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1. <u>Title of Investigation</u>: Acoustic Tactile Sensing

2. <u>Senior Investigator</u>: H. J. Shaw

3. <u>Objectives</u>:

The objective of this project is to develop an acoustical method for providing for an artificial sense of touch, both in position and magnitude.

4. <u>Approach</u>:

The initial approach is to use a small liquid-filled, thin wall flexible tube such that when the tube is deformed at some position, as a result of touching an object, there will be a reflection of acoustic power which delineates the position and magnitude of the deformation. Four of these tubes mounted in parallel would then provide for area coverage.

An "acoustic tactile sensor" consists of a 0.001" thick mylar sheet clamped between two blocks of lucite to form an extremely thin tubing to be filled with water, as medium for sound propagation. Mylar was chosen because it is flexible, transparent and can be obtained as a thin sheet. Transparency is a very useful property because we can detect bubbles when we filled the tubing with water. Bubbles must be eliminated because they reflect the acoustic beam at undesirable spots.

At one end of the "sensor" is a piezoelectric transducer glued to the tubing through a 0.001" thick square gold electrode. Inside is a quarter wave plate of quartz to reduce the insertion loss and the "ringing" time of the transducer by decreasing the impedance mismatch between PZT and water. The transducer sends out acoustic pulses 20 μsec long, 500 μsec apart, as a probe. Thus any perturbation imposed at any point along the tubing [like an object touching the tubing] acts as a reflector of sound waves at that point. The time the reflected wave reaches the transducer, which is both a transmitter and a receiver, gives the position of the perturbation. Resolution of approximately 5 mm has been achieved.

5. <u>Progress</u>:

At the beginning of this period we were concentrating on the problem of making an array of four tubings (Fig. 1) to provide for area coverage. The modes in the cylinder that we expect to use are of low order, with so-called "pressure-release walls" as boundary conditions. Similar low order modes in piezoelectric cylinders are used to form transducers for excitation of the acoustic waves. Propagation loss is only 0.14 dB/cm at the operating frequency of 1 MHz. The experimental setup for one "acoustic tactile sensor" is shown in Fig. 2 where the "triggering circuit" puts out four trains of pulses, all separated in time, with each

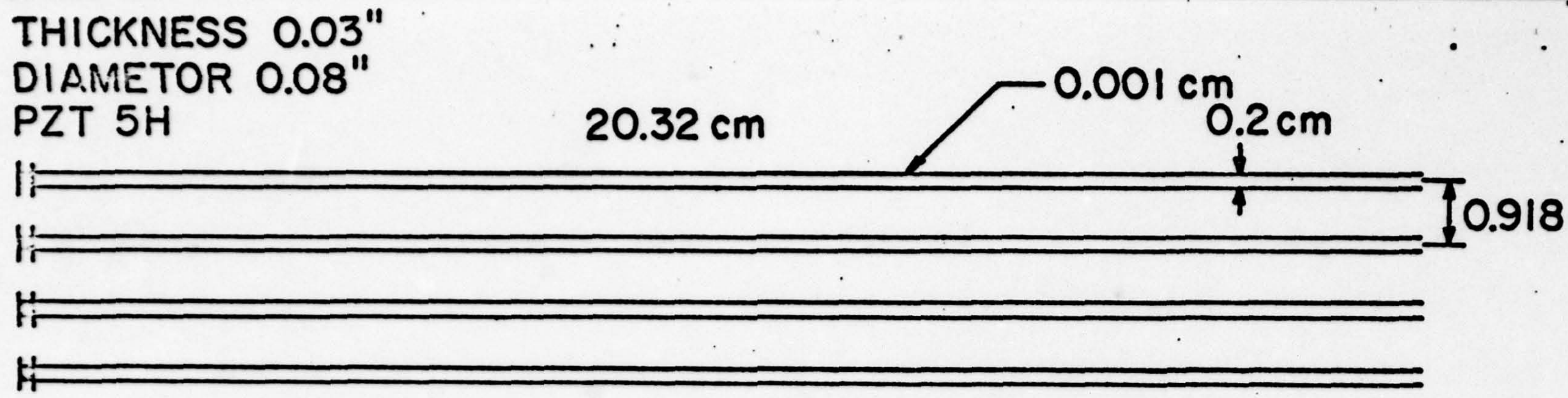

FIG. 1--Scale schematic diagram of the array of sensors.

