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G. S./Kino
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W.W. Hansen Laboratories of Physics
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A storage correlator has been operated for the first time as an inverse filter by operating in a feedback loop to iteratively converge via the LMS algorithm to the desired filter. A pulse and a ghost echo have been deconvolved to a single pulse with the sidelobe level 9 dB below the original echo level.

The ZnO magnetron sputtering system is operating well; ZnO on Si convolvers have been constructed with better efficiency (-55 dBm) than any we have previously made. A -45 dBm efficiency $\Delta v/v$ waveguide convolver has been constructed.

Delta (v)/v

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ACOUSTICALLY SCANNED OPTICAL IMAGING DEVICES

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1 January - 30 June, 1979

Principal Investigator:

G. S. Kino
(415) 497-0205

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G. L. Report No. 3006

August 1979

Edward L. Ginzton Laboratory
W. W. Hansen Laboratories of Physics
Stanford University
Stanford, California

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I. MANAGEMENT REPORT

A. SUMMARY

The development of our ZnO technology is continuing to make good progress. We have constructed several ZnO convolvers and, in addition, we have made waveguide convolvers on an associated contract using this technology. In each case, the performance of the convolver was better than any we had seen in our previous runs. Furthermore, the waveguide convolver gave a convolution efficiency of -45 dBm , a result better than any ever obtained with monolithic convolvers, and almost as good as the best air-gap convolver that we have measured.

We have tested Schottky diode convolvers and correlators. We were able to make a reasonably efficient Schottky diode convolver, but because of excess test voltage applied to the plate, the device exhibited breakdown and we were not able to obtain correlation.

We have had a major breakthrough in the use of the ZnO correlator to carry out inverse filtering of deconvolution in an iterative mode. We have continued to make progress on the early results discussed in the last Management Report. We have used a simple double-pulse signal and programmed the filter to turn this into a single pulse. Typically, we can obtain a reduction in the level of the unwanted second pulse or ghost echo of the order of 9 dB after 22 iterations. Furthermore, the results obtained are in excellent agreement with computer simulations of the process. We now feel that we have a very good understanding of the operation of the storage correlator in this mode and that we will be able to capitalize on it to make systems demonstrations suitable for communications, signal processing, radar processing and processing in the nondestructive testing field.

This device is far faster in operation than any competitive inverse filter with its bandwidth. Because it operates in a feedback mode, no computer for setting the taps is required and the device has the ultimate capability of processing signals with as much as 100 MHz bandwidth. We expect to demonstrate that it cannot only be used as an equalizer or inverse filter, but it can also be used to remove unwanted interfering signals. We have already shown that it can remove cw signals, but we believe that the device is far more flexible than this, and can be employed to remove a wide variety of interfering signals.

One of the problems with the storage correlator in the past has been the feed-through of spurious signals from the input port to the output port. An advantage of this iterative mode of operation has turned out to be that the device automatically adjusts to minimize the feed-through and cancel it out.

Because the ZnO correlators have such important systems applications which we wish to demonstrate, and because the ZnO technology is going so well, we wish to devote most of our efforts to these developments. For this reason we have put aside most of our work on GaAs. It would seem at this stage that it would not be wise to divide our efforts in too many directions. We believe that the results we have obtained are so important that it is vital to emphasize the silicon work, and therefore will not be continuing the GaAs work.

B. RESEARCH PROGRAM PLAN

We are testing the deposition of ZnO on different metals and will continue to do so. One of the aims is to build Schottky diode devices suitable for use as correlators, which we hope to demonstrate during the next period. The theory and experiments on equalization and inverse filtering will be developed further.

C. MAJOR ACCOMPLISHMENTS

We have demonstrated an equalizer operating in an iterative mode. The results obtained are in excellent agreement with computer simulations and indicate the importance of this type of device.

D. PROBLEMS ENCOUNTERED

No major problems have been encountered.

E. FISCAL STATUS

Total amount of contract	$504,302
Expenditures & commitments through 6/30/79	$375,460
Estimated funds required to complete work	$128,842
Estimated date of completion of work	30 Sept. 1980

F. ACTION REQUIRED BY ARPA/ONR

No action required at the present time.

II. TECHNICAL PROGRESS REPORT

A. INTRODUCTION

The major success in the last six months has been the demonstration of an adaptive filter using the storage correlator. For the first time, we have shown that the storage correlator can be employed in a feedback configuration as an adaptive filter operating with an LMS algorithm. Because the storage correlator can take both correlation and convolution of the two signals, as well as store them, all the operations required for the LMS algorithm can be obtained in one device without the use of external computer control. Thus, by this means, we have been able to demonstrate that we can suppress secondary echoes in a communications system by 9 dB . We have demonstrated that the results are in excellent agreement with computer simulations, and we have shown that the iterations required for the filter to adapt to a given input waveform to produce a desired output waveform can be carried out within a few hundred microseconds.

Our first demonstrations were carried out with a relatively crude storage correlator with a bandwidth of 8 MHz . Already, they showed that some of the disadvantages of the storage correlator were automatically nulled out because feed-through signals were suppressed by the adaptive process itself. Furthermore, we would expect that as we improve our devices to obtain far larger bandwidths, we shall be able to demonstrate far more sophisticated signal processing techniques to remove distortions in a communications system, to eliminate interference, and to adapt to slowly varying signals using this relatively simple device.

A paper on this device has been submitted to Electronics Letters. This paper is enclosed with the report as an Appendix. An invited paper on this work is being given at the Ultrasonics Symposium.

We have therefore tended to change the direction of our work to take maximum advantage of this major breakthrough in systems technology. Thus, in the body of this report there is a discussion of our theoretical work on Sezawa modes which can lead to far higher bandwidth devices. We shortly expect to be constructing Sezawa mode devices with very large bandwidths of as much as 100 MHz .

In the same way, we are developing Schottky diode devices which would lead to correlators which could adapt far more quickly, as the turn on time of such correlators would be far faster than those using pn diodes. Moreover, we should be able to obtain devices with far more control over the characteristics and lower threshold voltages, both of which are desirable characteristics for our storage correlators.

A major reason why we can envisage a radical improvement in these devices is because of the improvement in our ZnO on Si technology. It now appears to be highly reproducible, particularly with regard to the deposition of ZnO on SiO_2 layers, a process which is required for all storage correlators. In the past, this has been a highly unreproducible process which has led us to difficulties in making reproducible ZnO on Si correlators. Now, convolvers and correlators made by this technique appear to be reproducible. Because we are now using higher substrate temperatures during the deposition, we are encountering a problem with deterioration of the gold layers in the transducer region. Consequently, the transducers we are making have been somewhat worse than the earlier transducers. We are presently investigating the correct conditions for deposition and are in the process of changing the use of gold layers to the use of platinum layers which should eliminate this difficulty.

Because of the good progress with our ZnO on Si system and because we have been able to make demonstrations of sophisticated devices employing these techniques, we have put the GaAs work to one side. Now, it is not apparent that GaAs would provide any major advantage over Si . Earlier, we had thought that the difficulties with ZnO would make it necessary to investigate GaAs , which is a piezoelectric semiconductor. As the GaAs technology has its own attendant difficulties, and the results we are obtaining are of such importance, we have decided to pursue ZnO on Si technology for our further devices rather than to divide our efforts.

B. ADAPTIVE FILTERING USING THE STORAGE CORRELATOR

Introduction

Adaptive filtering[1] is useful in removing distortions from signals, particularly when the distortion varies in time. Adaptive filters have been used to perform deconvolution of a distorted echo pulse in an acoustic imaging system,[2] to equalize the distortion in a telephone channel,[3] and to suppress an interfering signal.[4]

Most adaptive filters have been implemented using digital techniques. The limitations of the digital approach are the limited bandwidth (5 MHz at the most) and the practical limit on the number of taps dictated by the complexity and power consumption of this approach.[5]

An analog-digital hybrid approach has been implemented using MOS LSI technology.[6] This has the advantage of lowering the power consumption and allowing 32 taps to be used without undue external complexity. Large dynamic range was obtained with this technique (60 dB), but the bandwidth was limited to less than 1 MHz .

Most analog implementations of an adaptive filter have been made using CCD's with analog tap weights held in sample and hold circuits.[7] The limitations here are the narrow bandwidth and variations across the chip in the gain and threshold levels. The alternative approach used at Hughes for implementing a wideband adapting filter is to employ tapped ASW filters with extremely complex computer-controlled systems for adjusting the tap weights.[8]

We shall describe here a relatively simple all-analog approach to adaptive filtering which uses the least mean squared (LMS) algorithm to find the optimal set of tap weights. A SAW monolithic ZnO/Si storage correlator with 8 MHz bandwidth and the equivalent of 24 taps was used.[9] The advantages of this approach are: (1) fast iteration rate (100 kHz) which means a short learning time (~100 μs) and a good ability to track time varying signals; (2) large potential bandwidth (100 MHz); (3) large potential number of taps (1000); (4) lower power consumption (.1 W); and (5) it is suited for radar and communications systems because it can operate directly at the IF frequency. A disadvantage of this system is that at the present time the dynamic range is less than for digital systems.

A brief introduction to the LMS algorithm is provided, followed by a description of two adaptive filter experiments which used the storage correlator. In the first experiment, an undesirable time-delayed ghost pulse is removed. The results of this experiment are compared to computer simulators with the LMS algorithm. Conclusions are drawn regarding which properties and nonlinearities of the storage correlator are limiting the performance of the adaptive filter. In the second experiment, ringing in the impulse response of an acoustic transducer is removed by adaptive filtering.

The LMS Algorithm

Consider an adaptive filter with an input $X(t)$ and output $Y(t) = X * W$. The tap weights W are adjusted after each iteration such that the output $Y(t)$ converges to a desired signal $D(t)$. The time it takes for convergence to occur is commonly called the learning or training time. After the optimum W is determined, the filter can be used to remove the distortions in signals. For example, in a TV system with a ghost, the filter can be trained on the sync signal (which occurs at the end of each line) to remove the echo sync signal, and then the entire TV line can be passed through the filter, and the "ghosts" will be removed.

