Communications Research Centre

PROCEEDINGS OF THE CANADIAN WORKSHOP ON ACOUSTIC SURFACE WAVES

by

D.B. Wohlberg and G.W. Farnell

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CANADA

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PREFACE

The prime objective of the Canadian Workshop on Acoustic Surface Waves was to bring together Canadians interested in, or influenced by, the technological area of surface acoustic waves for mutual education and an assessment of the Canadian scene. Since the participants represented a wide technological base, from basic research to systems applications, technological depth was considered to be of secondary importance and the presentations were tutorial in nature.

Since this report constitutes the record of the Workshop, it also is meant to be only an introduction to surface-wave technology but covering a broad range of interest. It is not intended for the reader seeking an in-depth treatment of, or state-of-the-art dissertation on, surface-wave technology.

Section 2 summarizes the objectives of the Workshop, and the method by which the Workshop attempted to meet these objectives. Section 3 is a summary of the technical content of the Workshop. In Section 4 we have attempted to draw, from our interpretation of the discussions surrounding the technical presentations and the discussion in the general wind-up session, a summary of Canadian needs, capabilities and directions for future activity. Summaries of the technical presentations written by their respective authors, are included as appendices.

Don Wohlberg

Jerry Farnell

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ABSTRACT

This report constitutes the record of the Canadian Workshop on Acoustic Surface Waves, which was held in Ottawa, January 30 – 31, 1974. The Workshop was sponsored by the Department of National Defence and the Department of Communications and jointly organized by McGill University and the Communications Research Centre. The invited tutorial presentations, which ranged in subject matter from materials and basic physics to systems applications in communications and radar, are summarized. It is concluded that there exists in Canada sufficient interest, needs, and capabilities to support a moderate level of acoustic surface wave research, development and manufacturing activity.

RÉSUMÉ

Le présent rapport constitue le procès-verbal de l'Atelier canadien sur les ondes sonores de surface qui a eu lieu à Ottawa, les 30 et 31 janvier 1974. Cet Atelier, placé sous l'égide du ministère de la Défense nationale et du ministère des Communications, a été organisé conjointement par l'Université McGill et le Centre de recherches sur les communications. Les causeries présentées par les conférenciers invités, qui ont traité de sujets allant des matériaux et de la physique fondamentale aux applications des systèmes dans les domaines des télécommunications et du radar, ont été résumées. On conclut qu'il existe au Canada un intérêt, des besoins et des capacités suffisants pour appuyer, dans le domaine des ondes sonores de surface, des activités de recherche, de développement et de fabrication, sur une échelle moyenne.

1. INTRODUCTION

The Canadian Workshop on Acoustic Surface Waves was held in Ottawa, January 30th - 31st, 1974, to answer a need for a meeting of Canadians working in, or influenced by, this important new technological area. In the context of the Workshop, "surface waves" refers to waves of mechanical displacement (acoustic waves) which propagate along the surface of solids. The technological area encompasses the research, development, manufacture and application of surface-wave devices which are based upon electro-acoustic interaction. A need for such a workshop had arisen because Canadian effort in this complex and diverse technological area lacks cohesion. Several small, but highly qualified, research and development groups in universities and industry have been working with little cross-pollination and with much

less interaction with potential manufacturer and user groups. Most potential user groups have only a passing acquaintance with surface-wave technology in terms of its strengths, weaknesses and practicability and of Canadian capability in the area.

This report constitutes the record of the Canadian Workshop on Acoustic Surface Waves. While most of the value of the Workshop lay in the discussions and observations stimulated by the presentations, an attempt is made in Section 3 and the Appendices to summarize the main ideas expressed during the meeting. In Section 2 the objectives of the Workshop are summarized, and the method by which the Workshop attempted to achieve these objectives is outlined. Section 4 is an attempt to draw, from the technical presentations and a general wind-up session, a summary of Canadian needs, capabilities, and directions for future activity. Section 5 records overall conclusions of the Workshop.

2. WORKSHOP OBJECTIVES AND MODUS OPERANDI

In very succinct terms, the objective of the Workshop was to effect a synergism of surface-wave activity in Canada. This overall objective can be broken down into three more specific objectives. First, to establish contact between the various groups involved in research and development, manufacturing and applications. Second, to become familiar with each group's technological involvement in this area and to gain an appreciation for each group's needs and capabilities. Third, to establish what has been attained to the present, and what directions should be pursued in the future. An example of an objective in the second category was to introduce the basic theory and properties of surface waves and basic fabrication techniques of surface-wave devices to the applications engineer, so that he can begin to judge for himself where surface-wave devices can and should be used, and also suggest to the research, development and fabrication sector where they might strive for better properties. An objective of the workshop from the third category was to evaluate the threat to surface-wave technology from competing technologies in order to assist research and development groups in deciding whether to augment, de-emphasize, or terminate, certain facets of their programs.

As the title implies, the Workshop was intended to be a forum for discussion, exchange of ideas and mutual education. Since the participants were of widely varying backgrounds, this involved keeping the technical presentations at a layman's level for a particular discussion leader's discipline. It also involved participation by invitation to keep the number of participants down to a workable level and to involve particularly those known to have an active interest in the area. (Doubtless, some have been overlooked, and the organizers apologize for this.)

Technical details of many state-of-the-art surface-wave devices and their system applications are presented in the following two general references:

1. Component Performance and Systems Applications of Surface Acoustic Wave Devices. Proceedings of an International Specialist Seminar, Aviemore, Scotland, September 1973. IEE Conference Publication No. 109.

2. Proceedings of the 1973 Ultrasonics Symposium, Monterey, California, November 1973. IEEE Doc. No. 73 CHO 807-8SU.

3. TECHNICAL PRESENTATIONS

In communication systems many different types of signal processing operations such as filtering, delay, storage, encoding and decoding, pulse compression, correlation, transformation and sampling may be required. In recent years a new class of components has become available to the system designer to assist in such signal processing functions in the hundred-megahertz frequency range. These components employ elastic surface waves propagating on the surface of a solid and are thus called *surface-wave devices*. The designer must consider performance specifications, cost, reproducibility, size, power consumption and environment sensitivity in making his choice of any component, and it is being found that in several applications, to be illustrated below, the surface-wave device is competitive with or superior to, other existing components and that future developments could well enlarge the number of signal processing functions delegated to such devices.

A surface acoustic wave is a wave which propagates along the free surface of a solid and involves mechanical displacement of the solid near that surface. The amplitude of displacement is largest near the surface and decays exponentially with depth into the solid so that the mechanical energy is concentrated within a region of the order of a wavelength below the surface. Since the velocity of propagation is 10^3 to 10^4m/s, the wavelengths are very small, about 30 microns at 100 MHz, and the energy confinement near the surface is great. Therefore, wavelength - dependent dimensions of devices using these surface waves can be many orders of magnitude smaller than counterparts using electromagnetic waves.

The low dispersionless velocity of surface acoustic waves gives rise immediately to broad-band delay-line applications, for example delays of 3.2 microseconds per centimeter on the ST cut of quartz which has a zero temperature coefficient of delay. Delays longer than the 10 μs or so, compatible with convenient crystal lengths, are currently limited by the difficulty of providing a convenient broad-band reflector. Several methods of providing long delays have been demonstrated, such as wrapping the acoustic beam around from the top to the bottom crystal surface to form a helical path and the use of a component called a multistrip coupler to provide multiple tracks on the same surface, but these approaches need further development.

If the solid substrate is a piezoelectric, the deformations produced by the elastic wave induce local electric fields, these fields propagate with the mechanical wave and extend into the space above the surface of the solid.

The electric field will interact with any metal electrodes deposited on the surface and in turn with external electric circuits connected to such electrodes. Thus by suitable choices of electrode number and form and of the external circuits one can excite, detect or modify the surface wave in a manner leading to a wide range of possible frequency or time responses. In the hundred-megahertz frequency range electrode structures are fabricated by standard photolithographic techniques and can be quite complicated to provide system transfer functions, difficult to realize by other means, with devices that are miniature in size and compatible with the planar technology of other integrated-circuit components.

3.1 TRANSDUCERS

The fundamental building block of the electromechanical transducer coupling the surface wave to external circuits consists of a pair of parallel electrodes of width d and centre-to-centre spacing L, which are parallel to each other for an "overlap" distance W (Fig. A.1.2). If an electrical impulse is applied to this pair of "fingers", the piezoelectric effect will result in a deformation of the substrate in the region of the electrodes and this deformation will produce a surface wave which propagates away from the fingers along an axis perpendicular to the active length W of the fingers. The spatial shape of the propagating pulse is related to the electric-field distribution produced under the fingers by the applied electrical impulse. To a reasonable approximation this shape will be one cycle of a sinusoidal wave of wavelength $\lambda = 2L$. The wave exists over a transverse width W and propagates with the surface-wave velocity v. If, after propagating some distance along the substrate, the one-cycle wavelet crosses a pair of fingers of a receiving transducer with overlap greater than W and of spacing of the same order as the original L, a voltage will be induced between the electrodes and hence across any connected load. This voltage is, in time, one cycle of a sinusoidal wave of frequency $f = v/\lambda$ and of amplitude proportional to the transmitting overlap W, and is delayed by the propagnation between the two pairs of fingers. The voltage received is thus the impulse response of this fundamental system.

Now let us assume that the input transducer consists of many finger pairs of different spacing L_n and overlap lengths W_n, and that the output transducer has only a few finger pairs of constant overlap (greater than the largest value of W_n) and constant spacing. The output transducer can be considered as an all-pass network. The electrical output response to an impulse on the input transducer will cover a time span $t_0 = D/v$, where D is the overall length of the input transducer, and in each interval n of this time span there will be one cycle of a sinusoid of frequency $\omega = \pi\, v/L_n$ weighted by the overlap W_n of the nth pair in the input transducer and with a phase of 0 or π depending on which finger of the pair is connected to which transducer bus. Thus within the time span t_0 the impulse response will be approximately $S_n\, W_n \cos \omega_n\, \tau_n$ in each successive time interval $0 < \omega_n\, \tau_n < 2\pi$, with $S_n = -1$, 0 or +1 (zero if both fingers of the pair are connected to the same bus). The higher harmonics are ignored here.

The frequency response is given by the Fourier transform of the impulse response. Thus, given the impulse response of a transducer, the frequency response can be calculated directly; conversely, in the design case, the desired impulse response is given or calculated from the inverse transform of the frequency response, and the problem is to approximate as closely as possible this time response by the choice of S_n, W_n and ω_n along the finite length of the transducer.

Now for a simple transducer consisting of finger pairs of equal spacing L_0 and overlap W_0, the impulse response is $W_0 \cos \omega_0 t$ truncated at $t = t_0/2$ ($\omega_0 = \pi v/L_0$) and thus the fundamental frequency response of a simple transducer is

$$F_1(\omega) = \int_{-t_0/2}^{t_0/2} W_0 \cos \omega_0 t \, e^{i\omega t} \cong K t_0 \frac{\sin (\omega_0 - \omega) t_0/2}{(\omega_0 - \omega) t_0/2}$$

The simple transducer has band-pass characteristics about the resonant frequency and the longer the transducer, the higher the resonant response and the narrower the bandwidth. The above has assumed that the second transducer is short enough to be regarded as an all-pass network. If this assumption is not valid, the overall transfer function should be

$$F(\omega) = F_1(\omega) \, F_2(\omega) \, e^{i\omega l/v}$$

where $F_2(\omega)$ is the frequency response of the second transducer and where the phase shift of a path of length l between transducer centres is included.

3.2 BAND-PASS FILTERS

The basic step in band-pass filter design using surface waves is to make the surface deformation in space under the transducer, as nearly as possible, a replica of the desired impulse response in time of the filter. Thus the first step is to determine the impulse response corresponding to the given frequency response. The finger pairs are located in space at the points corresponding to the time instants at which the phase of an impulse response is a multiple of π (or the imaginary part is zero) and the bus connections of the pair depend on the sign of the slope of the impulse response at this instant. The overlap of the pair W_n is proportional to the magnitude of the impulse response at the instant corresponding to the pair location.

Since the transducer length is finite, the infinite time span of the exact impulse response can only be approximated and in a design it is necessary to calculate the effects of this truncation on pass-band ripples and out-of-band response to decide on the transducer length required. Several other second-order effects must be taken into account in precise filter design, (Appendix A 1). The latter include spurious bulk waves generated by the transducers, triple-transit echoes due to reflections from the transducers themselves, and losses in the transducers. Current technology is such that surface-wave bandpass filters are being prototype-tested in colour television IF strips and are being included in other IF - type applications of communications equipment.

3.3 TRANSVERSAL FILTERS AND PSEUDO-RANDOM-NOISE GENERATORS

Surface-wave devices are of realized and potential usefulness in applications other than the band-pass filtering and simple delay mentioned above. For example if the input transducer to a surface-wave delay line is broad-band and if there are many taps along the acoustic path, summing the outputs of the taps with arbitrary weighting provides a convenient transversal filter. Such a filter is somewhat more general in character than those in which the adding and weighting is built into the design of a single multi-pair interdigital transducer. The external weighting allows the possibility of varying the weighting with time to produce an adaptive filter. Integrated versions of such adaptive filters have not been constructed though piezoresistive taps in the form of pressure-sensitive MOS transducers might make such filters possible. Programmable phase-coded transducers have been fabricated in a partially integrated form.

One important application of surface-wave devices appears to be in the domain of spread-spectrum communication (Appendix A 3). In a bi-phase version, the transmitter sends a carrier whose phase is reversed at a high rate according to a pseudo-random sequence so that the output spectrum approximates that of broad-band noise. However, a detector at the receiver, reversing phase reference in synchronism with the known code, will produce an output pulse for each transmitted sequence. The surface-wave realization of a pseudo-random noise sequence generator is conceptually simple and is commercially available up to 511 chips*. Let us consider an interdigital transducer consisting of consecutive groups of finger pairs, where (i) each group contains a number of pairs equal to the number of cycles of the centre frequency desired in each chip of the code, and (ii) the relative phase of the fingers in the group is that corresponding to the phase desired in that chip of the code. Then an electrical impulse applied to the transducer will produce a spatially phase-coded surface wave which will give the desired phase code in time at a broad-band output transducer. In a surface-wave realization of a pseudo-random noise generator, the correlator which does the detecting, that is, the regeneration of the applied impulse at the transmitter, is a device identical to that at the transmitter, and decoding synchronization is automatic. Some of the advantages of the noise-like transmitted signal of a spread-spectrum communication system are listed in Appendix A 3.

* a "chip" is the smallest unit of phase-coded signal with a single phase

3.4 PULSE-COMPRESSION

Another application in which surface-wave technology is proving to be of importance is in pulse-compression radars. Here the peak value of the transmitted power is limited and thus, with the long pulses needed to provide reasonable echoes, some form of pulse-compression system is needed to provide range resolution. For types using bi-phase codes, the output pulse has the phase of the carrier switched according to a selected code. The received energy can be passed through a surface-wave device for which one of the transducers is phase coded as the time reversal of the transmitted phase code and produces a short electrical output pulse only during the time when the echo signal is exactly within the receiving-transducer length. The operation is similar to the pseudo-random-noise case except that here the criteria for

the code are different. For example the code chosen and its realization should provide low time-sidelobes on the compressed pulse.

In the chirp-type of pulse-compression radars the frequency is swept during the transmitted pulse (Appendix A 4), say linearly with time from some value at the beginning to a higher value at the end. The returning echo is passed via a broad-band launching transducer through a surface-wave delay line in which the finger spacing of the pick-up transducer varies linearly along the transducer length, the more closely spaced fingers being closest to the launching transducer. The low-frequency signals which return first from the antenna travel a longer acoustic path and thus are delayed more than the higher-frequency signals which arrive later in the echo pulse. This results in a short output pulse from the device after all the echo has been received. Here suppression of the time sidelobes can be aided by weighting the finger overlap length along the transducer length. Time × bandwidth products of 1000 are currently realizable in operational surface-wave devices and values of several thousand have been experimentally demonstrated. For large time × bandwidth products there is advantage to providing the path length variable with frequency by the use of reflective arrays of etched grooves of graded period.

3.5 MATERIAL AND FABRICATION CONSIDERATIONS

For most signal-processing devices it is desirable that the bandwidth of the fundamental mechanism on which the device is based be as large as possible. In surface-wave devices the fundamental mechanism is the elastic wave on a free surface which is essentially dispersionless over a wide frequency range. However, in order to obtain the bandwidths in the transducers and associated circuitry, the device designers frequently wish to operate at as high a frequency as possible. There is a fundamental loss mechanism in the substrate whereby the coherent surface-wave beam is coupled to the incoherent thermal vibrations of the solid. The attenuation factor for this type of loss is proportional to the square of the frequency, with the proportionality constant dependent on the material chosen. In general, materials in polycrystalline or amorphous form have a higher attenuation factor at a given frequency than does the same basic material in single crystal form; for example at 1 GHz the attenuation of crystalline quartz is about 8 dB/cm while that of fused quartz is some 40 dB/cm. Thus the designer of broad-band surface-wave devices is led to single-crystal substrates of selected low-loss materials which can be conveniently polished to a roughness much less than an acoustic wavelength and whose surface finish withstands aging and photolithographic processing.

In the surface-wave devices mentioned above, there is usually a desire to have a piezoelectric substrate to allow convenient coupling from the electrodes to the surface wave. The stronger the piezolectric interaction, the larger is the inherent bandwidth of the device. Bandwidth can usually be traded against gain. The common measure of the piezoelectric coupling is the relative change in velocity of the surface wave produced by a short circuit, a thin metal layer, on the surface. Values of this parameter $\frac{\Delta v}{v_\infty}$ for the most useful crystal cuts are shown in Table A.2.2 of Appendix A 2. Propagation in the Z - direction of Y - cut lithium niobate (YZ $LiNbO_3$) combines the largest $\frac{\Delta v}{v_\infty}$ with the smallest attenuation per unit delay of any available piezoelec-

trics, and it is against this cut that the merit of other materials must be judged for specific applications. To date most operational devices have used YZ $LiNbO_3$ substrates. However, in certain cases, a particular factor might lead to the choice of another material; for example the temperature coefficient of delay of $LiNbO_3$ is large and for stable delays the designer might be willing to accept the larger number of fingers necessary with ST quartz which has a low temperature coefficient; for a tapped delay line, electrodes on a YZ $LiNbO_3$ substrate will perturb the propagating wave more than on a substrate with lower electromechanical coupling; for long delays the lower velocity of bismuth germanium oxide might be attractive despite its lower coupling and higher loss.

