut)	1580	0.0230	38.0

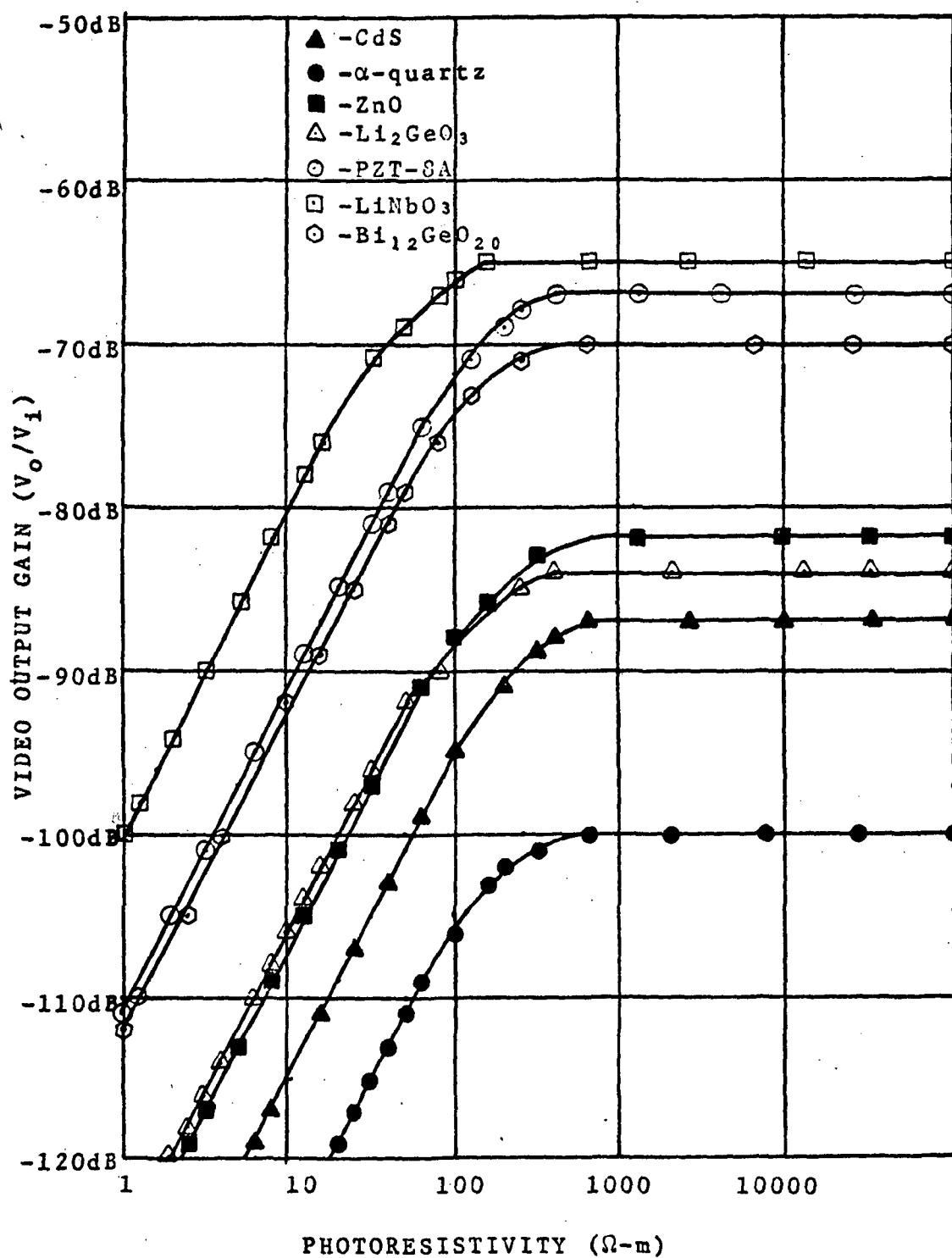
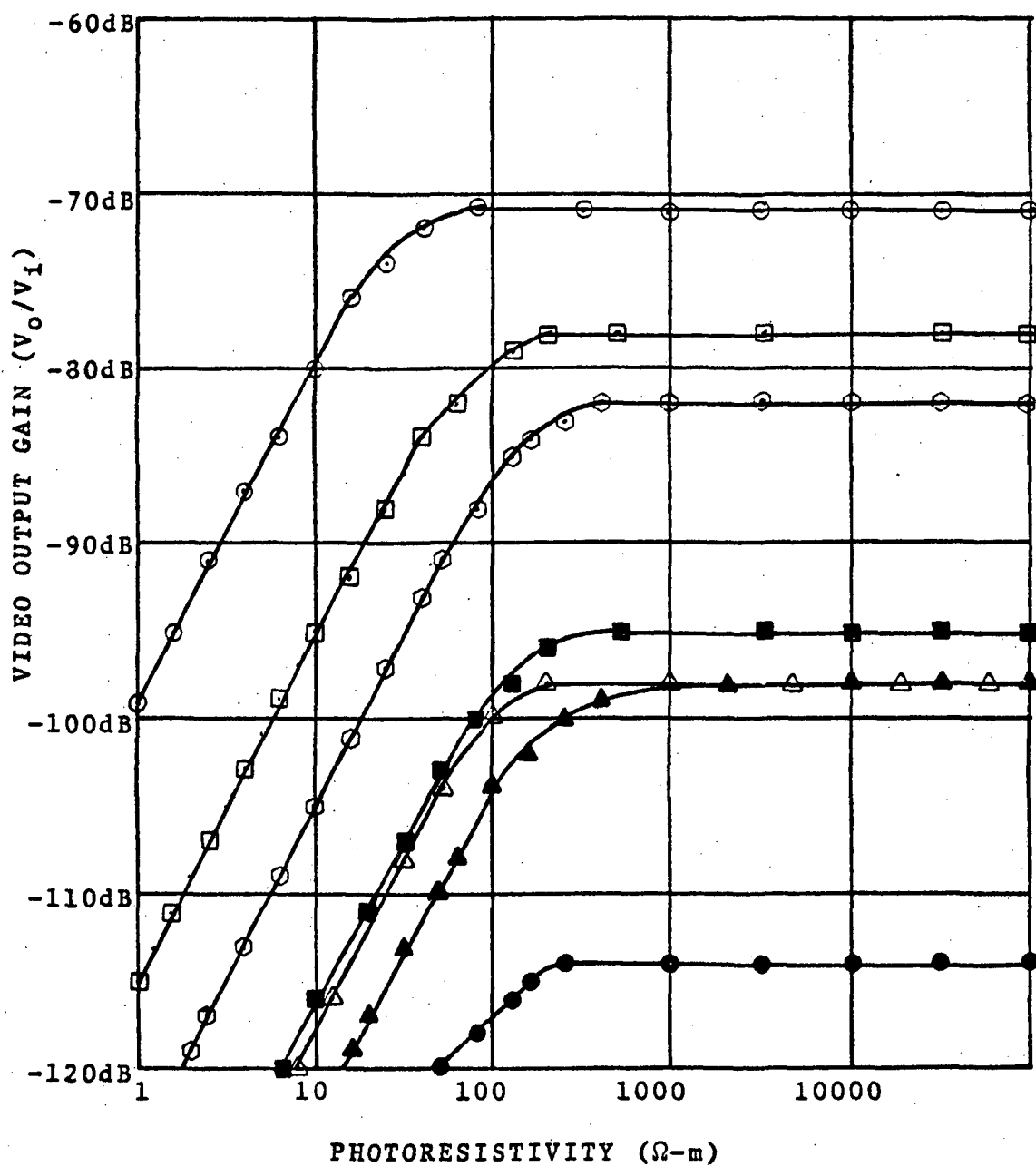