The error $\varepsilon(t)$ between the desired signal $D(t)$ and the output of the filter $Y(t)$ is

$$\varepsilon(t) = D(t) - Y(t) \tag{1}$$

where

$$Y = X \bigstar W \tag{2}$$

where $\bigstar$ indicates convolution. Then the LMS algorithm specifies that to minimize the error, W must be changed by ΔW such that

$$\Delta W = 2\mu X * \varepsilon \tag{3}$$

where $*$ indicates correlation.

Thus, it follows from Eqs. (1), (2), and (3) that

$$\Delta W = 2\mu X * (D - X \bigstar W) \tag{4}$$

Therefore, for each iteration, a convolution with X, and a correlation with X must be performed. The ASW storage correlator is ideally suited to this purpose, as it can perform these operations directly within the device.

The method we have used for implementing the LMS algorithm with the storage correlator is shown in Fig. 1. In the first step, Fig. 1a, the distorted signal $X(t)$ is applied to the top plate, and the filter output $Y = X * W$ is delayed and subtracted from the desired signal $D(t)$ to obtain the error signal $\varepsilon(t)$. In the second step, Fig. 1b, the tap weights are adjusted. After several iterations and after the filter has converged, it can be used as a fixed inverse filter, Fig. 1c.

The actual method of implementation is indicated in Fig. 2a. If all three ports of the storage correlator were used, Fig. 2b, then the external delay line and the switches would not be needed.

The storage correlator is not an exact implementation of the Widrow type LMS adaptive filter for two reasons. First, the LMS algorithm requires that each tap be changed individually and the error signal for the next tap be calculated after the previous tap is changed. However, in our implementation, the entire error signal is calculated, and the entire set of taps is changed at once. This difference is not significant except for the case of very high gain and very fast convergence. The second difference is that the effect of the plate signal on the tap weights in not linear (Fig. 3). If the error signal is less than the threshold (4 V) the tap weights are unaffected. The error signal is clipped around 9 V so only ~6 dB of dynamic range is available at the tap plate. The characteristic used in the computer simulation is also shown in Fig. 3. If the error signal is fed into an acoustic port (as in Fig. 2), then at least 35 dB dynamic range should be available.

Experiments in Echo Suppression

In this experiment, a square pulse .4 μs long is followed by an echo pulse. For an echo which is 6 dB less in amplitude than the main pulse (Fig. 4a), the sidelobe suppression after 22 iterations (450 μs) is 15 dB, as shown in Fig. 4b. The dependence of sidelobe suppression on echo height is shown in Fig. 5. The results of computer simulations of the LMS algorithm with 24 taps and using clipping and a threshold 6 dB below the clipping level are also shown in Fig. 5. The computer simulation agrees very well with experimental results except that the maximum sidelobe suppression is 23.5 dB which is 4.5 dB higher than was experimentally obtained. We note that clipping of the signal increases the rate of convergence radically, as has been noted by others. The algorithm employed is therefore known as the clipped LMS algorithm.

An important result obtained in this experiment is that spurious acoustic signals generated by the plate readout signal can be suppressed by up to 13 dB as a result of the adapting process. The filter does not distinguish between echoes and distortions generated externally or by the device itself. This result is demonstrated in Fig. 6. The upper trace is the adaptive filter result after removing an echo from a .4 μs long pulse. If all signals except the plate readout signal are removed, the output (lower trace) is the spurious signal generated by the plate signal. A large spurious signal can be seen when previously there had been a null.

The advantage of computer simulation is that the threshold and clipping levels may be easily changed to see what effect they have on the performance of the adaptive filter. These results are summarized is Table I. The computer-simulated linear LMS result is given in the first row. If a threshold level is included, then the computer simulation converges much faster, but to worse results. The values obtained are in agreement with experimental results. If the feedback gain is increased so that the error signal is now clipped, then much better sidelobe suppression is obtained in both the experimental and computer simulation cases.

Regardless of the shape of the desired signal (D) and input signal (X), it was always experimentally observed that the feedback gain must be large enough to strongly clip the error signal during the first few iterations for the optimum filtering. After many iterations, the error signal is only slightly clipped.

The results are, on the whole, in excellent agreement with the computer simulations. Thus, it appears that we are operating the storage correlator in the optimum manner, and have a good understanding of the operation of the device.

Experiments on Reduction of Bulk Transducer Ringing

The object of this experiment was to improve the impulse response of a bulk wave 1.25 MHz acoustic transducer used for acoustic NDE. The impulse response is shown in Fig. 7a. If the impulse response is correlated with itself (Fig. 7b), the highest sidelobe is 1.7 dB smaller than the peak. However, if the correlator is used as an adaptive filter, then the sidelobe can be reduced to 7 dB below the peak after 10 iterations (Fig. 7c) and 10 dB below the peak after 35 iterations.

The dependence of peak, sidelobe, and spurious signal levels on the number of iterations is shown in Fig. 8 for the bulk transducer experiment. Spurious signals are considered to be any of the peaks due to the readout signal. Sidelobe peaks are those peaks which result from the fact that the number of taps is finite, not infinite, and consequently the filter output is not exactly a single pulse.

Linear LMS theory predicts[1] that the time averaged mean square error (MSE) should decay exponentially to a constant value. The ratio of this constant value to the Wiener solution is called the misadjustment M. The misadjustment is approximately related to the decay constant τ by the relation[1]

$$M = N/4\tau \, , \tag{5}$$

where N is the number of tap weights. Thus, the faster the convergence the larger the misadjustment.

The experimentally observed decay of the MSE for the bulk transducer case is shown in Fig. 9. The decay is exponential except for the first few iterations when the error signal is strongly clipped. The decay constant is .136, and the misadjustment calculated from Eq. (2) is ≈ .8. We interpret this to mean that the final result is close to (but slightly worse) than the Wiener solution.

Limitations

A major limitation of this device is the bandwidth (8MHz). It can work well as an adaptive filter for a 1.25 MHz transducer, but it works poorly for a 2.5 MHz transducer. The diode array length (3 μs) is also a limitation since we cannot adapt signals which are longer than this. Also, since the correlation signal is truncated, the filter output is distorted. These two limitations are manifestations of the fact that if the correlator had a larger time bandwidth product than 24 , then it would equivalently have more taps, and could adapt a broader class of signals and do a better job of it. Note, however, that Eq.(5) predicts that if the number of taps is increased, then the convergence time also increases (for a given level of misadjustment). Thus, a larger number of taps is not desirable for applications in which the distortion is changing rapidly. For example, if the timing or amplitude of the echo significantly changes over a time period of 300 μs (10 iterations), then a larger number of taps would not be desirable.

Conclusions

It was demonstrated that a -6 dB echo could be suppressed to -15 dB in 400 μs (22 iterations). Computer simulations of the LMS algorithm with a threshold and clipping agree with experimental observations.

The sidelobe of the impulse response of a 1.25 MHz acoustic bulk transducer can be reduced from -2 dB to -10 dB with adaptive filtering.

The advantages of using a clipped LMS algorithm with a storage correlator over other techniques are (1) faster iteration rate coupled with a smaller number of iterations needed for convergence;

(2) broader bandwidth (100 MHz should be attainable); (3) less power consumption; and (4) the correlator can work directly at the radar or communications system IF frequency.

References

1. J. M. McCool and B. Widrow, IEE Conf. Publ. 144, 84, (1976).
2. D. Corl, El. Lett. 14, 60, (1978).
3. R. W. Lucky, Bell System Tech I, 66, 547 (1965).
4. P. M. Grant, and G. S. Kino, El Lett, 14, 562 (1978).
5. D. Behar, G. S. Kino, H. Olaisen, D. Corl and P. M. Grant, "The Use of a Programmable Filter for Inverse Filtering," Submitted for Publication, Electronics Letters, August, 1979.
6. B. K. Ahuja, M. A. Copeland, and C. H. Chan, IEEE J. Solid-State Cir., 14, 148 (1979).
7. D. F. Babe et al, IEEE J. Solid-State Cir., 13, 34 (1978).
8. W. K. Masenten, "Adaptive Processing for Spread Spectrum Communications Systems, Report No. TP 77-14-22, Hughes Aircraft Co., Sept. 27, 1977.
9. D. Behar, G. S. Kino and H. Olaisen, "The Storage Correlator as an Adaptive Inverse Filter," Submitted for Publication, Electronics Letters, August, 1979.

FIGURE LEGENDS

1. Use of storage correlator adaptive filter.
2. Actual (a) and proposed (b) implementation of SAW adaptive filter.
3. Correlator output as a function of plate (readout) pulse height.
4. (a) Input signal; and (b) Output signal after 22 iterations.
5. Experimental and computer simulation results for echo suppression experiment.
6. Echo reduction after 10 iterations (upper trace). Spurious signals generated by plate read-out signal (lower trace).
7. (a) Impulse response of 1.25 MHz bulk acoustic transducer; (b) Autocorrelation of impulse response; and (c) Filter output after 10 iterations of adapting.
8. Signal levels during adapting process.
9. Decay of mean squared error with time for adaptive filtering of bulk wave transducer impulse response.