For compatibility with other integrated circuits there is interest in exciting surface waves on certain non-piezoelectric substrates such as sapphire by depositing a piezoelectric layer onto the substrate and fabricating the transducer in this layer region. Such excitation arrangements have been demonstrated but, because of the difficulties in producing highly piezoelectric layers and because of the losses and dispersion in the layers, these devices are not yet competitive with their counterparts on, say, YZ $LiNbO_3$.

Because the substrates are single crystal they are elastically anisotropic and care must be taken to ensure that the centre line of the transducers is carefully aligned along the specified crystal axis. Transducer pairs must obviously be aligned so that their fingers are parallel to within a fraction of an acoustic wavelength so that the centre lines are colinear, however misalignment of the common centre line with respect to the crystal axis will result in the beam emitted by one transducer being refracted by the anisotropy so that it is not completely intercepted by the other. Such axis misalignment is called beam steering and results in an extra loss.

The effective width or aperture of the transducer is a finite number of wavelengths and thus the radiated beam has a diffraction pattern much like that of a slit in optics or a two-dimensional end-fire antenna. Most surface-wave devices are operated in the Fresnel region, that is, the receiving transducer is placed close enough to the transmitting transducer so that the energy propagating from the latter remains in beam form and is thus almost completely intercepted by the receiver. Beam spreading due to diffraction can introduce insertion loss into the device; however, it is usually small except for long delays or transducer regions with very short finger-overlap. Fortunately, the anisotropic elastic effects are self-collimating on YZ $LiNbO_3$ so that the distance between transducers for a given diffraction loss is many times greater than on a similar isotropic substrate.

Other loss mechanisms which must be included in precision designs include the ohmic losses due to the currents flowing in the metal fingers and the energy radiated into bulk acoustic waves in the substrate. The latter tend to be troublesome not so much for the loss they represent but for the spurious signals they can produce at the output transducer if allowed to reflect from the bottom surface of the substrate. Another annoying spurious signal, especially in high coupling materials, can be the reflection from the output transducer which is reflected again from the input transducer to return to the output transducer. The elimination of this "triple-transit" signal will not be discussed here; (see Appendix A 1).

Surface-wave devices are produced sometimes by depositing complicated arrays of metal electrodes on a polished substrate. Recalling that a frequency of 100 MHz corresponds to a wavelength of some 30 microns and that electrode tolerances must be a small fraction of a wavelength, it is seen that the standard mask-making and photolithographic techniques of the planar technology of integrated circuits can be used for the reproducible fabrication of surface-wave devices up to a few hundreds of megahertz. For frequencies above one gigahertz photolithography is not practical, in large part because of the optical diffraction limitation on line resolution. Here the scanning electron microscope can be used to expose the photoresit but the process, while precise, is slow and expensive. Ion-beam etching (Figure 1, Appendix A 2) shows promise as a technique for the fabrication of high-frequency transducers and reflective arrays. It should be noted that above about two gigahertz the acoustic losses become a dominant effect at room temperature.

3.6 AMPLIFICATION

Surface waves can be amplified by means of the electroacoustic interactions in which the carriers in a semiconductor drifting in a DC electric field are bunched by the electric field associated with a surface wave on a piezoelectric. The semiconductor can be the piezoelectric itself (say CdS), a semiconductor deposited onto the piezoelectric (say InSb on $LiNbO_3$) or a semiconductor such as silicon maintained less than a wavelength above the free piezoelectric surface. It is possible to build electric amplifiers consisting of input and output transducers with the electroacoustic interaction region between, but such amplifiers offer few characteristics not more easily realized with transistors. However surface-wave amplifiers are considered for use as an integrated component in other surface-wave devices to compensate for propagation losses encountered in long delays or insertion loss in weakly-coupled applications. Realizable characteristics of surface-wave amplifiers are summarized in Appendix A 5. The interest in such amplifiers has been cyclic; each time design consideration has been given to incorporating a surface-wave amplifier into a component some new development has replaced the amplifier.

3.7 NON-LINEAR EFFECTS

Because the acoustic energy of a surface wave is concentrated within a wavelength of the surface the energy densities produced by even moderate power levels are quite large. Thus it is relatively easy to encounter non-linear elastic effects with surface-wave propagation. For example in $LiNbO_3$, power levels in excess of 10 milliwatts per millimeter of beam width at one GHz produce very appreciable second and higher order harmonics due to the elastic non-linearities.

While non-linearity causes harmonic generation and mixing, it can be a useful phenomenon for certain specialized devices such as parametric amplifiers or convolvers. One geometry for the convolution of two signals has the two signals modulated onto carrier waves which propagate in opposite directions into a non-linear interaction region where they set up a third wave, at the sum frequency, which can be integrated over the overlap region of the two signals by means of a simple comb transducer to produce the con-

volution of the two modulation signals. To increase the figure of merit to practical values it is necessary to enhance the non-linearity, over the values due to elastic deformation, by introducing a semiconductor into the interaction region so that the non-linearity in the transport equation for bunched carriers can be used. Current figures of merit are listed in Appendix A 5.

3.8 OPTICAL PROBING

When a light beam is incident upon the region of a crystal surface propagating an elastic surface wave the normal reflection and transmission of the beam can be affected either by the variations in the optical index of refraction due to the strains associated with the surface wave, or by the displacement ripples produced on the surface itself. The former phenomenon appears to be significant in optical beam deflectors especially when the optical beam is also a guided wave in a thin surface film. The latter effect is very useful as a probe of surface waves to measure the distribution of acoustic energy, beam steering effects, wavefront distortion, conversion to bulk modes, etc.

If a laser beam is incident upon a surface rippled by the surface wave the beam is reflected by this moving diffraction grating into several diffraction orders which are angularly separated from each other. The intensity of a diffracted beam is proportional to the intensity of the sound wave in the region where the light beam is incident. Where two counter-directed surface waves are involved as in, say, reflection measurements, the separate amplitudes of the two waves can be resolved by using an interferometer in the diffracted beam (as shown in Appendix A 6) to separate the two different Doppler-shifted frequencies produced by the interaction of the two waves.

In this section an attempt has been made to combine the material presented by the various workshop speakers. The titles and summaries of the individual papers are presented in the Appendix.

4. ASSESSMENT OF CANADIAN NEEDS AND CAPABILITIES, DIRECTIONS FOR FUTURE ACTIVITY

From the tutorial presentations, from the discussions which followed each paper and from the discussion in the general wind-up session to the Workshop, a brief assessment of Canadian needs and capabilities and directions for future activity can be made. This will be divided into three parts which deal separately with research and development, manufacturing, and applications sectors of surface wave technology.

4.1 RESEARCH AND DEVELOPMENT

It is apparent that this is the strongest sector in surface-wave technology in Canada. Research has been conducted for up to seven years in some Canadian universities and the resulting research units are capable of undertaking many facets of surface wave technology and are highly regarded by

similar units in other countries. This facilitates the exchange of information. R & D capability in Canadian industry, though not as well established, is also good. Funding is a continual need of the R & D sector. Surface-wave research tends to be expensive since state-of-the-art laboratory equipment in the photolithographic, electron-beam and ion-beam technologies is required to establish new frontiers.

Some directions for future research include the areas of programmable matched filters, large time × bandwidth-product devices, non-linear devices and integrated semiconductor/surface-wave technology. Materials research is of great importance in the development of integrated semiconductor/surface-wave technology and the general area of realiability. Applied R & D of optical techniques is almost certain to play an important role in the development of high frequency and large time × bandwidth-product devices and in materials research.

4.2 MANUFACTURING

No large-scale manufacturing capability exists in Canada. However, at least two companies have demonstrated the capability to fabricate small quantities of special-order devices and seem to be prepared to assemble a production capability when markets warrant it. In fact, this is the greatest need of the manufacturer - a market and an assessment of future markets, because they are confident of their capability to fabricate devices to specification. Cost-effectiveness is a major stumbling block but, with the decrease in material costs and increase in surface-wave device capability due to better fabrication techniques, this block is being whittled away.

A very desirable future activity in the manufacturing sector is the establishment of steadily selling device product lines, perhaps introducing these as signal-processing components in their present product lines. Market research and systems-applications research activities are necessary to achieve this result, as well as surface-wave device research within the companies and cooperating universities. Besides establishing steady product lines, a desirable future activity is the acceptance of state-of-the-art special order jobs to increase the manufacturing capabilities of the companies and perhaps establish new product lines in spinoffs.

4.3 APPLICATIONS

Sufficient high-technology applications exist in Canada to support a moderate level of research, development and manufacturing activity. These applications include spread-spectrum systems, both for communications and radar, and applications related to spacecraft electronics. Because of the highly desirable physical characteristics of small size, low power drain and ruggedness, surface-wave devices are expected to find wider and wider use in military electronics where they can be used in delay line, filter and many other signal-processing roles. Applications in commercial and consumer electronics are receiving strong cost competition from presently mass-produced components and devices, but lower material costs and less expensive mass-fabrication techniques in surface-wave-device manufacture could dramatically reverse the trend. Basic needs of the applications sector are demon-

strated successes in the implementation of systems utilizing surface-wave components and, especially for the high technology applications, reliability research and analysis. The applications sector requires first-hand experience in working with surface-wave devices to assess where and how they can be used to advantage.

A direction for activity can be derived from the consideration of surface-wave components in systems applications and the procurement of suitable prototype devices for evaluation in those applications where they look promising. It is important for the applications sector to participate in the development rather than wait for finished surface-wave components to be offered. As in the case of crystal filters, it is not possible to establish profitable product lines, because they cannot be general enough. The range of possible surface-wave devices is expansive and close customer-manufacturer-researcher interaction is required to exploit profitably (for all involved) the technology.

5. CONCLUSIONS

The first observation to be made is that there is a great interest and enthusiasm in surface waves in Canada, in itself a revelation. This was exemplified in the high level of attendance and participation at the Workshop. Originally, invitations were to be limited to twenty or twenty-five people. However, several others expressed an interest and were subsequently invited, with the result that nearly fifty people attended. Distribution was good as to professional interest in surface waves (research, development, manufacturing and applications), but poor as to geographical location (only two from outside Quebec and Ontario).

Another general observation is that Canada has been strong in R & D and weak in manufacturing and applications.

Although R & D work has reached the point where surface waves can be put to good use in electronics and communications, it appears that further work is still required to overcome shortcomings of surface-wave devices and to develop more sophisticated devices. In this latter category, the integrated semiconductor/surface-wave device is prominent.

Manufacturers, while not enjoying a large market at present, can expect to supply specialized devices for selected high-technology applications. It would be in their best interest to have steady product lines, however, so as not to have to rely on risky high-technology supply.

Engineers in electronics and communications can start to consider the use of surface-wave devices in their systems. If they expect to use these and realize their advantages, however, they must begin early to procure prototype surface-wave devices so that they and the manufacturer can interact during development phases.

In summary, it appears that the objectives of the Workshop have been fulfilled. The various groups involved with surface-wave technology in

Canada have met and exchanged points of view. Each group gained an appreciation for the others' technological position, and increased coordination of Canadian activity is implicit as a result of the Workshop.

6. LIST OF ATTENDEES

E.L. Adler	McGill University
M. Ahmed	DSS
D.P. Akitt	NRC
S. Barber	Bell Northern Research
M.L. Blostein	INRS-Telecom
M. Bouchard	DOC
A. Brown	RCA
C.K. Campbell	McMaster University
P.Y. Chan	RCA
S.M. Chow	DOC
R. Clark	RCA
D. Connor	Bell Northern Research
C.B. Cornick	DND
D. Cox	SEMCO Instruments
M. Dodson	Northern Pigments
D.W. Edmunds	DND
G.W. Farnell	McGill University
J.F. Gehrels	C.R. Snelgrove
G.E. Haslam	DOC
B. Hughes	DND
D.H. Hurlburt	RCA
M.C. Jain	Dalhousie University
M. Katchky	Canadian General Electric
J. Lit	Université Laval
H. Lysons	NRC
R. McAuley	McGill University
H.J. Moody	RCA
E.T. Mullen	MOT
J.E. Nicholson	DND
V.M. Ristic	University of Toronto
D.J. Ross	DND
L.G. Rowlandson	DRB
A.H. Secord	DND/Sinclair Radio
W.S. Stachuk	MOT
G.I.A. Stegeman	University of Toronto
M.S. Suthers	McMaster University
W.V. Tilston	Sinclair Radio
A. Torrens	DOC
T.W. Tucker	DRB
J. Vrba	University of British Columbia
E.M. Wade	DND
A.W. Ward	Westinghouse Canada
J.A. Whittaker	DND
D.B. Wohlberg	DOC

APPENDIX A1

Interdigital Transducers And Acoustic-Surface-Wave Filters

by

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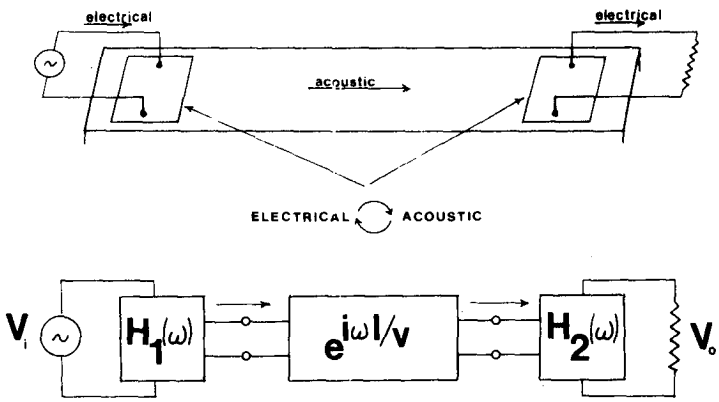
RCA Limited
Ste. Anne-de-Belluvue, Quebec

An acoustic-surface-wave filter can be represented by the idealized filter configuration shown in Figure A1.1. The input and output structures which convert the electrical energy to acoustic energy and vice versa have frequency responses $H_1(\omega)$ and $H_2(\omega)$, respectively, while the delay line separating the input and output provides a phase shift which varies linearly with frquency. The input and output structures are interdigital transducers as shown in Figure A1.2 and are characterized by the four parameters L, d, W, D as shown. The frequency response $H(\omega)$ of such a transducer can be determined from the impulse or time response of the device. Figure A1.3 shows both the acoustic response and the time response (voltage) of an interdigital transducer when excited by a brief voltage impulse.

The time response for such a transducer can be written as a summation of harmonic terms, which are related to the parameters of the transducer, as shown in Figure A1.4. The application of the Fourier transform to the time response given the frequency response which is calculated for the simple transducer shown. Thus, one can calculate the frequency response from the known time response. Conversely if the desired frequency response is known, the required time response can be calculated from the inverse Fourier transform, and the application of this principle is shown in Figure A1.5. The desired frequency response determines the time response which is built into the transducer as shown in Figure A1.5(a), and the measured frequency response of the transducer is shown in Figure A1.5(b). One factor which must be taken into consideration when designing a surface-wave filter using this approach is that the calculated time response will be infinite in extent, which will require an infinitely long transducer. Since this cannot be physically realized the time response must be truncated at some instant in time. The point at which truncation can occur without adversely affecting the frequency response is usually determined in a trial-and-error fashion by the designer using the Fourier transform to evaluate the truncated time-response.