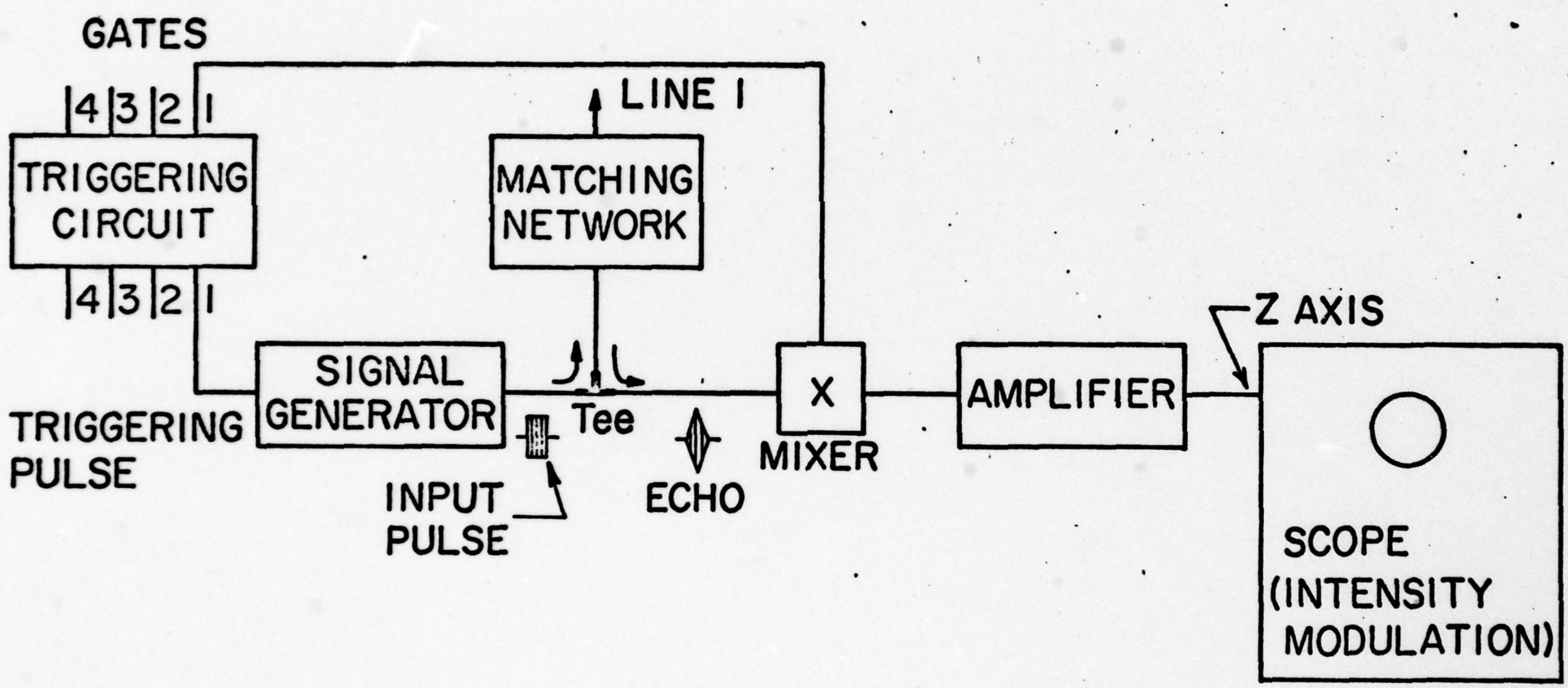

FIG. 2--Experimental setup for 1 line.

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one triggering a different rf source. The echo is then gated, amplified and displayed on the z axis of a four-channel scope as a bright spot. Thus four spots can be seen at any single time.

With one finger pressing across the array of sensors, one gets a bright line made of four dots on the scope. Measurement of the velocity of sound wave in the 2 mm tubing gives a value of 1.15×10^5 cm/sec. The scope was set at 500 μsec/cm. Thus the demagnification ratio is:

$$\frac{\text{distance as seen on scope}}{\text{distance on the tubing}} = \frac{2 \times 0.2 \times 10^5}{1.15 \times 10^5} = 1/3 \quad .$$

If one submits the film to many exposures, then more interesting patterns can be obtained such as letters of the alphabet.

An attempt was made to measure the least amount of pressure needed to cause an echo. Only 0.33 g/mm^2 was needed to give a spot. It is possible to generate at least two echoes coming from two deformations separated in space on the same tubing if one carefully controls the pressure at each perturbation center. We have been able to generate three echoes with our present mylar tubing. A "tactile sensor", to be useful, should not only detect the position but also the magnitude of any perturbation acting upon it. The detected dynamic range of our "sensors" is small: 8 gms above threshold.

6. Current Program:

We would like to concentrate our work on finding a better tubing material which not only incorporates the properties of mylar (transparent, thin, flexible...) but includes other desirable properties that mylar tubing lacks. Our mylar tubings tend to be deformed permanently after being exposed to too many perturbations so that all have slightly different propagation velocities. It is found that if one increases the area of deformation by having a tubing with a flat top instead of a cylindrical one, then the sensitivity is improved by at least a factor of two. A material that can be made into a flat tubing and retain its shape after being deformed is very desirable. A larger array will increase the area of coverage.

The use of an array of small liquid-filled, thin wall flexible tubes to provide for an artificial sense of touch has given encouraging results and indicates that this approach may be applicable to artificial limbs, robots and sensing in remote inaccessible regions.

1. Title of Investigation: Video Bandwidth Compression using Surface Acoustic Waves

2. Senior Investigator: H. J. Shaw

3. Objectives:

The objective of this investigation is to extend the library of signal transformations of rf pulse sequences using banks of passive recirculating SAW delay lines. One such transformation which accomplishes an operation equivalent to interchanging of rows and columns of a matrix of modulated rf pulses is the row-to-column conversion described in the previous report and also in a recent publication.[1] Another transformation accomplishes coherent addition of separate rf pulses in a delay line bank. The most important potential application of the coherent addition of rf pulses may be as an intermediate step in the process of computing the inner product of two vectors.

4. Approach:

The principal element in our rf signal transformation system using surface acoustic waves is the recirculating SAW delay line. The recirculating delay line permits the storage of one complete data sequence of rf pulses in real time. This stored sequence may be sampled from the delay line at the original bit rate or its integer multiples. Alternatively, providing certain conditions on the external loading of the READ-WRITE interdigital transducer are met, another sequence transmitted at a later time may be added coherently to the one already in circulation on the surface of the delay line.

In order to make the operation of coherent addition feasible, a nonreciprocal circuit element with suitable two-part loading characteristics must be interposed between the external transmission line and the interdigital transducer used to WRITE the sequence on the surface of the recirculating delay lines comprising the storage bank. The nonreciprocal device makes it possible to store the incoming data on the delay line without significant leakage of the data already stored into an external load. A transducer directly connected and matched to an external transmission line would leak approximately 1/2 of the incident acoustic power. This would, of course, make coherent addition impractical because of the high inefficiency involved and also the problem of reflection of a part of the stored sequence directly to the source. The data stored in the delay line would likewise be sampled using a high input impedance active element (FET). It must be emphasized that the active elements are used to provide isolation

[1] C.M. Fortunko and H.J. Shaw, "Signal Transformation with Recirculating SAW delay Lines," IEEE Trans on Sonics and Ultrasonics, SU-21 (1 January 1974).

only and not to provide the nonlinear interaction required to multiply two rf signals.

5. Progress:

We have been working on the development of electronic semiconductor circuitry necessary to interface the banks of SAW delay lines with the data bus lines. The problem of thermal stabilization of the delay lines to preserve the phase coherence of the stored data has also been considered.

6. Current Program:

The interface circuitry may be divided into two categories. One type of circuit is required to provide the nonreciprocal transfer characteristics necessary to mismatch the electrical part of the SAW transducer, the other is required to preattenuate the incoming data stream in order to bring its power level to that of the data stream already in circulation in the delay line.

