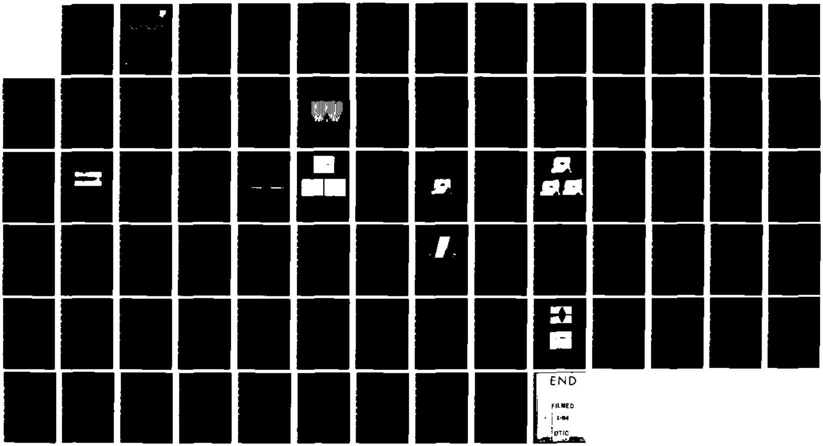
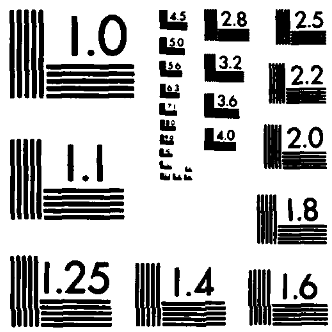
AD-A135 686 INVESTIGATION OF HIGH EFFICIENCY LARGE TBW LINE ACOUSTIC WAVE CONVOLVERS(U) ILLINOIS UNIV AT URBANA COORDINATED SCIENCE LAB B J HUNSINGER ET AL. OCT 83 1/1

UNCLASSIFIED RADC-TR-83-111 F19628-81-K-0031 F/G 20/1 NL





MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

(12)

AD-A135686

RADC-TR-83-111
Final Technical Report
October 1983

INVESTIGATION OF HIGH EFFICIENCY LARGE TBW LINE ACOUSTIC WAVE CONVOLVERS

University of Illinois

Bill J. Hunsinger
Robert L. Miller
Glenn Pieters

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

ROME AIR DEVELOPMENT CENTER
Air Force Systems Command
Griffiss Air Force Base, NY 13441

This report has been reviewed by the RADC Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be releasable to the general public, including foreign nations.

RADC-TR-83-111 has been reviewed and is approved for publication.

APPROVED: Richard T. Webster

RICHARD T. WEBSTER
Project Engineer

APPROVED: Allan C. Schell

ALLAN C. SCHELL
Chief, Electromagnetic Sciences Division

FOR THE COMMANDER: John P. Huss

JOHN P. HUSS
Acting Chief, Plans Office

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER RADC-TR-83-111	2. GOVT ACCESSION NO. AD-A135686	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) INVESTIGATION OF HIGH EFFICIENCY LARGE TBW LINE ACOUSTIC WAVE CONVOLVERS		5. TYPE OF REPORT & PERIOD COVERED Final Technical Report 15 Oct 80 - 30 Dec 82
		6. PERFORMING ORG. REPORT NUMBER N/A
7. AUTHOR(s) Bill J. Hunsinger Robert L. Miller Glenn C. Pieters		8. CONTRACT OR GRANT NUMBER(s) F19628-81-K-0031
9. PERFORMING ORGANIZATION NAME AND ADDRESS University of Illinois/Coordinated Sciences Lab 1101 W. Springfield Ave. Urbana IL 61801		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 61102F 2305J530
11. CONTROLLING OFFICE NAME AND ADDRESS Rome Air Development Center (EEAC) Hanscom AFB MA 01731		12. REPORT DATE October 1983
		13. NUMBER OF PAGES 80
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) Same		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE N/A

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

Same

18. SUPPLEMENTARY NOTES

RADC Project Engineer: Richard T. Webster (EEAC)

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Line Acoustic Waves	Cleaving
Surface Acoustic Waves	Multistrip Couplers
Guided Elastic Waves	Acoustic Mode Conversion
Elastic Convolvers	
Convolver Analysis	