The surface-wave device designer must be familiar with some of the practical problems which can interfere with the operation of surface-wave filters. There are three basic problems, phase-front distortion; internal reflections; and triple-transit signals. These problems and the methods for correcting them are illustrated in Figures A1.6 to A1.8, respectively. In conclusion, the design of surface-wave filters is based on the relationship between the interdigital transducer and its corresponding time-response. The frequency response is then given by the Fourier transform of the time-response. There are, however, some practical problems of which the designer must be aware as well as the methods for solving these problems and the trade-offs involved.



$$\frac{V_o}{V_i} = H_1(\omega) H_2(\omega) \left| e^{i\omega l/v} \right|$$

Figure A1.1. Idealized Acoustic Surface Wave Filter

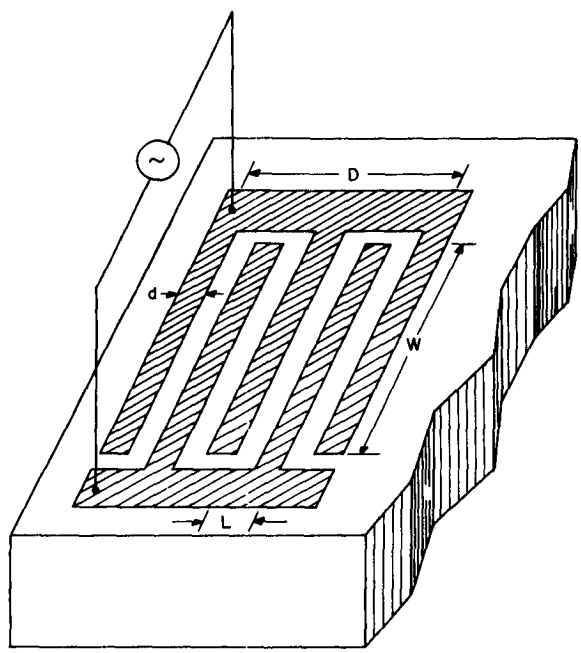


Figure A1.2. Interdigital Transducer on a Piezoelectric Substrate

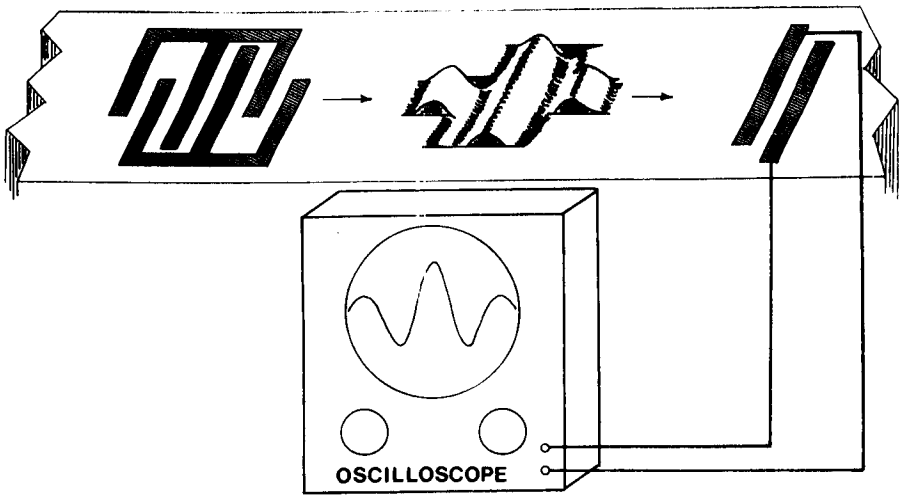


Figure A1.3. Acoustic and Time Response of an Apodized Transducer

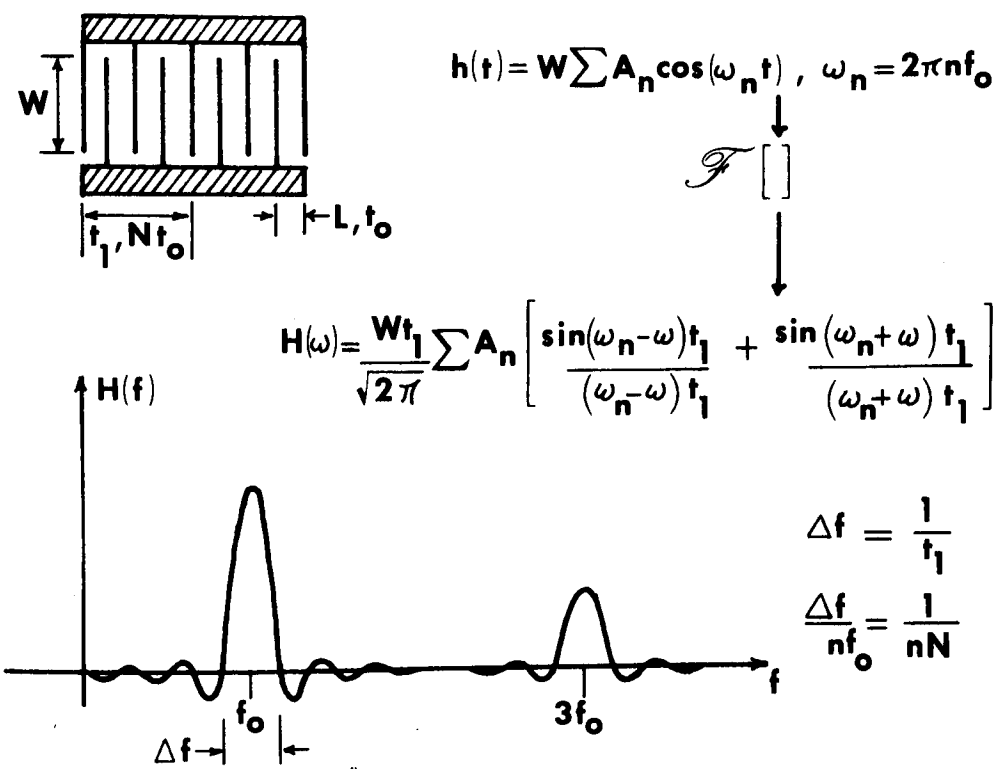
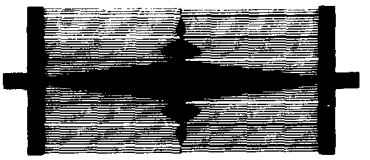
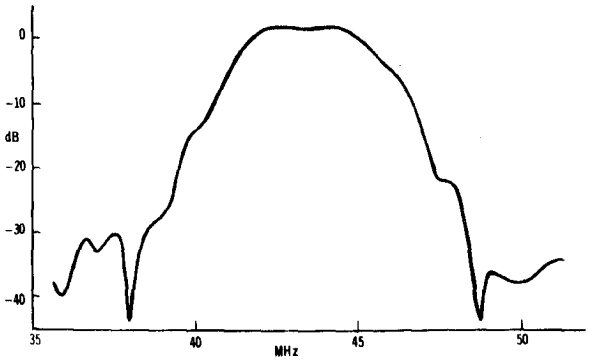


Figure A1.4. Calculation of the Frequency Response for a Simple Transducer



5(a) **APODIZED IDT**



5(b) **FREQUENCY RESPONSE**

Figure A1.5. Bandpass Filter

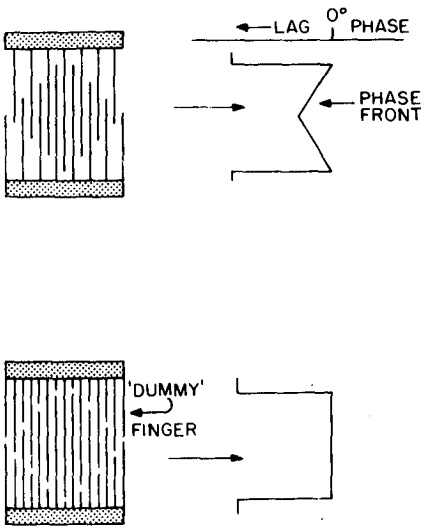


Figure A1.6. Phase Front Distortion

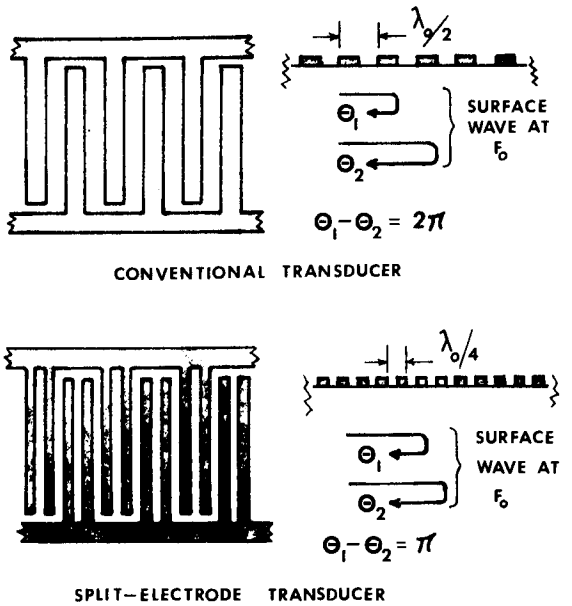
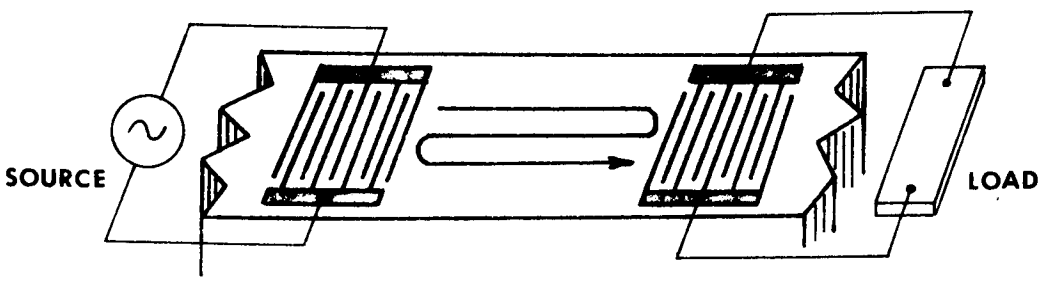


Figure A1.7. Internal Reflections



SOLUTIONS:

1. REDUCE COUPLING CONSTANT } INCREASED I/L
2. MISMATCH SOURCE & LOAD }
3. "ECHO-TRAP" (m.s.c.) INCREASES I/L BY 3 dB

Figure A1.8. Triple-Transit Signals

APPENDIX A2

Fabrication Technology And Materials

by

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Department of Electrical Engineering
University of Toronto

The principal objectives of this presentation are (i) to assess certain aspects of surface-acoustic-wave (SAW) fabrication technology having relevance to an up-to-date SAW device design, and (ii) to review the characteristics of the most promising acoustic materials for use in various SAW devices.

1. Fabrication Technology

The early SAW fabrication methods reflected those used in fabrication of other solid-state devices (e.g., conventional photolithograph). Later, the need for SAW devices operating above 1 GHz was the main stimulus for researchers in contributing to the development of modern fabrication methods (scanning electron-beam lithography and ion-etching). In the last year, SAW research has contributed a completely novel fabrication technique (soft x-ray lithography), and the characteristics of the three lithographic methods presently used for fabrication of SAW devices are shown in Table A2.1. In addition, the ion-etching fabrication method has been proven to yield SAW devices with an unusually low content of spurious modes, thus allowing the fabrication of SAW devices with very large time X bandwidth products.

2. Materials

A conventional SAW device consists of a conducting thin film deposited on a piezoelectric substrate. Thus, the performance of the device is strongly dependent on the characteristics of the material used for the substrate. Three types of materials are considered: single crystal; thin piezoelectric film deposited on a nonpiezoelectric substrate, (which results in a mixture, single crystal material and polycrystallines); and piezoelectric ceramics. Some properties of single crystals are shown in Table A2.2. The use of single crystals is wide-spread in the fabrication of SAW devices. Several good devices have been obtained with thin piezoelectric film. This approach requires more research in order to obtain films with reproducible acoustic characteristics. Some properties of thin films are shown in Table A2.3. The piezoelectric ceramics in Table A2.3 offer a prospect of low-cost SAW devices operating below 50 MHz. More research is needed to understand the influence of aging on the substrates and SAW device realizations.

TABLE A2.1

Lithographic Methods Used in the Fabrication of Surface-Acoustic-Wave Devices

Lithographic Methods Used in The Fabrication of Surface-Acoustic-Wave Devices

Method	Routine-Practice Linewidth up to Date	Depth of Focus at 1 μm Linewidth Resolution	Recording Medium	Cost	Complexity	Processing Speed
CONVENTIONAL PHOTO-LITHOGRAPHY	2 μm	4 μm	Conventional photoresist	low	low	high
SCANNING ELECTRON BEAM*	0.1 μm		Polymethyl methacrylate (PMMA)	very high	very high	very low
SOFT X-RAYS**	0.1 μm	60 μm	PMMA KMNR	low	low	high

* beam diameters used are typically 500 Å.

** requires masks generated by scanning electron beam.

TABLE A2.2

Some Properties of Single Crystals

Crystal	Plate Normal	Prop. Direction	Piezoelectric Coupling $\frac{\Delta v}{v_\infty}$	Temp. Coeff. of Delay (ppm/°C)	Surface Wave Velocity v_∞ (m/s)	Surface Wave Atten in Air at 1 GHz (dB/μs)
$LiNbO_3$	Y	Z	0.024	85	3488	0.88
$LiNbO_3$	41.5°	X	0.028	67	4000	0.75
$LiTaO_3$	Z	Y	0.006	67	3329	0.77
$LiTaO_3$	Y	Z	0.003	35	3230	0.94
Quartz	Y	X	0.0009	-24	3159	2.15
ST Quartz	Y+42.75°	X	0.0006	0	3158	2.62
$Bi_{12}GeO_{20}$	001	110	0.0068	128	1681	1.64

Electromechanical Power Flow Angle is zero in all cases.

BeO; v_∞ = 6620, slightly piezoelectric, thermal conductivity exceeding that of copper.

TABLE A2.3

Some Properties of Thin Films

Crystal/Crystalline Form	Piezoelectric Coupling, $\frac{\Delta v}{v_\infty}$	Temp. Coeff. of Delay, (ppm/°C)	Surface Wave Velocity, (m/s)
ZnO (on Si or fused quartz)	0.008	40	2700
CdS (on fused quartz)	0.0059	--	1702
AlN (on sapphire)	0.0072	--	6160

Piezoelectric Ceramics	Piezoelectric Coupling, $\frac{\Delta v}{v_\infty}$	Curie Temperature	Reduction of Trands. Eff. Starts at Temp	Surface Wave Velocity, (m/s)	Temp. Coeff. of Delay (ppm/°C)
PZT(EC-64)	∿ 0.02	350°C	100°C	∿ 2000	∿ 80
$BaTiO_3$(EC-31)	∿ 0.03	120°C	80°C	∿ 3000	∿ 700

APPENDIX A3

Systems Applications and Implementation I: Communications

by

D.B. Wohlberg
Communications Research Centre
Department of Communications

1. Introduction

Surface-acoustic-wave (SAW) devices possess many properties attractive to the communications systems engineer (Table A 3.1). Since surface waves propagate slowly, SAW devices tend to be very small in comparison with their electromagnetic-wave counterparts. Surface-wave attenuation is low and penetration is shallow, thus facilitating the storage, tapping and manipulation of a large quantity of signal information (time X bandwidth products as large as 5000). This provides the communications engineer with a device which can perform a powerful, real-time signal-processing function. SAW devices are passive and easily made rugged. Planar construction compatible with that of the huge semiconductor industry, and possible semiconductor/SAW integrated systems, await only the discovery of suitable material processing techniques.

TABLE A 3.1

SAW Properties of Interest to Communications and Radar Systems Applications

Velocity of Propagation:	∿3000 m/s (10^{-5} "c")
Delay:	3.3 μs/cm
Wavelength for 300 MHz:	10 μm (10^3 Wavelenths/cm)
Attenuation:	1.5 dB for 10^4 Wavelengths
Penetration Depth:	About one Wavelength
Non Dispersive (Velocity does not vary with frequency)	
Devices are Planar	

Significance of These Properties

Synthesis of a tapped delay line with a powerful, real-time signal processing capability is possible.

Physical attributes are attractive: small, passive, rugged.

Devices are highly reproducible and inexpensive in large numbers.

The purpose of this presentation is to outline several applications to communications for SAW devices and to discuss the trade-offs between conventional and SAW implementation. As an example, spread-spectrum communications will be discussed in some detail, drawing attention to size, cost, reliability, operational use and security trade-offs.

2. Communications Applications for SAW Devices

2.1 General

Several SAW devices of interest to the communications engineer are listed in Table A 3.2 along with salient features and some possible applications. The list is representative only and is not intended to be complete or detailed as it is not practical to do so in a short presentation. Detailed discussions of devices and applications can be found in the literature. It is apparent that there is a wide variety of SAW devices that can be used in systems applications. Not so apparent is when and there they should be used. The following discussion regarding the use of SAW devices in spread-spectrum systems will deal with these considerations for a specific system.

TABLE A 3.2

DEVICE	FEATURES	APPLICATIONS
DELAY LINE	non-dispersive	delay equalization
	easily tapped	signal storage and processing
		image coding
BANDPASS FILTER	no adjustments	IF
	reproducible	RF
	small, lightweight	
MATCHED DETECTION FILTER	match easily to arbitrary impulse response	demodulation at IF
	IF device	
PSEUDO-NOISE GENERATOR	IF device	spread spectrum modulation and demodulation
		system testing
		system identification
		synchronization
FREQUENCY DISCRIMINATOR	IF device	FM demodulator
		automatic frequency control
	Practical range of operation:	
	Centre Frequency: 10 MHz to 2 GHz	
	Time-bandwidth product: up to 5000	

TABLE A 3.2 (CONT)

DEVICE	FEATURES	APPLICATIONS
OSCILLATOR	small, rugged	satellite
	lightweight	portable transceivers
	fundamental operation to GHz frequencies	emergency beacon transmitter
	FM capability	
CONVOLVER	electronically tunable filter	adaptive signal detection
AMPLIFIER		automatic gain control
		TV IF filter – amplifier
HYBRID SEMICONDUCTOR/SAW	integrated system	programmable filters
HADAMARD TRANSFORM	real-time transformation	image coding
DISCRETE FOURIER TRANSFORM		signal analysis

2.2 SAW Devices in Spread-Spectrum Communications

A spread spectrum (SS) communication system is one in which the RF bandwidth is much wider than the information or message bandwidth (e.g., RF bandwidth = 10 MHz, message bandwidth = 10 KHz). Of the many schemes available for band-spreading, pseudo-random bi-phase coding is by far the most commonly used. Table A 3.3 defines and outlines characteristics of such a system. Applications of SS are basically military-oriented except for the use of SS in synchronization (or, equivalently, ranging) schemes or mixed-modulation schemes. The usefulness of SS in mixed-modulation schemes stems from the fact that it is possible to sum a SS signal with many other signals, perhaps frequency-modulated, which occupy the same frequency band and to receive all signals with imperceptible degradation due to crosstalk.

TABLE A3.3
SPREAD SPECTRUM

DEFINITIONS:

Biphase coded spread-spectrum communication system

One in which the carrier is phase-reversal keyed according to a pseudo-random binary sequence (code).

Processing gain

ratio of the RF bandwidth to the information bandwidth

CHARACTERISTICS OF A SPREAD-SPECTRUM SYSTEM:

RF Bandwidth – about equal to phase switching rate

TABLE A3.3 (CONT)
SPREAD SPECTRUM

CHARACTERISTICS OF A SPREAD-SPECTRUM SYSTEM: (CONT)

Demodulation – requires knowledge of the code and its time of arrival (synchronization)

Discrete Address – only receivers with the correct code can receive

Multiple Access – several SS signals can occupy the same frequency band

Low Detectability – low signal density, often below noise

Anti-Jam – jammer effectiveness reduced by an amount equal to the processing gain

APPLICATIONS:

Satellite communications

Sonobuoy transmissions

Other military communications

Mixed modulation schemes

Operation of a SS system is outlined in Figure A 3.1 using an example where the RF bandwidth is 12 times the information bandwidth (processing gain = 10.8 dB). The carrier phase is switched pseudo-randomly between 0 and π radians according to the combined (modulo-two added) message and code. Only when the code is removed at the receiver by switching the received carrier phase according to an identical synchronized code is the message recovered. Any unwanted signal that is present at the receiver will not correlate with the receiver code and only wideband noise will result.

