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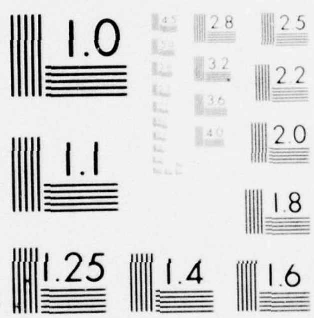

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Interim Technical Report
February 1977

MICROWAVE ACOUSTIC AND BULK DEVICE TECHNIQUE STUDIES

Stanford University
Edward L. Ginzton Laboratory
Stanford, California 94305

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Work on a monolithic parametric convolver using guided surface acoustic waves in a piezoelectric zinc oxide film on a silicon substrate, and related topics, has been submitted for publication. Construction has been completed on the electronics package and microcomputer control system for an 8-bit A/D converter with 2 μsec conversion time, using a SAW delay line as a linear signal processing element, and the system is ready for initial testing. High

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conversion efficiency has been observed in barium titanate capacitor laminates used as electrostrictive transducers. These elements, and also poled polyvinylidene fluoride films, are being investigated as nonlinear signal processing elements for use in focussed two-dimensional phased arrays.

FOREWORD

This is the fifth Interim Technical Report for Contract F30602-74-C-0038, Job Order Number 55730707, prepared by the Edward L. Ginzton Laboratory at Stanford University, Stanford, California, for Rome Air Development Center, Griffiss Air Force Base, New York. This report, whose secondary number is G. L. 2602, covers the period 1 November 1975 – 30 April 1976.

Professor Marvin Chodorow and Dr. H. J. Shaw are the co-responsible investigators for this contract. Henry Friedman, OCTE, is the RADC Project Engineer, together with Paul H. Carr, ETEM.

I. ACOUSTIC WAVES ON NONPIEZOELECTRIC MATERIALS

The preceding report described a monolithic waveguide zinc oxide on silicon convolver operating at a center frequency of 125 MHz. The zinc oxide is originally deposited over the whole substrate and then etched to form a waveguide. The waveguide width is 1/10 of the beam width at the input transducers, which should yield a 20 dB improvement in efficiency over a normal convolver with a beam width equal to the transducer width, after accounting for the loss in the input tapers. Such an improvement was observed in experimental devices. During the reporting period this material was submitted for publication.[1]

A detailed theory of the monolithic convolver, developed in cooperation with other programs in the Laboratory, and described in the preceding report, has since been submitted and accepted for publication in Trans. IEEE on Sonics and Ultrasonics. An improved method of designing coupled resonator networks for wideband excitation of interdigital surface wave transducers, also described in the preceding report, has since been submitted for publication.[2]

No further research was done in this area during the reporting period.

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[1] P. Khuri-Yakub and G. S. Kino, Electronics Letters 12, 11, 271 (27 May 1976).

[2] P. Khuri-Yakub and R. L. Joly, Electronics Letters 12, 11, 266 (27 May 1976).

II. SIGNAL PROCESSING WITH LINEAR SURFACE ACOUSTIC WAVE DEVICES

A. INTRODUCTION

As described in preceding reports, a new type of analog-to-digital (A/D) converter using surface acoustic wave delay lines has been devised. It uses a linear interaction mechanism, involving a basic property of surface acoustic wave transducers which has not heretofore been applied. It operates by comparing a reference signal, having a linearly varying amplitude versus time, with the analog input signal whose amplitude is to be digitized. The present device differs from standard integrating-type A/D converters in that the reference signal is produced by passing an rf tone pulse through an interdigital surface acoustic wave transducer which, because of its basic convolution property, can produce an accurate linearly varying voltage ramp. This process offers potential advantages in terms of speed and temperature stability. An integrated circuit comparator is used to relate the amplitude of a sampled analog bit from the analog signal to the ramp amplitude, and an integrated circuit counter then outputs the corresponding digital count. The basic principles of operation were discussed in a previous report.

Comparing with standard types of A/D converters, our device is most similar to the integrating type. Both use a triangular reference voltage, which is compared with the input voltage to produce a third voltage which controls a digital clock. The advantages of using a SAW delay line to produce the triangular reference voltage, as compared to the current integrator of the standard device, are the temperature independence of the linearity of the SAW ramp, and the speed of the SAW device. The new device, then, has the potential of being faster and more stable than its integrating counterpart. However, it is not basically as fast as the fastest successive approximation type of standard A/D converters. On the other hand, the SAW devices, unlike the successive approximation types, can be run in parallel. The SAW output can be amplified and distributed to a number of comparators, allowing many analog signals to be converted simultaneously. The throughput of the system can then exceed that of a successive approximation device.