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

Line acoustic waves (LAW) are guided modes which follow the sharp edge of a crystal substrate. They offer non-dispersive propagation, tight acoustic energy confinement, and the availability of a signal pickup geometry which can be much more efficient than that of surface acoustic wave (SAW) beam-width compressor devices. The objective of this program was to carry out theoretical and experimental investigation leading to wide bandwidth LAW transducers and to explore the feasibility of large time-bandwidth LAW

convolvers. Broadband LAW generation was performed by converting SAWs to LAWs in multistrip mode converters (MSMCs). An MSMC having a bandwidth of 25% and conversion loss of 5 dB has been demonstrated. Theoretical comparisons between LAW and SAW convolvers indicate that the LAW convolvers should have significantly higher efficiency once they are fully developed. Fabrication of long, straight, chip-free edges was investigated. Improved techniques for cleaving crystals are described and significant progress toward a versatile new technique for sawing high quality edges is reported. Areas requiring additional work are identified and potential applications of LAW devices are discussed.

TABLE OF CONTENTS

TABLES

FIGURES

REPORT SUMMARY

A. TASK OBJECTIVES

The major objective of this contract was to improve the bandwidth of line acoustic wave (LAW) transducers and to determine the feasibility of the LAW convolver. The contract stated four specific objectives:

1) Investigate new techniques for wideband excitation of LAWs.

2) Carry out a fundamental study of the parameters which determine the efficiency and bandwidth of a LAW convolver.

3) Investigate the feasibility of a LAW convolver with a TBW greater than 1000, with a goal of 10 microseconds.

4) Deliver to RADC/EEA one LAW convolver with the largest TBW available resulting from the above efforts.

B. TECHNICAL PROBLEM

Line acoustic waves (LAWs), guided modes which follow a sharp edge of a substrate, offer a number of advantages for signal processing devices such as convolvers. Among these are non-dispersive propagation, tight acoustic energy confinement which is not dependent on the shape of the metal electrode, and the availability of a signal pickup geometry which can be much more efficient over a broad bandwidth than that of surface acoustic wave (SAW) beamwidth compressor devices.

Previous LAW convolver devices demonstrated high efficiency, but were severely limited in bandwidth, due to fundamental limitations in the concept of direct LAW generation by means of interdigital transducers at the substrate edge. These limitations, as well as some of the fabrication difficulties, needed to be overcome in order to make large TBW LAW convolver devices possible.

C. GENERAL METHODOLOGY

This research was a combination of theoretical and experimental work. The SAW to LAW conversion process and the coupling of the convolver output electrode was analyzed theoretically. The performance of various configurations of the multistrip mode converters (MSMCs) which performed the conversion of SAW to LAW was measured experimentally. In addition, several LAW device fabrication techniques were experimentally investigated.

D. TECHNICAL RESULTS

The technical goals of this program were met as illustrated by the following accomplishments:

1) A multistrip mode converter (MSMC) having a 25% bandwidth and a 5 dB conversion loss has been demonstrated.

2) A study was performed which identifies those parameters which affect efficiency and bandwidth of a LAW convolver. Theoretical comparisons between LAW and SAW convolvers indicate that the LAW convolvers should have significantly higher efficiency once they are fully developed.

3) Improvements have been made in the fabrication techniques used in the realization of LAW devices. Some work has been done to demonstrate the possibility of generating long straight edges by saw cutting. Other work has resulted in improved length,

straightness, and quality of cleaved edges.

4) A broadband LAW convolver of the degenerate type has been delivered to RADC/EEA. It has the characteristics shown in Table I. Its purpose was to verify the model and the results obtained with it demonstrated that the model does accurately predict the performance of a LAW convolver. However, the device was not designed to optimize efficiency and later devices designed taking advantage of the findings of this research will be significantly more efficient.

E. IMPORTANT FINDINGS AND CONCLUSIONS

The MSMC has proven to be an excellent technique for generating LAWs. The conversion efficiency of narrowband (5% or less) MSMCs should exceed -1 dB in well designed devices. The efficiency of 25% bandwidth MSMCs has been demonstrated to be better than -5 dB in spite of the fact that the photomask considerations (see Appendix A) forced the MSMC design to be far from optimum. The next generation wideband MSMCs should be considerably more efficient when the photomask is made to comply with good MSMC design considerations.