The electrical mismatching of the ID transducer will be accomplished with hf transistors. At the present time the D-MOS series of devices manufactured by Signetics, Inc., appears to be best suited for this role. The D-MOS devices are characterized by high input impedance as well as good high frequency response similar to that of standard rf bipolar transistors. At present we are considering the choice of a particular circuit design.

The rf pre-attenuator used to bring the amplitude of the incoming data stream to the derived level is designed using p-i-n variable resistance diodes arranged in a "T" network. The amount of attenuation is controlled by a specially designed analog circuit whose time variation may be chosen to match the rate of propagation loss in the crystal. This attenuator can be digitally controlled.

Our initial experiments designed to examine the feasibility of electronically shifting the rf phase of the acoustic signal have not been successful primarily because of the high dc bias voltages required to obtain a significant effect. As an alternative, we are considering controlling the phase of the stored signals by thermal feedback techniques.

1. Title of Investigation: Rotation Sensing by Bulk Acoustic Waves

2. Senior Investigator: H. J. Shaw

3. Objectives:

It appears that acoustic waves may be applicable to the accurate sensing of the rotation parameters of certain high speed gyros. The present investigation is an initial one to determine the suitability of acoustic waves for such purposes, and to determine the prospects of such waves for providing greater accuracy in gyroscope measurements as involved in inertial guidance systems.

4. Approach:

The approach assumes a rotor located within a fixed housing that surrounds it, with a small uniform spacing between the rotor and the inside of the housing. Means for exciting acoustic waves are placed near the surface of the rotor, without necessarily placing any mechanical structures on the rotor surface. In this way volume or surface acoustic waves are excited in the rotor. The purpose of the project is to look for and optimize ways in which the patterns of acoustic wave propagation contain information regarding the rotation rate or orientation of the rotation axes, or rates of change of either of these quantities.

5. Progress:

In the last report a ray analysis was given for the effects of rotation on volume wave propagation through a spherically-shaped rotor. It was seen from this that the sensitivity of rotation detection is not sufficiently sensitive to enable one to measure practical rotation rates with a single acoustic transit. Multiple transits must be used, and this requires an acoustic material of high Q . Field, rather than ray, calculations for this problem have also shown that undesirable diffraction effects are quite large. Because of these difficulties, attention has shifted to surface wave techniques for rotation sensing.

6. Current Program:

Continued research on surface wave rotation sensing will be carried out under other support.

1. <u>Title of Investigation</u>: Calculation of Fourier Transforms at High Data Rates using Surface Acoustic Wave Delay Lines

2. <u>Senior Investigator</u>: H. J. Shaw

3. <u>Objectives</u>:

This is a new project which we propose to undertake at this time. Its objective is to investigate the use of surface acoustic wave delay lines for the calculation of the Fourier transforms of arbitrary waveforms in real time. This investigation is based on the current development in this Laboratory of experimental surface acoustic wave delay lines of high data rates and new orders of magnitude of time-bandwidth product. This project differs in both approach and technique from Project "Video Bandwidth Compression using Surface Acoustic Waves" described above, which also uses surface acoustic wave delay lines. The delay lines used in that project are one-port, closed-loop delay lines having a single-transducer per delay loop. These are used in groups or banks, and the information stored in these banks is processed with the aid of semiconductor circuitry. The present new project uses a more recent form of wrap-around delay line, which is a two-port delay line using a surface wave beam in the form of a helix. In this project, the Fourier transform of the input waveform will be calculated in a single delay line.

Fourier transforms are presently commonly calculated using digital computers programmed with the fast Fourier transform (FFT) algorithm.[1] The FFT algorithm has reduced the computation time sufficiently to make it practical to calculate the Fourier transform of arbitrary waveforms using digital systems, in the sense that the computation time is brought within reason with the use of this special algorithm. Because of the need for Fourier transform analysis of waveforms in virtually all branches of science and engineering, and because of the well-known advantages of carrying out filtering operations in the transform plane rather than in the original data plane, these computations have become very important. The principal recent advances over the past few years have been in the development of specialized computers for performing the FFT. There is a continuing effort at various laboratories to develop faster and smaller ditital systems, using higher speed multipliers and parallel processing approaches. The thrust of our program is to explore the possibility of surface wave systems that have speeds surpassing those of digital systems and, at the same time, reduced size and cost.

4. <u>Approach</u>:

It has been pointed out by Alsup, Means, and Whitehouse[2] of the Naval Undersea Center in San Diego that surface acoustic wave delay lines have a

[1] G.D. Bergland, "A Guided Tour of the Fast Fourier Transform," IEEE Spectrum, p. 41 (July 1969).

[2] J.M. Alsup, R.W. Means, and H.J. Whitehouse, "Real Time Discrete Fourier Transforms using Surface Acoustic Wave Devices," 278, Proceedings of the International Specialist Seminar on Component Performance and Systems Applications of Surface Acoustic Wave Devices, Aviemore, Scotland (Sept. 1973).

very important potential application in the calculation of Fourier transforms. A surface acoustic wave delay line with a suitable distribution of electrodes on its surface can perform the discrete Fourier transform of an arbitrary function in real time. Several types of arrays, both conducting and nonconducting, are possible for use on the delay line surface, and our approach will be to evaluate such array systems for different ranges of total number of analog samples in the unknown waveform and different ranges of computation time for the Fourier transform.

5. Progress:

An initial survey of the capabilities and potential of current digital approaches for calculating Fourier transforms has been carried out, to establish the comparative properties and potential of surface acoustic wave systems as a basis for this new project. The time-bandwidth product and data rates achievable with surface wave delay lines appear to be sufficient to allow large extensions of processing speeds for a given number of data points, together with very substantial reduction in cost and size, over the now-standard digital approach (involving analog time sampling of the input waveform, A/D conversion, and processing in a special-purpose FFT processor and host computer).

A very important new kind of surface wave delay line, in which the usual arrays of conducting electrodes are replaced by arrays of nonconducting reflectors, has recently been demonstrated.[3] Possible combinations of both conducting and nonconducting arrays will be considered for our particular application.