The spectral properties of the SS signal are basically determined by the code. The autocorrelation function and frequency power density spectrum for a well known class of binary codes (M-sequences) are shown in Figure A 3.2.

Conventional techniques for achieving SS modulation and demodulation are outlined in Figure A 3.3. Implicit in the demodulator are code-synchronization circuits, carrier-recovery circuits and binary pseudo-random code generators. Conventional SS equipment tends to be bulky, complex and requires strict system discipline and rather long synchronization times. They can be made to be "arbitrarily secure" by selecting long and complex codes. This should not, however, be confused with "arbitrarily high" processing gain, which is fixed by bandwidth considerations.

SAW devices can be used to implement SS systems which achieve identical performance to conventional SS systems within the code length limitations imposed by SAW fabrication technology with the important difference that no code synchronization is required. This is possible because the whole pseudo-random code can be stored at IF in a SAW device. This is illustrated in Figure A 3.4. Such a SAW device is a perfect matched-filter receiver for a SS signal generated by an identical SAW device.

Figure A 3.5 illustrates equivalent conventionally and SAW-implemented SS systems. The configuration of an experimental SS modem being constructed at the Communications Research Centre is shown in

Figure A 3.6. Waveforms illustrating the circuit's operation, taken from various points indicated in Figure A 3.6 are shown in Figures A 3.7(a) to A 3.7(f).

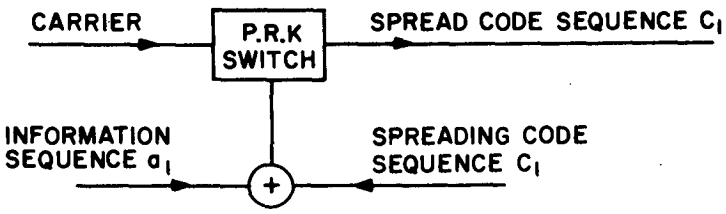
Trade-offs between conventional and SAW SS implementations are summarized in very general terms in Table A 3.4. Generalities are necessary since there is such a wide range of SS applications. It is safe to draw the following firm conclusions, however. Presently available, fixed-coded SAW devices are unsuitable for high-security applications, because the most complex coded devices available contain only in the order of 1000 chips. Certain applications in which SS was formerly impossible to implement are now highly practical (low-cost, large numbers, medium security). With the advent of sophisticated, programmable-code SAW devices, SAW-implemented SS modems will be smaller, cheaper, more reliable and have much shorter synchronization time than present SS modems while providing the same security.

TABLE A 3.4
SPREAD-SPECTRUM IMPLEMENTATION TRADE-OFFS

	CONVENTIONAL	SAW
Size:	Large	Small
Cost:		
Small Quantity	Moderate	High
Large Quantity	Moderate	Low
Security:	High	Fixed SAW – Low Programmable SAW – High
Reliability:	Moderate	High
Acquisition Time:	Long	Short

3. Conclusions

Many possible communications systems applications exist for SAW devices and doubtless many more will be identified. The question of when to use SAW devices in communications is a matter of cost, desired physical characteristics, desired system characteristics and flexibility. In most commercial or consumer electronics applications, cost is prohibitive. However, in many military systems or satellite systems, the advantages of SAW devices over conventional implementation techniques outweigh the cost disadvantage and in many cases can result in lower overall cost.



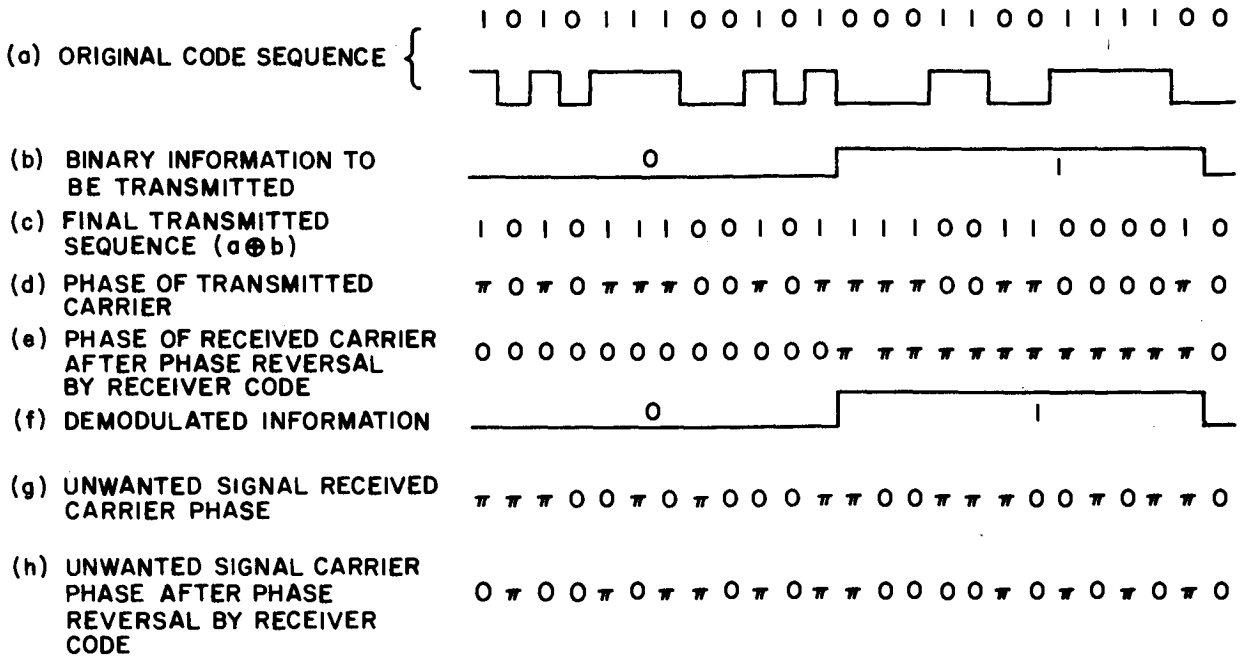


Figure A 3.1. Basic Operation of a SS Modulator and Demodulator

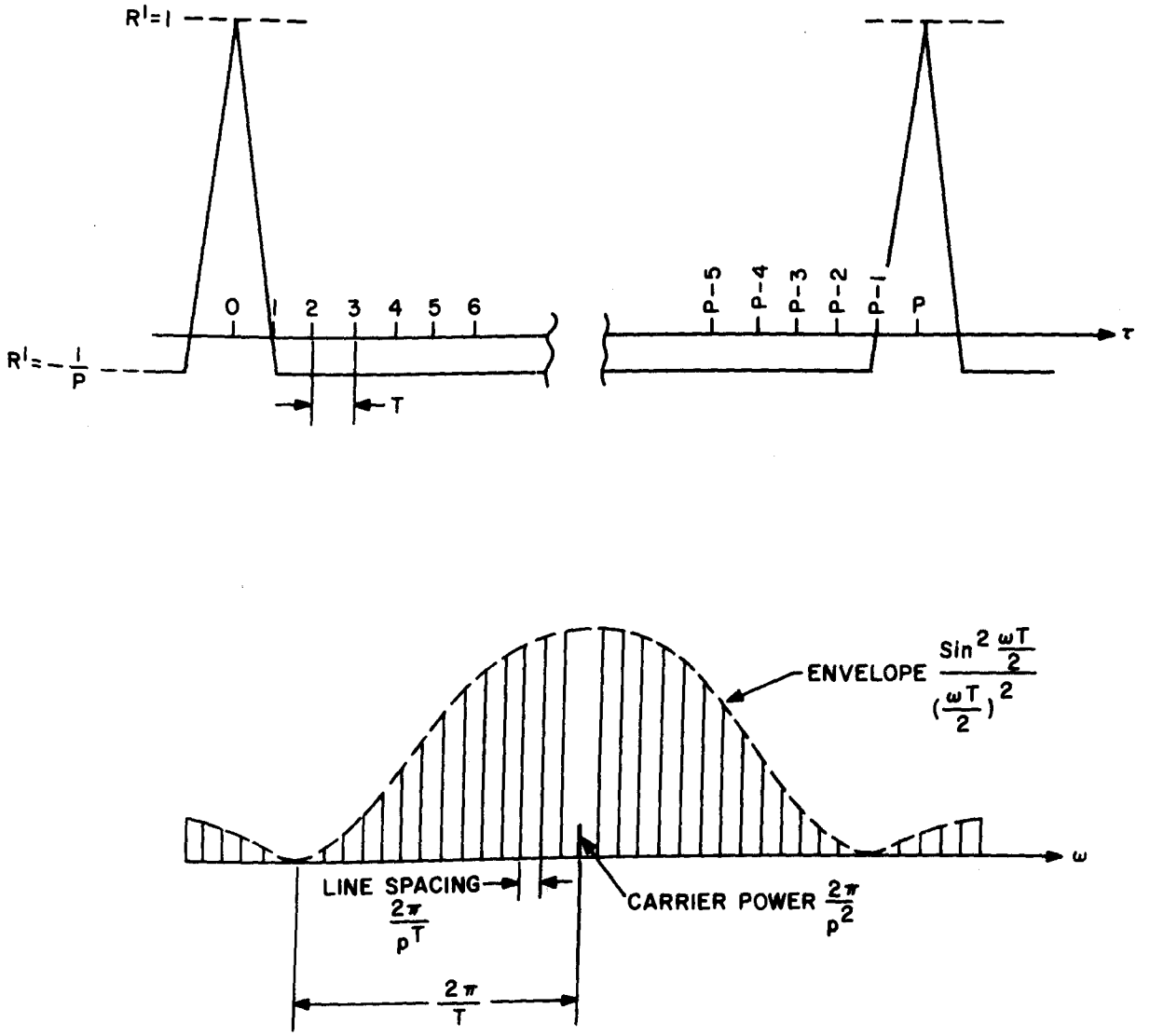
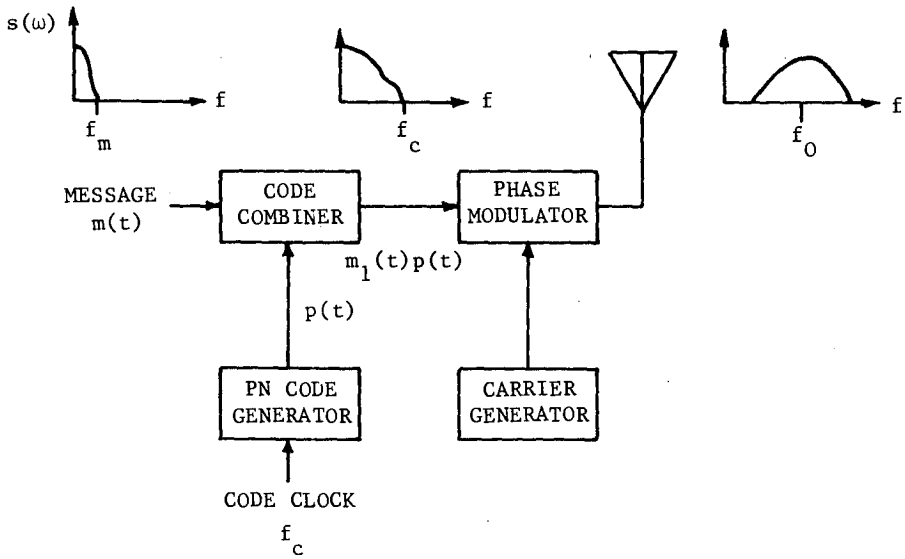
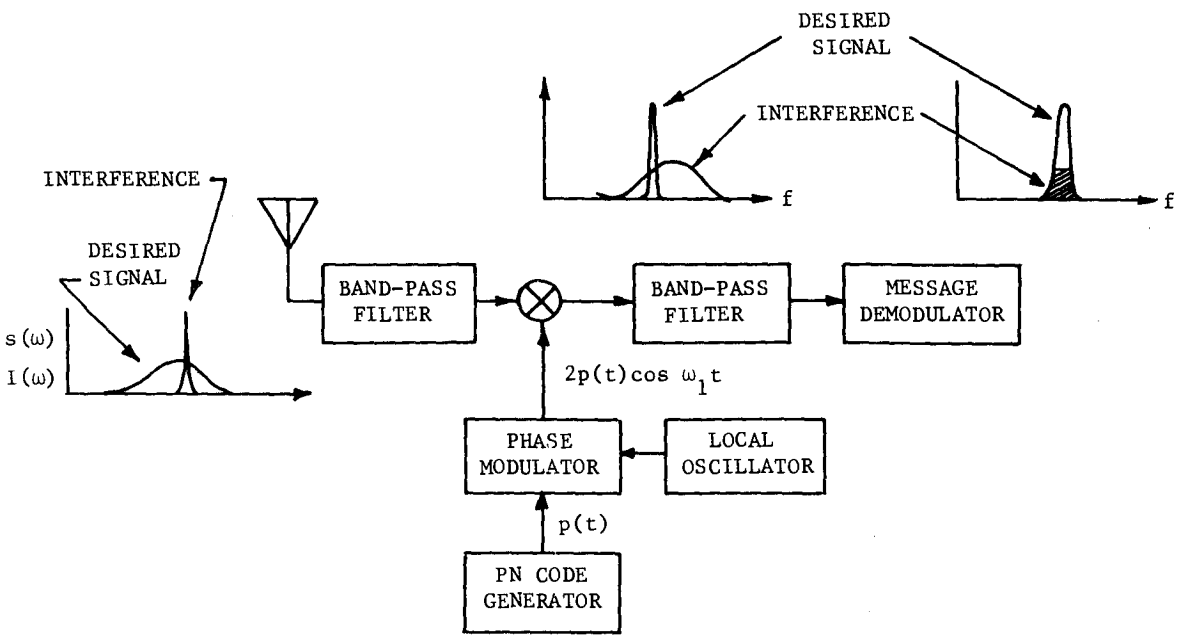


Figure A 3.2. Autocorrelation Function and Frequency Power Density Spectrum of a Linear Maximal Length Binary Sequence



(a) Conventional modulator



(b) Conventional demodulator

Figure A3.3. Conventional SS Implementation

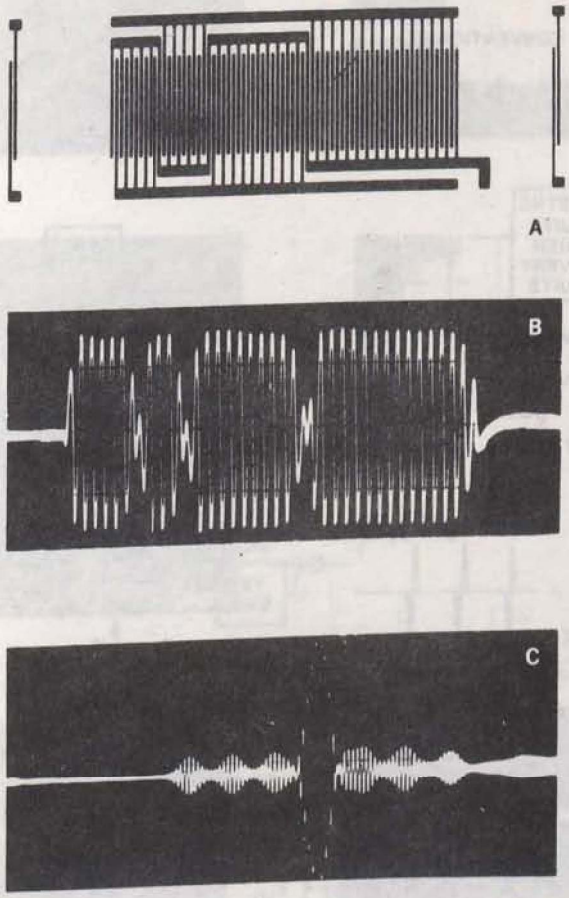


Figure A 3.4.

A – The transducer structure which stores a 7-bit Barker code.

B – Output of the surface-wave device for an impulse input.

C – Output for a 7-bit Barker coded input.