Figure 15

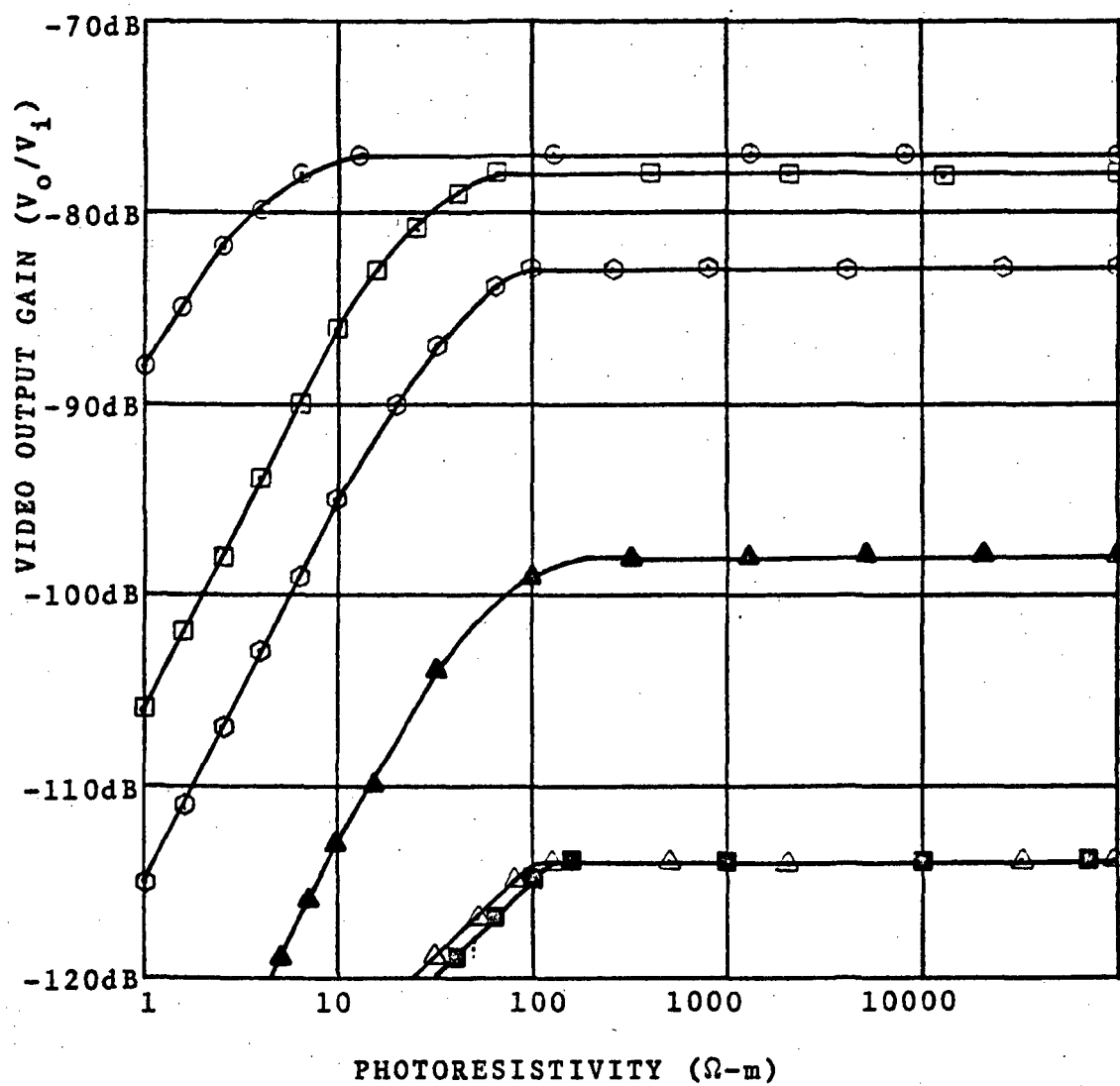
Voltage gain vs. photoresistivity for 125-element array, for seven different piezoelectric substrate materials.



- ▲ -CdS
- - α -quartz
- -ZnO
- △ -Li₁₂GeO₃
- -PZT-8A
- -LiNbO₃
- -Bi₁₂GeO₂₀

Figure 16

Voltage gain vs. photoresistivity for 250-element array, for seven different piezoelectric substrate materials.



- ▲ -CdS
- - α -quartz
- -ZnO
- △ - Li_2GeO_3
- -PZT-8A
- - LiNbO_3
- ⊙ - $\text{Bi}_{12}\text{GeO}_{20}$

Figure 17

Voltage gain vs. photoresistivity for 500-element array, for seven different piezoelectric substrate materials.

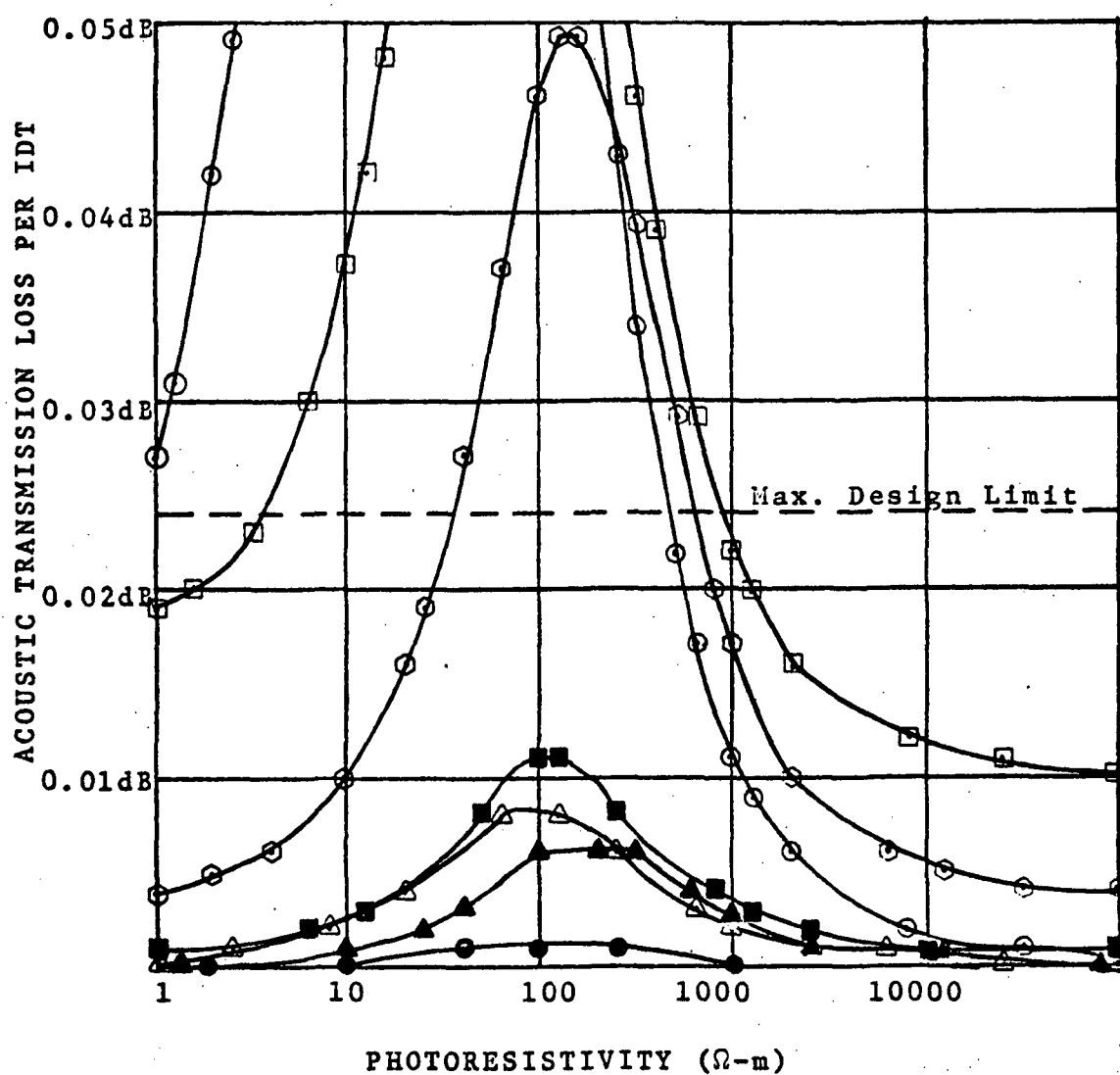
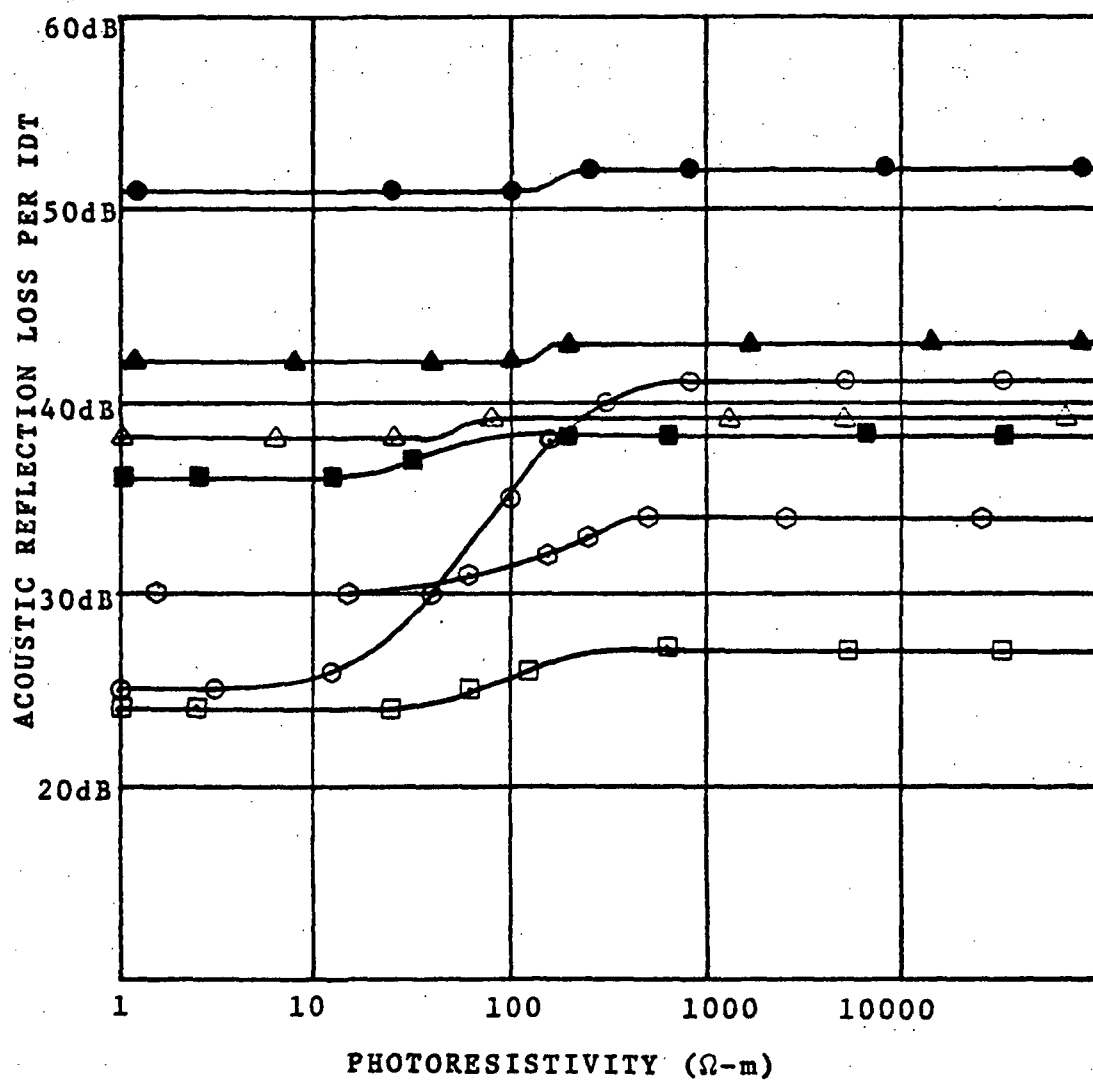