6. Current Program:

Various types and geometries of arrays for use on the delay line for transform processing will be analyzed, and their suitability for use with the chirp-Z transform algorithm will be evaluated. We have shown that the propagation characteristics of surface waves over very long paths can be equalized by IDT's to provide operation over large bandwidths. Similar considerations with regard to the Fourier processing arrays will now be studied.

Experimental work with these systems will be facilitated by the wide range of surface acoustic wave delay line parameters which are now available. In this Laboratory we have developed surface acoustic wave delay lines of the wrap-around type which have been successful in extending the time delays available in surface delay lines into the millisecond range. We have also recently shown that long delay lines of this kind have large

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[3]R.C. Williamson, "Large Time-Bandwidth-Product Devices Achieved Through the use of Surface-Acoustic-Wave Reflection Gratings," 181, Proceedings of the International Specialist Seminar on Component Performance and Systems Applications of Surface Acoustic Wave Devices, Aviemore, Scotland (Sept. 1973).

bandwidth capabilities,[4] so that surface wave delay lines with increased time-bandwidth product become feasible. For example, a delay line with a time-bandwidth product of 10^4 has already been developed under another contract[5] for different applications than the Fourier transform adaptations being considered here. We are presently constructing delay lines designed for a time-bandwidth product of 6×10^4.

Initial experiments on Fourier transform processing under the new project will utilize modest time-bandwidth products, working up to the larger values subsequently. Concurrently, further work with the basic large time-bandwidth delay lines will continue in order to achieve basic refinements which are relevant to this application. We find an interesting difference between the passband characteristics of delay lines for which the wave propagation characteristics are matched to those of transducers having a linear modulation function,[4] as opposed to those which do not, and we will carry out an analysis of this effect under the project.

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[4] H.J. Shaw, "Long Time Delays," 61, Proceedings of the International Specialist Seminar on Component Performance and Systems Applications of Surface Acoustic Wave Devices, Aviemore, Scotland (Sept. 1973).

[5] Contract DAAB07-73-C-0134 Semiannual Report for the period 1 April 1973 – 30 September 1973 (December 1973).

1. <u>Title of Investigation</u>: Signal Processing and Scanning of Optical Patterns with Acoustic Waves

2. <u>Senior Investigator</u>: C. F. Quate

3. <u>Objectives</u>:

The objective of this research is to explore the use of nonlinear acoustics in the scanning of far infrared images focussed on a semiconductor retina.

4. <u>Approach</u>:

The use of acoustic surface waves to scan an optical image on a silicon retina has been well established by workers in this laboratory.[1,2] The fundamental physics of this scanning experiment consists of three simple processes:

(a) The filling of Si surface states with majority carriers by the field pattern of a strong surface acoustic wave;

(b) The spatially varying discharge of these filled surface states by photon-generated carriers of an optical image;

(c) The measurement of the spatially varying state of charge of the surface states using acoustic surface waves.

The infrared imaging device we are presently working on is very similar, in principle, to the optical device, except that we rely on thermally generated rather than optically generated carriers to produce the spatial variation in the state of surface charge.

5. <u>Progress</u>:

Shortly after our initial conception of the infrared imaging device, we verified the practicality of measuring variations in the state of surface charge produced by thermal generation. We did this by using the optical imaging device as one element of the imager and scanning the temperature of the entire unit. The results matched our theoretical expectations.

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[1] N.J. Moll, O.W. Otto, and C.F. Quate, "Scanning Optical Patterns with Acoustic Surface Waves," J. de Physique C-6 Supplement <u>33</u> (Nov-Dec. 1972), pp. 231-234.

[2] O.W. Otto, "Nonlinear Coupling between a Piezoelectric Surface and an Adjacent Semiconductor," Ph.D. Thesis, Microwave Laboratory Report No. 2175, May 1973.

The basic remaining problem is to replace the continuous silicon films used in the optical imaging work with an array of silicon sensing elements. These elements must be thermally isolated from each other and from their environment so that impinging radiation produces significant temperature changes in the elements. There are 2 basic steps in the fabrication of such an array or retina:

a) The production of a large number of silicon elements;

b) The integration of these elements into a thermally insulating, supporting matrix.

The first step can now be routinely achieved by using standard photolithography techniques and a hydrazine-water etch[3] to define individual Si structures as small as 50 μm thick and 100 μm on a side.

We have devoted considerable effort to the matrix which must support these elements. The first approach we took was to attempt to cast a thin (less than 10 μm thick) plastic film around the retina elements after they're etched. However, the problem of cure shrinkage of such plastic films has proved to be difficult and because of this we are beginning to explore other methods.

6. Current Program:

We are presently pursuing two avenues in our efforts to produce arrays of thermally isolated Si elements. The first is to bond a thin (6 μm) plastic film onto the retina elements following etching. This approach eliminates the cure shrinkage problems, but requires some rework of the mask used for defining the retinal elements to provide a flat surface for bonding.

The second approach, which presently is under consideration as an alternative, is the use of small thin (1 μ thick x 10 μ diameter) plastic spacers to bond each sensing element to the acoustic delay line, foregoing the plastic supporting film altogether. This method appears to compare well with the other two in terms of thermal isolation.

We are confident that one of these techniques will allow us to fabricate the array of thermally isolated cells. The success of this program will lead to an infrared imaging device which should be relatively simple and give images which are comparable to those which are available for current devices.

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[3] D.B. Lee, "Anisotropic Etching of Silicon," J. Appl. Phys. 40, 11, (October 1969), pp. 4569-4574.

1. <u>Title of Investigation</u>: New Concepts for Scanning and Focusing of Acoustical Images

2. <u>Senior Investigator</u>: G. S. Kino

3. <u>Objectives</u>:

The objective of this research is to explore new concepts for scanning and focusing low frequency acoustic images. In particular, we are interested in using surface acoustic wave delay lines to provide reference phase for multiple arrays of transducers, to arrive at new methods of obtaining focusing, as well as accurate range information. New methods of designing the small transducer arrays are also required for this purpose.