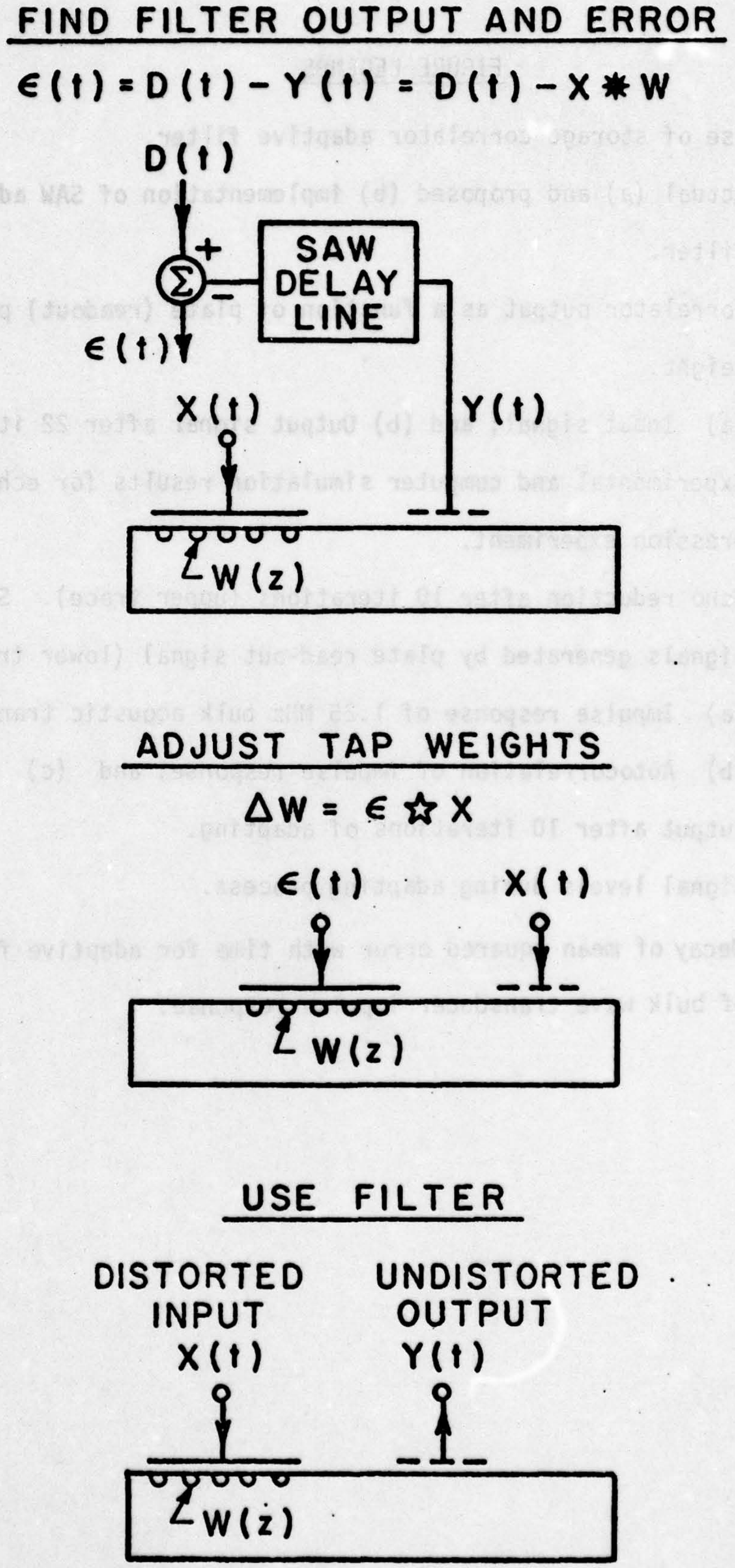

FIND FILTER OUTPUT AND ERROR
$\epsilon(t) = D(t) - Y(t) = D(t) - X * W$
D(t)
+
Σ
−
SAW
DELAY
LINE
ε(t)
X(t)
Y(t)
W(z)
ADJUST TAP WEIGHTS
$\Delta W = \epsilon \star X$
ε(t)
X(t)
W(z)
USE FILTER
DISTORTED
INPUT
X(t)
UNDISTORTED
OUTPUT
Y(t)
W(z)

Fig. 1.

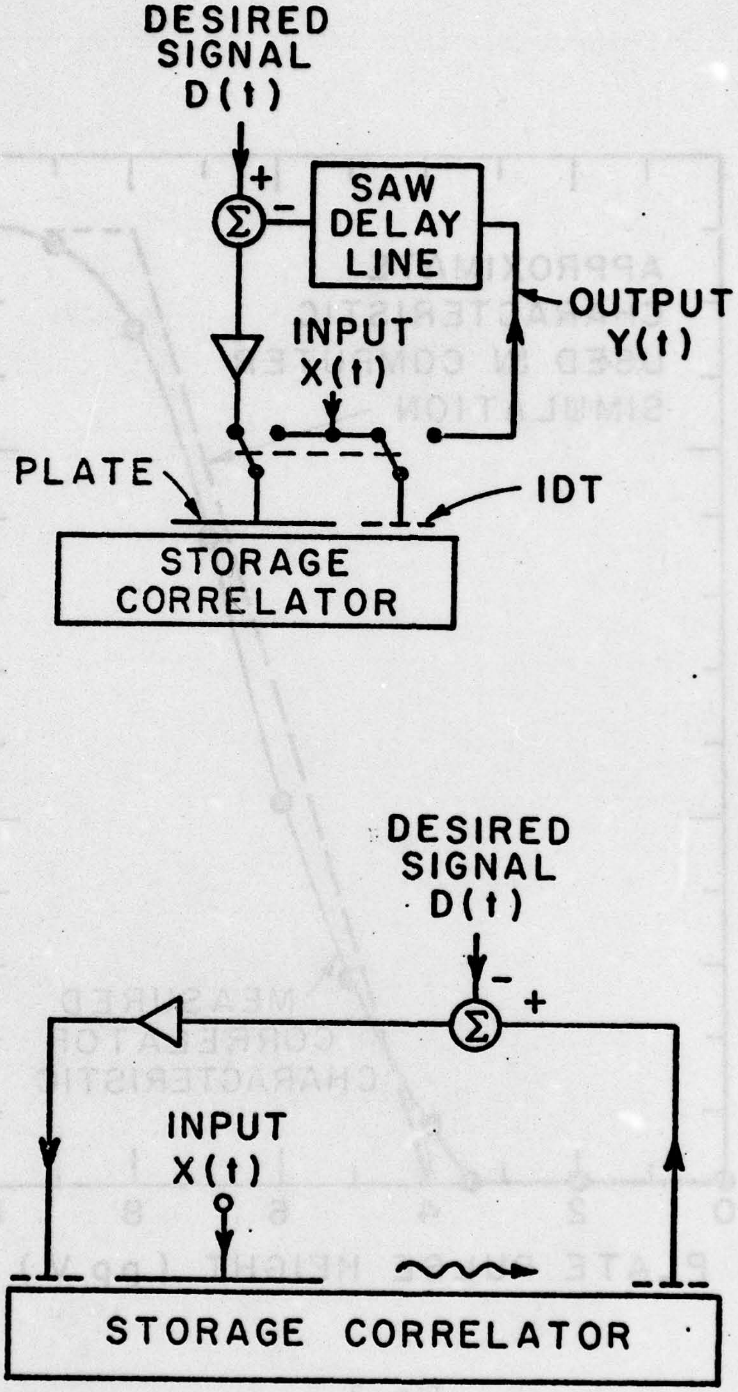

DESIRED SIGNAL D(t)
+
−
Σ
SAW DELAY LINE
OUTPUT Y(t)
INPUT X(t)
PLATE
IDT
STORAGE CORRELATOR
DESIRED SIGNAL D(t)
−
+
Σ
INPUT X(t)
STORAGE CORRELATOR

Fig. 2.

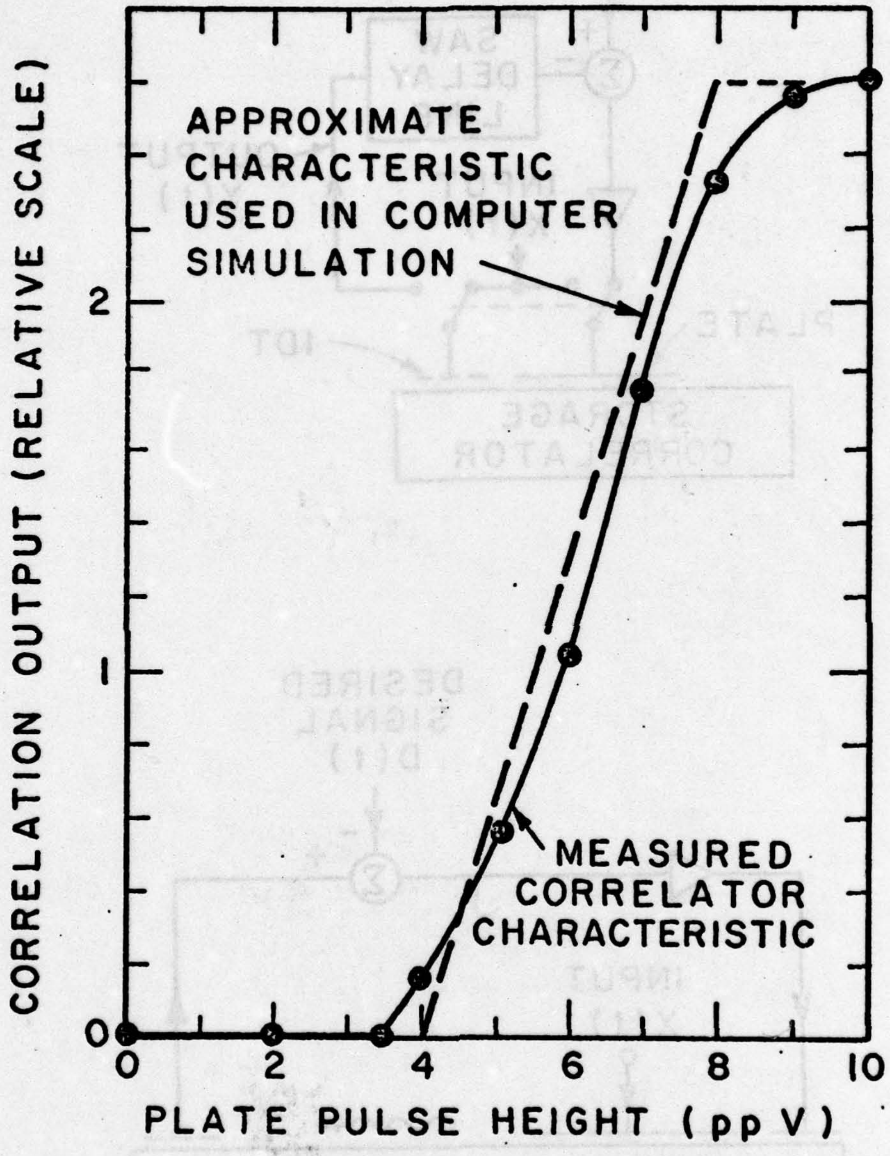

APPROXIMATE CHARACTERISTIC USED IN COMPUTER SIMULATION
MEASURED CORRELATOR CHARACTERISTIC
CORRELATION OUTPUT (RELATIVE SCALE)
0
1
2
0
2
4
6
8
10
PLATE PULSE HEIGHT (pp V)

Fig. 3.