Figure 18

Transmission loss curves for 250-element array, for the 250-element array design.



- ▲ - CdS
- - α -quartz
- - ZnO
- △ - Li_2GeO_3
- - PZT-8A
- - LiNbO_3
- ⊙ - $\text{Bi}_{12}\text{GeO}_{20}$

Figure 19

Reflection loss curves for 250-element array, for the 250-element array design.

the range of photoresistivity of interest, insertion loss not only of LiNbO_3 , but also of PZT-8A and $\text{Bi}_{12}\text{GeO}_{20}$ are far too high to be of use here.

To provide a comparison of the performance of the four remaining materials, we calculated the merit functions for these. The results, given in Table 6, show ZnO to be the optimum material for the 125 and 250-element arrays and X-cut CdS for the 500-element array. The design parameters for the 250-element array are given in Table 7. From Figure 16, the voltage gain for this array is seen to range from -98 db to -116 db, as the photoresistivity varies from 10,000 to 1,000 ohm-cm.

Since a voltage gain of -100 db to -120 db is a very large amount of attenuation, it is necessary to compare expected output voltages with the expected noise voltages. If we assume an input pulse voltage of 100 volts (as used in a number of our experiments), then for a voltage gain of -120 db to -100 db, the output pulse amplitude ranges from 10^{-4} to 10^{-3} volts. To determine the RMS Johnson noise, we note that the impedance at the video amplifier input terminals is R_v in parallel with 250 IDT-sensor combinations. Since the principal resistance viewed by the video amplifier for each combination here is the 100,000-ohm isolation resistor R_s , the equivalent noise-determining resistance here is $100,000/250$ ohms, or 400 ohms. For, say, 15 MHz bandwidth, the 300°K noise voltage is $2\sqrt{KT\Delta f R} = (9.5)(10^{-6})$ volts. Accordingly, the output voltage for minimum signal level here is still 10 times the RMS noise voltage. Indications are, however, that for arrays having an excess of 500 elements per line, an additional look at methods of improving output signal levels may be necessary.

Table 6

Merit function values for optimum
integrated array design combinations.

<u>IDT Substrate Material</u>	<u>MERIT Function Values for Optimum Design</u>		
	<u>125x125 Array</u>	<u>250x250 Array</u>	<u>500x500 Array</u>
α -quartz (Y-cut)	4.3078×10^{-7}	3.4558×10^{-7}	1.8782×10^{-7}
ZnO (X-cut)	<u>3.2685×10^{-6}</u>	<u>3.4495×10^{-6}</u>	1.5129×10^{-6}
CdS (X-cut)	8.7142×10^{-7}	3.3315×10^{-6}	<u>6.0679×10^{-6}</u>
Li_2GeO_3 (Y-cut)	2.9483×10^{-6}	2.0547×10^{-6}	1.4427×10^{-6}

The optimum design combination value for each of the three arrays is underlined.

Table 7

Design parameters for 250-element array

IDT Array Parameters

Resonant frequency: 13.375 MHz on X-cut zinc oxide.
 Width (W): 1.0 cm.
 Separation between input and output stages: 4.3 mm.
 Input IDT input impedance: $249 - j17,450$ ohms.

Electrical Input Network

Pulse generator impedance (Z_i): 50 ohms.
 Shunt capacitance (C_i): 10 pF.

Sensor Element Design

Photoconductor thickness (t): 0.805 microns.
 Side dimension of photoconductive cell (3d/4): 0.175 mm.
 Photoconductor material: CdS, CdSe, or a mixture.

Video Element Network

Video output load resistance (R_v): 10,000 ohms.
 Video output load capacitance (C_v): 10 pF.
 Sensor element capacitance (C_λ): 3.2 pF.
 Series isolation resistance (R_s): 100,000 ohms.
 Parasitic capacitance across R_s : 0.1 pF

Array Design Merit Function: 3.4495×10^{-6}

VII. EXPERIMENTS

Prior to the present work, only the principle of the surface elastic wave scanned sensor array had been demonstrated,⁽²⁾ and only in a rather primitive manner. It was the purpose of experimental work accompanying this analysis to examine the operation more fully, to compare experimental with calculated results, and to attempt to discover possible unforeseen problems. Although the most desirable demonstration of operation of the sensor would have been to construct a completely integrated array in the manner described in Section VI, it was soon evident that the use of discrete photoresistors in the off-substrate array configuration would also provide the desired information--without the need of a long integrated array development program. Accordingly, a number of experiments with discrete elements were carried out. We briefly describe three of these.

1. Five MHz Systems

The schematic diagram of an array constructed of a 10-pair IDT array on Y-cut quartz, with each pair shunted by a photoconducting element, is shown in Figure 3. The IDT's were deposited on Y-cut alpha quartz; were 1 cm long; and had electrode fingers 0.158 mm wide, with 0.158 mm gaps between fingers. This corresponds to an IDT resonance frequency of 5 MHz. Separation between input and output transducers was 1 cm. Grease was applied near the ends of the quartz to eliminate reflections from the edges.

After an examination of the characteristics of four commercial photocells and the variations in output voltage that could be predicted,

Clairex Type CL 905L photocells were chosen as the sensor elements. These units were found to have a resistance that varied from 33,000 ohms in 0.5 foot-candle illumination to 1000 ohms in 50 foot-candles. Their shunt capacity, measured in the dark, varied from 1.0 to 1.5 picofarads.

Figure 20 shows representative wavetrains of output voltage as the light intensity incident on the photocells was varied from 0.01 foot-candles to 45 foot-candles. The reduction of output with increase in light intensity was as expected.

The gradually rising intensity in output with time seen here was quite possibly due to a gradual increase in light intensity from one side of the array to the other. Some slight irregularities in pulse height are probably due to small differences in sensitivity of the various photocells. Both the gradual increase as well as the irregularities could also be due to spurious reflections, as well as some bulk wave interference. Both of these effects are expected to be reduced with closer spacing of transducer fingers, i.e., higher frequency of operation.

Another source of interference that was found was electrostatic coupling from the 55 volt input pulse, since no attempt at shielding was made here. This direct coupling can be minimized by shielding and eliminated completely by amplifier "keying," i.e., by permitting amplification only after the electrostatically coupled pulse has passed.