4. <u>Approach</u>:

We have been able to scan a piezoelectric transducer array by mixing the output signal from each element of the array with a signal from a corresponding tap on an acoustic surface wave delay line. By sending a short pulsed signal along the acoustic surface wave delay line, a signal is obtained at the product frequency from an individual transducer only at the time a pulse passes by the corresponding tap. Thus the system can be used to scan an array of transducers. Furthermore, if instead of using a short pulse along the acoustic surface wave delay line, when a more complicated signal such as a linear FM chirp is inserted, the system forms a matched filter in which the array behaves like an "electronic lens", which can be focused on a point some distance from the array; the focal length of this "electric lens" can be changed by varying the chirp rate, and the image is scanned at the acoustic surface wave velocity because the FM chirp is moving along the delay line. The method thus provides us with an entirely new approach to focusing acoustic waves akin to the use of an electronically scanned phased array antenna system. We have already demonstrated that good focusing of an image illuminated by a 5 MHz acoustic wave in a water tank can be obtained.

5. <u>Progress</u>:

We have been concentrating on the design of acoustic arrays required for a focusing system. In some cases we require the individual elements to have corss-sectional dimensions comparable to their length. In other cases we use individual elements, which are several inches long in a direction parallel to their surface, but have approximately a square cross section of the order of 30 mils on a side. For our purposes we need to be able to predict the rf properties of these transducers, their resonance frequency, their input impedance, the effect of matching into water or other media, and the effect of backing materials on the transducers. We also need to know whether there is coupling between neighboring transducers. Closely related to the coupling problem is the problem of the acceptance angle of the transducers. For a good focusing system it is necessary for the transducer to respond to rays approaching the transducer well off its axis. Ideally, we would like to have an acceptance angle of as much as 30° to either side of the normal. When the coupling between the transducers is strong, the acceptance angle is relatively small. When it is weak, and if the transducers' dimensions are chosen correctly, typically a width of the order of a wavelength in water, the acceptance angle should be large.

We have been carrying out theoretical analyses using variational techniques and coupled mode theory to predict the properties of these transducers. We find with the long rectangular transducers we can predict the frequency relatively accurately, and our early results indicate a fairly good understanding of the input impedance of these transducers. We can also predict the acceptance angle of an individual single element transducer. However, our correlation between experiment and theory is only over a very limited range, and we are extending the theory to account for a wider range of parameters which may be of interest in the future and which will increase our understanding of the nature of the mode of these kinds of transducers.

At the same time we are carrying out an experimental program to measure the properties of these transducers. We have already measured the acceptance angle of such transducers and found in many cases that although we can predict it accurately for one element alone, the results are quite different when we use a large array of elements. This is basically because of coupling between the elements. We have set up a system to make these measurements, which can also measure the response of the transducer along its length. With this system we are currently carrying out further measurements to determine how eliminating coupling between the elements, i.e., removing a wax filler from between the elements affects the results. Early indications are that the acceptance angle is considerably increased by removing the source of coupling between transducers.

In addition we have been carrying out theoretical analyses to try and extend the electronic focusing principles which we had originally formulated during the last year. We are particularly interested in obtaining ways of obtaining range information with good accuracy, as well as being able to focus the system accurately in the transverse direction, i.e., we wish to focus on a small point in space in all three dimensions. At the moment we use quasi cw signals, and like any lens, the system is capable of giving a good focus in the two directions parallel to the surface of the array with a definition comparable to that of a lens of the same size operated at the same wavelength. Because the signals are cw, definition in the direction normal to the array is like that of a lens of the same aperture, i.e., the depth of focus increases with distance from the lens. This should be compared with a typical radar system or its acoustic sonar equivalent in which the definition bases on using short pulses is excellent in the direction normal to the array, but poor in the direction parallel to the array. We are hoping to obtain the best of both worlds.

In our system we use FM chirps both in the transmitter and the receiver. It is well known, of course, that FM chirps can be used in radar systems with the use of a matched filter, which can give excellent range information. By taking the theory further, we have been able to show that by using the right combination of chirps it should be possible to operate this quasi cw system and process the signal through a dispersive filter so as to obtain a short pulse output corresponding to a particular range. The concept is still in its infancy but it appears to be a viable one.

We carried out some very crude experimental tests of some of the basic ideas by using a standard broadband commercial piezoelectric transducer. The received signal was put into a matched dispersive delay line filter and we were able to obtain a short pulse output, just as done in a chirp radar system. We were able, with this system, to obtain good unipolar pulse echoes approximately 0.3 μsec wide, and observe multiple echoes. The shape of the individual pulses was unipolar (no negative ring in the pulse) far better than is normally obtained in a pulsed echo acoustic system. In addition the system had the great advantage that the power required into the transducer and hence the voltage across the individual elements is relatively small for the relatively long time (40 μsec) extent of the chirp. We believe that we can use the same concepts in our focused system using a chirped transmission signal rather than a single frequency transmitted signal to obtain good range information and to limit the peak voltages required to be placed into the individual elements of the transmitter array. This is particularly important for a focused system where the individual elements are so small and where it is convenient to use miniature circuitry to excite the individual elements.

6. Current Program:

We intend to continue with our work on theory of the transducer array elements so as to be able to treat cubic resonators as well as rectangular resonators so as to arrive at a viable theory suitable for design of such transducers taking account of acoustic loading, coupling between the transducers, and electrical loading. We have satisfied ourselves that we have the nucleus of a useful design theory far simpler in its form and more useful for design purposes than the complicated and restricted ones available in the literature. But much remains to be done to check this theory and extend it to covering a wide range of parameters.

We also intend to try out some of our new imaging concepts, extend the theory and in particular concentrate on the problem of obtaining good range information. If we are successful, we should, in the end, be able to make a focused system with good definition in the direction parallel to the array as well as good definition in the direction perpendicular to the array.

1. <u>Title of Investigation</u>: Heat Transfer from High Power Lasers

2. <u>Senior Investigator</u>: H. Heffner

3. <u>Objectives</u>:

The aim of this project is to develop a realistic mathematical model of the temperature distribution within a metal on the surface of which is impinging a moving high power laser beam. From this model, one wants to determine distribution of temperature, time of heating and cooling and the width of the heat affected zone.

4. <u>Approach</u>:

First an analytic model is made under simplified conditions. Next the model will be extended to include such effects as variation in the coefficient of reflectivity, ablation, heats of melting and evaporation, etc. Such a model must be programmed for computer solution.