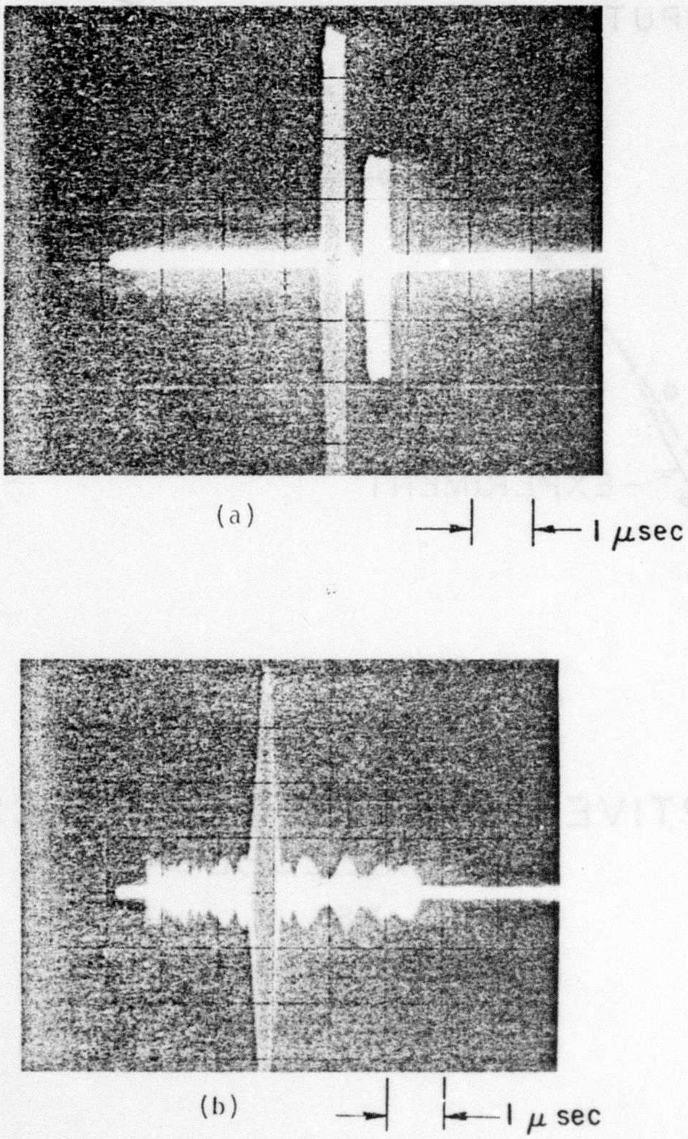


Fig. 4.

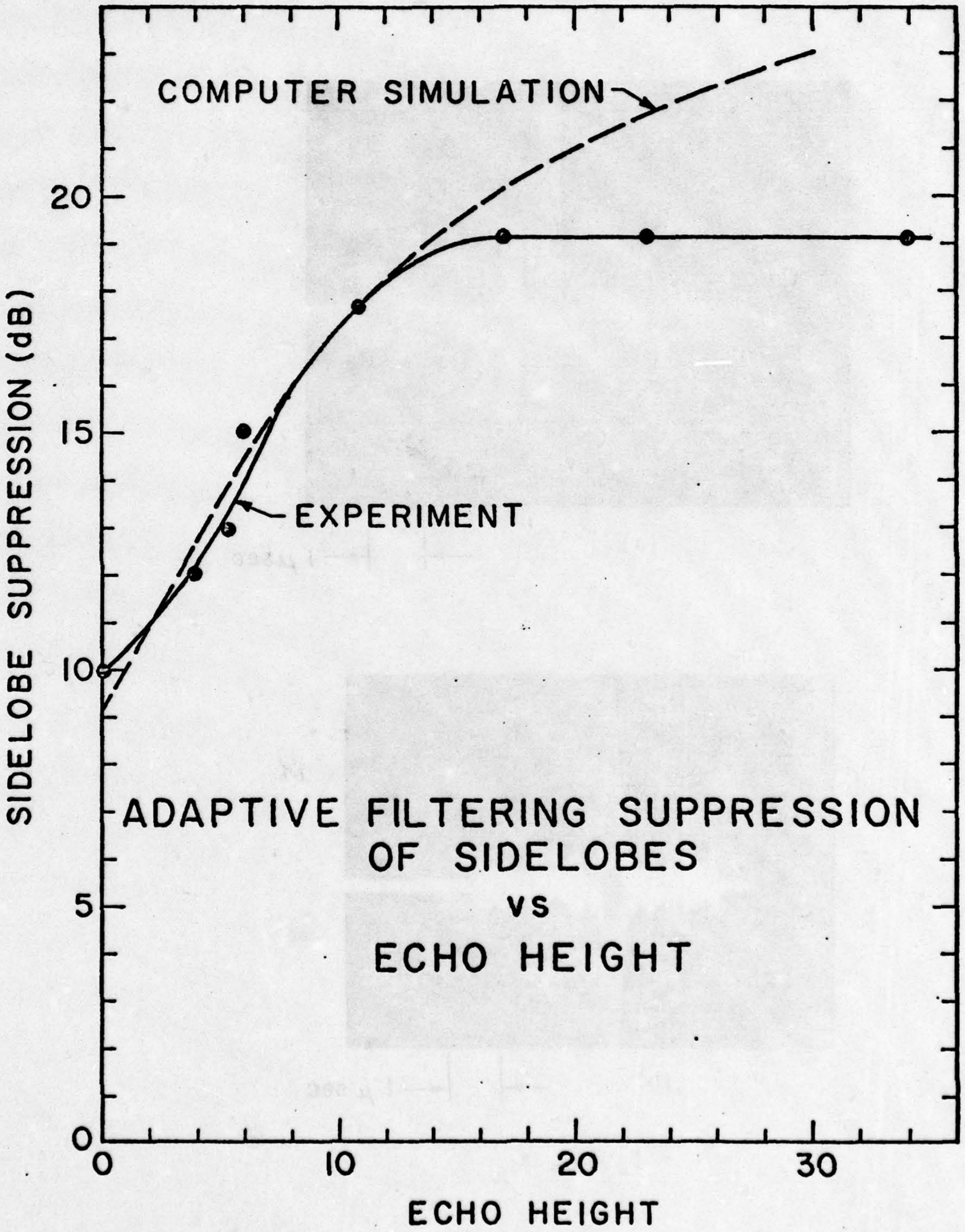

COMPUTER SIMULATION
EXPERIMENT
ADAPTIVE FILTERING SUPPRESSION OF SIDELOBES vs ECHO HEIGHT
SIDELOBE SUPPRESSION (dB)
0
5
10
15
20
0
10
20
30
ECHO HEIGHT

Fig. 5.

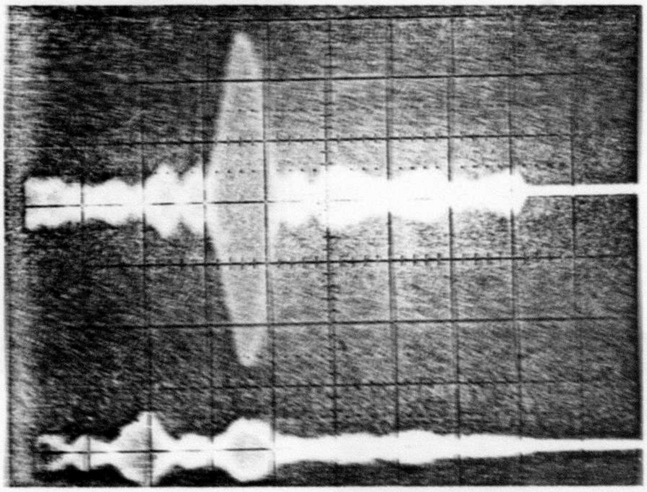
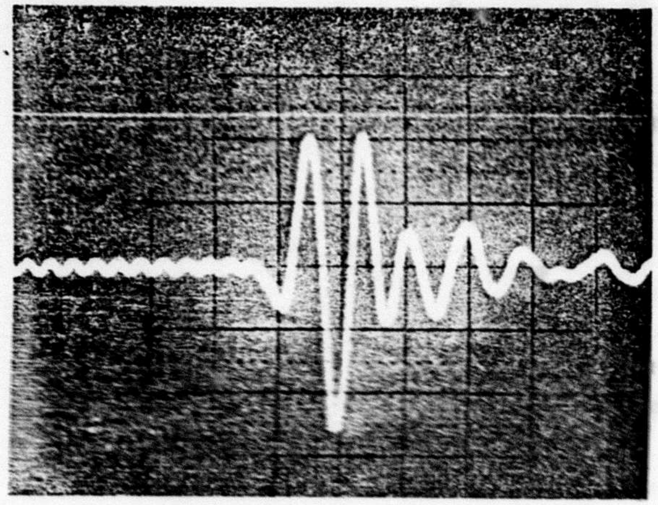
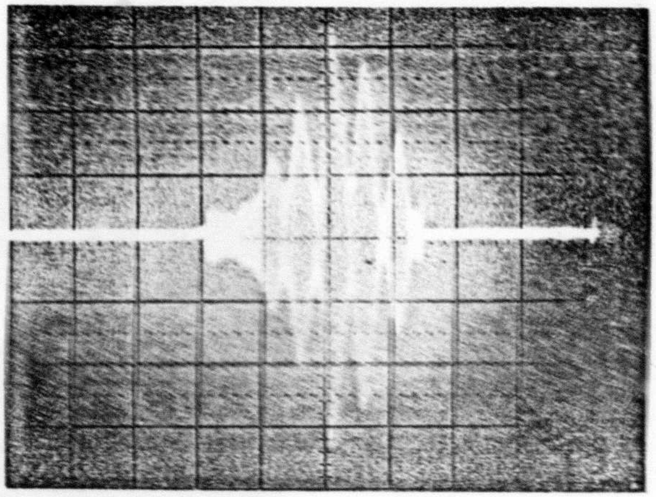


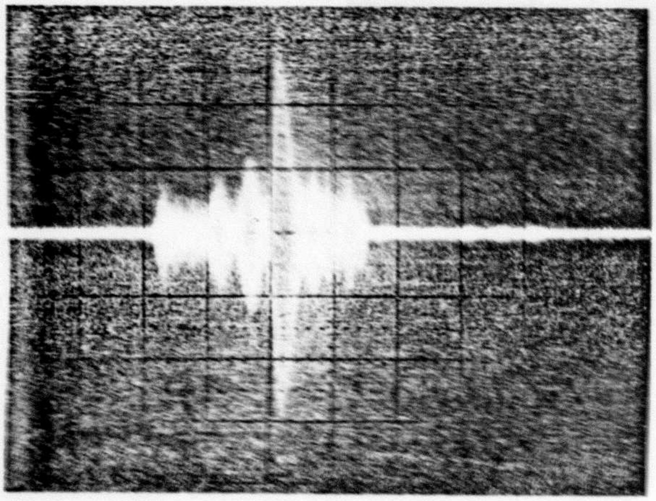
Fig. 6.