The resolving capability for this prototype array is shown in Figure 21. It is seen that the resolution is of the order of one IDT pair, so that IDT pairs shunted by a sensor element can be adjacent,

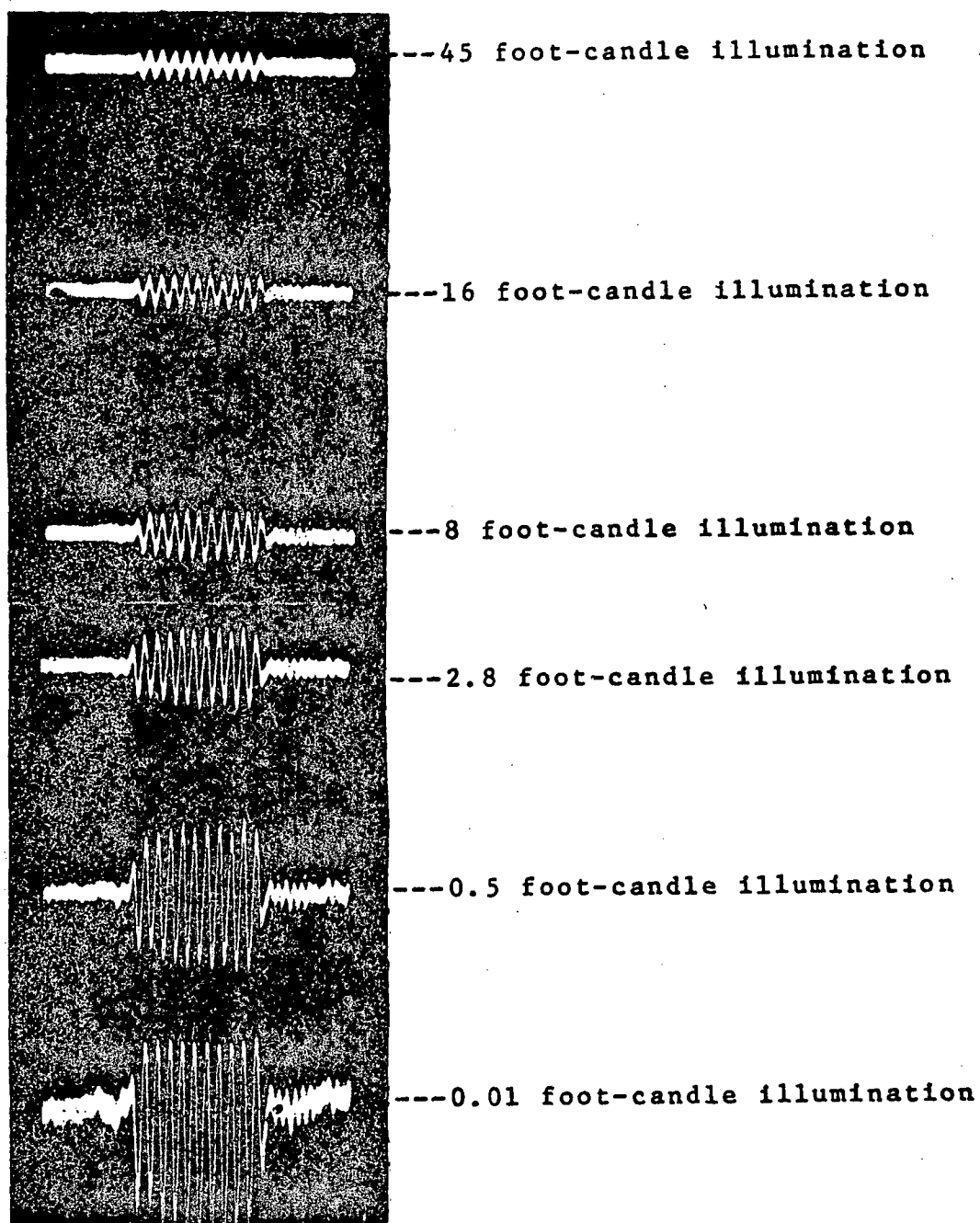


Figure 20

Output voltage wavetrains for 5 MHz_z sensor array, as light intensity was varied from 0.01 to 45 foot-candles. Horizontal scale: 0.5 microseconds/division; vertical scale: 165 microvolts/division. Input was a 55-volt pulse of 0.1 microseconds duration.

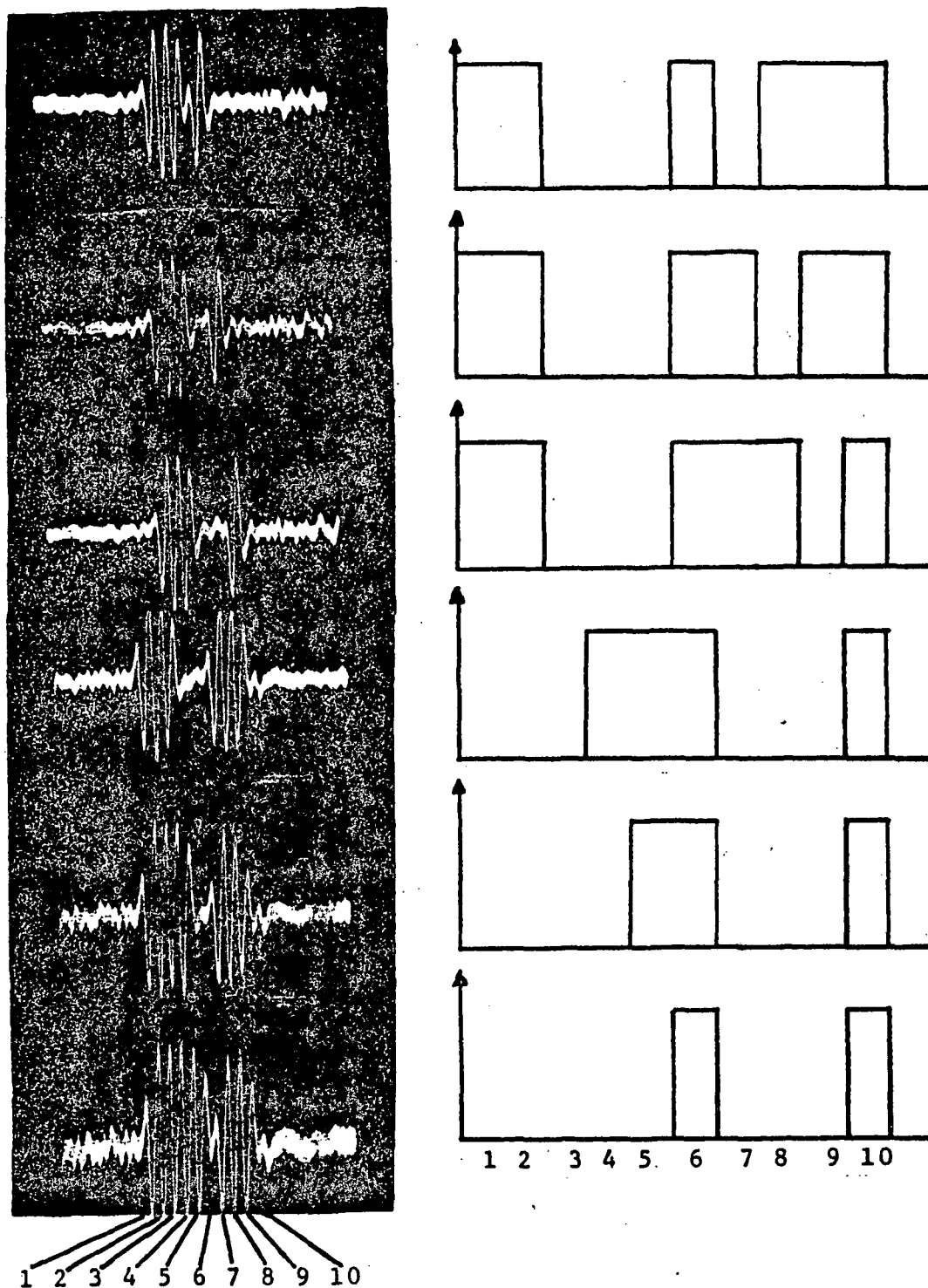


Figure 21

Output voltages obtained from 5 MHz sensor array, showing the resolving capability of the array. Left: Oscilloscope traces; right: light intensity distribution on the 10 sensing elements, to produce the oscilloscope traces shown. Peak value of light intensity: 100 foot-candles.

as in Figure 3. For somewhat finer resolution than seen here, IDT's can be spaced a wavelength or two apart, instead of being adjacent. Such an array was also fabricated and performed successfully.

2. 10 MHz Systems

To verify the analyses discussed in Section VI, a sensing array of 40 video elements, operating at an IDT resonant frequency of 10 MHz, was constructed and tested. Sensing elements used were (1) Clairex Type CL905HL photocells, chosen because they had a range of photoresistance that most closely fit into the range that should be obtainable for an integrated sensor element in accordance with calculations for an operating frequency of 10 MHz (and several other rather arbitrary conditions); (2) sets of resistors that could be interchanged with the photocells by simple substitution of printed circuit boards. These resistor boards were used to perform accurate measurements of output signal amplitudes for specified values of photoresistance.