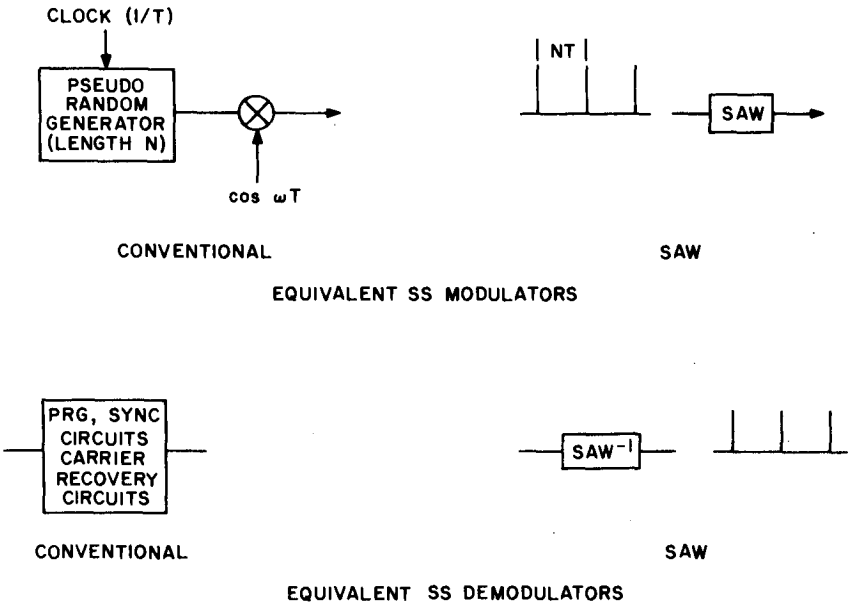
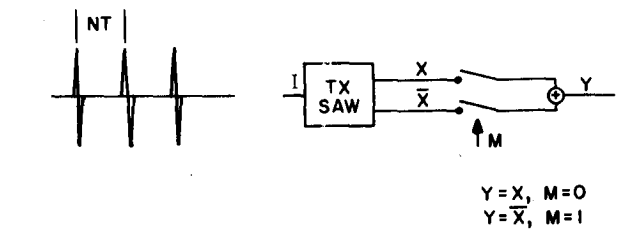
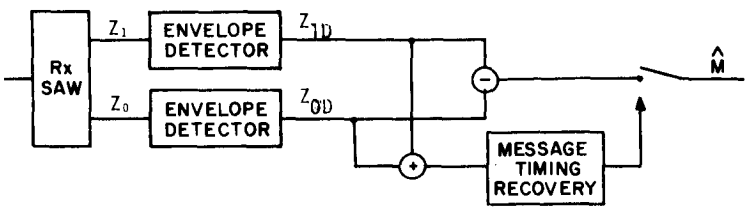


Figure A 3.5. Equivalent Conventional and SAW-Implemented SS Modems



SPREAD SPECTRUM MODULATOR



SPREAD SPECTRUM DEMODULATOR

N	=	127
T	=	20 ns
NT	=	2.6 μs
CENTRE FREQUENCY	=	190 MHz
BANDWIDTH	=	50 MHz
DATA RATE	=	390 k bit/s
PROCESSING GAIN	=	127 (21 dB)

Figure A 3.6. CRC Experimental SS Modem and its Characteristics

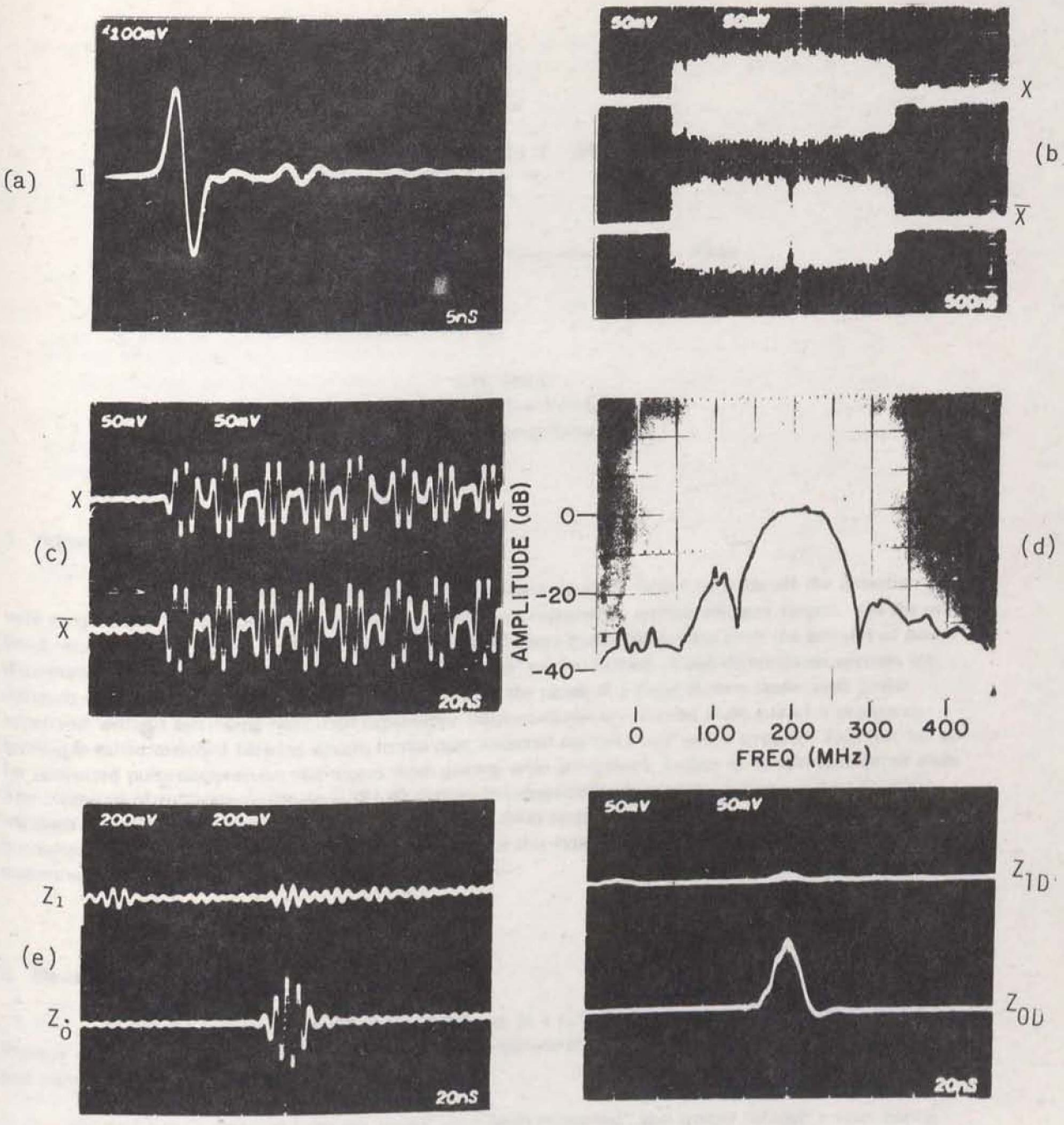


Figure A 3.7. Waveforms and Spectrum Associated with CRC Experimental SS Modem, Figure 6

(a) Input to TX SAW (via 30 dB coupler)

(b) Output to TX SAW, X and $\overline{X}$

(c) Same as (b), expanded time scale

(d) Spectrum of TX output, Y

(e) Rx SAW output

(f) Rx envelope — detected output

APPENDIX A4

Systems Applications And Implementation II: Radar

by

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Department of Communications

1. Introduction

In conventional pulsed radar systems, the designer is often forced to trade-off the detection range with range-resolution capability. Short-duration pulses are required to resolve adjacent targets. On the other hand, when the peak power of the transmitter is limited, short pulses effectively limit the amount of power illuminating the target and thus impose a range limitation on the system. Pulse-compression systems are designed to overcome these problems, that is, to extend the range of a radar system under peak-power constraint without sacrificing resolution capability. Pulse-compression systems make use of a processing technique called matched filtering which, in the past, required complex and costly circuits. This fact has so far prevented pulse-compression techniques from gaining wide acceptance, except in certain specialized areas. The invention of surface-acoustic-wave (SAW) devices has drastically changed the picture and by their use matched filtering can be easily implemented. Although SAW technology does not change the theory or the fundamentals of pulse-compression systems, it does make this type of system more simple and rugged and less expensive, and hence, more practical.

2. Matched Filter

Figure A4.1 shows a simplified block diagram of a pulse-compression system. A SAW having impulse response h(t) is excited by a pulse from a pulse generator. The signal h(t) is "up-converted" to RF and transmitted after amplification.

The echoes reflected from the targets are "down-converted" and passed through a filter having impulse response $h^*(-t)$, (where * denotes a complex conjugate). For certain selected signals h(t) the output of the filter having a response $h^*(-t)$ takes on the form of short bursts of IF. After envelope-detection, pulses appear at the display at a time $2\tau_i$ after the appearance of the pulse from the pulse generator where τ_i is the time required for a signal to travel from the antenna to the target. Thus one can obtain the range of the target by observing the time of appearance of the peaks.

The filters having impulse responses h(t) and $h^*(-t)$ form a matched filter pair. The input to the envelope detector can be expressed as a convolution of h(t) and $h^*(-t)$:

$$O(t) = K \int h(\theta)\, h^*(\theta + t)\, d\theta \qquad (K = \text{constant})$$

The right-hand side of the equation can be recognized as the auto-correlation function of h(t). The input after the envelope detector can be expressed as a magnitude:

$$|O(t)| = |K\ h(\theta)\ h^*(\theta + \tau)d\theta|$$

From the above discussion, one can see that if h(t) is actually considered as a radar signal the performance of a pulse compression radar system employing matched filter depends upon the choice of h(t). Generally speaking a "good" radar signal has two characteristics:

(a) It should have a uniform amplitude over the duration of the pulse: (This allows the transmitter to be driven to its limit).

(b) It should have an auto-correlation function which consists of a narrow peak with low side peaks: (This characteristic of the signal permits the resolution of closely spaced targets).

3. Examples of Desirable Radar Signals

Two types of radar signals satisfy the requirements stated above and are commonly used as pulse compression radar signals; these are:

(a) Linear FM (Chirp);

(b) Pseudo-random binary sequence.

3.1 Chirp

Figure A4.2 shows a chirp waveform. A chirp is a burst of RF in which the frequency varies linearly with time. The matched filter for this signal is a filter whose delay varies linearly with frequency. The output of the matched filter has the envelope of:

$$|O(t)| = \frac{K \sin\left(\frac{rt}{2}\right)(T - |t|)}{rt} \qquad -T \leqslant t \leqslant T$$

$$r = \frac{2\pi\,\Delta f}{T}$$

3.2 Binary PN Sequence

Figure A4.3 illustrates a binary PN sequence. The PN sequence consists of a burst of RF in which the phase is changed by 180 degrees in what appears to be a random fashion. The sequence is characterized by the parameters τ, N and f_0 where τ is the duration of one bit, N is the total number of bits, and f_0 the centre-frequency of carrier. The auto-correlation function of such a sequence exhibits a high central peak with relatively low side peaks. Before the appearance of surface-wave devices, a particular type of sequence called a maximal-length sequence was popular because it was easy to generate with flip-flops. Also, when repeated periodically, this type of sequence has a centre-peak to side-peak ratio of N. However, the central peak to side peak ratio of the auto-correlation function is reduced to $\sqrt{N}$ when this sequence is aperiodic. Since surface-wave techniques do not use flip-flops to generate the sequence, the use of maximal-length sequences appears to have little advantage.

3.3 Figure of Merit for Pulse-Compression

In both of these cases the width of the auto-correlation peak is proportional to the bandwidth W. In the case of the chirp waveform, W is the frequency change between the start and the end of the pulse. In the case of PN sequence, W is essentially the bandwidth of one bit. A Figure of Merit called the "compression ratio" can be defined which measures the efficiency of the pulse-compression system. This figure is the ratio of the duration of transmitted pulse h(t) to the duration of the auto-correlation peak. It may be written thus:

Compression ratio = TW,

where T is the duration of the transmitted pulse. For the above reason, the radar system designer often calls for signals with a large "time X bandwidth" product.

The synthesis of radar waveforms with a large TW has heretofore been very difficult. However, by using surface-wave devices, a TW of the order of 10^2 to 10^3 is well within the state-of-the-art with expectations that a TW of 10^4 – 10^5 can be achieved in the future. Therefore, it is predicted that the development of surface-wave devices will have a strong impact of future development of pulse-compression radars.

4. Temperature Effects

One probelm encountered in using these devices in the matched-filter configuration is that they are sensitive to changes in ambient temperature. That is, if the transmitter and receiver SAW devices are at different temperatures the correlation peak can be significantly degraded (5 dB for ±10°C on lithium niobate). The extent of this degradation is a function of many factors such as code, code length, bandwidth, and centre frequency. All of these factors have to be considered if one wishes to quantitatively predict the effect of a temperature difference on a particular pair of SAW devices.

One convenient way of relating all the above factors is by means of the "ambiguity function". This function was originally derived to express the output of a matched filter pair used in radar systems when the echo is reflected from moving targets.

This function is usually expressed thus:

$$x(\tau, \varphi) = \int_{-\infty}^{\infty} h(t)\, h^*(t+\tau)\, e^{j2\pi\phi t} dt$$

where ϕ is the Doppler shift. In the present study the effect of the temperature difference can be considered to be analogous to that of a Doppler frequency shift because a change in temperature actually "time scales" the impulse response of the surface-wave devices. The magnitude of the matched-filter output, O(t), can be expressed as:

$$|O(t)| = |x(t,\varphi)|$$

where $\phi = \Delta T \times f_0 \times \delta$,

ΔT is the temperature difference,

f_0 is the centre frequency of the device, and

δ is the temperature coefficient.

A loss factor, ρ, can be defined as the fractional reduction of peak size,

$$\rho = \frac{|x(0,\phi)|}{|x(0,0)|}$$

If the energy contained in h(t) is normalized to unity, then

$$\rho = |x(0,\phi)|$$

For a PN sequence of N bits each with duration D, it can be shown that

$$|x(0,\phi)| = \left|\frac{\sin \pi\phi T}{\pi\phi T}\right|$$

where $T = ND$.

An experiment to measure temperature effect was set up as shown schematically in Figure A4.4. The receiving SAW was placed in an oven. As the temperature of the oven is varied the peak of correlation is decreased, and at the same time, the side lobes of the correlation peak are increased. However, by changing the translation frequency f'' we can restore the peak to the original level. As shown in Figure A4.5 the frequency change versus temperature is linear. The fractional change in the critical dimensions of the device is reflected in the change of the code centre frequency f_0. Thus, by measuring the amount of frequency offset ($f_c \times \delta$) that was required to restore the correlation level, one can compute δ. In the foregoing experiment $f_c \times \delta$ was found to be 19.0 kHz/°C (see curve A); the value of f_c at room temperature was found to be 2×10^8; and thus δ is computed to be 9.5×10^{-6}.

Having found δ, we can calculate ϕ and hence ρ at any temperature. The measured and calculated results are shown in Figure A4.5.

5. Conclusions

The development of surface-wave devices will have a significant effect on the future development of pulse-compression radar. By using these devices, efficient matched filters for signals characterized by high TW products can be readily synthesized in small, compact and rugged configurations. One problem of which the user must be aware, is the possible mismatch when a temperature difference exists between the matched filter pair. This effect is not noticeable for low TW product signals but becomes more pronounced in more efficient systems with large TW products.

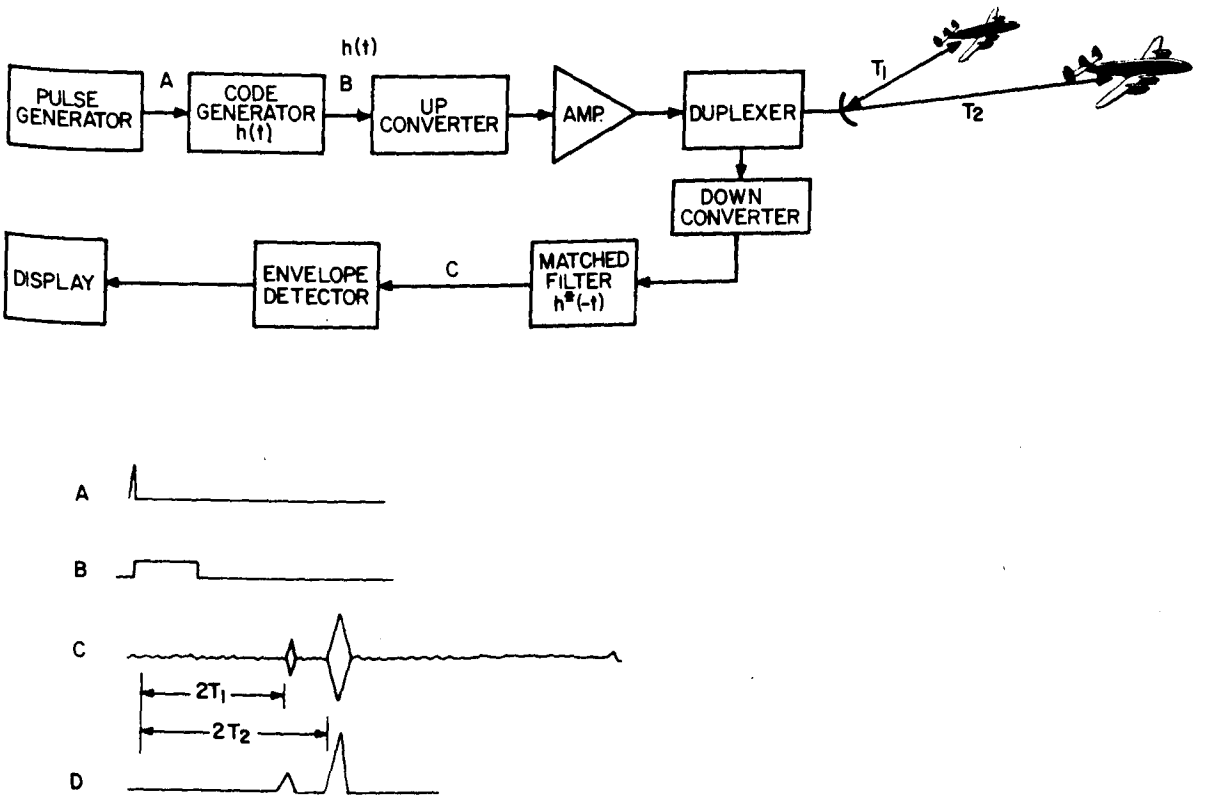
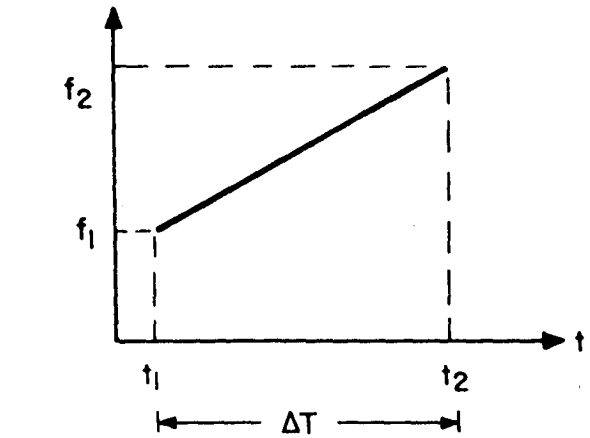
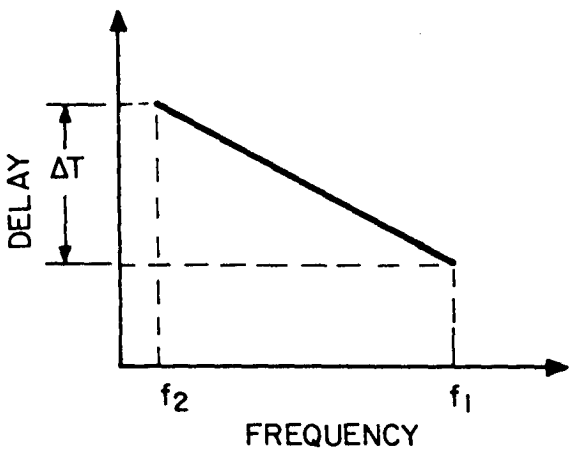