(a)

(b)





(c)

Fig. 7.

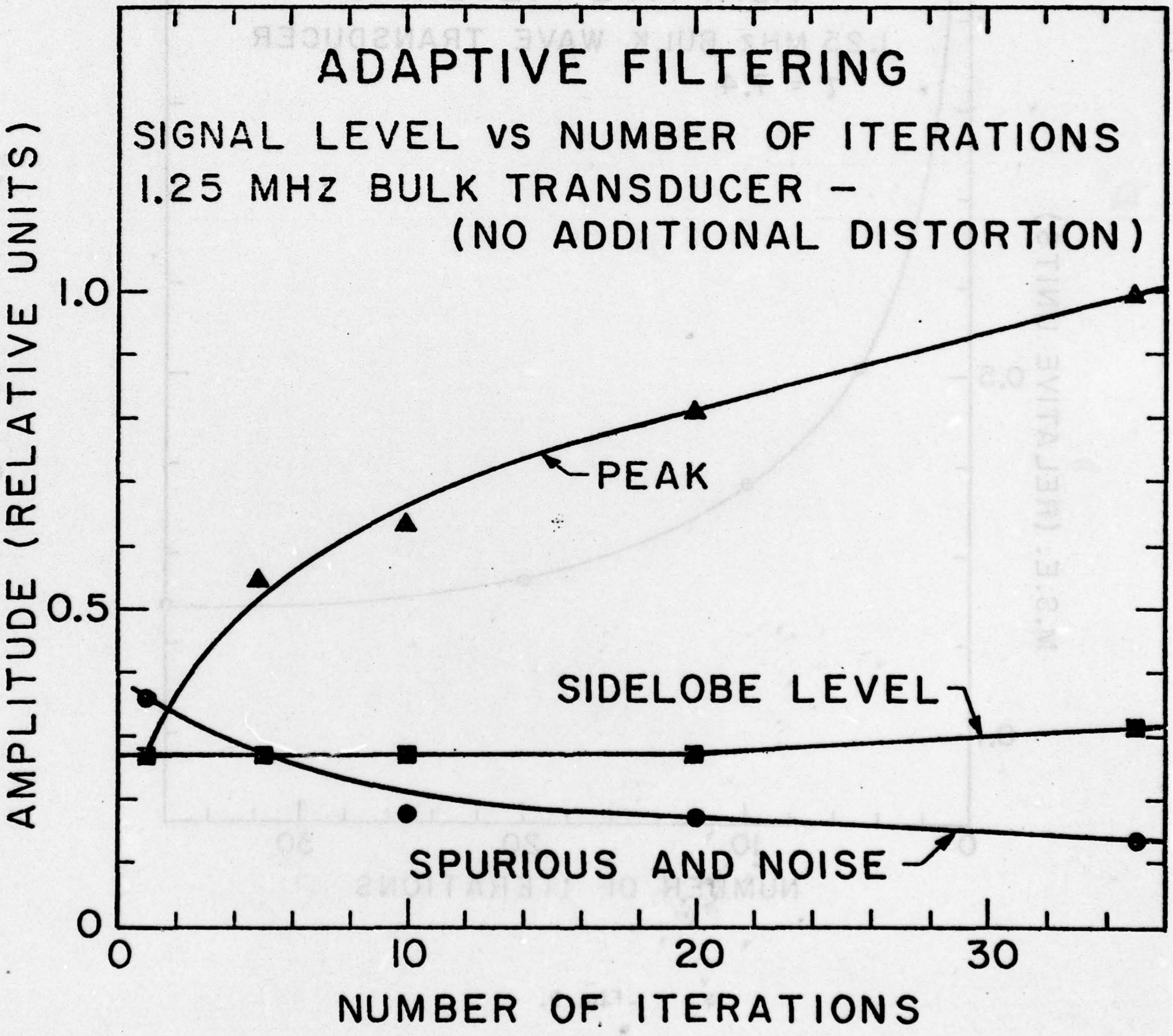

ADAPTIVE FILTERING
SIGNAL LEVEL vs NUMBER OF ITERATIONS
1.25 MHz BULK TRANSDUCER – (NO ADDITIONAL DISTORTION)
AMPLITUDE (RELATIVE UNITS)
1.0
0.5
0
PEAK
SIDELOBE LEVEL
SPURIOUS AND NOISE
0
10
20
30
NUMBER OF ITERATIONS

Fig. 8.

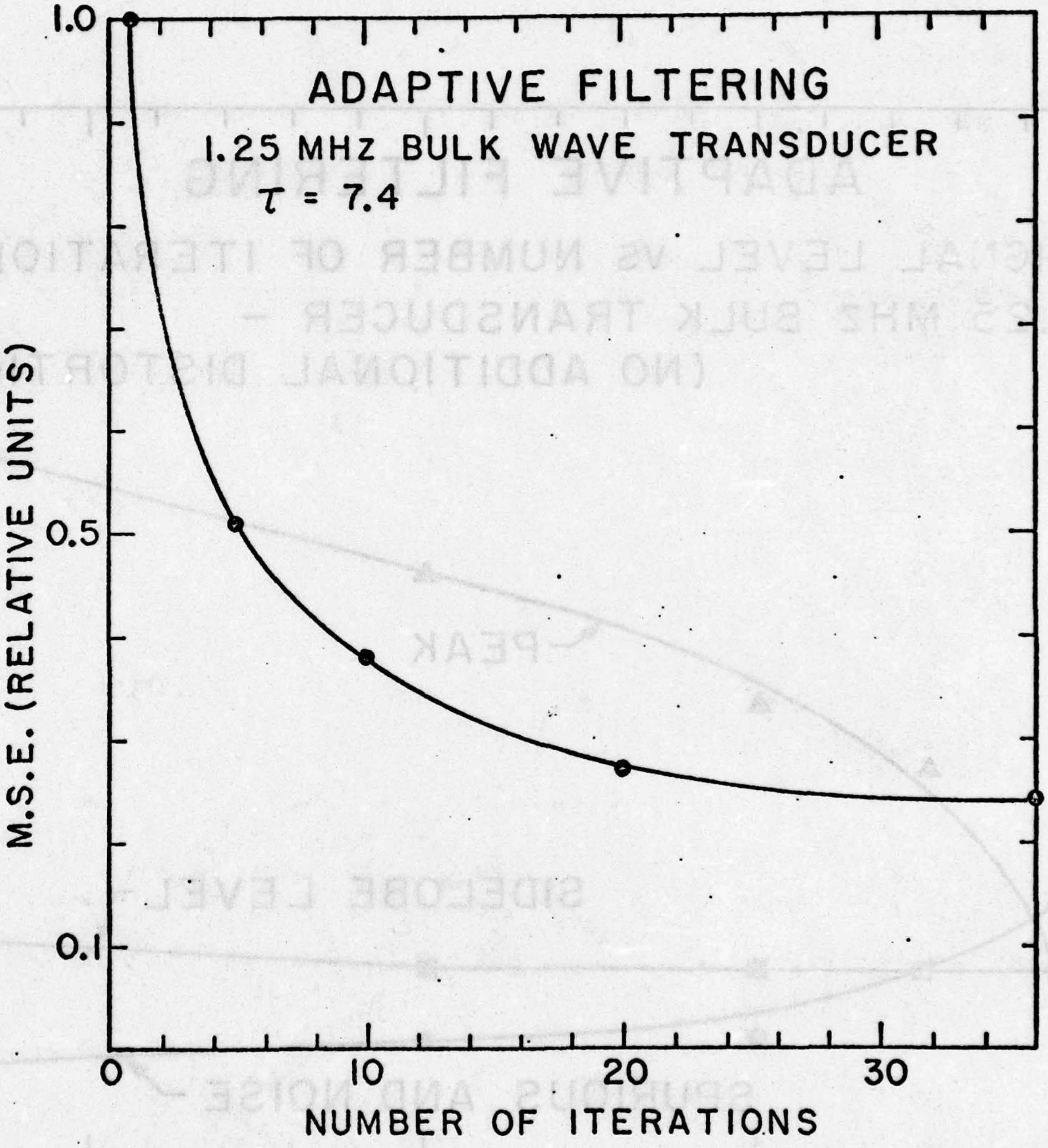

ADAPTIVE FILTERING
1.25 MHz BULK WAVE TRANSDUCER
τ = 7.4
M.S.E. (RELATIVE UNITS)
1.0
0.5
0.1
0
10
20
30
NUMBER OF ITERATIONS

Fig. 9.

TABLE I

Experimental Results And Computer Simulations For A Filter Input Of A .4 μs Wide Pulse With A 60 dB Echo.
The Computer Simulation Uses 24 Taps.

	STORAGE CORRELATOR RESULTS		COMPUTER SIMULATION	
	Sidelobe Suppression (dB)	Number of Iterations for Convergence	Sidelobe Suppression (dB)	Number of Iterations for Convergence
Linear	---	---	14.0	25
Threshold*	10.0	5	10.7	4
Threshold and Dipped	14.8	10	14.2	6

*The maximum feedback signal (ϵ) was not more than 6 dB above the threshold level.