The LAW convolver is considerably more versatile than the SAW elastic convolver because the output electrode does not double as an acoustic wave guide. It is possible to shape the output electrode to make non-degenerate or weighted output function convolvers because the wave is guided by the edge and not by the output electrode. If the output electrode of a SAW elastic convolver is non-uniform, the SAW propagation is disturbed and the expected convolution is disrupted.

TABLE I

CHARACTERISTICS OF DELIVERED

LAW CONVOLVER

Measured Internal Efficiency	-72 dBm (tuned)
Load Resistance	50 ohms
Center Frequency	98 MHz
Wavelength	36.7 · 10^{-6} m
Effective Plate Length	1 c.
Convolution Electrode Gap	1/2 1 wavelength
Time-Bandwidth Product	28.[illegible]

An accurate model for the calculation of LAW convolver efficiency in terms of frequency, bandwidth, integration time, and output matching has been derived and verified.

The nonlinear material factor which determines the convolution output level of a LAW convolver is about one half that of a SAW convolver built on the same material; however, the highly confined propagation path and the elimination of the weak coupling capacitor easily overcomes this lack of nonlinear interactions. The overall result is that LAW convolvers have an internal efficiency bandwidth product that exceeds that of SAW convolvers by 10 to 20 dB depending on the specified parameters.

The fabrication of chip free, straight, long edges is still a problem. Cleaving provides chip free edges, but there is a problem of making them straight. The techniques for cleaving were improved considerably in this program, but it is still difficult to cleave edges that are straight to 1 part in 10,000 as required for a good convolver. The sawing technique has more versatility and shows promise as a practical technique for fabricating high quality edges, but the edge quality in terms of chips is still not sufficient. Significant progress was made during this program and further work may be able to overcome the chipping problem.

F. IMPLICATIONS FOR FURTHER RESEARCH

It has been demonstated that LAW convolvers have the potential to provide wideband elastic convolvers with more versatility and improved efficiency. It will be necessary to develop better edge fabrication techniques before that potential can be realized.

It has also been demonstrated that the output electrode of a LAW convolver may be made of any shape without disturbing the LAW propagation. Non-degenerate convolvers that operate with the signal and reference at different frequencies now become possible. Such convolvers are important because they eliminate the largest noise source of an elastic convolver; self-convolution noise. It will also be possible to weight the convolver output to reduce Gibbs ripples in the convolution product. These applications alone may make it worthwhile to try to overcome the fabrication problems involved with the edges.

I. INTRODUCTION

Line acoustic waves (LAWs) are waves that propagate along the sharp edge of a piezoelectric substrate at a velocity that is less than that of surface acoustic waves (SAWs). These waves are confined to this sharp edge by the same boundary conditions that cause surface acoustic waves to be confined to the surface. As long as SAWs are allowed to propagate freely along the surface, they are single-moded and non-dispersive. However, when they are confined to a narrow propagation path, the field distributions and propagation velocities depend upon the frequency, and more than one mode can propagate in a given structure.

It is important for convolver applications to be able to confine surface acoustic waves to a narrow beam in order to get strong fields in a beam with a reasonable acoustic power. The most common structure for doing so is a long narrow metal strip running in the direction of propagation that is typically 3 to 8 wavelengths wide. In the case of surface acoustic wave convolvers, the signal is propagated in one direction along the metal strip, while the reference is propagated in the opposite direction and the metal strip is used as an electrode to pick up a charge that is proportional to the non-linear action of the counter-propagating waves. Thus, the long narrow metal strip doubles as (1) a guiding structure for the surface acoustic wave and (2) as an electrode to pick up the interaction between the counter-propagating waves which represents the convolution of the signals that generated them. One might think this is an ideal situation because one structure performs two functions, yet this double duty actually becomes a rather serious constraint and limits the versatility of the device design.

For example, it would be desirable to be able to shape the metal pickup electrode in special ways to make it more efficient, pick up different frequencies, suppress sidelobes, etc. Unfortunately for SAW convolvers, any tailoring of this pickup electrode tends to degrade its guiding ability, hence these improvements cannot be implemented.