B. PRESENT STATUS

In an earlier report, we demonstrated a 4-bit A/D converter of the above kind, using a surface acoustic wave (SAW) delay line as a signal processing component. Based on the successful results with that system, a study was undertaken of similar systems with sufficient accuracy to demonstrate commercial feasibility. In this work, a design goal of 8-bits and 2 μsec conversion time were adopted as adequate specifications, as compared to capabilities of present commercial A/D converters. In the preceding report, it was shown that several commercial A/D converters of the successive approximation type exist having conversion times in the range of approximately 1/5 μsec to 8 μsec, with the 1/5 μsec device being a recently-announced state of the art device. One of the major applications of A/D converters is in data acquisition systems, where the purpose is to gather information in analog form, convert it into digital form, and then output this quantized information into a computer. Typically there are numerous input channels, and the useful throughput of the system is represented by the number of input channels digitized and computed per unit time. In such systems the speed of A/D converters represents one of the major limitations on the real time information handling capacity. The SAW systems being investigated here, through the use of parallel operation, have the potential for substantially exceeding the channel capacity of the commercial devices just cited, since successive approximation converters are not susceptible to parallel operation. Commercial converters of the integrating type, which can be operated in parallel, have individual conversion time exceeding that of our present SAW specifications by about an order of magnitude. Using the specifications given above for the SAW device, a 32-channel system, operating from a single SAW delay line, would have a throughput of 32×10^6 channels per second.

During the reporting period the design of the 8-bit A/D converter has been finished and construction of an experimental prototype is nearing completion. The electronics sections have been completed. A microprocessor suitable for supplying input data and analyzing output data during the testing of the device has been completed. Work on SAW delay line refinement is continuing. Initial testing of the device can be carried out using the delay line from the 4-bit device.

C. DESCRIPTION OF 8-BIT SAW A/D CONVERTER

A photo of the electronics sections of the new A/D converter is shown in Fig. 1, and a schematic diagram is shown in Fig. 2. As seen in Fig. 2, the circuitry comprises four sections, namely a control section, an analog input section, a counter section, and an output section. The map of Fig. 3 identifies the locations of these sections in the photo of Fig. 1. The control section interfaces with the computer. It decodes the computer instructions into four operations:

(1) Clear - resets all counters to 0;
(2) Convert - starts conversion cycle;
(3) Output digitized analog input;
(4) Output digitized reference input.

The analog input section contains all the comparators whose digital outputs determine how many pulses the counters may count. The counter section counts the digital pulses from the input section and stores the resultant digital words. The output section interfaces the counters and the computer.

The device of Fig. 1 is a two-channel system, which could be readily expanded into a larger N-channel system by simply replicating the existing channels the desired number of times. These multiple channels would then allow the SAW delay line to carry out parallel conversion of analog signals from N-1 input channels. In the processing procedure which we have devised for this system, one of the N channels in the electronics package is used as an analog reference channel. In operation, a stable reference voltage would be applied to the input to this channel. The outputs of all other channels will then be digitally divided by the output of the reference channel, to obtain readings