The sensor response characteristics for this 40 unit array were first measured by using the fixed resistor boards. Then the photocell array board was substituted for the fixed resistor board and the response was measured by directly illuminating the array with various light intensities. A series of output voltage traces vs. light intensities for this array is seen in Figure 22.

When the initial results of voltage gain were compared with those predicted for an integrated array, a discrepancy of about 10 db was found. Upon further examination, it was found that the wiring required by the circuit boards and discrete elements had introduced a much larger capacitance than would exist in an integrated array. The effect of these

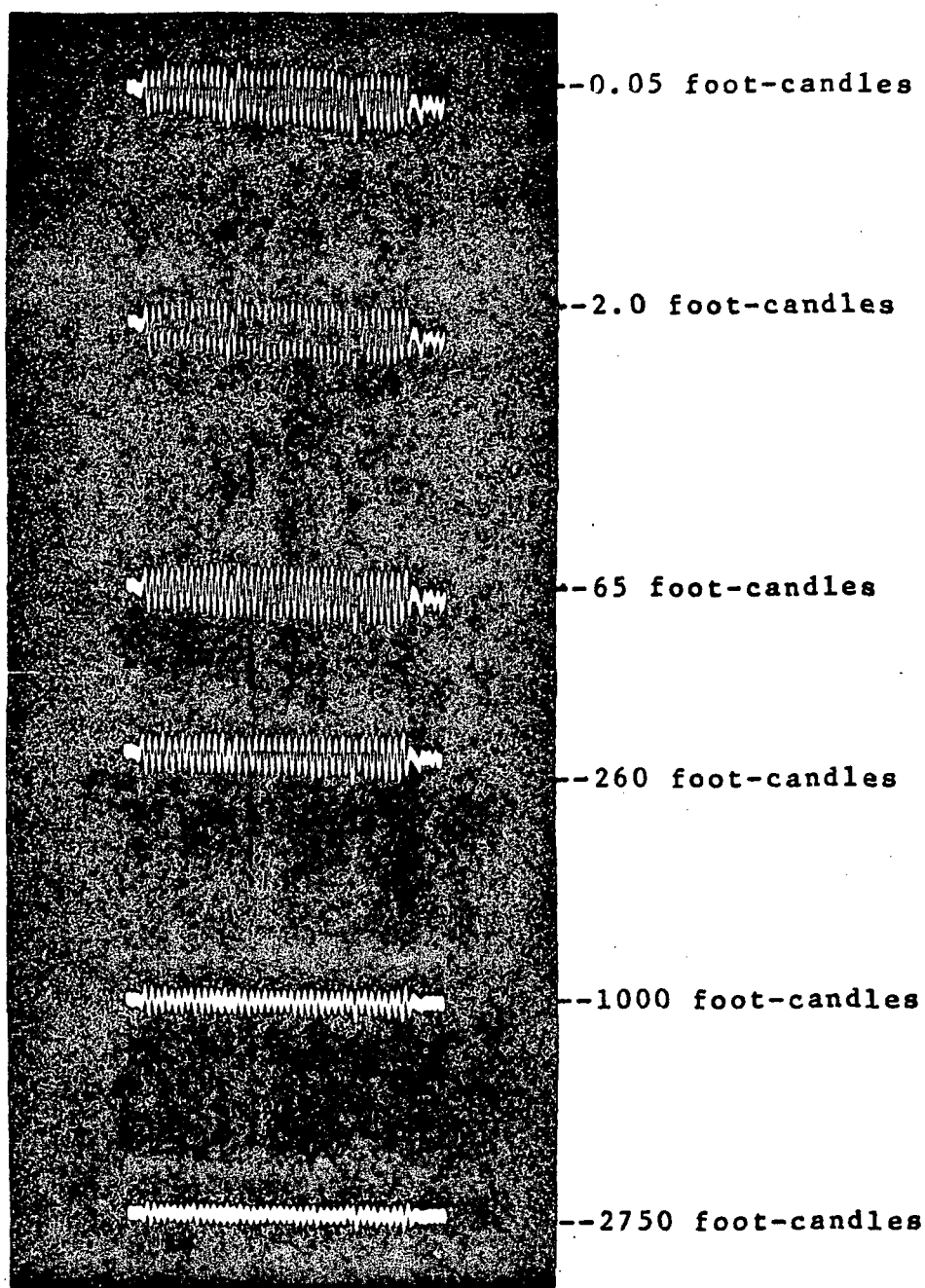


Figure 22

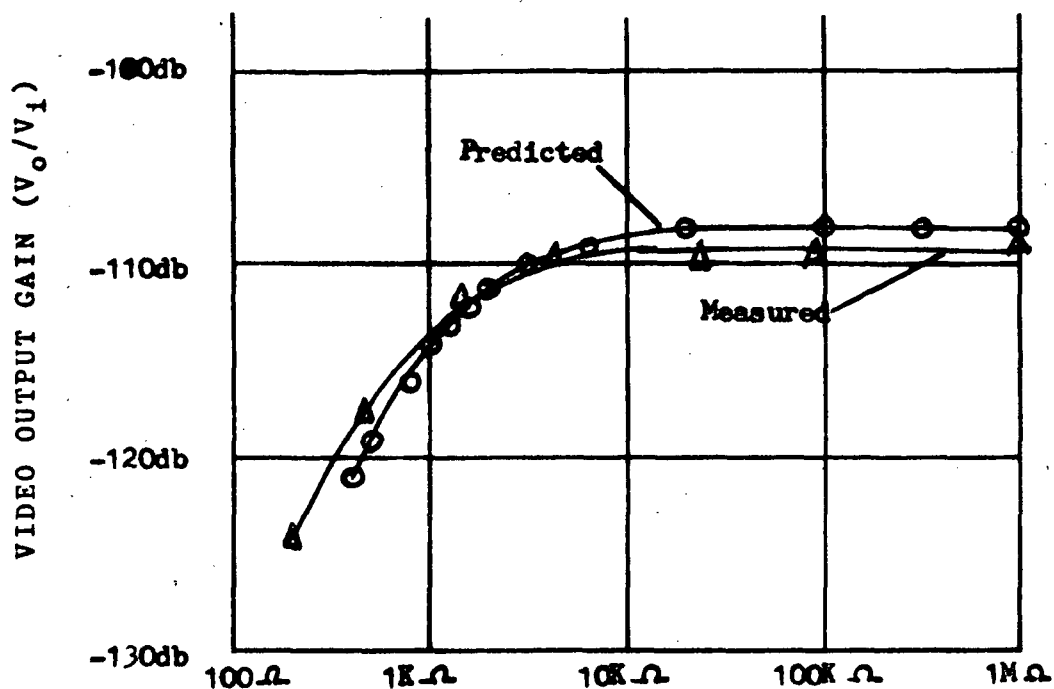
Output voltage wavetrains from 40-element, 10 MHz sensor array, as light intensity was varied from 0.05 to 2750 foot-candles. Horizontal scale: 0.5 microseconds per division; vertical scale: 116 microvolts per division. The two irregularities in the wavetrains are probably due to some difficulties with the two corresponding IDT's. Slopes in the vicinities of the irregularities are due to the use of a video amplifier that did not pass low frequencies.

larger values of capacitance was to reduce the overall gain and move the knee of the response curve to a lower value of photoresistance. After taking these extra amounts of capacity into account in another computer run, the curves of V_o/V_i vs. R of Figure 23 resulted. Satisfactory agreement is seen to exist.