C. SEZAWA MODE INVESTIGATION

A limitation of Rayleigh wave ZnO on Si storage correlators is the narrow bandwidth of the SAW transducers. The coupling coefficient $\Delta v/v$ in ZnO/Si is .005 , which is one fifth of the coupling coefficient in $LiNbO_3$. Consequently, the fractional bandwidths obtained with simple tuning circuits are only 5-10% rather than the 30-40% obtained in $LiNbO_3$/Si separated medium storage correlators.

One way to increase $\Delta v/v$ in ZnO/Si structures is to use thick layers of ZnO since a second maximum in $\Delta v/v$ occurs for hk ~3 (see Fig. 1). This approach has been used extensively by the Japanese to make TV IF filters. This approach has not been pursued here because very thick layers of ZnO are needed, and, in addition, the transducers must be at the ZnO/Si interface. This complicates the transducer fabrication.

A second method to increase $\Delta v/v$ is to use second order Rayleigh waves, commonly called Sezawa waves. Armstrong and Campin[1] have calculated $\Delta v/v$ for (Zx)ZnO on (Zx)Si and found coupling coefficients as high as .023 . Elliot et al[2] have experimentally supported this result, obtaining a value for $\Delta v/v$ of .019 . As this approach has many advantages, for instance, it employs a transducer on the top surface of the ZnO , we have decided to pursue it.

Our theoretical work on Sezawa waves has utilized the computer program[3] developed at Stanford for determining the velocity and potential distributions for surface acoustic waves propagating on substrates with a single layer on the surface. Our initial analysis has been on the structure (ZX)ZnO on (ZX)Si . Fig. 2 shows all of the different waves which can exist in this structure for a film thickness $h < 5/k$, i.e., $h/\lambda < 1$. All of our monolithic storage correlator work to date has utilized the first order Rayleigh mode with $hk = .5$, i.e., $h/\lambda x \cdot 1$. The two Love modes shown in Fig. 2 are not excited by interdigital transducers and thus do not cause spurious signals in the device.

The Sezawa mode is cut off at $hk = .70$, i.e., for radian frequencies ω less than $\omega_c = .70\ v_s/k$, the wave does not propagate. For $hk > .7$, the slope of the velocity curve in Fig. 2 for the Sezawa wave is less than for the Rayleigh wave at $hk = .5$, i.e., the Sezawa mode is less dispersive. This is important for large bandwidth signal processing applications.

The coupling coefficient for Sezawa waves for four different transducer configurations is shown in Fig. 3. Coupling coefficients as large as .028 are predicted by our computer analysis. Experimentally for Rayleigh waves, we have measured $\Delta v/v$ to be typically 85% of the theoretical value. This would give a value of $\Delta v/v = .024$, which is equal to the coupling coefficient of $LiNbO_3$.

Our future work in this area will include: (1) a theoretical study of ZnO/Si structures using (1) Si and (2) construction of a Sezawa wave delay line. If the experimental results are as encouraging as we expect, a Sezawa wave storage correlator will be constructed.

To summarize, the advantages of using the Sezawa waves rather than Rayleigh waves are: (1) higher coupling coefficient (this means broader bandwidth transducers and higher efficiency convolvers and correlators), and (2) less velocity dispersion. Sezawa waves also have higher velocity which means the devices can operate at a higher frequency with broader bandwidth, however, the use of higher velocity does not help the time bandwidth product.

References

1. G. A. Armstrong, and S. Crampin, Elec. Lett. 9, 322 (1973).
2. J. K. Elliott, R. L. Gunshor, R. E. Pierret and A. R. Day, Appl. Phys. Lett., 32 (9), 515 (1979).
3. R. Wagers, Ph.D. Thesis, Stanford University.

FIGURE LEGENDS

Fig. 1. $\Delta v/v$ vs. hk at constant frequency for the ZnO/Si structure with the orientations shown.

Fig. 2. A plot of the dispersion characteristics of various types of modes for ZnO on Si .

Fig. 3. Calculated coupling coefficients for Sezawa waves with a different configuration.

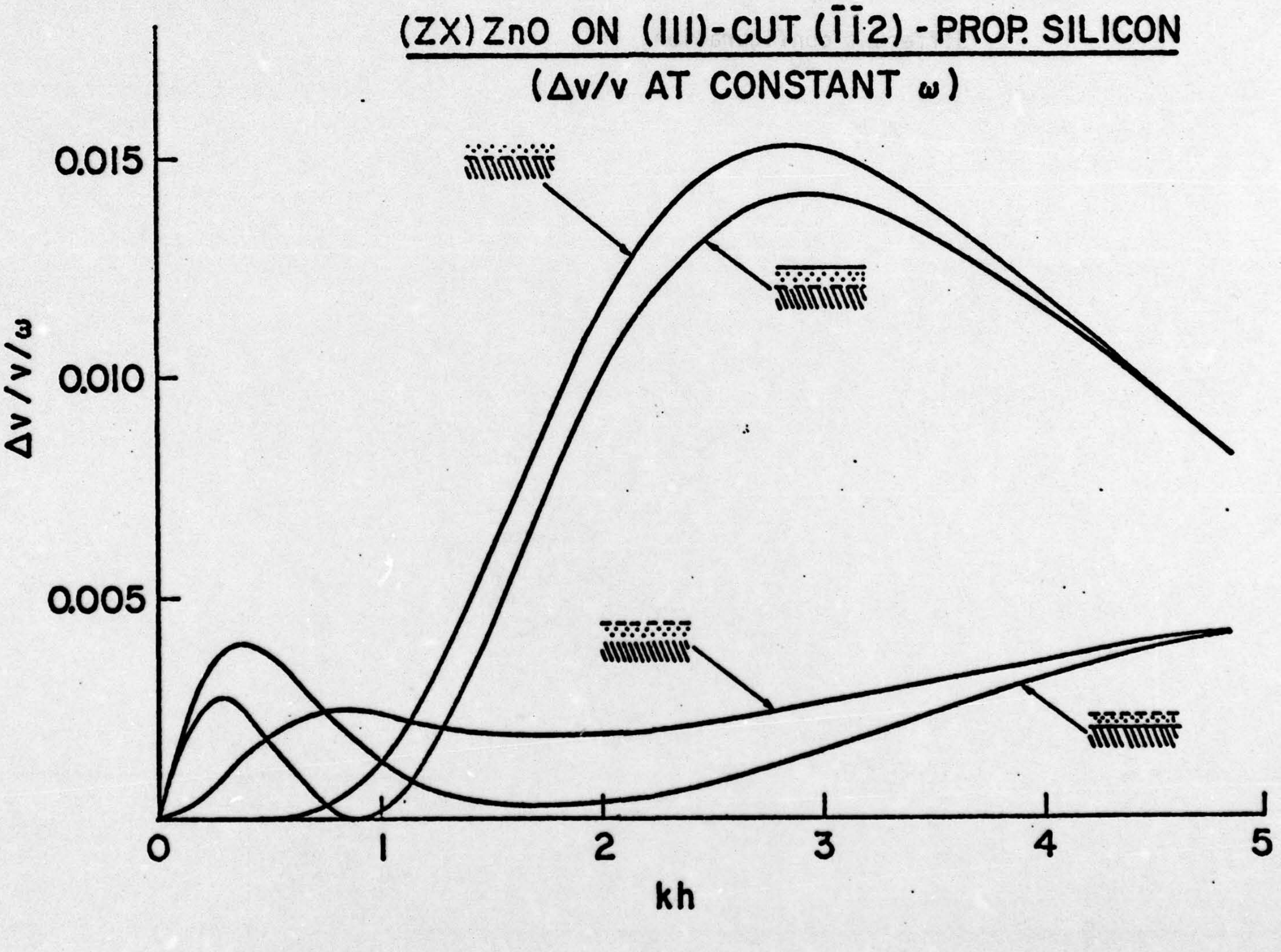

(ZX) ZnO ON (111)-CUT (1̄1̄2) - PROP. SILICON
(Δv/v AT CONSTANT ω)
Δv / v / ω
0.015
0.010
0.005
0
1
2
3
4
5
kh

Fig. 1.