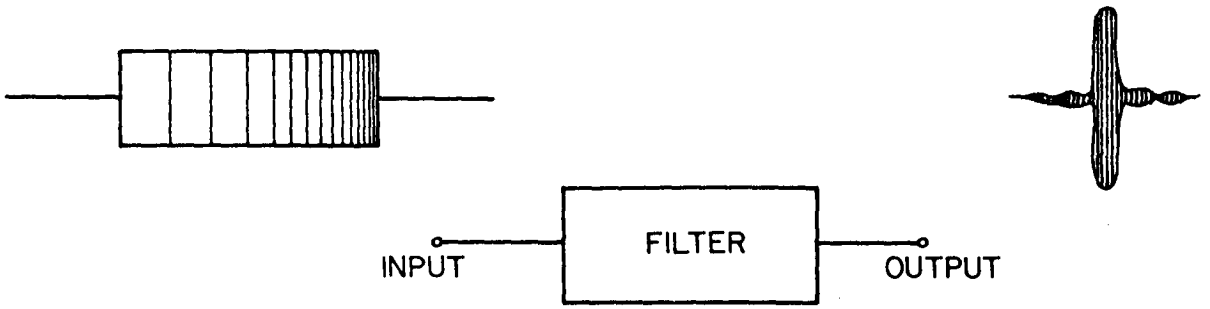
Figure A4.1. Simplified Block Diagram of a Pulse Compression System



(a) Input Signal Time-Frequency Plot



(b) Filter Characteristics



(c) Input-Output Characteristic

Figure A4 2 Frequency Chirp Filter Characteristics

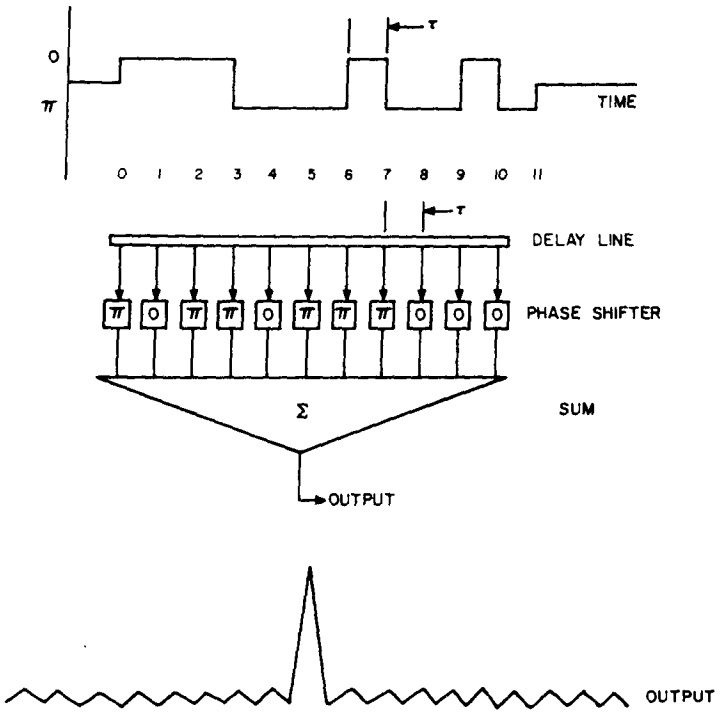


Figure A4.3. PN Sequence Correlation

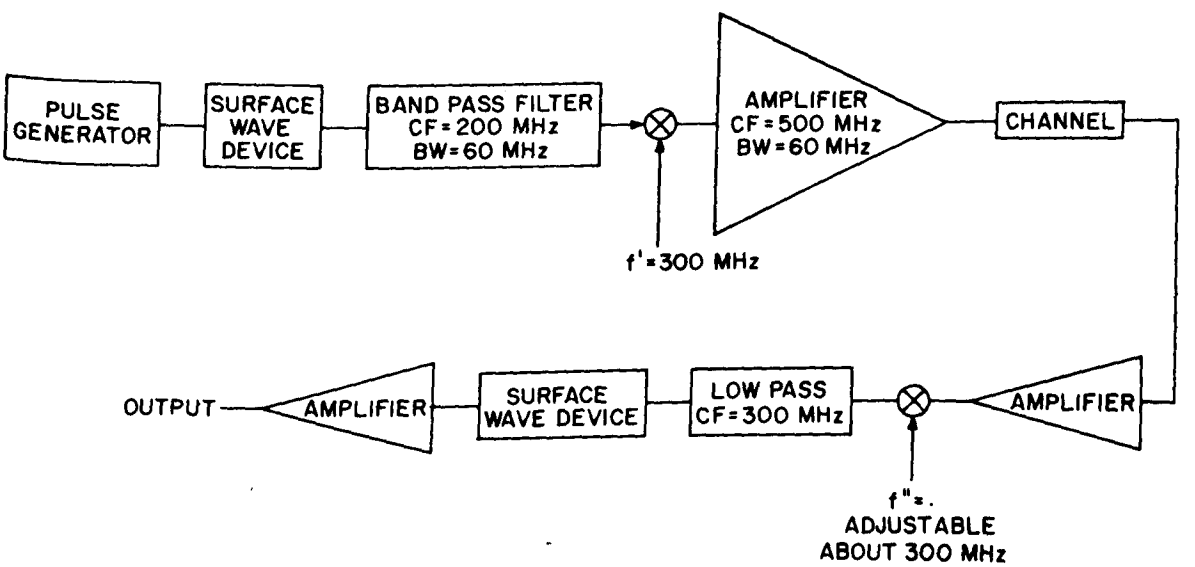


Figure A4.4. Block Diagram of the Experiment to Measure Temperature Effects

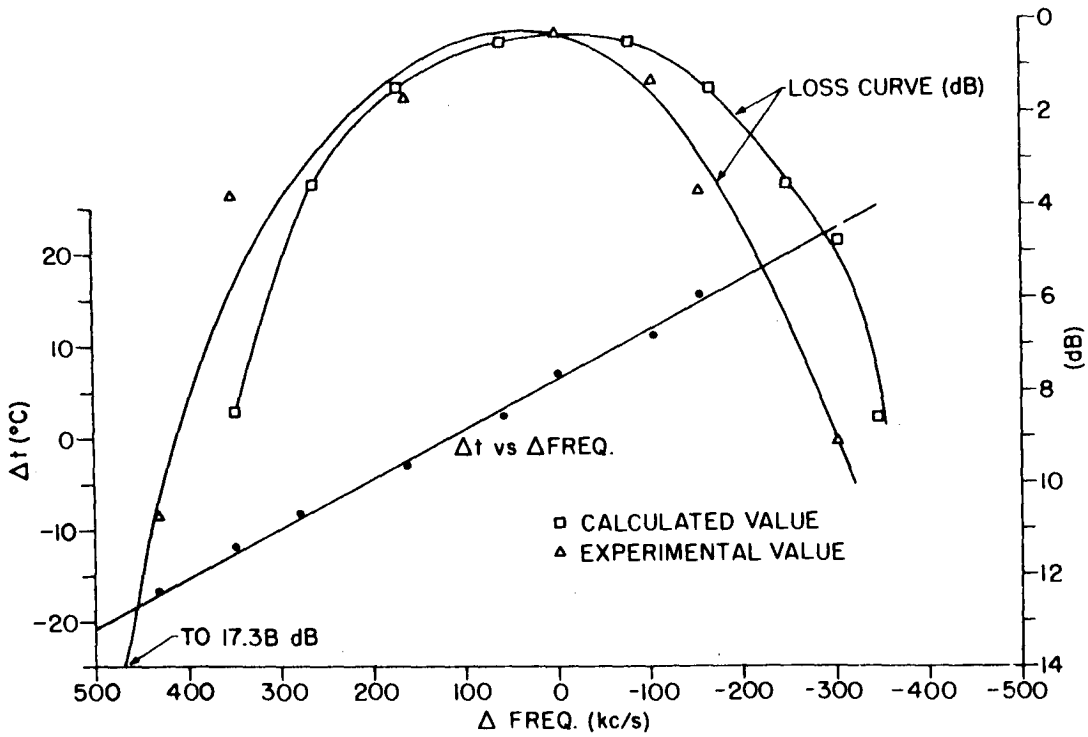


Figure A4.5. Effect of Temperature on $LiNbO_3$ 127 Bit PN Coded Device

APPENDIX A5

Nonlinear Effects – Amplifiers And Convolvers

by

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The first part of this paper summarizes the sources of nonlinearity as coming from the quadratic terms in the constitutive equations of materials, and the space-charge nonlinearity due to coupling to free carriers. The fact that nonlinearity produces intermodulation distortion and harmonic generation limits the dynamic range of a surface-wave device. However, one can take advantage of nonlinearities in the design of signal processors such as convolvers and correlators. In addition one can construct devices which will amplify surface waves either by parametric or electronic means. The presentation is divided into three parts each dealing with the present experimental situation. The first part deals with amplification of surface waves, the second part with harmonic-generation experiments, and the third part with convolver and correlator devices.

1. Surface-Wave Amplifiers

The structure of a separated-medium amplifier is shown in Figure A5.1. Amplifier gain; saturation and dynamic range; and device noise characteristics are summarized in Figures A5.2 to A5.4. The gain of such a device is proportional to $\frac{\Delta v}{v}$ and to the sheet conductivity of the semiconductor. From the gain characteristic of the device it is seen that considerable gains can be achieved. In particular, the data of Figure A5.3, obtained at 108 MHz, shows a dynamic range of 50 to 70 dB which depends on gain, and a saturation output power of the order of 1 mW. From the noise characteristic the best possible expected noise figure is of the order of 5 dB. Figures A5.5 to A5.7 pertain to the monolithic amplifier structure, consisting of a semiconductor film deposited onto a piezoelectric substrate. With the structure shown in Figure A5.5 the maximum gain obtained at 660 MHz is 60 dB of electronic gain for a net device gain of 20 dB. A dynamic range of 50 dB can be estimated from Figure A5.7.

2. Harmonic Generation and Parametric Amplification

Figure A5.8 shows a standard laser probe set up used to measure harmonic generation in surface waves. From the saturation characteristics of the fundamental as shown in Figure A5.9 it can be seen that a key power level limit is 10 mW/mm at one gigahertz. This would be the maximum useable power for linear devices. This limit roughly speaking, scales up as the frequency goes down. Figure A5.10 shows the ease with which harmonic generation can be measured. In fact, a significant fraction of the energy is contained in the harmonics as shown in these experiments. In Figure A5.11 a parametric amplifier experiment is shown as an illustration of what has been tried. The gain is very frequency selective as shown in Figure A5.12 and 6 dB of gain is obtained with the particular conditions stated.

3. Convolution Devices

Figure A5.13 shows the basic convolution structures and Figure A5.14 shows some experimental results obtained with these devices. The insertion loss, defined as output convolved power divided by the geometric mean of the two input powers, is of the order of 70 – 80 dB. In Figure A5.15 the configuration used for time-reversal is shown and Figure A5.16 shows time-reversal results obtained experimentally. The inclusion of a semiconductor film similar to that used in the separated-medium amplifier enhances the non-linear effect to such an extent that the device shown in Figure A5.17 has 40 dB or lower insertion loss than that of Figure A5.13 and it is anticipated that, with such a structure, 25 dB of insertion loss with 10 mW at each input is attainable. The actual improvement obtained with this device was 40 dB; potentially there is a 60 dB improvement capability. In Table A5.1, the figure-of-merit parameters are listed for various structures.

4. Summary

A brief outline has been given of the actual experimental situation as it exists today with respect to amplification, nonlinear effects and convolver devices. Stress has been given to actual experimental results in order to provide useful values such as the dynamic range and noise-figure capabilities of devices and device insertion loss.

Table A5.1 Figures of Merit for Various Plate-Type Convolver Systems

Convolver Systems	M (10^{-4} V m/W)	Reference *
$LiNbO_3$ YZ, (8.2 Ω-cm)	61.0	(a)
$LiNbO_3$ YZ	1.21	(b)
$LiNbO_3$ YZ	0.56	(c)
PZT, H_2O, Si (10 Ω-cm)	19.0	(d)
PZT, Si (10 Ω-cm)	4.8	(d)
PZT 8 (Basal) (All)	4.95	(b)
CdS (Basal)	5.4	(c)
$Bi_{12}GeO_{20}$ (001) (110)	1.02	(b)
$Bi_{12}GeO_{20}$ (211) (111)	0.025	(c)
ZnO (Basal) (All)	0.246	(b)
Quartz YX	< 0.033	(b)

* (a) input wavelength, $\lambda = 18\ \mu m$; acousto-electric loss is 4 dB/cm

(b) $\lambda = 104\ \mu m$

(c) $\lambda = 33\ \mu m$; acousto-electric loss is 4 dB/cm

(d) $\lambda = 180\ \mu m$

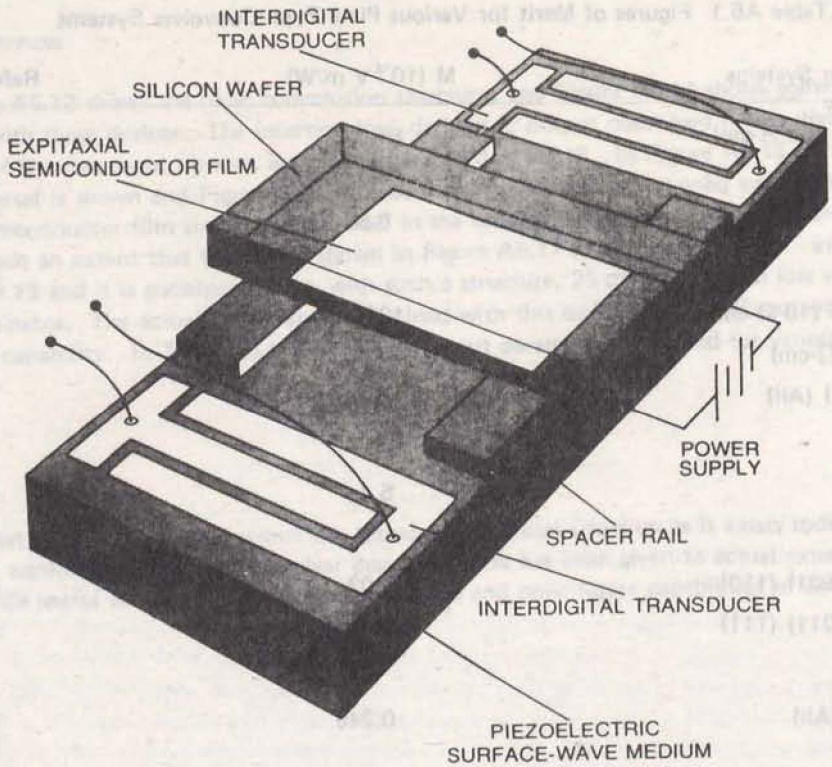

Figure A5.1. Separated Medium Surface Wave Amplifier. The Acoustic Surfave Wave Interacts With Drifting Electrons in the Silicon

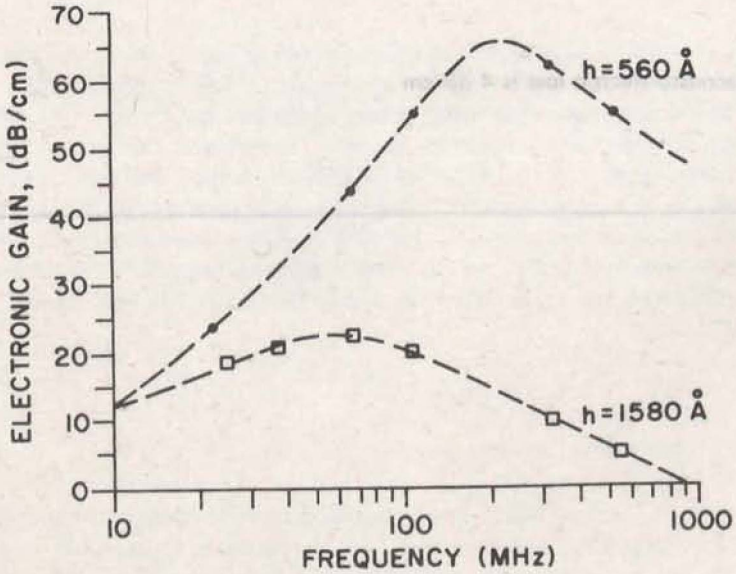

Figure A5.2. Electronic Gain vs. Frequency for a Separated Medium Surface Wave Amplifier, YZ $LiNbO_3$ and Epitaxial Si Film

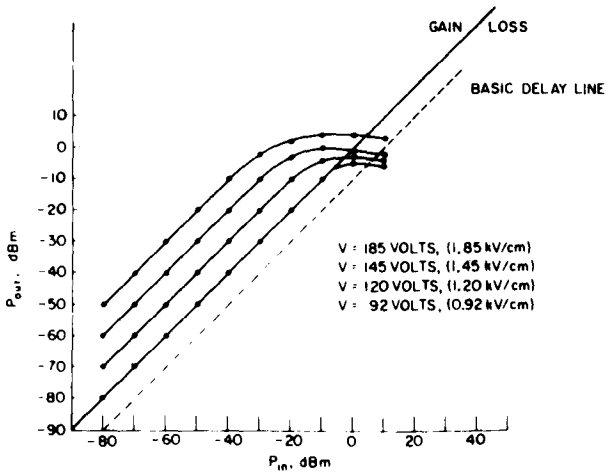

Figure A5.3. Power Saturation Characteristics of a Separated Medium Surface Wave Amplifier