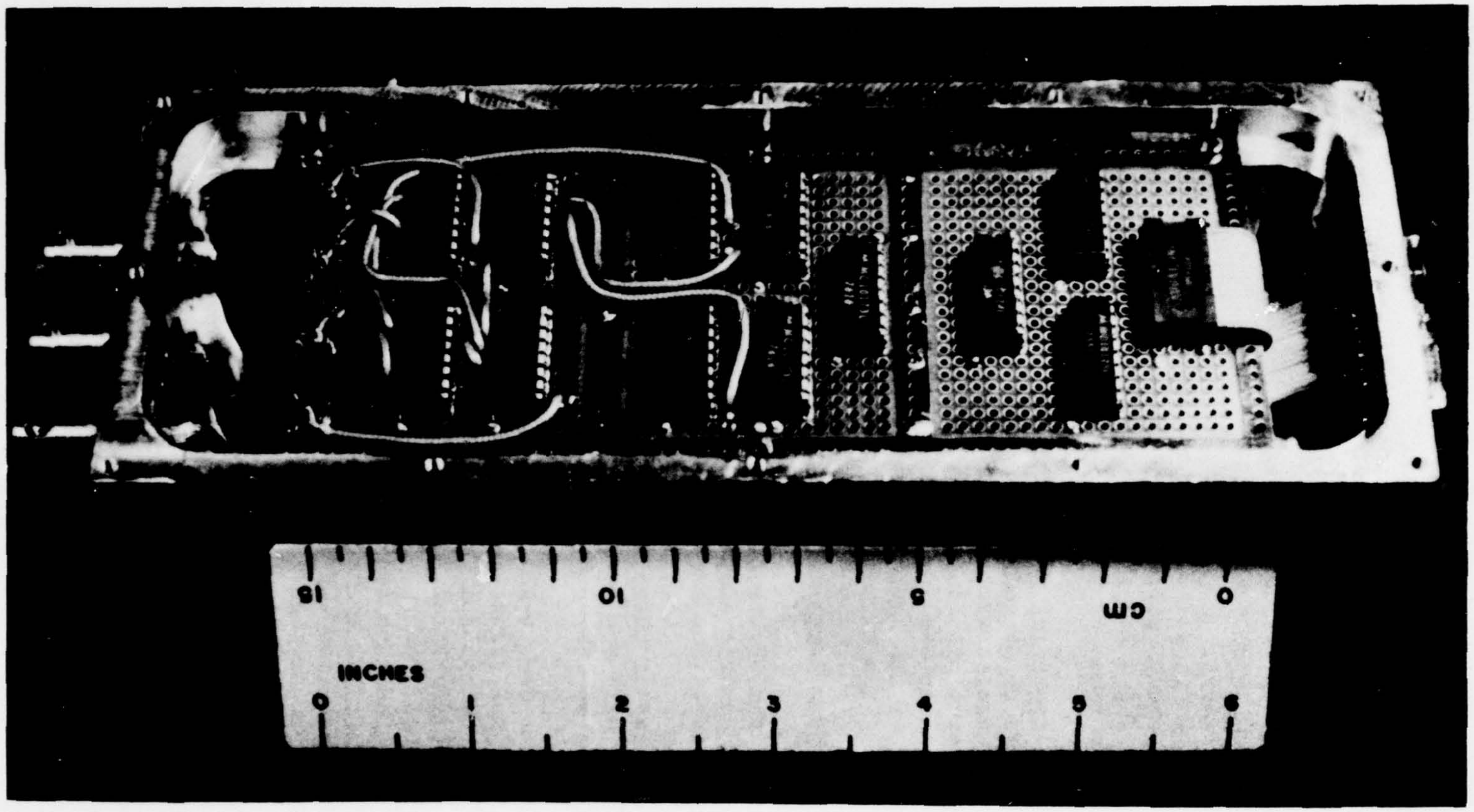


FIG. 1--Electronics sections of 8-bit A/D converter.

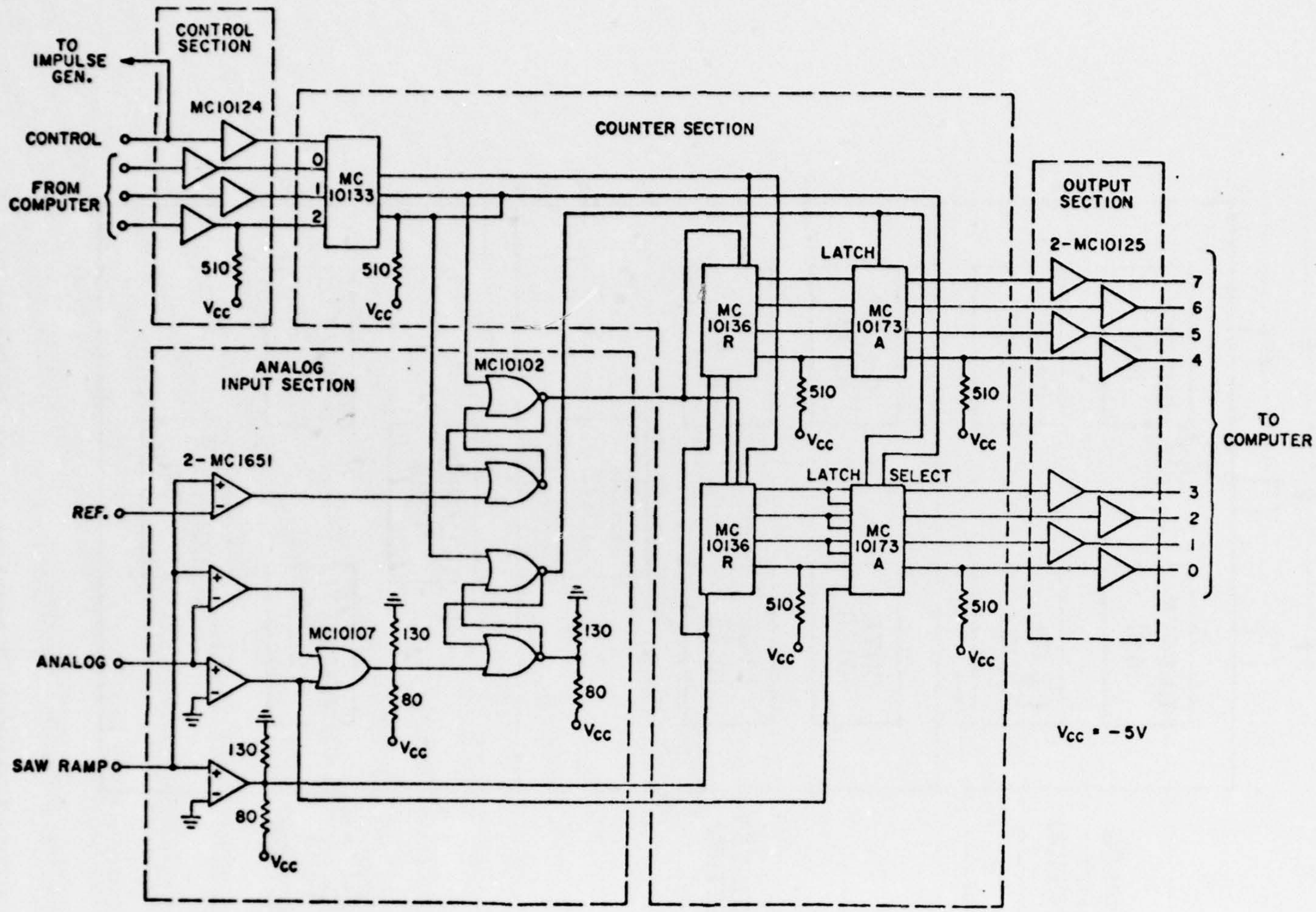


FIG. 2--Schematic of the electronics sections in the device of Fig. 1.