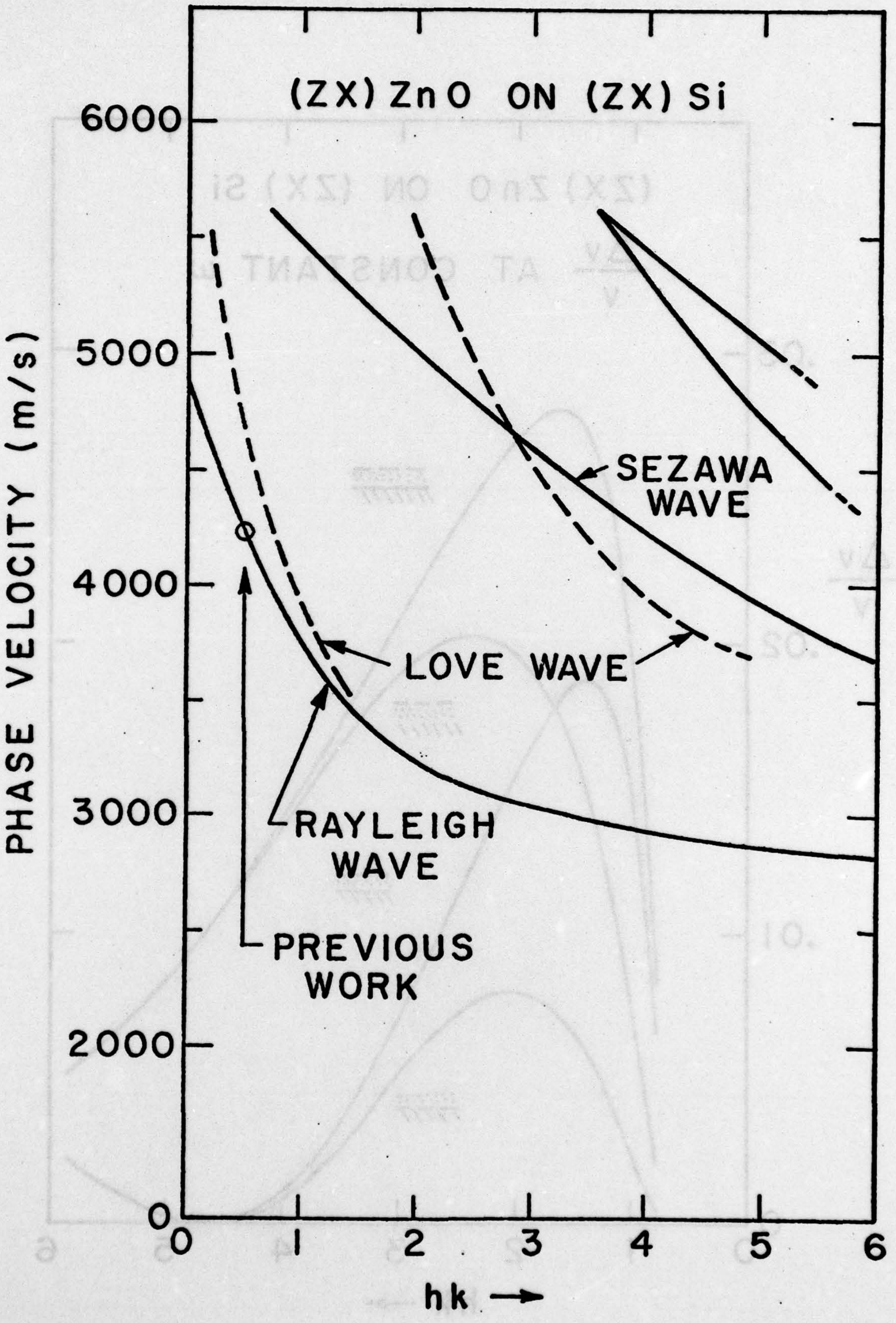

(ZX) ZnO ON (ZX) Si
PHASE VELOCITY (m/s)
6000
5000
4000
3000
2000
0
0
1
2
3
4
5
6
hk →
SEZAWA WAVE
LOVE WAVE
RAYLEIGH WAVE
PREVIOUS WORK

Fig. 2.

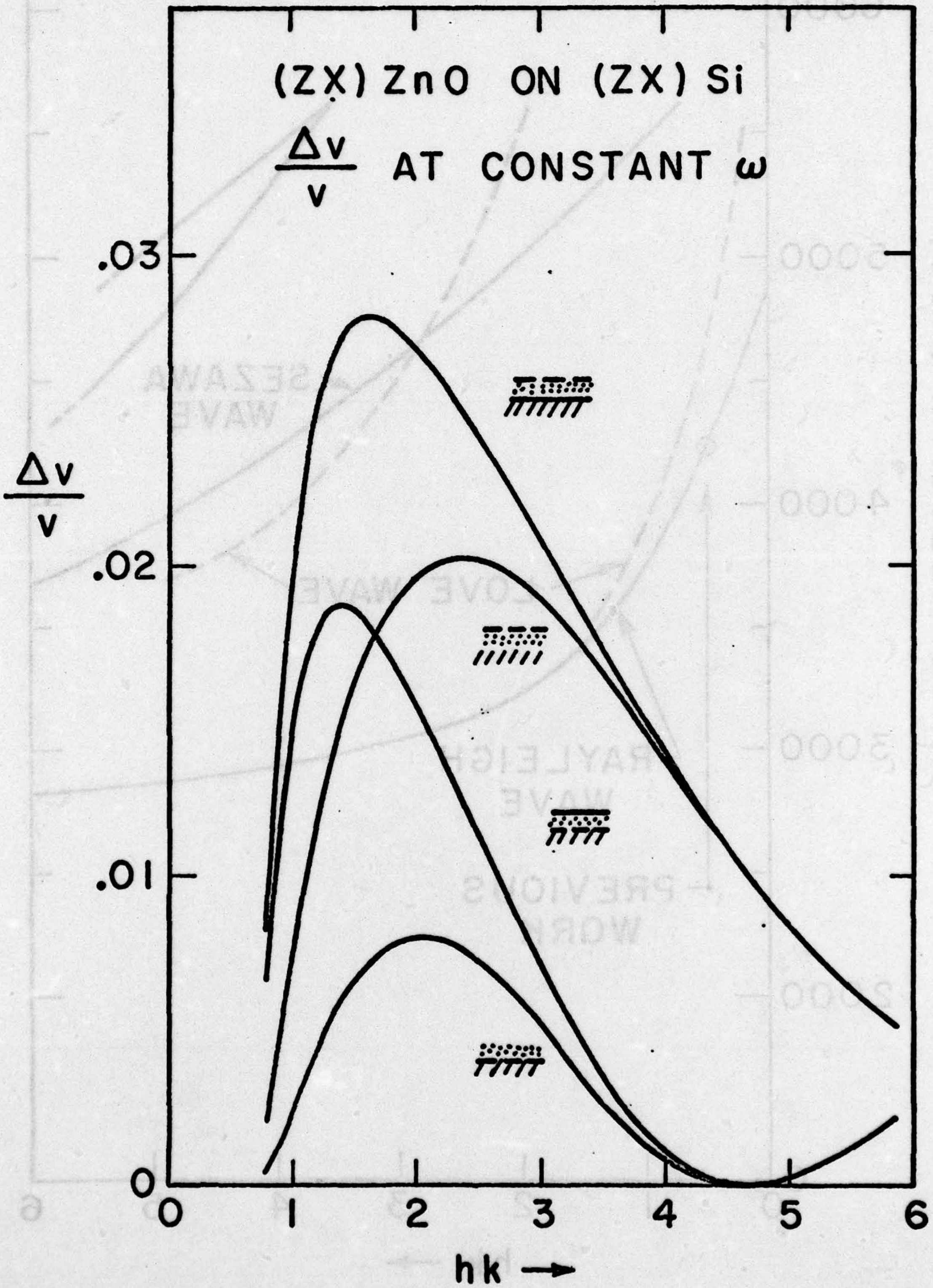

(ZX) ZnO ON (ZX) Si
$\frac{\Delta v}{v}$ AT CONSTANT ω
$\frac{\Delta v}{v}$
.03
.02
.01
0
0
1
2
3
4
5
6
hk →

Fig. 3.

D. SCHOTTKY DIODE STORAGE CORRELATOR

Introduction

During the last six months, we have embarked on a program to fabricate a Schottky diode monolithic ZnO on Si storage correlator. Such correlators would be advantageous because of their rapid turn on time (a fraction of a nanosecond), the predictability of their characteristics, their long storage times, and the fact that they should still be operable in the integration mode with long input integration times. Most of these concepts have been demonstrated with air-gap Schottky diode correlators, but have not been demonstrated with a monolithic ZnO on Si system, where they would yield the same advantages. We feel that we are now in a good position to make a device of the type illustrated in Fig. 1 because of the improvement in the ZnO on Si sputtering deposition technology, employing the magnetron sputtering system, which we now have operating in the laboratory.

ZnO on Si Schottky Diode Storage Correlator

The first part of this program was to develop an optimum Schottky diode fabrication process. We have had quite good success using platinum silicide as the metallization material. Due to the rather unique fabrication process, PtSi offers the advantage of a "self-aligning" diode array in that only one mask is needed to define both contact windows in an oxide layer and the metallization pattern for the platinum silicide. This is true because platinum, upon heating above ~600°C , reacts with silicon to form PtSi , but does not react with SiO_2 . Therefore, if one etches windows in the oxide and deposits a uniform layer of platinum, followed by the annealing process, one can subsequently etch the remaining free platinum and have PtSi diodes remaining.

Several large area test diodes were fabricated using this process, and, after overcoming initial problems with cleanliness of the surfaces, quite good diode characteristics were achieved. Fig. 2 shows the linearity of the forward characteristics, corresponding to n-values of around 1.02 and barrier heights of roughly .85v , in good agreement with expected values. The reverse breakdown voltage of all these diodes was well over 150 volts.

Using this technology, we are now in the process of fabricating storage correlators. We first made a convolver by this technique and obtained promising results yielding a device with a transducer insertion loss of 30.5 dB and an overall convolution efficiency of -68 dBm . These numbers have promise of improvement, as the ZnO quality from that particular run was not the best, as evidenced by a bulk rod with a round trip insertion loss of 12 dB , as compared to 9 dB or better with some of the better runs (see Section E). One of the problems with the ZnO on this particular run as well as some of the previous runs was a cloudiness in the ZnO film at the edges of the sample. This later was found to be due to a faulty thermocouple which was giving erroneously low readings for the substrate temperature when in fact the temperature was high enough to cause the gold to react with the titanium layer beneath it, thus presenting a very poor surface for deposition. This problem has since been corrected.

This device has been tested for storage effects by attempting to modulate the convolution efficiency via a pulse on the top plate, and the results looked quite promising, as shown in Fig. 3. It can be seen that the convolution efficiency decreases for the duration of a 1 ms pulse applied to the top plate, and returns to an enhanced value when the pulse is removed (due to charge storage in the diodes). As charge slowly leaks out of the diodes, the efficiency returns to its zero bias value.

Unfortunately, during the course of these experiments, an excessive voltage was applied to the top plate, breaking down the ZnO and shorting the top-plate to the diode array. Fabrication of new test devices is under way.

For long storage times, the quality of the oxide film over the diode array must be high, so that it is an effective insulator. With PtSi it is necessary to sputter deposit a layer of SiO_2 on top of the diode arrays before ZnO deposition, resulting in a less dense oxide than is possible with thermal oxidation. This concern has prompted us to consider another technology for the diode arrays. Tungsten silicide (WSi_2), when deposited on silicon, forms a Schottky barrier. Moreover, it is possible to grow a thermal oxide on top of a layer of WSi_2, partly using a Si substrate and partly consuming the Si in the WSi_2, forming W_2Si_5, which also forms a Schottky contact.

The prospect of growing a thermal oxide on top of the diodes seems at this point to be worth the disadvantage of having to use a two-step process for etching windows in the oxide with one mask, depositing WSi_2 over the entire surface, and then using a second mask to define the pattern of the metal. We are therefore in the process of fabricating and characterizing WSi_2 Schottky barrier diodes, along with investigating the possibility of depositing WSi_2 on bare silicon, etching through to the silicon to define the diodes and then growing an oxide everywhere. Thus, in the future, we will be pursuing both approaches for making Schottky diode correlators, and we will then choose the optimum one.