5. <u>Progress</u>:

The last quarter has been spent in setting a model for the temperature distribution within a slab of material along which a high power laser beam traverses. The ultimate aim is to develop a computerized model that will take into account not only the usual heat flow but also ablation, evaporation and change of reflectivity. At present we are completing the first step of this process, one that takes into account usual heat flow uncomplicated by evaporation, etc.

The basic equations one must solve for a material slab with a free surface at $z=0$ is

$$k \nabla^2 T - C_p \rho \frac{\partial T}{\partial t} = 0$$

$$T(\bar{r}, t=0) = 0$$

$$k \left.\frac{\partial T}{\partial z}\right|_{z=0} = f_0 e^{-\gamma r} \quad .$$

After taking the Laplace transform of $T(\bar{r},t)$ one can express the transformed temperature distribution in terms of a Green's function $G(r,r')$

$$T(r',s) = \int_0^\infty - G(\bar{r},\bar{r}') \, f_0 \frac{e^{-\gamma r}}{s} 2\pi r dr \quad .$$

One finds that the Green's function is

$$G(\bar{r},\bar{r}') = \frac{1}{8\pi R}\left[e^{-R\sqrt{s\, c_p\, \rho}} + e^{+R\sqrt{s\, c_p\, \rho}}\right]$$

where $R = \bar{r} - \bar{r}'$.

6. Proposed Program:

For the future we will begin to add other effects to the model. It is almost certain that the inclusion of many of these will render the problem incapable of an analytic solution and computer calculations will be required.

1. <u>Title of Investigation</u>: Ultrasonic Absorption by Phospholipid Vesicles; Acoustic Impedance Matching and the Design of Broadband Piezoelectric Transducers

2. <u>Senior Investigator</u>: M. Weissbluth

3. <u>Objectives</u>:

The objectives of this research are (1) to investigate the interactions of model membrane (phospholipid) systems with ultrasound and (2) to design broadband piezoelectric transducers by means of acoustic impedance matching.

4. <u>Approach</u>:

Ultrasonic absorption and velocity is measured in solutions containing phospholipid vesicles as functions of temperature, concentration and frequency. High efficiency, broadband response of piezoelectric transducers operating with a water load has been accomplished by means of multilayer acoustic impedance matching schemes.

5. <u>Progress</u>:

Acoustic measurements over a frequency range of 3 - 39 MHz have been made in solutions containing asolectin. The frequency dependence of the ultrasonic absorption is consistent with a single relaxation time of approximately 30 nanoseconds. The absorption is proportional to phospholipid concentration (0 - 0.06 gm/ml) and increases when the temperature is lowered (0 - 45°C).

The equations for piezoelectric transducers with acoustic impedance matching to the load were analyzed numerically. This information led to the design and subsequent fabrication of a lead zirconate — lead titanate transducer (1.55 MHz resonant frequency) with quartz and lucite transformers. Its performance was consistent with theory and showed an insertion loss of about 3 dB over a bandwidth of 70%.

6. <u>Current Program</u>:

As the research progresses toward finer details, highly purified substances must be used. In practice, such substances are available only in small quantities. This imposes restrictions both on the method whereby the phospholipid vesicles are produced and on the design of the ultrasonic spectrometer.

The transducer research is being continued and consideration is being given to applications to underwater acoustics, nondestructive testing and medical diagnostics.

1. Title of Investigation: Optical Picosecond Radar Instrument for Viewing Semi-Opaque Materials in Depth

2. Senior Investigator: R. Kompfner

3. Objectives:

We propose to use the continuous stream of ultrashort pulses available from recently developed mode-locked dye lasers to obtain, in combination with an efficient gating mechanism, an image of the distribution of reflection and scattering across a layer which may be several millimeters below the skin in living matter or equivalent depths in other materials — ceramics, etc. The longitudinal resolution, given by the pulse length and the gate discrimination should be a small fraction of a millimeter, and should be matched by a corresponding lateral resolution.

4. Approach:

Preliminary measurements have shown that attenuation in muscular tissue can be as low as 40 decibel per centimeter at a wavelength near 0.8 μm. A flying-spot scanning method using a narrow light beam consisting of a steady stream of pulses of about 1 picosecond length will allow the returning radiation to be gated and converted to a signal current in a photoelectric detector, and displayed on a C.R.O. after suitable processing and amplification. One method of gating uses reference light pulses, derived from the same source as the primary light but shifted in frequency so that nonlinear interaction between the primary and the reference radiation can be used to generate a difference frequency photocurrent, which is then amplified in a standard intermediate frequency amplifier.

5. Progress:

The components of a mode-locked dye laser have been designed and built and are ready for assembly and testing. A frequency shifter for producing the reference radiation, using the Fox rotary phase adder principle but using electronic rotation in an electro-optically active medium, is being designed.

6. Current Program:

Depending on the availability of effort and support, experiments with the mode-locked dye laser are going to be made to investigate the nature of the resulting pulses, to correlate their time and frequency domain behavior, and to explore the limitations on the mean and peak powers available. When the frequency shifter is built and working as expected, it is hoped that it may also play a role in the understanding of the nature of the pulses.

Another line of work concerns the study of biological or other semi-opaque materials as absorbers and scatterers of light. Such a study does not require ultrashort pulses and can be carried out with relatively crude lasers. We hope to correlate these experimental results with various theories dealing with diffusion of radiation.

1. <u>Title of Investigation</u>: Acoustic Waveguide Theory

2. <u>Senior Investigator</u>: B. A. Auld

3. <u>Objectives</u>:

To develop methods of analyzing acoustic waveguide problems arising in device applications.

4. <u>Approach</u>:

At the present time acoustic surface wave devices make use of acoustic beams that are uniform over a lateral distance that is large compared with an acoustic wavelength. The wave propagation geometry is essentially two-dimensional. Because of this, lateral diffraction spreading of the acoustic beam occurs. Such diffraction is undesirable for two reasons. First of all, it introduces additional insertion loss because the receiving transducer does not intercept the entire diffraction-spread beam. Secondly, it causes cross-talk between acoustic beams running side-by-side on the same substrate. This limits the information storage capacity of a substrate crystal, a very important consideration in many applications. Surface acoustic waveguides provide a technique for overcoming these problems and make it possible to realize wave control functions (such as directional coupling, changes of propagation direction, power division, etc.) that are not possible in a strictly two-dimensional system. The purpose of this project is to investigate methods of analyzing dispersion in anisotropic waveguides, cross-coupling between parallel guides, and scattering at waveguide junctions and terminations.