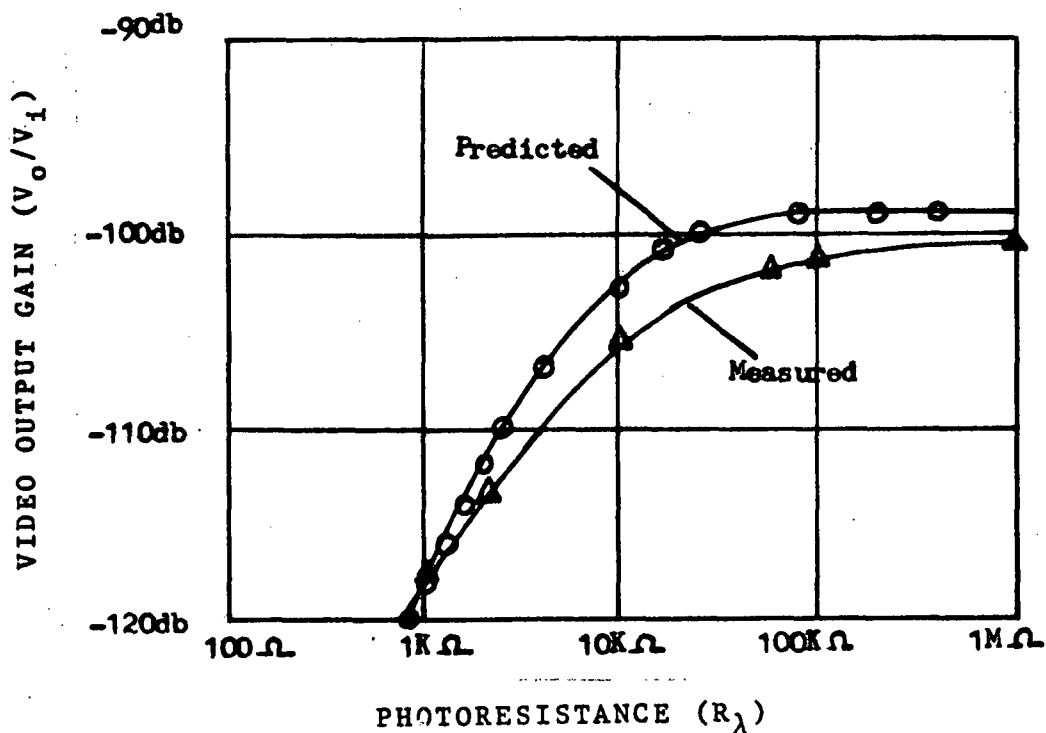
The 40-element sensor array was also placed behind an $f/4$ lens, so that light distribution from a white cardboard could be focused in the array. The array easily distinguished distributions of light on the cardboard, although, because of the unforeseen extra capacitance, very bright lights had to be used. The use of photocells of lower resistance would have allowed us to use lower light intensities, in a better demonstration.

With this 40 element array, it was not possible to make quantitative measurements of the acoustic transmission loss for each output IDT. However, it was observed that there was negligible decrease in the signal as it traversed the various IDT's, so that the loss was indeed small. The computer had predicted an acoustic transmission loss of less than 0.01 db per element, or less than 0.4 db for the entire array.

c. Phototransistor Array. Although no calculations on an array using phototransistor sensors had been made, we used the opportunity of work on the 40 unit array to investigate the use of this type of sensor. Accordingly, a circuit board of Motorola type MRD-450 phototransistor was used in place of the photocells. The results were very poor when the array was excited by the acoustic wave generated by the input pulse, for the output of the IDT was insufficient to properly excite the



-a-



-b-

Figure 23

Comparison of predicted curves of V_o/V_i for 40-element 10 MHz sensor with measured V_o/V_i for:

- a) Clairex type CL 905HL photocells.
- b) Resistor boards substituted for the photocells.

The curves for the two arrangements are different because the shunt capacitances for the photocells are larger than for the resistor boards.

phototransistors in this case. However, when input and output connections were reversed, and operation was as in the K-F experiment, the array was found to be considerably more sensitive than with photoresistive elements. The reason for this is that the excitation voltage applied to the phototransistor must be large enough so that a variation in the collector current due to a light variation can be obtained. It is conceivable that when operated in this manner the array could be used for sensing objects at light levels less than 1 foot-candles. One difficulty seen, however, was that the response varied considerably more from element to element than for photoresistors.

VIII. CONCLUSION

This paper has treated the use of acoustic surface waves for scanning of an array of optical sensors for imaging purposes. An analysis and design technique now available for such a scanning scheme has been applied to the proposed design for a number of integrated arrays.

The parameters for constructing the integrated arrays using photoconductive optical sensors have been derived and tabulated. A search of the literature has shown that these design parameters should be realizable. Practical arrays with more than 250 elements per line and an overall length of 5 cm should be possible.

Our experiments demonstrated the performance of small arrays using discrete sensor elements. The results are sufficiently optimistic for further experimental development work toward the construction of a completely integrated array. This technique of acoustic wave scanning could well have advantages in reliability and cost over other methods of sensor array scanning.

IX. ACKNOWLEDGMENT

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Appendix A

IDT RESPONSE TO PULSED SIGNALS

Since the operation of an elastic surface wave scanned sensor array is based on the use of pulsed electrical signals, some consideration was given to the output/input pulse response. Questions of particular interest were:

1. Will a half-sine-wave input signal to an IDT at one end of the line really result in a half-sine wave output at the other?
2. Are there advantages to the use of square pulses or triangular pulses over half-sine-wave pulses?

Although Tseng⁽¹⁸⁾ has given the frequency response of IDT's in analytical form, there is little discussion in the literature on the answers to the two specific questions above. We therefore performed some experiments to provide answers, using the experimental arrangement of Figure A.1. This represents an array of seven IDT's, with varying numbers of fingers. Their resonant frequency was 10 MHz; the piezoelectric material on which they were deposited was alpha-quartz. Three of the IDT groups were connected together in parallel and formed the output array, as shown in Figure A.1. The input IDT was one selected from the other four groups with the use of a movable input lead. No input or output matching networks were used, to prevent perturbation of the output waveform by the bandwidth characteristics of the networks.

The test setup used for the pulse study experiments is illustrated in Figure A.2. Three classes of input waveforms were studied--rectangular pulses of varying widths; single-cycle sine, triangle, and ramp waveforms; and sine wave tone bursts of varying duration.

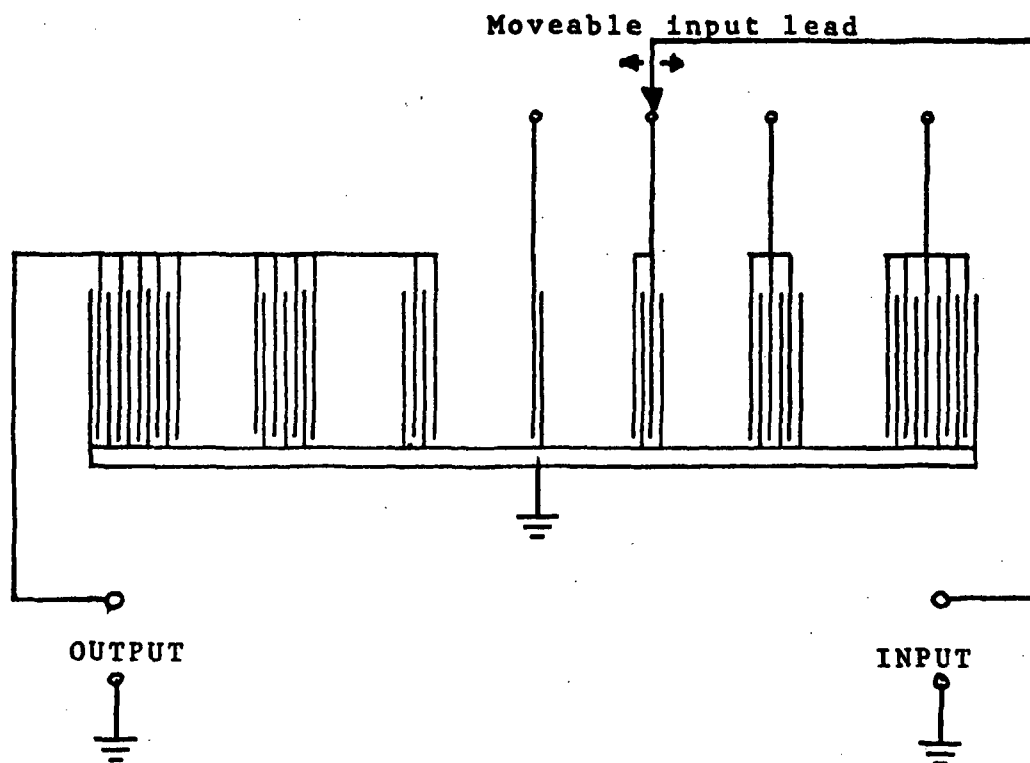


Figure A.1. IDT CONFIGURATION FOR PULSE STUDY EXPERIMENTS.