The situation is different for LAW convolvers, since line acoustic waves are automatically guided by the sharp edge of the piezoelectric substrate; no metal is needed to confine them. In fact, the LAWs are confined in two dimensions to such a degree that the power density in a line acoustic wave is approximately an order of magnitude higher than that of a typical guided surface acoustic wave of comparable power. Since the line acoustic wave is not guided by external structures, its non-dispersive and single-moded propagation characteristics remain intact. Since the pickup electrode is not required to be a waveguide, it may be shaped in complex ways in order to improve device performance and/or provide additional features. That is, since the waves are automatically guided, the convolver output electrode can be shaped like an interdigital transducer (IDT). This would allow non-degenerate convolver designs, in which the input frequency and reference frequency are different. A non-degenerate convolver can have much lower spurious echoes when matched for maximum external efficiency. No other convolver technology possesses such a combination of large dynamic range, efficiency, and design flexibility.

Line acoustic waves thus have good potential for the implementation of signal processing devices with dramatic performance improvements, if:

1) Efficient wide-band transducers for high power line acoustic waves are developed.

2) Long flaw-free edges suitable for line acoustic wave propagation can be fabricated.

Significant advances have been made toward achievement of these goals and this report summarizes the progress.

II. BROADBAND LAW GENERATION BY AN MSMC

The generation of wide bandwidth line acoustic waves is difficult because the LAW beam is very narrow and close to the edge. If an interdigital tranducer with a one-half wavelength overlap right next to the edge is used, it has a very high impedance and there is no way to connect to the grounded electrodes. The ground connection problem is solved by the use of triangular electrodes. When many electrode pairs are used the impedance levels are reasonable and the conversion efficiency is good. However, the bandwidth, which is proportional to the reciprocal number of electrode pairs, is narrow. Impedance matching curcuits can not be used to increase the efficiency of wideband LAW triangular transducers because they step the voltage up and cause burnout at the power levels required for convolvers.

An ideal approach to the generation of LAWs would be to generate a wide SAW beam with a conventional SAW IDT and then convert the SAWs to LAWs. The Multi-Strip Mode Converter (MSMC) is designed for precisely this purpose. The MSMC is an extension of SAW beam-compressor multistrip coupler technology. It is used to generate LAWs indirectly by the conversion of SAW energy to LAW energy. Figure 1 shows schematically the features of a typical MSMC.

The primary advantages of the MSMC over direct LAW generation using the triangle transducer are easier impedance matching to the generator, wider bandwidth, and higher power handling capability.

A. MSMC Design Considerations

1. Electrode Spacings

Clearly, the grating pitches on the SAW and LAW tracks must be different and adjusted to phase match to the wave velocities:

$$\frac{P_{SAW}}{P_{LAW}} = \frac{v_{SAW}}{v_{LAW}}$$

The velocities to be used in this equation must be the proper loaded grating velocities [1,2] of the respective waves as they travel inside the MSMC. The correct LAW velocity to use is that of a LAW travelling under a (narrow) grating which is loaded by both the capacitance of the SAW track grating and that of the transition region. Since the SAW track is much wider than the effective LAW beamwidth, the LAW velocity is approximately equal to the short-circuit grating velocity. Similarly, if the sum of the LAW track width and the transition width W_T is much smaller than the SAW track width, the SAW velocity is approximately equal to the open-circuit grating velocity.