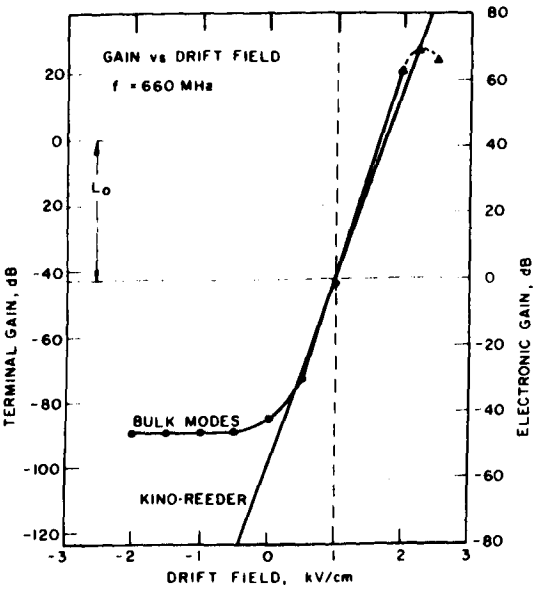

Figure A5.6. Gain vs. Drift Field

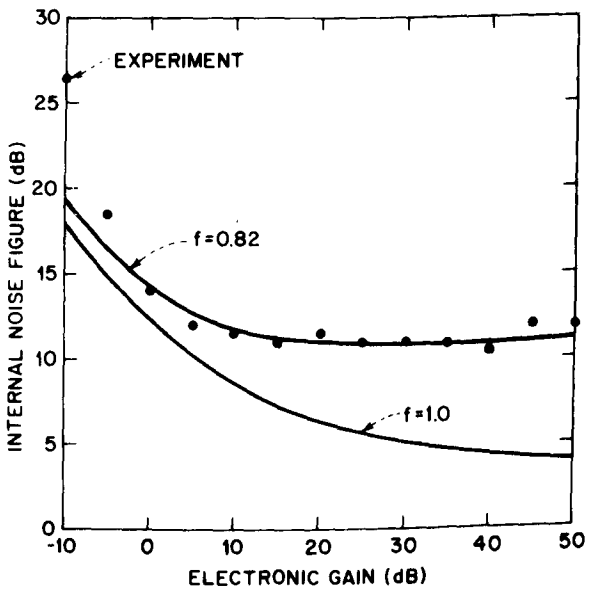

Figure A5.4. Theoretical and Experimental Noise Figure for a Separated Medium Surface Wave Amplifier

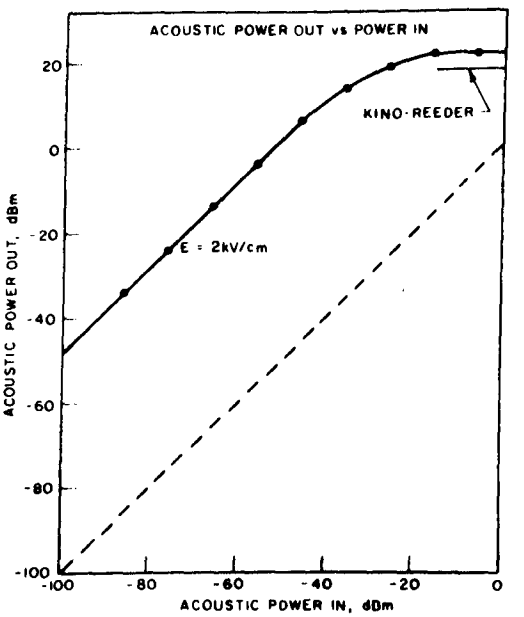

Figure A5.7. Acoustic Power vs. Power In

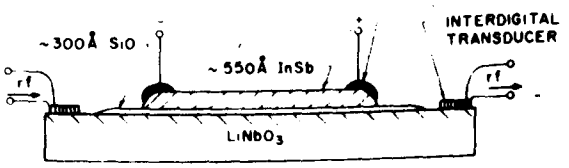

Figure A5.5. Amplifier Configuration

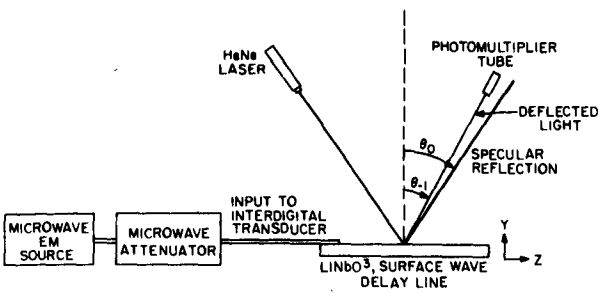

Figure A5.8. Optical Probe

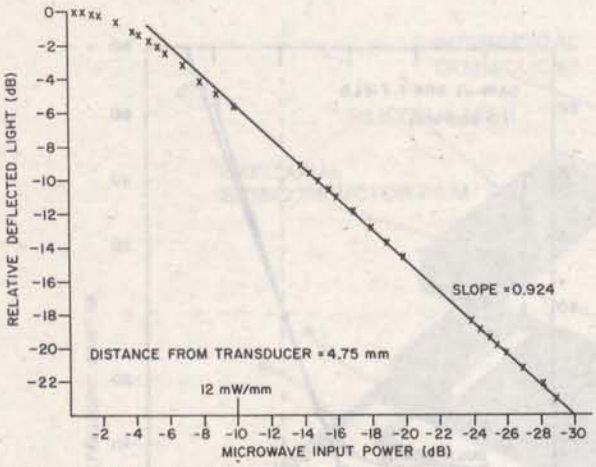

Figure A5.9. Light Deflected from a 905 MHz Fundamental Frequency Acoustic Wave as a Function of Microwave Input Power

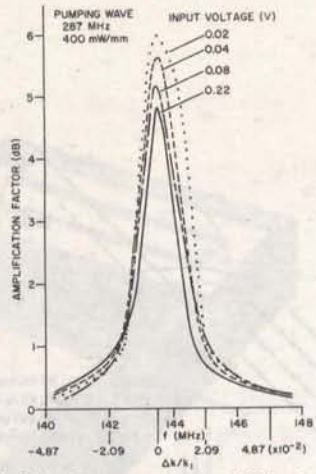

Figure A5.12. Parametric Amplification vs. Frequency of Signal Wave

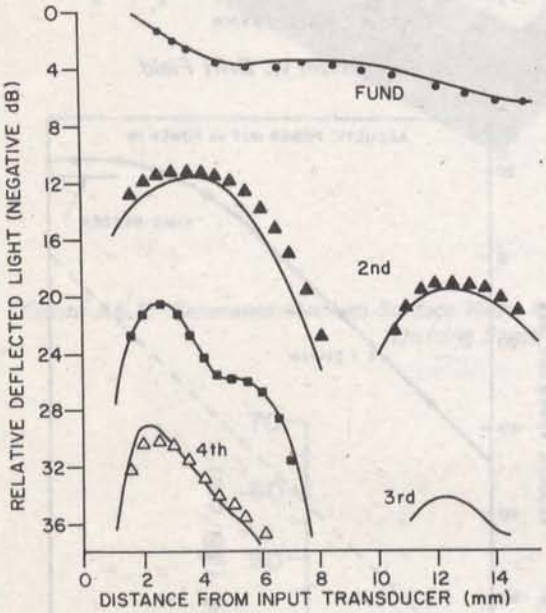

Figure A5.10. Solid Curves-Calculated Harmonic Generation. Circles, Triangles and Squares-Harmonic Generation Measured by Slobodnik

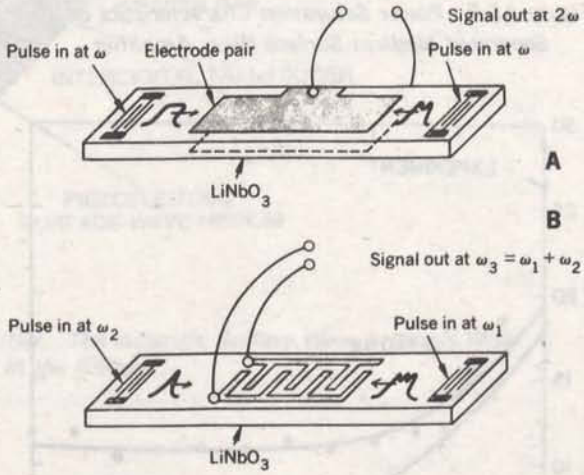

Figure A5.13. Transducer Configurations used for Harmonic Generation, Frequency Mixing, and Obtaining Convolution Between Two Signals

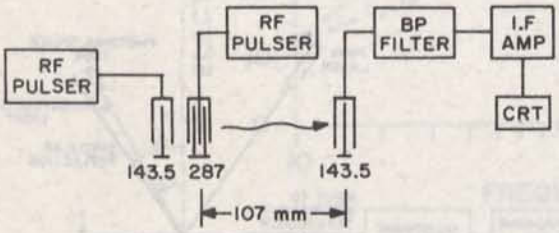

Figure A5.11. Block Diagram of Experimental Apparatus used for Parametric Amplification

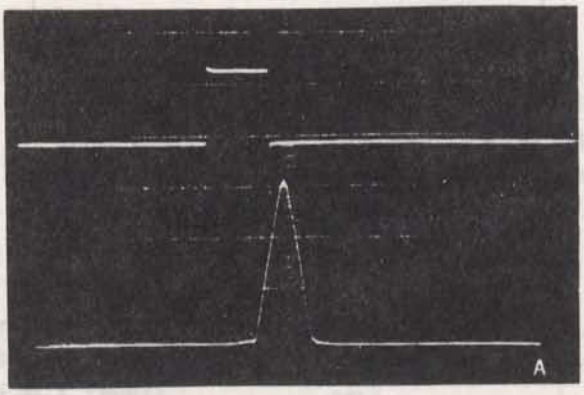

Figure A5.14(A). Autoconvolution of a Rectangular Pulse using a Surface Wave Convolver

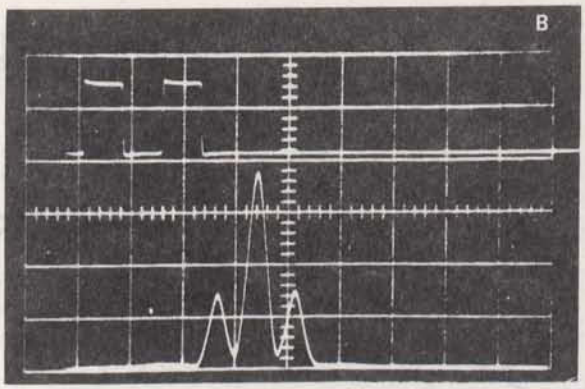

Figure A5.14(B). Autoconvolution of a Double Pulse

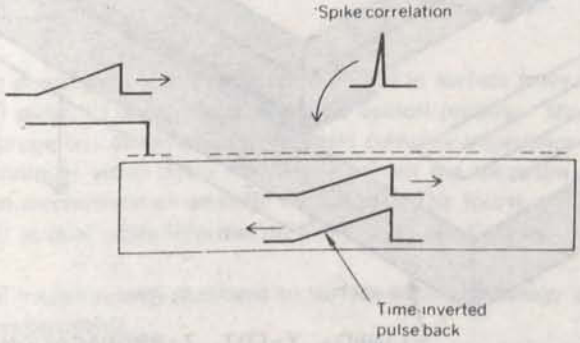

Figure A5.15. Sketch of the Configuration used to Obtain Time Reversal of an Input RF Pulse

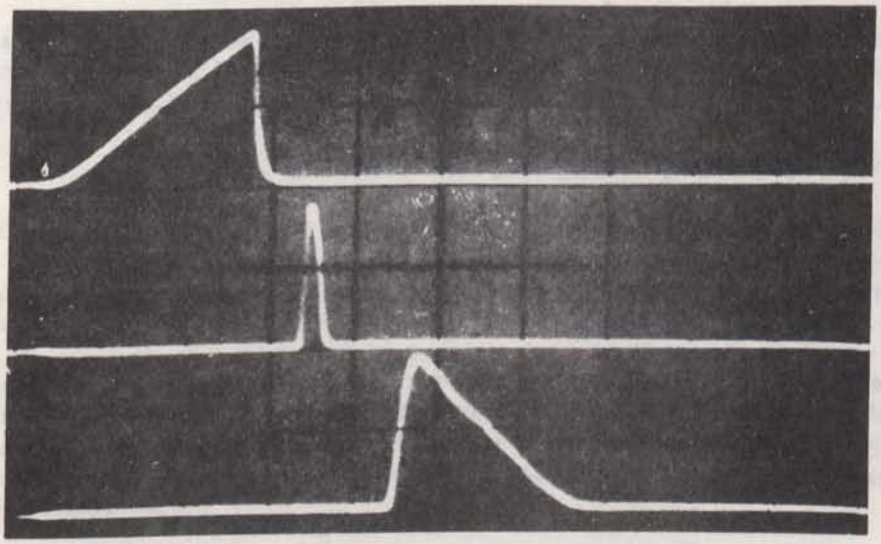

Figure A5.16. Experimental Time-Inversion of an Electronic Signal

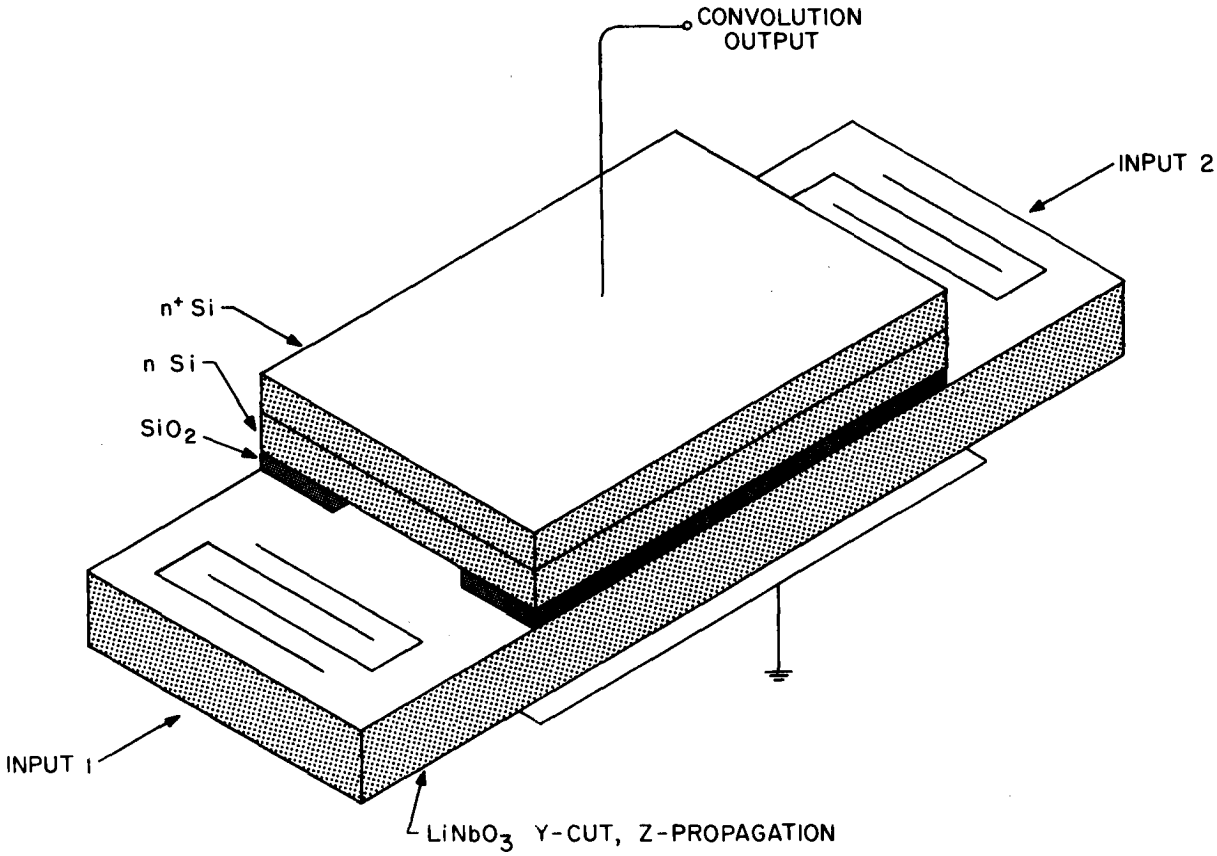

Figure A5.17. Surface Wave Convolver

APPENDIX A6

Optical Probing of Surface Waves

by

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There are four basic diagnostic techniques currently used in surface wave technology; 1) swept frequency (vector voltmeter); 2) pulse; 3) electrostatic probe; 4) optical probing. Methods 1) and 2) are used primarily to evaluate electrical properties of devices, for example complex impedance and signal distortion. However, none of the first three techniques yields direct information about the spectrum of acoustic modes excited in a device, or about attenuation mechanisms or acoustic reflections. The fourth technique, optical probing, does provide quantitative as well as qualitative information about such phenomena.

In this paper, typical measurements pertinent to surface-wave technology are presented in order to establish the feasibility of such experiments.

Consider a standing-wave pattern on the surface of a substrate, i.e.

$$S(z,t) = R_1 \sin(\Omega t - kz) + R_2 \sin(\Omega t + kz)$$

where R_1 and R_2 are the amplitudes of the surface wave propagating in the +z and -z directions respectively. When light of frequency ω_0 is reflected from the substrate surface, then, in addition to the specular reflection, two diffraction orders I_{+1} and I_{-1} of the form

$$I_{\pm 1} = \text{constant} \times C^2 \times \int_0^\infty \{R_1{}^2 \delta(\omega - [\omega_0 + \Omega]) + R_2{}^2 \delta(\omega - [\omega_0 - \Omega])\} d\omega,$$

are observed, where C is the optical reflectivity of the substrate. If only one wave is present on the substrate ($R_2 = 0$) then either I_{+1} or I_{-1} gives a direct measurement of the surface wave power ($\alpha R_1{}^2$). However the optimal use of the information available in the diffraction orders is to resolve, interferometrically, the two frequency components, one at $\omega_0 + \Omega$, the other at $\omega_0 - \Omega$.

An appropriate system for making such a measurement is shown in Figure A6.1. The confocal 50 cm Fabry-Perot interferometer is capable of separating spectral components separated by as little as 2 MHz in frequency. This system is therefore capable of measuring the power of two oppositely propagating surface waves, a feature crucial to the measurements of standing-wave ratios and the behaviour of surface waves under bidirectional interdigital transducers.