FIGURE LEGENDS

Fig. 1. Schematic of the ZnO on Si storage correlator.

Fig. 2. Forward characteristics of 2mm , ½ mm (numbered on reverse) diameter PtSi Schottky Barrier Diodes.

Fig. 3. Top Trace: Pulse applied to top plate.

Bottom Trace: Response of convolution efficiency to pulse.

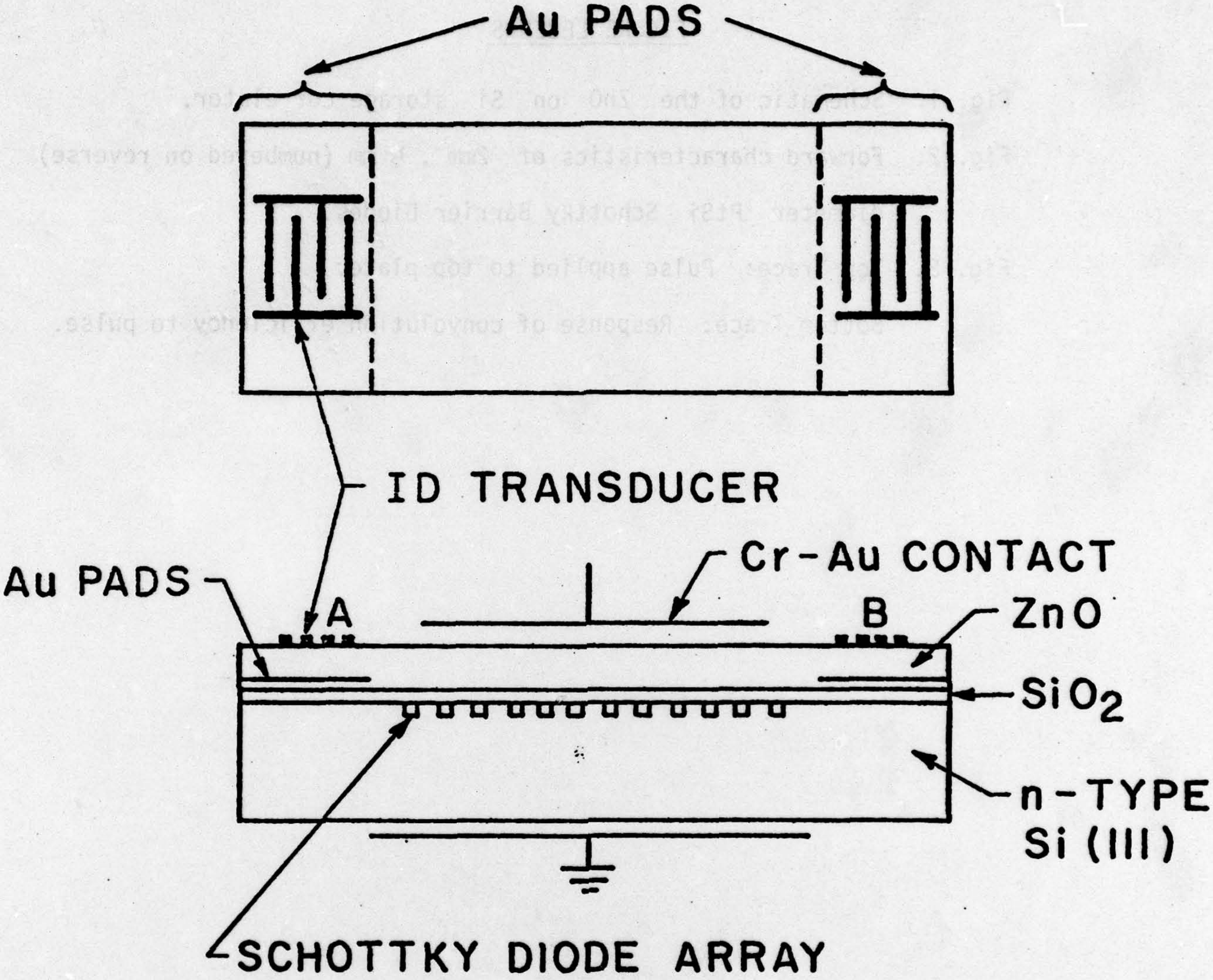
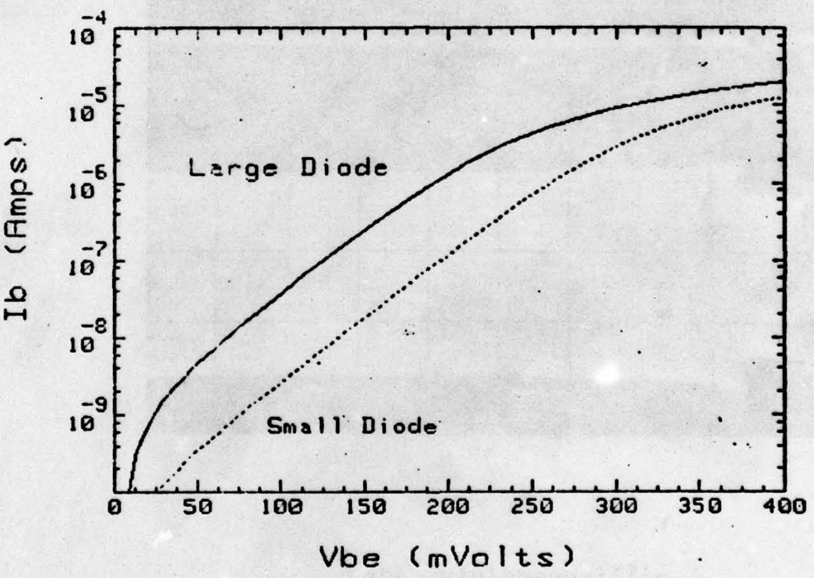

Au PADS
ID TRANSDUCER
Cr-Au CONTACT
Au PADS
A
B
ZnO
SiO2
n-TYPE
Si (III)
SCHOTTKY DIODE ARRAY

Fig. 1.



10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
Ib (Amps)
Large Diode
Small Diode
0
50
100
150
200
250
300
350
400
Vbe (mVolts)

Fig. 2.

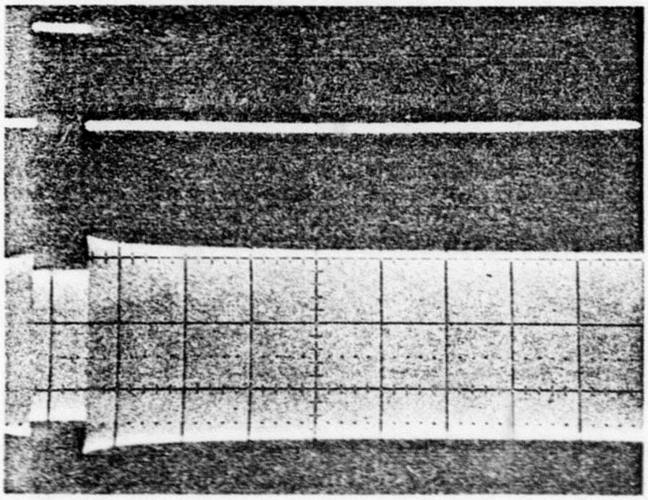


Fig. 3.

E. ZnO TECHNOLOGY DEVELOPMENT

In our last progress report, we described our new ZnO planar magnetron discharge sputtering system. This has the advantage of a radically increased sputtering rate (a factor of 6) over the previous system, and far better reproducibility than with the previous rf discharge system. For instance, we have made several essentially identical convolvers, and the quality of the films deposited on thermally-grown SiO_2 on Si is consistently far better than the layers that we were able to grow with the previous system, with no troubles with reproducibility.

There have been some problems with ZnO deposition on metal, especially Au because of the higher substrate temperatures with which we are now working in order to obtain near to epitaxial growth. Consequently, we are presently in the process of determining the optimum sputtering conditions on a variety of metallic substrates, namely Au, Pt, and Al. We decided to try sputtering on Pt and Al because the Ti-Au or Cr-Au systems tend to flow at the sputtering temperatures presently used and give a rough surface over which the ZnO is being sputtered. This deteriorates the efficiency of the piezoelectric coupling. A Pt layer instead of Au would eliminate this difficulty. The substrate temperature at which we expect to obtain our best ZnO films is 500°C, which corresponds roughly to one third of the melting temperature of ZnO. The quality of the ZnO films obtained is evaluated by measuring the round trip, tuned insertion loss of a bulk transducer resonant at 1 GHz, on a sapphire delay line 2mm long.

At a substrate temperature of 300°C, the insertion loss of the transducer is 10 dB for an Au film on the substrate, 8.5 dB for a Pt film on the substrate, and 13 dB for an Al film on the substrate. These latter results are encouraging, for they are far better than we had ever done before on these metals. We expect all these insertion losses to go down as the substrate temperature is increased. We hope to get the loss down to about 6 dB when the ZnO films should have a coupling coefficient of over 90% of the single crystal value. We will be evaluating the best ZnO films we obtain by x-rays and electron diffraction as we described in our previous report.

We have made several standard convolvers and Δv/v 100 μm wide waveguide convolvers (on another contract) on silicon using our ZnO technology in its present form. The standard convolvers had an overall efficiency of F_τ = -54 dBm, which is the best efficiency reported to date despite having transducers with a conversion efficiency 10 dB worse than our best previous convolver (F_τ = -57 dBm). Obviously, the ZnO film over the oxidized silicon is of excellent quality, far better than we had ever done in our previous sputtering system. Furthermore, every device made by this technique seems to show a comparable efficiency. Several Δv/v waveguide convolvers also gave excellent results, with an overall efficiency of -45 dBm, by far the best efficiency ever reported for ZnO on Si convolvers and comparable to the best observed efficiency for an air-gap convolver (-42 dBm). We should be able to improve the efficiency of both devices by about 10 dB once we realize the optimum conditions for sputtering on a metallized surface.