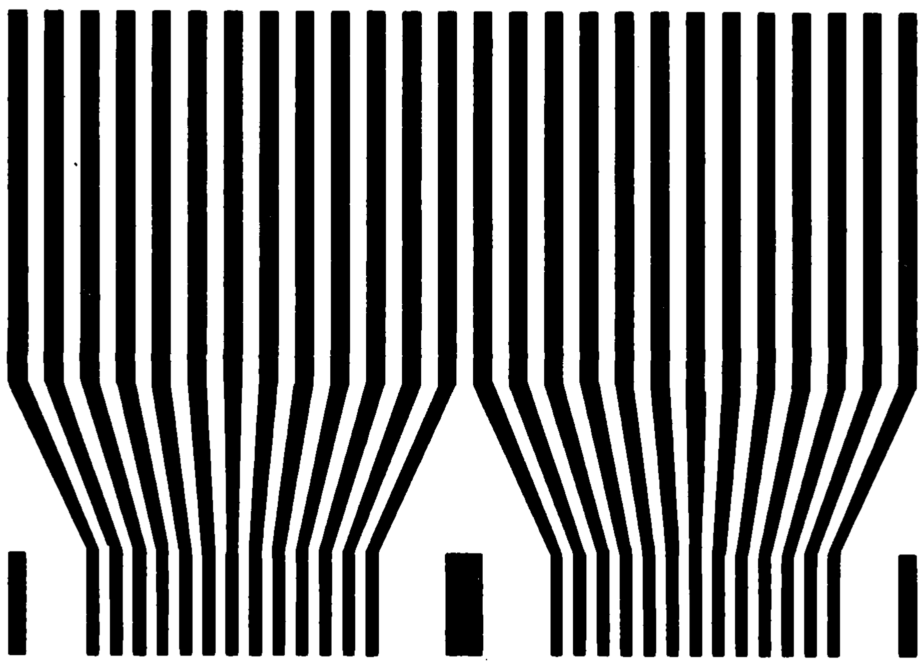


Figure 1. Method of coupler segmentation used in multistrip mode converter (MSMC). For clarity, only 2 segments are shown.

For surface waves, these grating velocities have been calculated by Maerfeld [2]. No such calculation has been performed for the effects of gratings on line wave velocities, but a good estimate is made by treating the LAW beam as if it were a narrow SAW beam. The velocities corresponding to free top surface and metallized top surface (both with unmetallized cleave face) are known. Using the SAW model, the calculated shorted and open surface LAW velocities, and the Maerfeld algorithm results in the following velocities for our MSMC:

v_{soc} = 3972 m/sec = SAW track open-curcuit grating velocity

v_{ssc} = 3909 m/sec = SAW track short-circuit grating velocity

v_{lsc} = 3527 m/sec = LAW track short-circuit grating velocity

v_{slg} = 3962 m/sec = SAW track loaded grating velocity

If the transition width is increased, the SAW grating is more heavily loaded, and v_{slg} changes. The wavenumbers **k**, which are the ratio of radian frequency to velocity, are related by:

$$k_{ssc} - k_{slg} = \frac{(k_{ssc} - k_{soc})\, W_{SAW}}{W_{SAW} + W_T + W_{LAW}}$$

SAW loaded grating velocity vs. W_T is plotted in Figure 2, which assumes that $W_{LAW} \ll W_T$, and $W_{LAW} \ll W_{SAW}$.