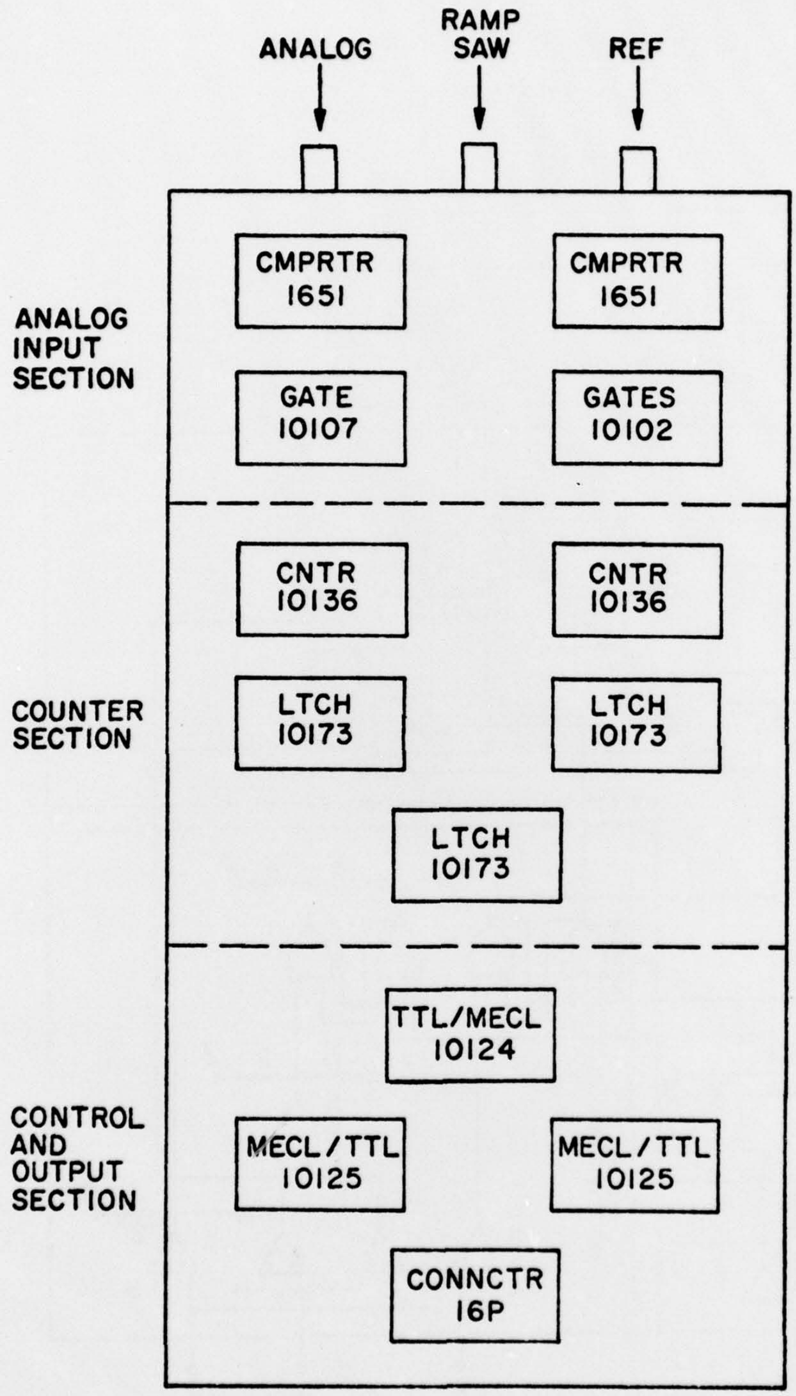


FIG. 3--Layout of sections in the device of Fig. 1.

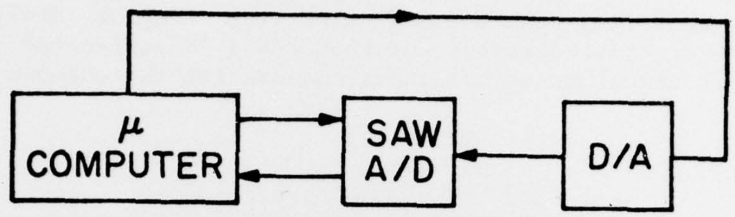
which are free of systematic multiplicative errors which can arise in components which are common to all channels, such as the impulse generator, the SAW delay line, and the post amplifier for the SAW delay line. Errors in the system will then be limited to those associated with the stability of the voltage source used on the reference channel and the linearity, as a function of time, of the output ramp from the SAW delay line. In the labelling on Figs. 2 and 3, one of the two analog input channels is designated as the reference channel, and the other as the input channel for the unknown analog signal.