5. <u>Progress</u>:

(a) <u>Dispersion and Cross-Talk in Surface Acoustic Waveguides</u>

The previous annual report described an equivalent transmission line approach to the problem of coupling between adjacent turns of a wrap-around surface acoustic waveguide delay line. During the period reported here, theoretical and experimental investigations have been directed toward obtaining a more realistic characterization of the waveguide itself and coupling between adjacent turns of the wrap-around line.

Two approaches have been used in the theoretical investigation: (1) a variational calculation that allows for anisotropy of the substrate, and (2) a scalar approach in which the waveguide is represented by a medium having a different propagation velocity and impedance than the region outside the waveguide. In (1) a variational expression has been constructed for calculating the frequency ω corresponding to an assumed propagation factor β . This expression is being programmed for the case of a metal strip ($\Delta V/V$) waveguide on an anisotropic substrate, using as a trial function combinations of uniform plane Rayleigh waves for the strip and surrounding regions. Methods have been studied for modifying the variational expression so as to include mass-loaded waveguides of both strip and slot types.

The scalar approach to the problem is based on an analysis developed for the treatment of surface wave reflection at an isotropic plating on an isotropic substrate.[1] In this treatment a strip or slot surface acoustic waveguide is shown to be represented very accurately by the model of an electromagnetic dielectric slab waveguide. Following this method, calculations have been made of the coupling length for two parallel $\Delta V/V$ waveguides on a (001)-cut (110)-propagating BGO substrate (Fig. 1). The same theory has also been used in another Microwave Laboratory project to design and construct prism couplers[2] for waveguides of the same type. Reasonable agreement between theory and experiments was observed.

(b) Junction Problems in Isotropic Plate Waveguide

A Lamb mode propagating on an isotropic plate waveguide has the interesting property that it does not scatter into a single mode of the same type when it encounters a discontinuity in material properties. This behavior occurs, for example, when the plate is terminated in a free boundary normal to the wave propagation direction or when two plates of different material properties are joined together. In these situations there is, in general, an infinity of scattered waves of both propagating and nonpropagating types. For the problem of a free boundary at the end of a plate in which only the fundamental modes are propagating, this leads to a phenomenon called end resonance.[3] This refers to a narrowband resonance-type change in the fundamental mode reflection coefficient at a certain critical frequency.

A study is being made of a variational approach to the analysis of problems of this kind. Following this method, calculations of the free boundary reflection have been made and end-resonance is observed.

6. Current Program:

(a) Dispersion and Cross-talk in Surface Acoustic Waveguides

Some preliminary experiments have been made on coupling between parallel $\Delta V/V$ waveguides on BGO. Cross coupling was observed, but was too weak to permit measurements of the coupling strength. On the basis of this result and the scalar theory mentioned above, a new experiment has been designed.

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[1] R.C.M. Li, A.A. Oliner, K.H. Yen, and H.L. Bertoni, "Properties and Applications of the Acoustic Wave Junction between Plated and Unplated Substrates," IEEE GMTT Int'l. Microwave Symposium Digest, (May 1971), pp. 54-55.

[2] K.H. Yen and R.C.M. Li, "Broadband Efficient Excitation of Thin Ribbon Waveguide for Surface Acoustic Waves," Appl. Phys. Letters 20 (1972) 284-286.

[3] P.J. Torvik, "Reflection of Wave Trains in Semi-Infinite Plates," J. Acous. Soc. Am. 41 (1967) 346-353.