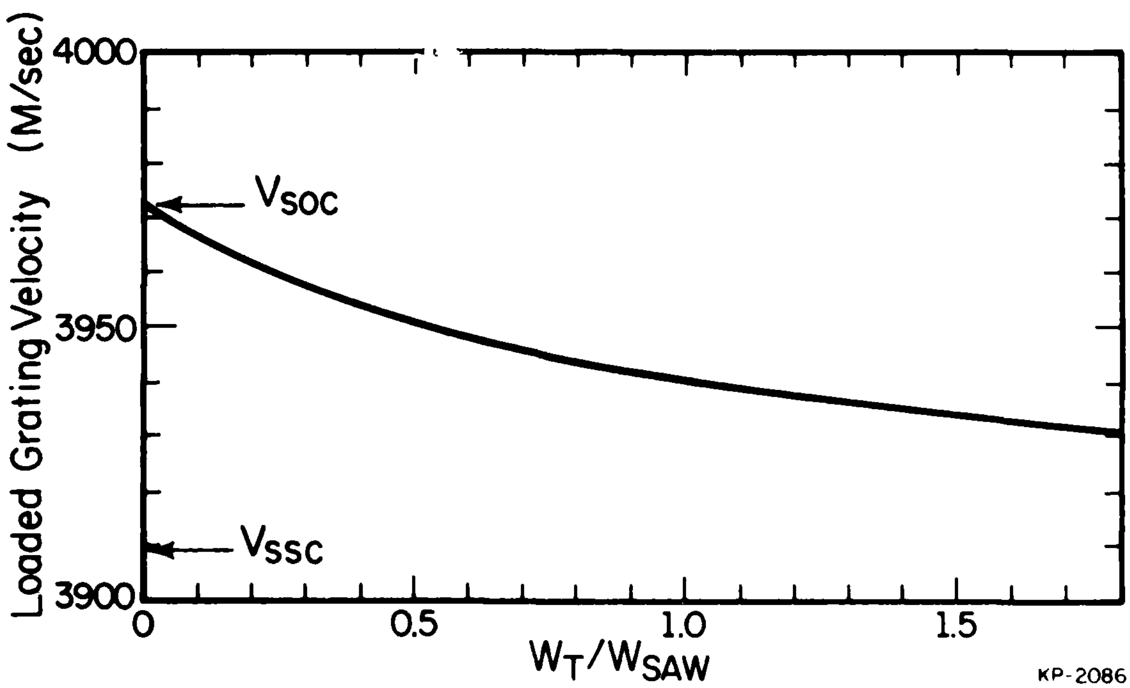


Figure 2. SAW loaded grating velocity vs. transition width W_T, for 128-degree $LiNbO_3$.

The phase match condition is very critical for a 1-segment MSMC. Figure 3 shows conversion loss of a single-segment MSMC plotted against phase match ratio r_p given by:

$$r_p = \frac{P_{LAW}}{P_{SAW}} \cdot \frac{v_{SAW}}{v_{LAW}}$$

For a segmented MSMC, slight errors in grating pitch may be compensated by a shift in center frequency.

Choices of actual values of grating spacing (P_{SAW} and P_{LAW}) are governed by additional factors:

a) Grating stopband frequency (the frequency at which SAWs cannot propagate through the MSMC because reflections of each strip add coherently) $v_{slg}/2P_{SAW}$ must be sufficiently removed from the desired passband.

b) The grating pitch ratio must be realizable by whatever mask generation techniques are to be used.

The choice of grating pitch is limited to some multiple of a basic size increment for the particular mask generation technique to be used. For instance, a MANN 3000 pattern generator has a position resolution of one micron. If one wished to make the pattern at final size with a MANN 3000, the only realizable pitch ratios would be ratios of whole numbers of microns. Appendix A describes the techniques we used to circumvent this difficulty, and the problems we encountered during mask generation.