D. TEST PROCEDURE

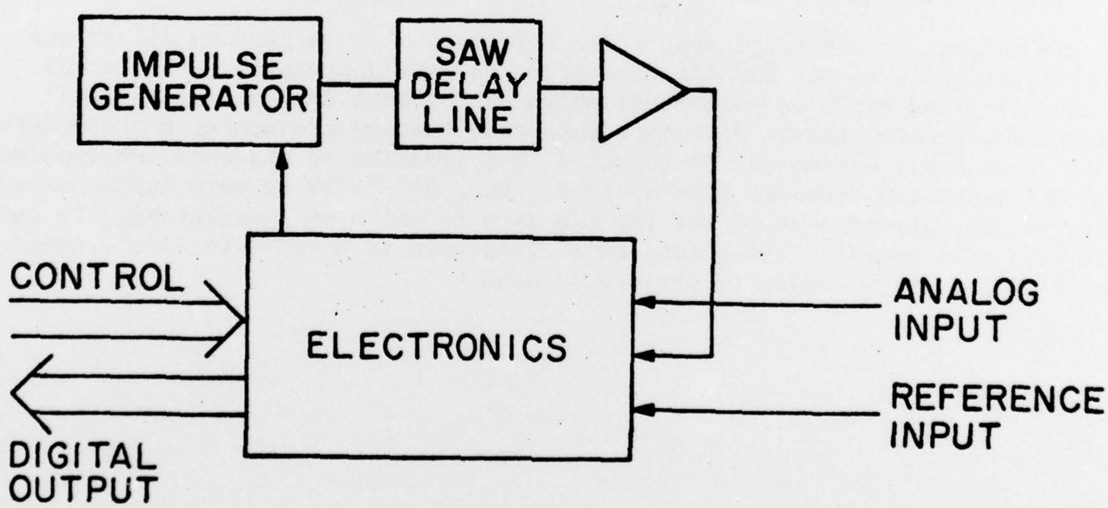
The A/D converter system (Fig. 4(a)) contains 3 subsystems: (1) the SAW A/D converter, (2) a standard digital-to-analog converter (D/A) for inputing a known voltage to the A/D converter, and (3) a microcomputer for control and data management. The SAW A/D subsystem (Fig. 4(b)) has four main components: (1) an impulsing circuit, which feeds a pulse to the SAW delay line to initiate the conversion process, (2) the SAW delay line, (3) an rf post amplifier, and (4) the A/D electronics package of Figs. 1, 2, and 3.

The system of Fig. 4(a) is configured for complete testing of the SAW A/D converter. In this operation, the computer outputs a digital word which is converted to an analog signal by the D/A and back to a digital word by the SAW A/D and then compared, by the computer, with the original digital word.

The purpose of the microcomputer in this system is to perform all of the experimental tests on the SAW A/D converter, thereby increasing the accuracy and expanding the range of parameters which can be covered, and greatly decreasing the testing time. With this automated testing procedure, the 256 data points of an 8-bit system may be obtained in a fraction of a second, as opposed to an estimated two hours if done by hand. Some 200 hours or more can be saved in testing the performance of the SAW A/D as a function of temperature. To run a complete data cycle of 256 points at 1° intervals from $-20^{\circ}C$ to $+100^{\circ}C$ would require well over 200 hours to perform by hand.



Subsystem breakdown



Components of SAW A/D subsystem

FIG. 4--System for testing of A/D converter.

III. NONLINEAR ACOUSTIC ELEMENTS FOR SIGNAL PROCESSING

A. INTRODUCTION

Further work in the area of nonlinear acoustic devices has become of interest to us with the discovery of some notable new properties of materials. Our attention is presently directed toward two materials, namely ceramic barium titanate laminates and plastic polymer polyvinyl(idene) fluoride (PVF_2) films. Under the present contract, it has been found that barium titanate ceramic sandwiches used in the construction of miniature capacitors have a very high electrostrictive coefficient. Also, it was discovered in Japan[3] that PVF_2 films can be rendered strongly piezoelectric by means of simple processing, and we have shown[4] under another program in this Laboratory that such films can be used for very broadband, efficient generation of high frequency acoustic waves using the linear piezoelectric mechanism. If these films have a large nonlinear piezoelectric coefficient, they could be important for nonlinear acoustic devices, because they also have some other unusual mechanical and physical properties, and we have undertaken to measure their nonlinearity under the present contract.

B. NONLINEAR ACOUSTIC WAVE GENERATION WITH BARIUM TITANATE

We have made some measurements on acoustic wave generation in barium titanate capacitor elements which show unexpectedly high efficiency and have led to a strong interest in the possible use of these elements in signal processing. The capacitors contain sintered multilayers of electroded ceramic plates, and those used in the experiments contained two layers having thickness of the order of 100 μ and area of the order of 10 mm^2, connected electrically in parallel. Signals in the form of both dc impulses and rf tone pulses were applied to the terminals, and acoustic waves radiated into water were measured using a broadband PZT transducer located within the water. With 60 volt impulses applied, the acoustic power density radiated was equal to that from a standard PZT transducer. The mechanism is different in the two cases, of course, as the PZT transducer operates as a linear piezoelectric element while the capacitor operates as a square-law electrostrictive element. Thus the conversion efficiency of the barium titanate is proportional to the input signal level, as compared to the constant efficiency of PZT transducers, and the comparison must be made as a function of input signal level. The present experiment indicates comparable efficiencies for the two devices at the signal level used. The barium titanate capacitors, having capacitance of the order of 0.01 μf, were poorly matched to the input circuit. It is expected that impedance

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[3] H. Kawai, Japanese J. Appl. Phys. 8, 975 (1965).