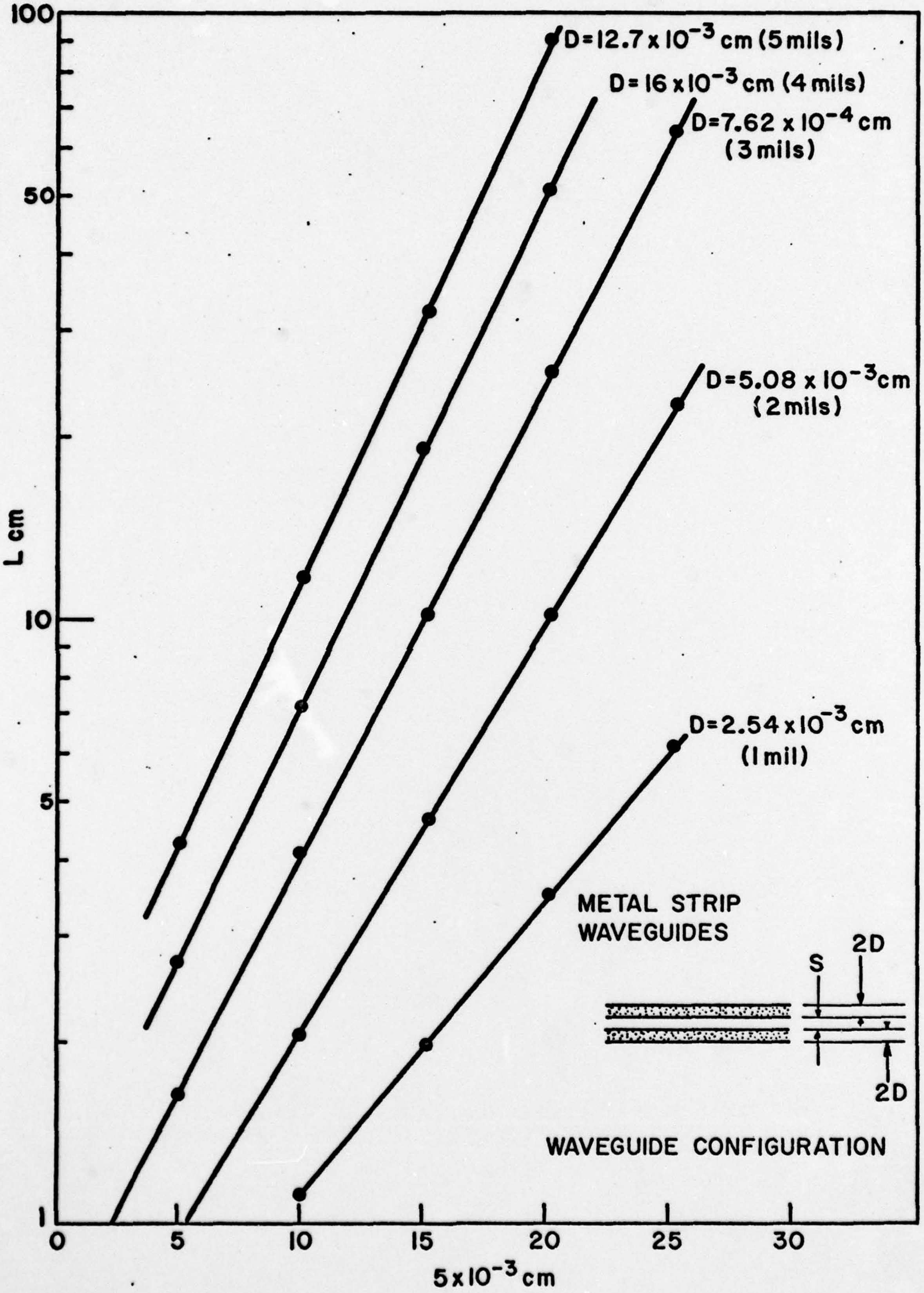

FIG. 1--Coupling length L vs waveguide separation s .

Figure 2 shows the arrangement. Instead of using small interdigital transducers firing into the ends of the waveguides, as in the first experiment, prism guide couplers are chosen. This will allow the acoustic field strength to be measured at several points spaced by a coupling length along the structure. In this way the power may be observed transferring back and forth between the two guides. Fabrication of this structure is almost completed and experiments will begin in the near future.

Experimental studies on waveguide bends are also projected, and a "racetrack" waveguide delay line, with two straight sections and two 180° bends is being designed. The rationale for this undertaking is to explore the feasibility of making serpentine, rather than wrap-around, delay lines for long time delays.

(b) Junction Problems in Isotropic Plate Waveguides

Refinements of the calculation are being carried out using the Rayleigh-Ritz procedure for systematically improving the variational procedure. The problem of scattering at a junction of plates with different material constants will also be considered.

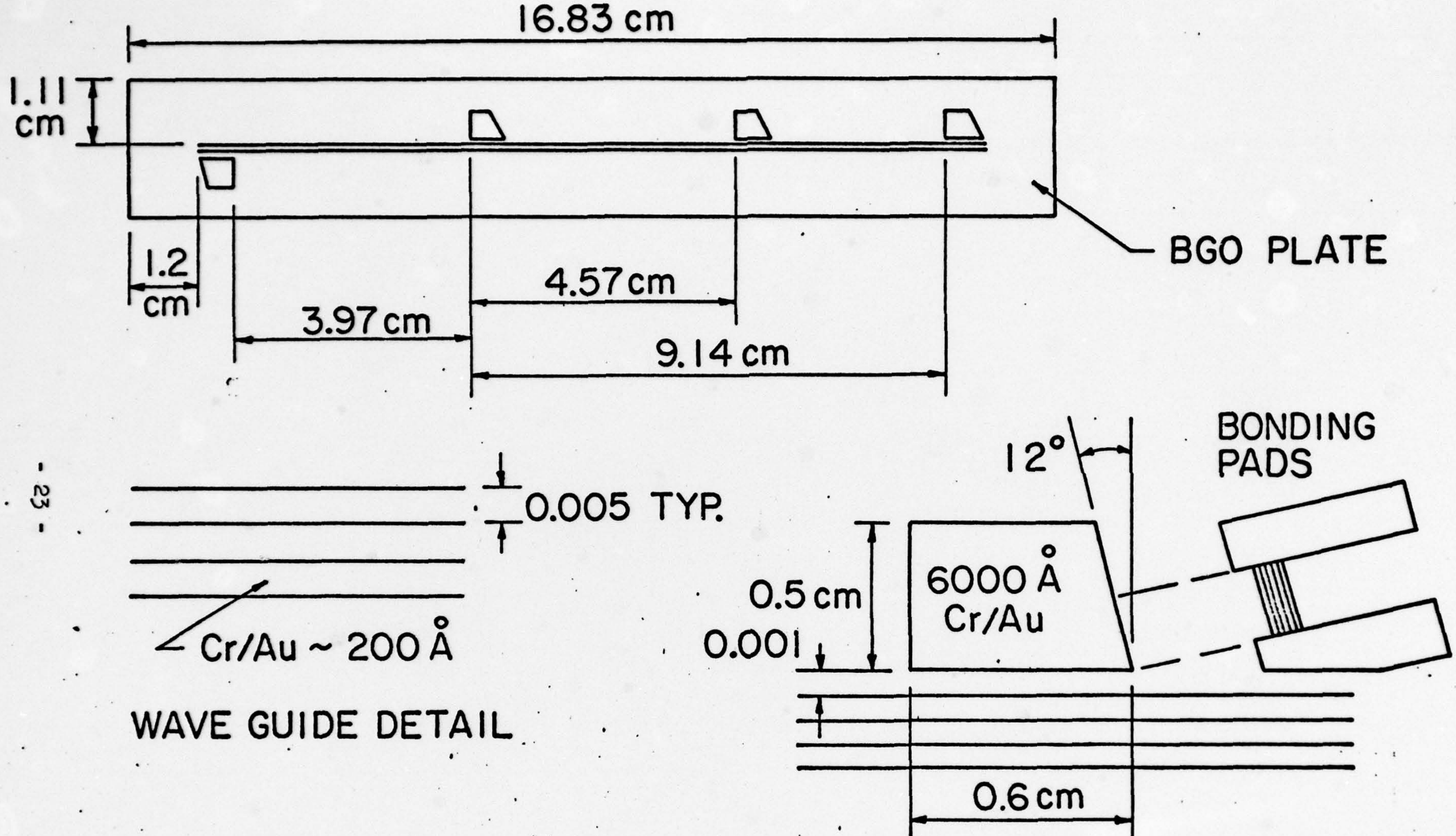

FIG. 2--Coupled waveguide experiment.