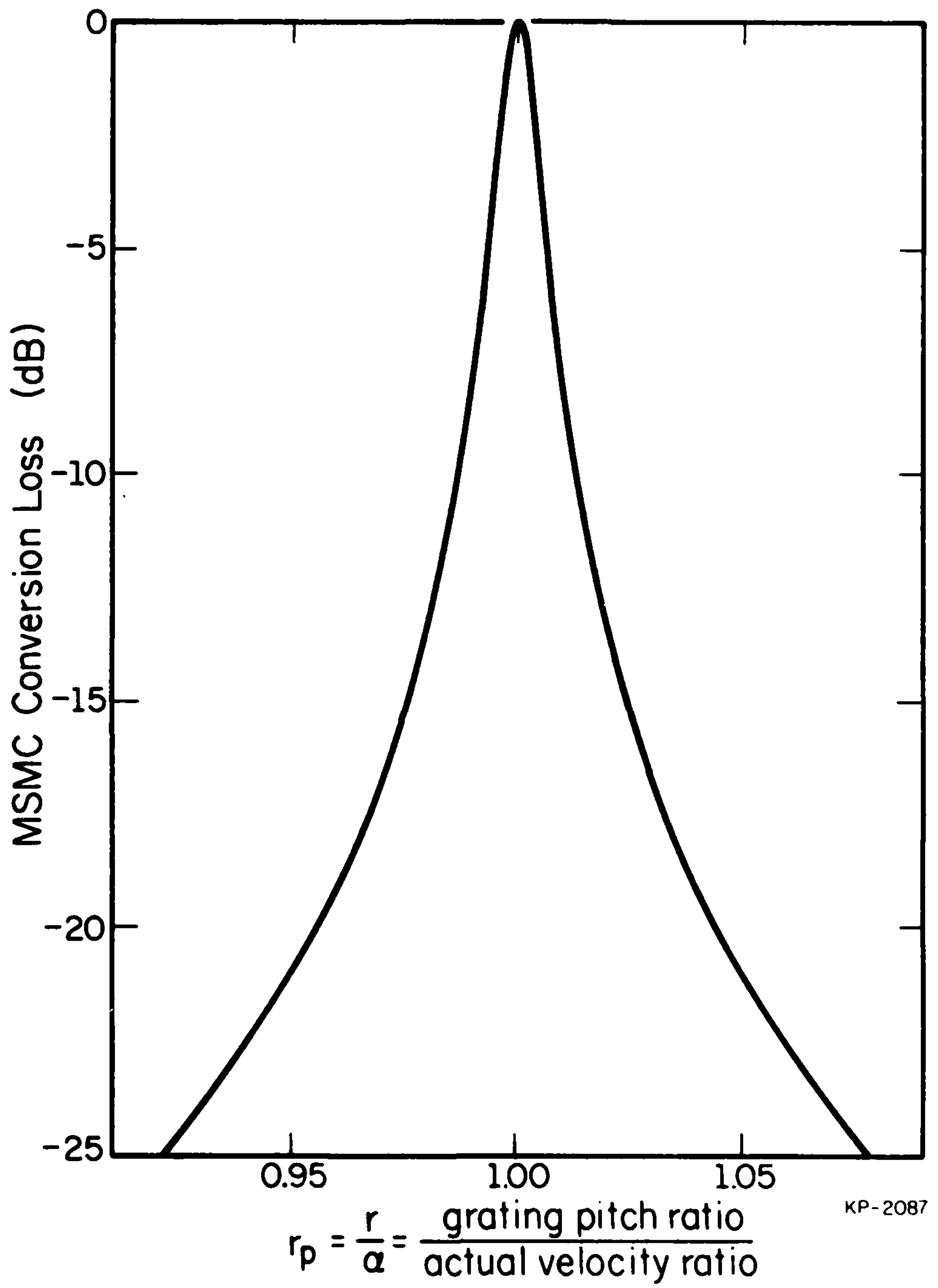


Figure 3. Conversion loss vs. phase mismatch for a <u>single</u> section MSMC.

2) <u>Gaps in LAW track</u>

As Figure 1 shows, gaps are typically made in the LAW track grating. Each gap is designed to be one wavelength long at the synchronous frequency, which is given by

$$f_{synch} = \frac{1}{d}\left(\frac{1}{v_{LAW}} - \frac{1}{v_{SAW}}\right)^{-1} = \frac{v_{LAW}}{L_{gap}}$$

Where: d is the length (in SAW track) of one coupler segment

These gaps serve several purposes:

a) They allow the use of a small transition width W_T without requiring the angled lines to be too severely tilted and therefore too narrow.

b) They can compensate somewhat for imperfect grating phase match, as explained below.

c) For our test devices, we have put metal rectangles on these gap areas, to provide a convenient place for laser probing.

The frequency response of an MSMC is roughly sin x/x shaped, at least for large N. Figure 4, an experimental curve made on an earlier design [3], shows that the 4 dB bandwidth of a segmented MSMC is inversely proportional to the number of segments N_S.

If the grating pitches do not exactly phase match the waves in the SAW and LAW track, the center frequency f_o of the MSMC response will shift away from the synchronous frequency given by the previous equation.