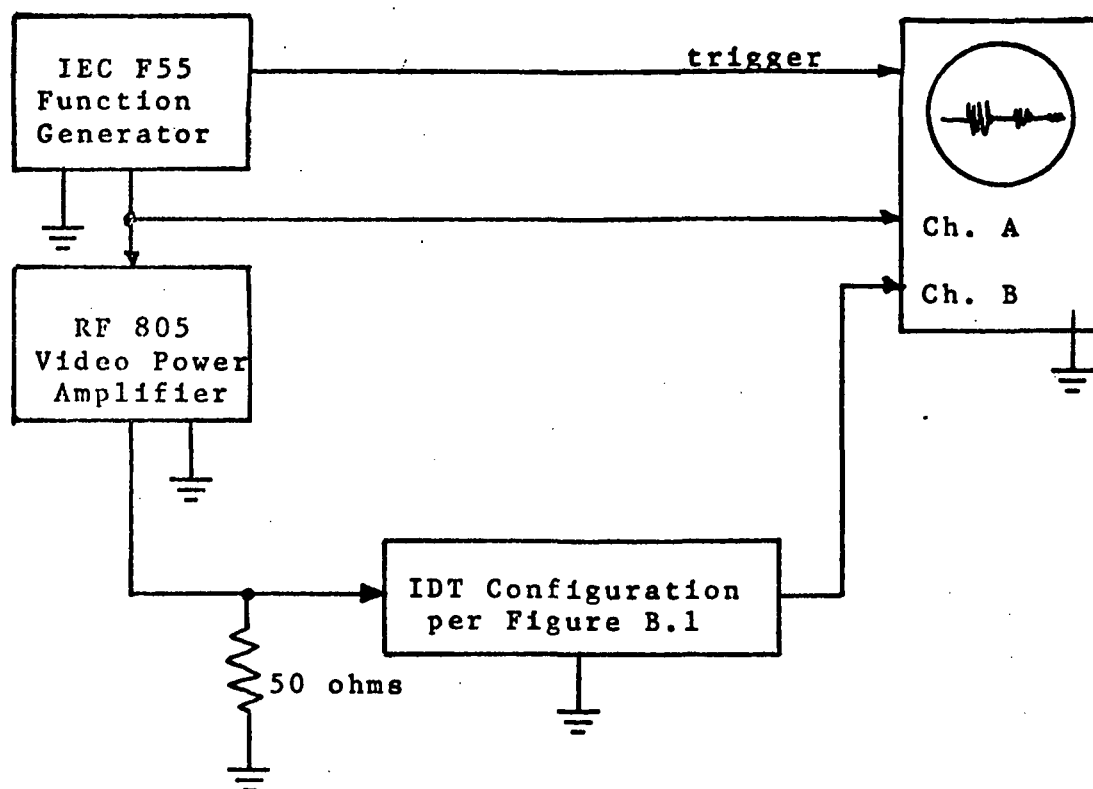


Figure A.2. TEST SET-UP FOR PULSE STUDY EXPERIMENTS.

Some of the oscilloscope traces observed for the input waveforms and the associated output waveforms are shown in Figures A.3 through A.5.

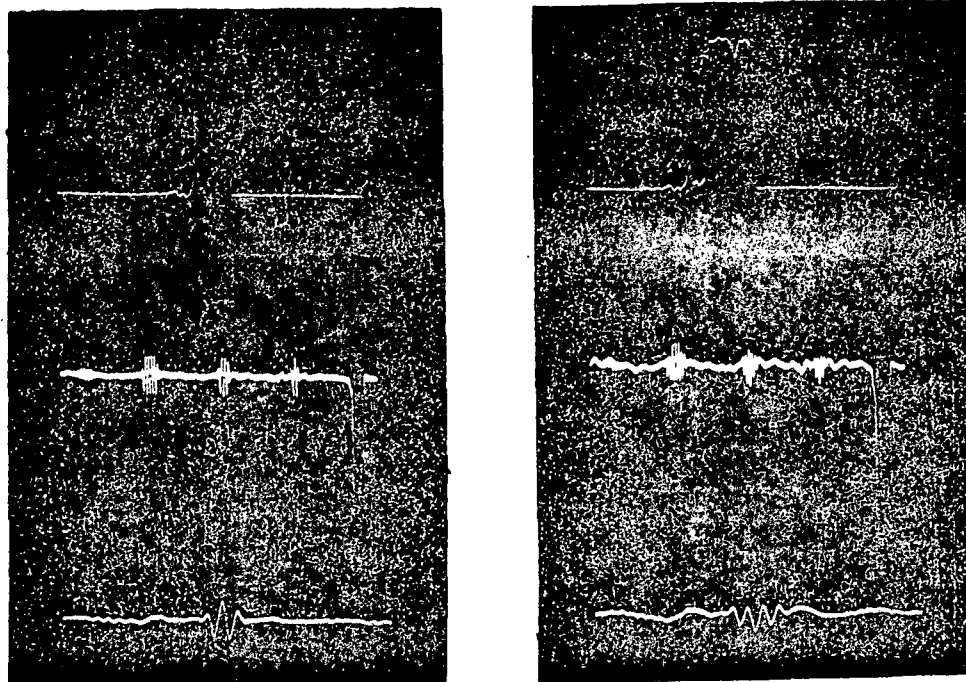
The output waveform in all cases was primarily a sine wave burst at the IDT resonant frequency, regardless of the shape of the input waveform. The input pulse width, however, did have a marked influence on the amplitude and duration of the output waveform. This was as expected, since the IDT's are resonant devices and the pulse width controls the spectral content of the input excitation. The only effect that a change of the input shape has is to eliminate the spectral components that are unnecessary for the output, provided the duration of the pulse is equal to that of a half-cycle of the resonant frequency of the IDT's.

As a result of the study, the optimum input waveform for scanning purposes is a rectangular or half-sine pulse with a duration equal to $1/2f_0$, where f_0 is the IDT resonant frequency. As shown by the oscilloscope traces in Figure A.3, the resultant waveform for each IDT pair is a single cycle at the resonant frequency.

The relation between the number of cycles of output signal to the number of cycles of input signal, as found from these experiments, is

$$n_o = n_i + (N_i - 1) + (N_o - 1) \quad (A.1)$$

where n_i and n_o are the number of cycles at the resonant frequency in the input and output waveforms, respectively. N_i and N_o are the number of electrode pairs in the input and output IDT's, respectively.



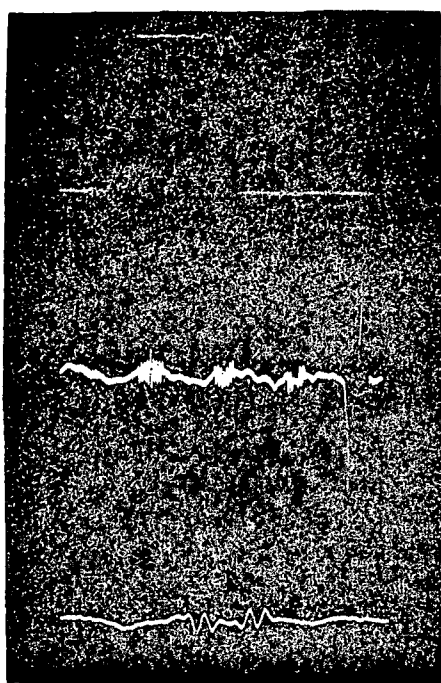
$\tau/2$ Input Pulse

$3\tau/2$ Input Pulse

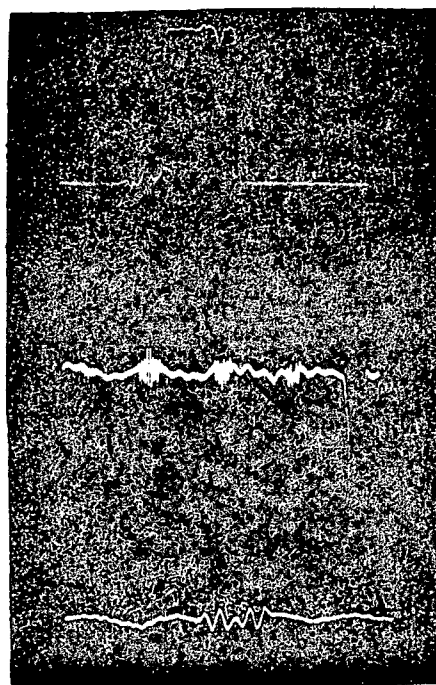
Figure A.3. OUTPUT WAVEFORMS FOR RECTANGULAR INPUT PULSES OF VARYING DURATION.

The upper trace in each photograph is the input pulse with a horizontal scale of $0.1\mu\text{sec}/\text{div.}$ and a vertical scale of $20\text{V}/\text{div.}$ The center trace is the output waveform for three IDT groups of 2, 3, and 5 pairs connected in parallel. The horizontal scale for this trace is $1\mu\text{sec}/\text{div.}$, and the vertical scale is $1\text{mV}/\text{div.}$ The lower trace is the output for the 2 pair IDT with a magnified time scale of $0.2\mu\text{sec}/\text{div.}$

(τ is equal to one divided by the IDT resonant frequency.)