[4] L. Bui, H. J. Shaw, and L. T. Zitelli, "Experimental Broadband Transducers Using PVF_2 Piezoelectric Film," accepted for publication in Electronics Letters.

matching will improve the circuit efficiency and decrease the input signal level required for high conversion efficiency. Using tone pulses with center frequency in the vicinity of 2 MHz, acoustic wave pulses centered at 4 MHz are observed, in accordance with the quadratic electrostrictive characteristic, and their amplitude is found to depend on the square of the input signal amplitude, as it should.

The barium titanate elements have also been operated with dc bias in addition to the rf input signal, which provides an offset in the parabolic characteristic relating acoustic strain to applied rf voltage. The acoustic generation then has a large linear component which gives acoustic wave generation at the same frequency as the input signal, as in the case of piezoelectric generation. This mode of operation is convenient for making measurements on the acoustic resonant frequencies of the element. First indications are that the acoustic resonance in the present samples is close to the frequency of the acoustic output waves, in the vicinity of 4 MHz, which give best efficiency in the nonlinear mode. Measurements with bias can also be used to measure the slope of the electrostrictive parabola, and hence deduce the nonlinear coefficient. Measurements as a function of bias show an apparent dependence of resonant frequency on bias, shown in Fig. 5, which is interesting and is being investigated further.

C. NONLINEAR ACOUSTIC WAVE GENERATION WITH POLY(VINYLIDENE) FLUORIDE

Films of PVF_2 plastic film are available in thicknesses ranging from a fraction of a mil up to many mils, with large areas. Films of 2 mil thickness and less can be rendered strongly piezoelectric by means of simple processing, producing piezoelectric response approximately equal to that of crystalline quartz. The processing involves prestretching, followed by poling by applying a dc electric field across the thickness of the film in the range of a few hundred KV/cm to one MV/cm, at temperatures in the range of 80 to 120°C, for periods up to several hours, depending on circumstances. The films are electroded on both sides with vacuum evaporated gold electrodes prior to poling. When an rf voltage is applied across the electrodes of a poled sample, it behaves much like a classical piezoelectric resonator in both thickness and extensional vibration modes. Very clean resonances have been observed, under another contract, at frequencies up to 40 MHz with Q values entirely adequate for practical applications.[5] When bonded on one side to backing rods, these resonators can perform as very broadband, efficient piezoelectric transducers.[4] For example, transducers radiating acoustic beams into water, with response flat from zero to 20 MHz, and very clean impulse response, have been demonstrated.

Under the present contract, we have set up an experiment to measure the nonlinear behavior of PVF_2 acoustic resonators. The arrangement is shown in

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[5] L. Bui, H. J. Shaw, and L. T. Zitelli, "Study of Acoustic Wave Resonance in Piezoelectric PVF_2 Film," submitted for publication in Trans. IEEE on Sonics and Ultrasonics.