Examples of the application of this diagnostic technique arise in measurements made under interdigital transducers. At frequencies below surface-wave resonance, scattering occurs from the transducer strain field only. The results of a typical measurement are shown in Figure A6.2. The observed dip is caused by substrate damage or finger lift-off and is an example of the non-destructive testing of interdigital grids. Growth

of surface-wave power under an active transducer is shown in Figure A6.3. This measurement leads directly to the evaluation of the electromechanical-coupling coefficient. Coupled with vector-voltmeter measurements, the fraction of the electrical power absorbed by a generating transducer which is converted into surface-wave energy can be measured as a function of frequency or the number of finger pairs (Figure A6.4). Furthermore the proportion of energy available in each of the spatial harmonics can be measured as well as the absorption of acoustic energy under a receiving transducer. The fraction of surface-wave energy reflected and transmitted at a receiving transducer can also be measured as a function of the electrical load.

Optical probing experiments are used to measure surface-wave propagation on a substrate. The generation of harmonics as a function of propagation distance can be measured directly from the I_{+n} diffraction order where n refers to the n'th harmonic. The attenuation of surface waves due to intrinsic damping, air loading, beam diffraction and nonlinear power losses is measured by point optical-probing along the substrate. Thus all the loss mechanisms can be evaluated.

The spurious bulk-modes generated into the substrate can also be studied by optical probing. Light is passed through the side of the substrate and diffraction occurs due to the bulk waves, longitudinal or shear, which are present under the transducer. These experiments lead to an identification of which spurious bulk-modes are generated and their absolute intensity.

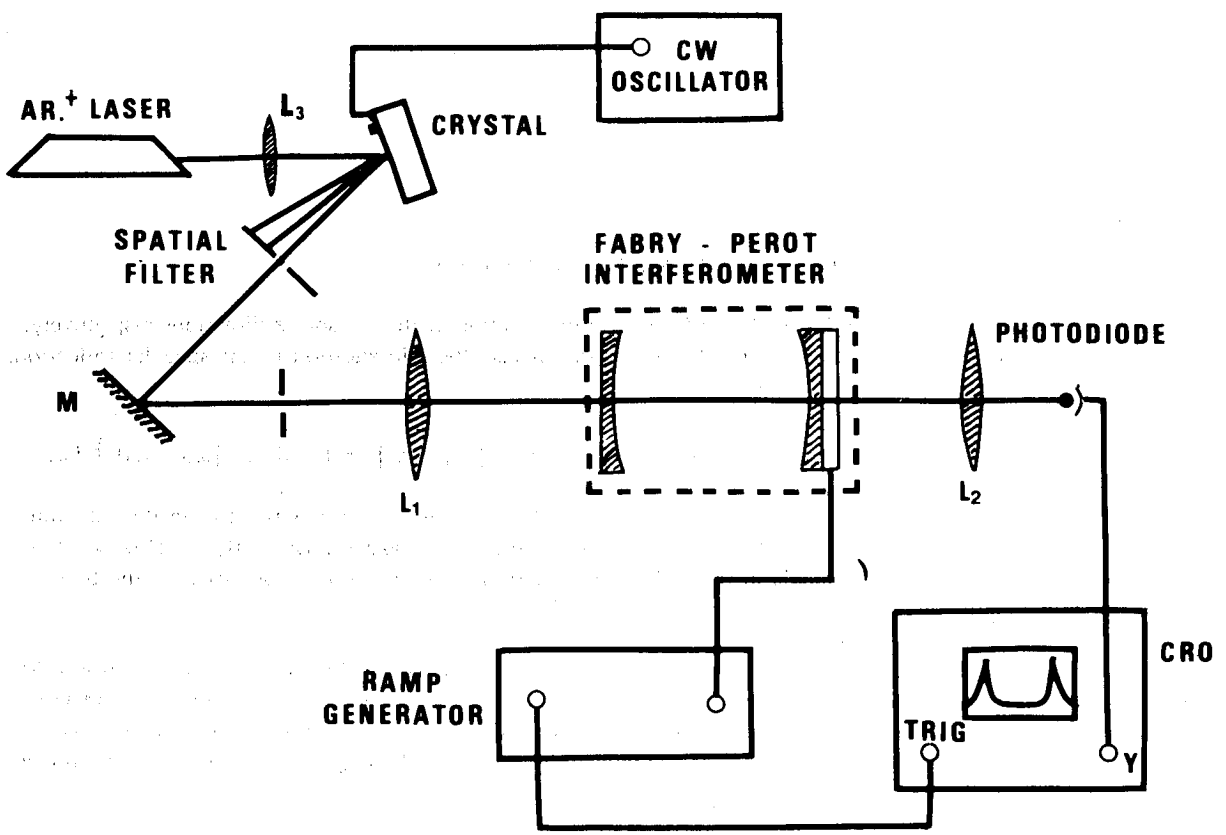

Figure A6.1. System for Optical Probing of Acoustic Surface Waves

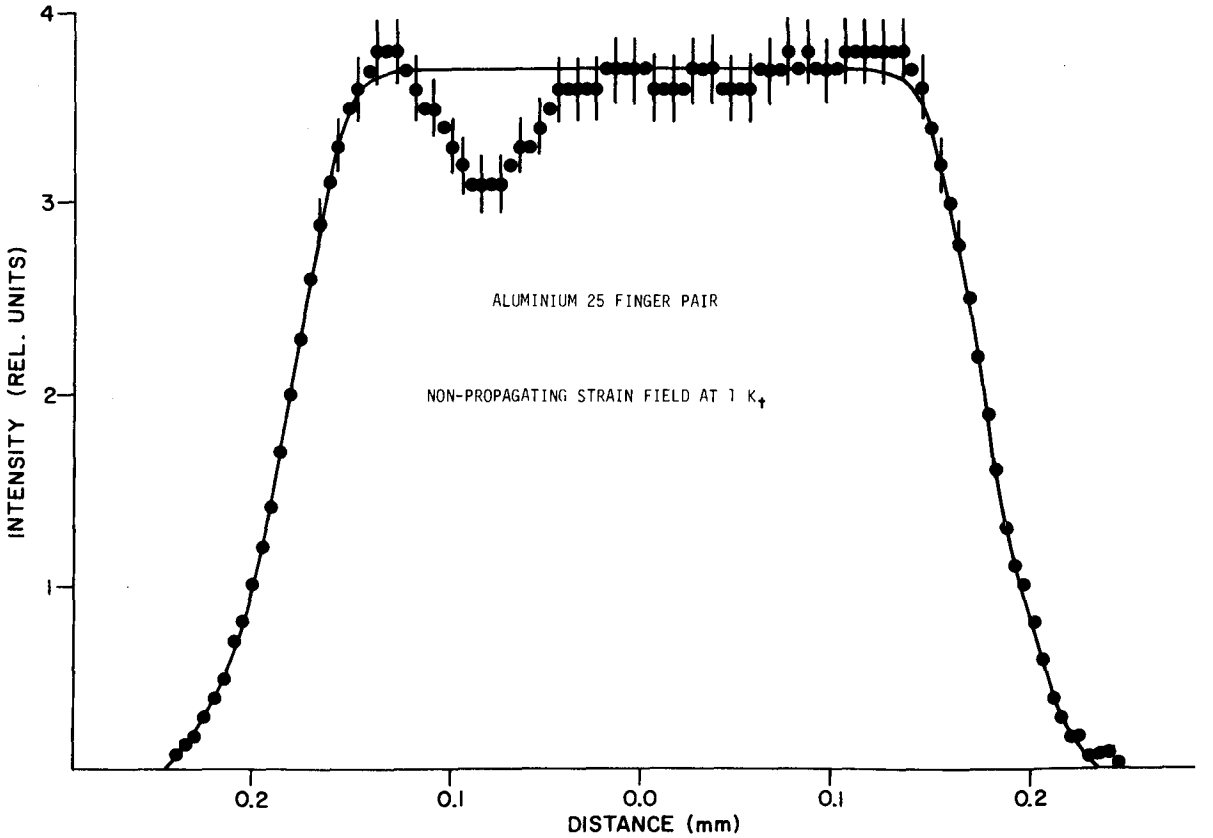

Figure A6.2(a). Output of Optical Probing System Illustrating Non-Destructive Testing of a Surface-Wave Device

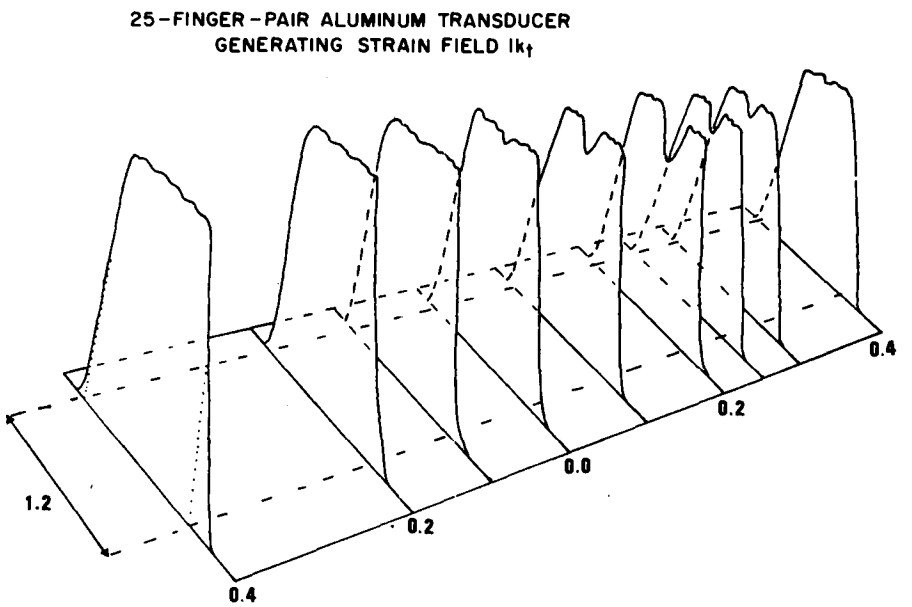

Figure A6.2(b). Output of Optical Probing System Illustrating Non-Destructive Testing of a Surface-Wave Device, Two Dimensional Plot

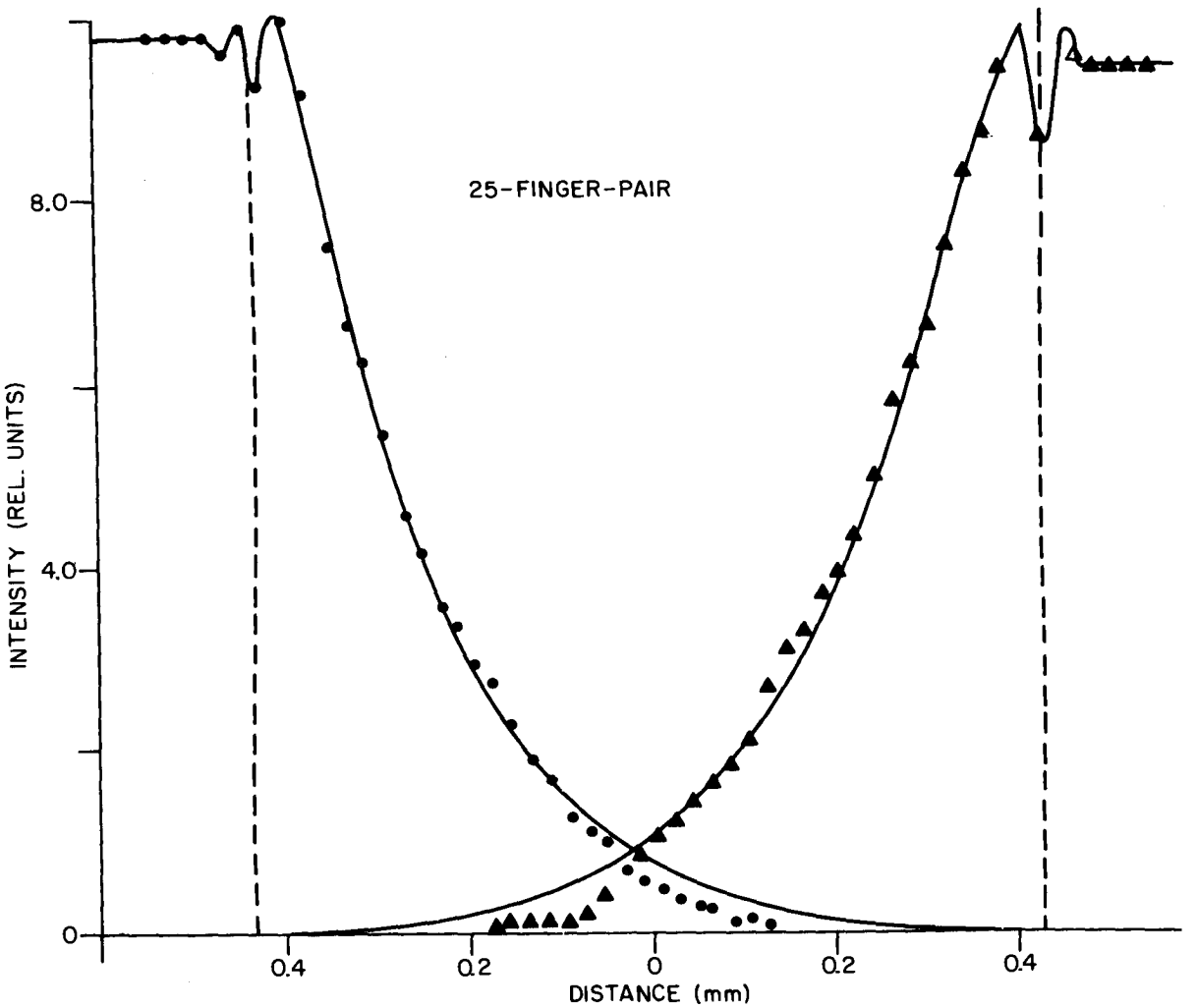

Figure A6.3. Measurement of the Growth of Surface-Wave Power Under an Active Transducer

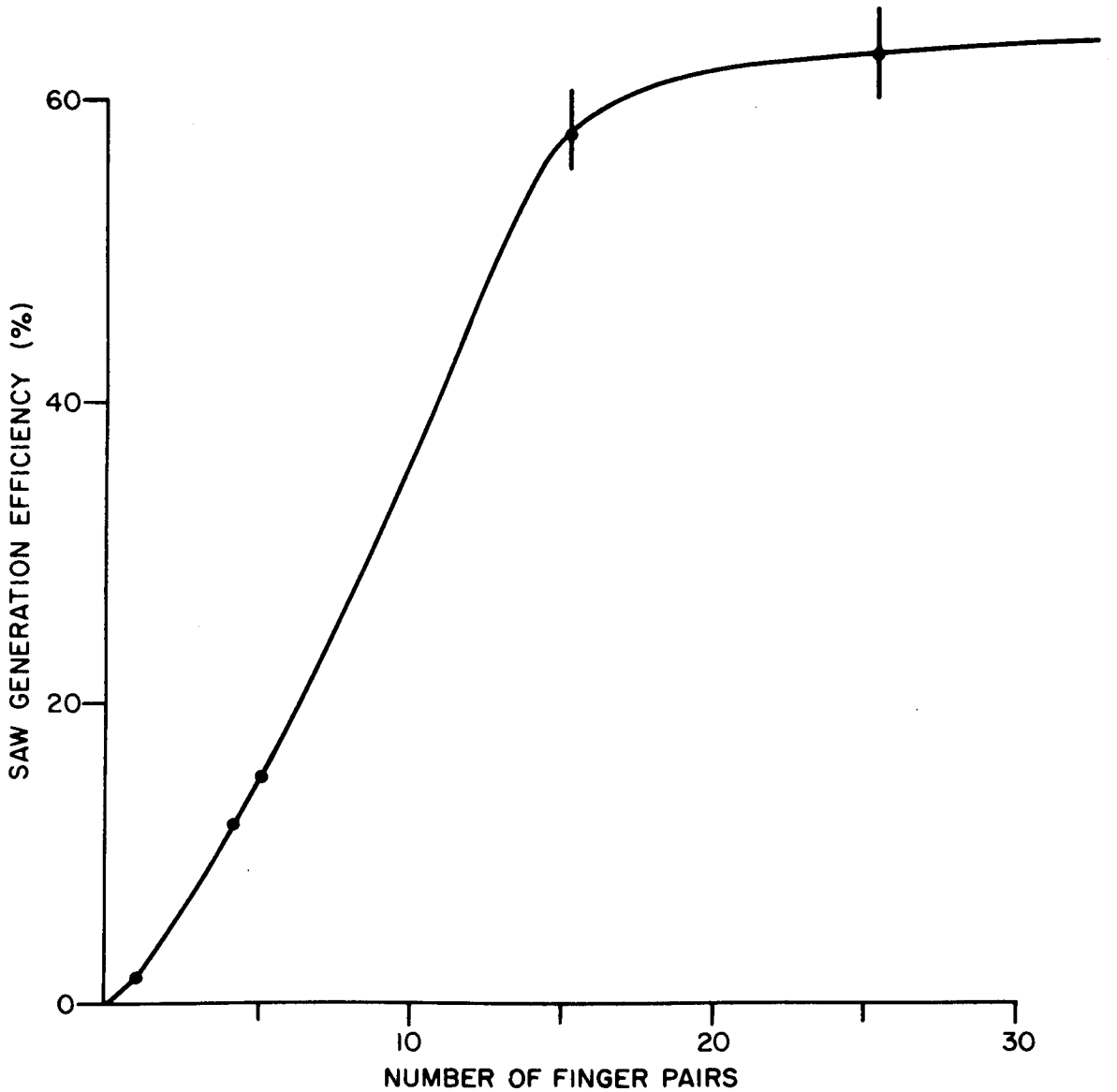

Figure A6.4. SAW Generation Efficiency as Measured by an Optical Probing System

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8. ABSTRACT: This report constitutes the record of the Canadian Workshop on Acoustic Surface Waves, which was held in Ottawa, January 30 - 31, 1974. The Workshop was sponsored by the Department of National Defence and the Department of Communications and jointly organized by McGill University and the Communications Research Centre. The invited tutorial presentations, which ranged in subject matter from materials and basic physics to systems applications in communications and radar, are summarized. It is concluded that there exists in Canada sufficient interest, needs, and capabilities to support a moderate level of acoustic surface wave research, development and manufacturing activity.

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