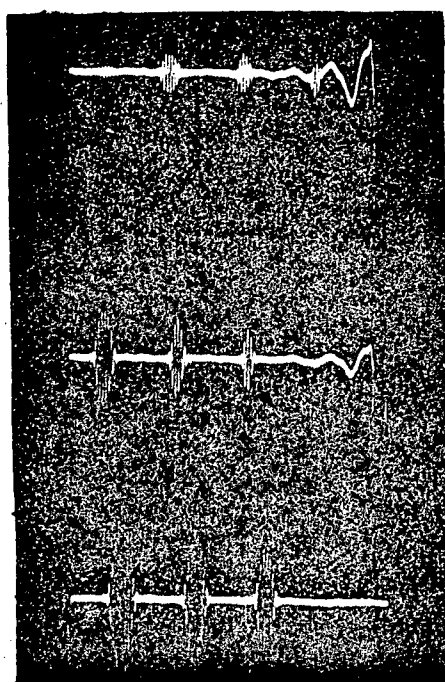
$7\tau/2$ Input Pulse



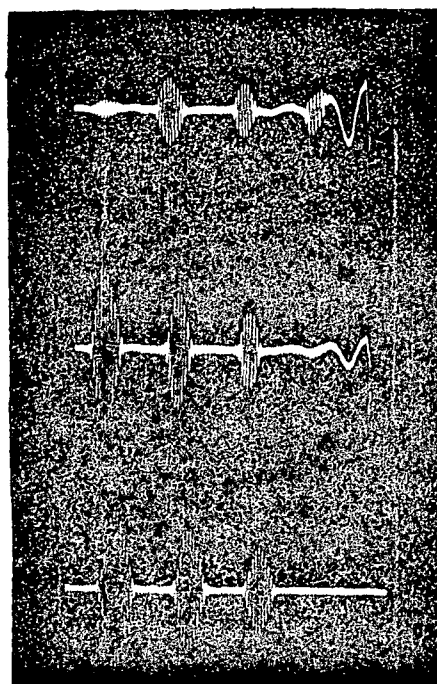
$5\tau/2$ Input Pulse

Figure A.4. OUTPUT WAVEFORMS FOR RECTANGULAR INPUT PULSES OF VARYING DURATION.

Trace information is same as for Figure A.3.



Two cycle sine wave
tone burst input



Five cycle sine wave
tone burst input

Figure A.5. OUTPUT WAVEFORMS FOR TONE BURST INPUTS AND VARIOUS COMBINATIONS OF INPUT/OUTPUT IDT ARRAYS.

The above traces are the outputs for IDT's with 2, 3, and 5 pairs connected in parallel and with a different amount of delay time between input and output for each. The input waveforms are as described above beneath the photographs. The upper traces in each photograph are for an input IDT with one pair. The center and lower traces are for input IDT's with 2 and 5 pairs, respectively.

Horizontal scale: 1.0 microseconds per division.

Vertical scale: 1.0 millivolt per division for all traces except lower right. 2.0 millivolts per division for lower right.

Another expression that indicates the minimum number of resonant cycles in the input burst for the maximum possible peak output amplitude is

$$n_i \geq N_I + N_0 - 1 \quad (\text{A.2})$$

Examples of the two above relations are shown in the traces for Figure A.5.

Appendix B

SCATTERING MATRIX ANALYSIS FOR IDT SYSTEM

If the admittance parameters are available for a network, then the basis-free, normalized scattering matrix for the network can be obtained by combining equations 2.13b and 2.21 given by Kuh and Rohrer⁽⁹⁾. The resulting matrix equation is

$$\begin{aligned} [S] &= [\sqrt{g}] \left([Y] + [y] \right)^{-1} [y^*] - [Y] [\sqrt{g}] \\ &= -[1] + 2[\sqrt{g}] \left([Y] + [y] \right)^{-1} [\sqrt{g}] \end{aligned} \quad (B.1)$$

where $[1]$ is the unit matrix, $[\sqrt{g}]$ is the square root of the real part of the reference admittance matrix, $[y]$ is the reference admittance matrix for the ports, and $[Y]$ is the admittance matrix for the network.

For the IDT network, the reference impedance for all of the ports is chosen to be the acoustic impedance R_0 , i.e., the electrical analog representing the elastic propagation characteristics of the IDT substrate. (See text material, pp. 22-24). Since R_0 is real, $[y]$ is real and equal to $[g]$. Thus:

$$[y] = \begin{bmatrix} 1/R_0 & 0 & 0 \\ 0 & 1/R_0 & 0 \\ 0 & 0 & 1/R_0 \end{bmatrix} = \begin{bmatrix} G_0 & 0 & 0 \\ 0 & G_0 & 0 \\ 0 & 0 & G_0 \end{bmatrix} \quad (B.2)$$

$$[\sqrt{g}] = \begin{bmatrix} \sqrt{G_0} & 0 & 0 \\ 0 & \sqrt{G_0} & 0 \\ 0 & 0 & \sqrt{G_0} \end{bmatrix} \quad (B.3)$$

The IDT scattering matrix has a symmetry due to the similarity of the two acoustic ports. The general IDT scattering matrix is

$$[ST] = \begin{bmatrix} ST_{11} & ST_{12} & ST_{13} \\ ST_{12} & ST_{11} & -ST_{13} \\ ST_{13} & -ST_{13} & ST_{33} \end{bmatrix} \quad (B.4)$$

By use of the admittance matrix for the in-line, or series-resonant model of an IDT, given as Equation 2, page 22, and B.2 and B.3 in B.1, we obtain the scattering matrix for the series-resonant IDT network, where $T = \omega_0 C_S / 8G_0$ in the following equations.

$$ST_{11} = \{1 - j(T/N) + 8T^2\}^{-1} \quad (B.5a)$$

$$ST_{12} = ST_{11} \cdot \{8T^2 - j(T/N)\} \quad (B.5b)$$

$$ST_{13} = ST_{11} \cdot (-j4T) \quad (B.5c)$$

$$ST_{33} = ST_{11} \cdot \{1 - j(T/N) - 8T^2\} \quad (B.5d)$$

To obtain the scattering matrix for the video element circuit is a little more complicated. The reference impedances for the two ports are not the same, since port 1 should have a reference equal to R_0 , so that interconnection of the IDT and video element circuit scattering matrices is possible without complicated matching techniques. Port 2 should have a reference related to the input impedance of the video amplifier. To keep things simple, this reference was chosen to be the real part of the video amplifier's input impedance, with the imaginary part to be contained

within the video element circuit. The output voltage will not be affected since the imaginary part is assumed to be in parallel with the real part of the input impedance.

Therefore, by carrying out the steps given below, we obtained the generalized scattering matrix for the video element circuit.

$$[y] = \begin{bmatrix} G_0 & 0 \\ 0 & 1/R_V \end{bmatrix} \quad \text{and} \quad [\sqrt{g}] = \begin{bmatrix} \sqrt{G_0} & 0 \\ 0 & \sqrt{1/R_V} \end{bmatrix} \quad (\text{B.6})$$

$$[SV] = \begin{bmatrix} SV_{11} & SV_{12} \\ SV_{21} & SV_{22} \end{bmatrix} \quad (\text{B.7})$$

where

$$SV_{11} = (2/\Delta R_0) \cdot (YV_{22} + 1/R_V) - 1 \quad (\text{B.8a})$$

$$SV_{12} = (2YV_{12})/(\Delta\sqrt{R_0 R_V}) \quad (\text{B.8b})$$

$$SV_{21} = (2YV_{21})/(\Delta\sqrt{R_0 R_V}) \quad (\text{B.8c})$$

$$SV_{22} = (2/\Delta R_V) \cdot (YV_{11} + 1/R_0) - 1 \quad (\text{B.8d})$$

$$\Delta = (YV_{11} + 1/R_0) \cdot (YV_{22} + 1/R_V) - YV_{12} \cdot YV_{21} \quad (\text{B.8e})$$

Now the scattering matrices for the IDT and the video element circuit can be combined to form a single three-port scattering matrix, by use of the interconnection methods discussed by Kuh and Rohrer⁽⁹⁾ in Section 6.6 of their book.

The resulting composite scattering matrix has the symmetry exhibited by equation (B.10). The expressions for the individual coefficients of the matrix are also given.

$$[SPV] = \begin{bmatrix} SPV_{11} & SPV_{12} & SPV_{13} \\ SPV_{12} & SPV_{11} & -SPV_{13} \\ SPV_{31} & -SPV_{31} & SPV_{33} \end{bmatrix} \quad (B.9)$$

$$SPV_{11} = ST_{11} + (SV_{11} \cdot ST_{13}^2 / D) \quad (B.10a)$$

$$SPV_{12} = ST_{12} - (SV_{11} \cdot ST_{13}^2 / D) \quad (B.10b)$$

$$SPV_{13} = ST_{13} \cdot SV_{12} / D \quad (B.10c)$$

$$SPV_{31} = ST_{13} \cdot SV_{21} / D \quad (B.10d)$$

$$SPV_{33} = SV_{22} + (SV_{21} \cdot SV_{12} \cdot ST_{33} / D) \quad (B.10e)$$

$$D = 1 - SV_{11} \cdot ST_{33} \quad (B.10f)$$

The importance of the above calculations is contained in the coefficients given by equation set B.10. The amount of incident acoustic power reflected by the IDT is given by $SPV_{11} \cdot SPV_{11}^*$; the amount of acoustic power remaining after passage under the IDT is given by $SPV_{12} \cdot SPV_{12}^*$; and the video output for the acoustic power incident upon port 1 is given by $SPV_{31} \cdot SPV_{31}^*$.

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