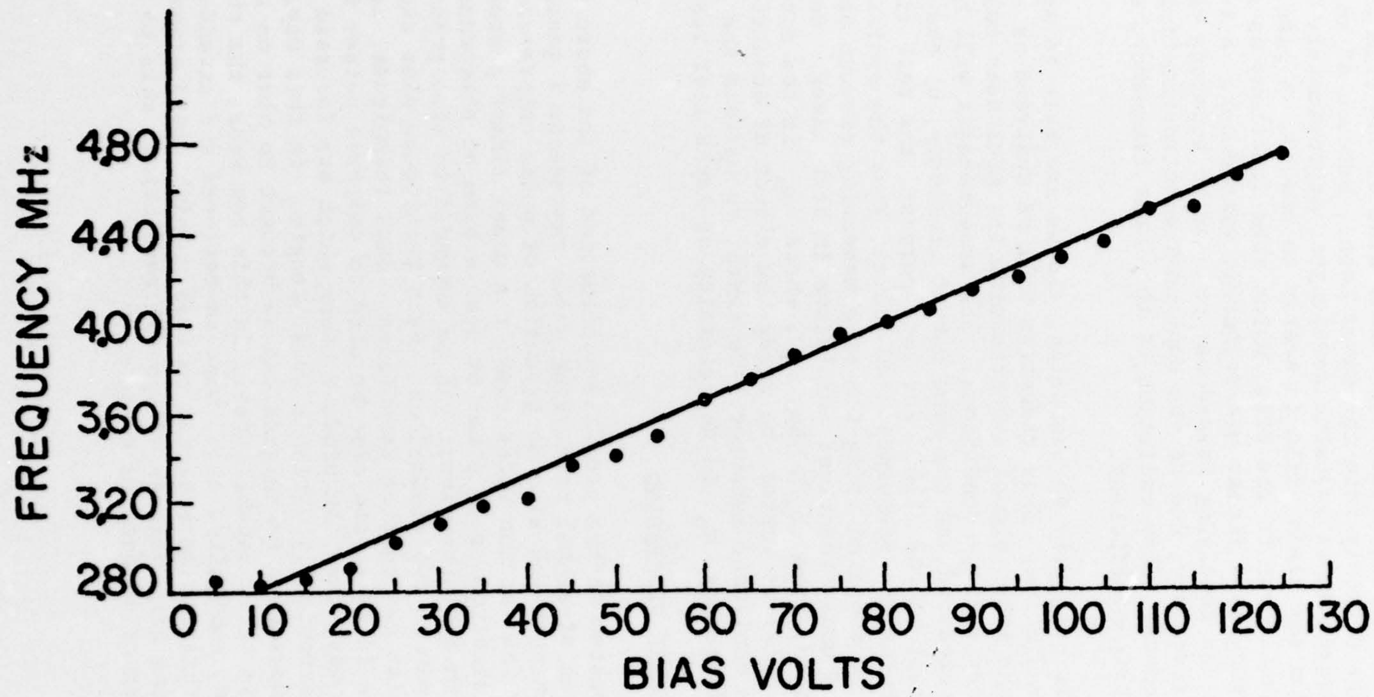

FIG. 5--Dependence of acoustic resonant frequency of barium titanate capacitor on bias voltage.

Fig. 6. The test film is a piece of electroded, poled PVF_2 film, of 2 mil thickness and approximately 1 in^2 area, stretched drum-head fashion over a pair of mating circular clamps, much like an embroidery hoop. The hoop is supported on a water-tight cavity, so that one side of the film looks into air and is acoustically unloaded. The other side of the film contacts the water and radiates directly into the water bath. Because of the high frequency and consequent short acoustic wavelength, approximately 75 μ, the beam radiated from the planar film is nearly columated. A plan reflector returns the acoustic beam to the film, which then functions as a receiving transducer operating as a linear piezoelectric transducer. A tuned amplifier on the output of the receiving transducer is used to separate radiation at twice the input frequency, due to the nonlinear electrostrictive coefficient of the test transducer, from radiation at the input frequency, due to the linear piezoelectric coefficient.

The system is presently in operation, and we are able to measure the second harmonic radiation. This radiation will be analyzed as a function of the level of the input signal, to determine the nonlinear coefficient of the test film under various conditions. The measurements will be normalized to the intensity produced, at the same output frequency, by the known piezoelectric coefficient of the film. For this purpose, the test film will be excited also at twice the frequency used above. Thus the nonlinear and linear coefficients can be compared using the same measuring circuit operating at the same frequency and under identical conditions in both cases. Only the input frequency is changed, from $\omega_o/2$ to ω_o, where ω_o is the output frequency. Furthermore, ω_o will be varied, to study the effect of acoustic resonance in the film upon the nonlinear behavior. We expect to operate the test film with the output frequency ω_o in the vicinity of mechanical resonance.

D. NONLINEAR SIGNAL PROCESSING

We are interested in the possible application of the above nonlinear elements in an area of signal processing which represents a generalization of phased array techniques and also an extension of pulse compression techniques. Through nonlinear interaction mechanisms, the usual linear phased array techniques which can electronically steer or scan a beam of electromagnetic or ultrasonic waves in two dimensions, can be extended to also produce electronic focusing of the beam in two dimensions. Such techniques also represent a generalization of pulse compression techniques. Such techniques, used in radar to compress pulses in time, can also be used to compress pulses in space. When used in this way, they can produce beams which are focussed as well as scanned, with electronically variable focal length. In this way, the generality of pulse compression techniques can be brought to bear on radiating arrays, to increase their capabilities. In this new area, the theory of side lobes, apodization, ambiguity, etc., must be tailored and extended to apply to the new format. This can be expected to lead to high speed scanning beams of various kinds having high degrees of spacial resolution, able to form real time image displays of objects in space.

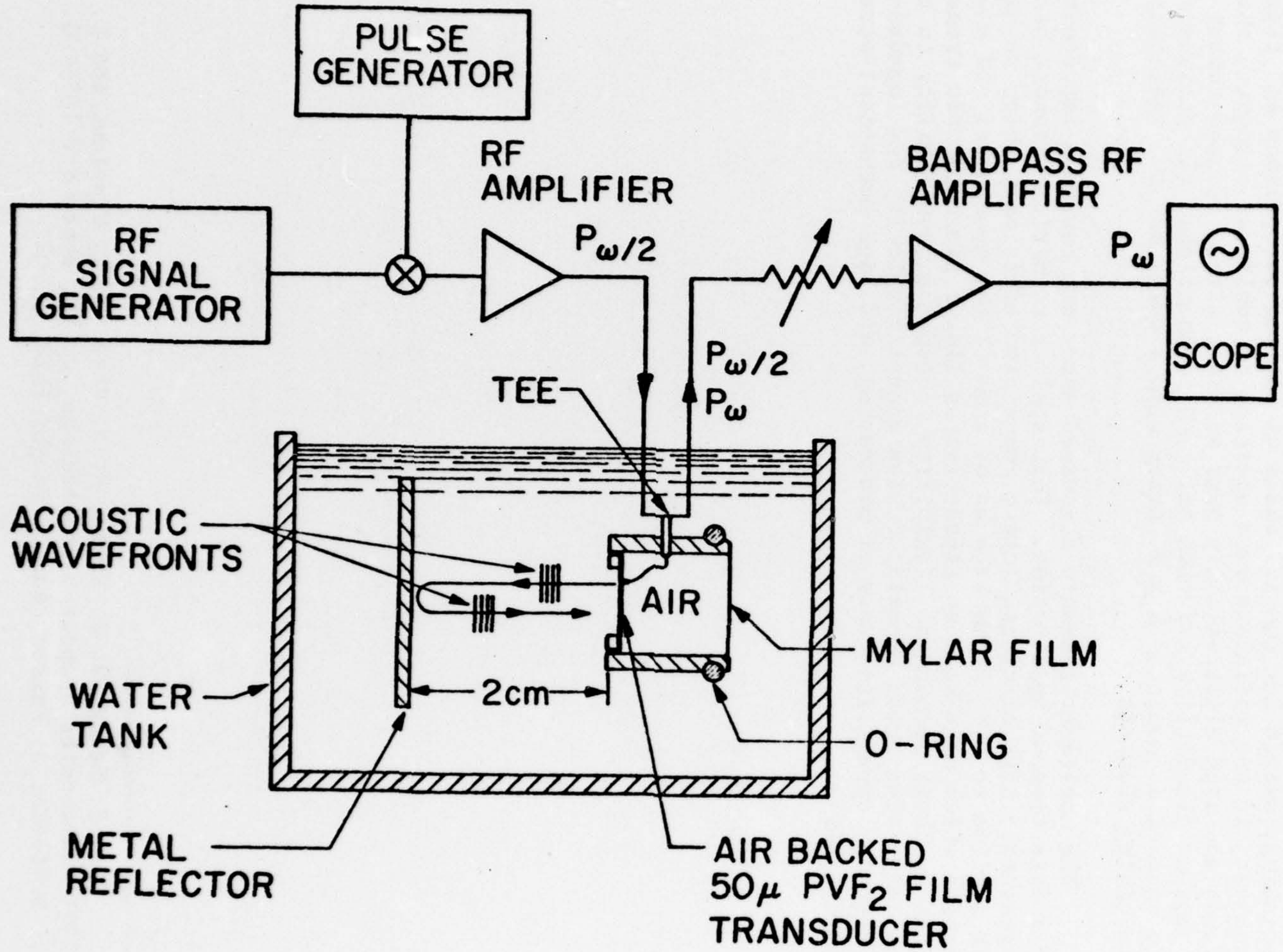

FIG. 6--Schematic sketch of apparatus for measuring nonlinear acoustic properties of PVF_2 film.

We have been working on such arrays under other programs in the Laboratory, whose radiating elements are linear acoustic transducers, and which form image displays of objects scanned by the acoustic beam.[6] It turns out that, when the transducers operate as linear piezoelectric elements, as they do in the present devices, one is then effectively limited to one-dimensional scanning, except for special cases of limited performance and flexibility. However, if the radiators were operated as nonlinear elements, then one could focus and scan electronically over an area, with a focused raster scan, with complete flexibility and with only $2N$ connections, all peripheral, required to control a complete $N \times N$ array with a total of N^2 radiating and/or receiving elements.

The nonlinear elements discussed above are possible important candidates for this type of application. This applies to barium titanate because of the apparently high electrostrictive conversion efficiency which we have observed. It applies to PVF_2 films because of some of the mechanical and physical properties which make them so attractive as linear piezoelectric transducers, such as their mechanical flexibility, cheapness, availability in thin films of large area, good acoustic Q, low acoustic velocity and impedance, high frequency capability, ease of processing, and high mechanical strength and durability.

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[6] W. P. Leung, R. A. Mills, H. J. Shaw, D. K. Winslow, and L. T. Zitelli, 1975 Ultrasonics Symposium Proceedings, p. 84, September 1975; G. S. Kino, C. DeSilets, J. Fraser, and T. Waugh, ibid, p. 94.

IV. SUMMARY

Work on a monolithic parametric convolver using guided surface acoustic waves in a piezoelectric zinc oxide film on a silicon substrate, and related topics, has been submitted for publication. Construction has been completed on the electronics package and microcomputer control system for an 8-bit A/D converter with 2 μsec conversion time, using a SAW delay line as a linear signal processing element, and the system is ready for initial testing. High conversion efficiency has been observed in barium titanate capacitor laminates used as electrostrictive transducers. These elements, and also poled polyvinylidene fluoride films, are being investigated as nonlinear signal processing elements for use in focussed two-dimensional phased arrays.

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