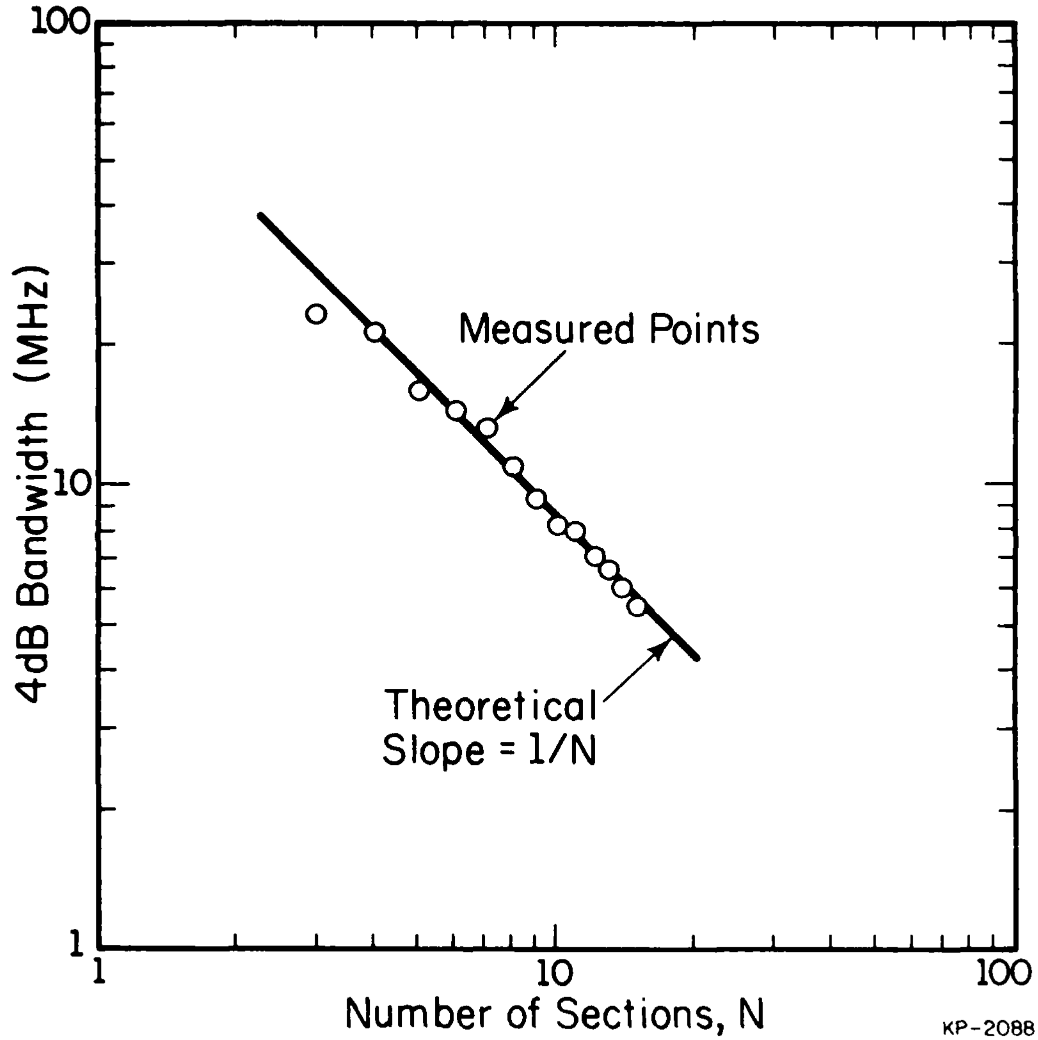


Figure 4. Bandwidth vs. number of sections for a 100 MHz MSMC.

At the synchronous frequency, the device can be modelled as if it were a single-segment MSMC. If the grating pitches are not phase matched, then the conversion loss at this frequency should be as previously shown in Figure 3.

3) Coupling Length

It has been shown [4] that a line acoustic wave on an acute cleaved wedge of 128-degree $LiNbO_3$ may be modelled as a SAW beam 1/2 wavelength wide. This allows N_T to be estimated by the same scaling law used to design SAW beamwidth compressor MSMC's [1].

$$N_T = \frac{1}{K^2 \eta \gamma} \; \frac{W_{SAW} + W_{LAW} + W_T}{2(W_{SAW} - W_{LAW})^{\frac{1}{2}}}$$

Where: K^2 is the SAW coupling factor
γ is the grating pitch in wavelengths
η is the measure of effective coupling factor of grating, approximately equal to $(1-\gamma)$

4) Recommended Segmented MSMC Design Procedure

a) Choose grating pitches P_{SAW}, P_{LAW}:

i) realizable ratio very close to V_{SAW}/V_{LAW},

ii) F_{STOP} far enough away from desired passband.

b) Choose $W_T << W_{SAW}$, $W_{LAW} << W_{SAW}$.

c) Calculate N_T from scaling law.

d) Calculate L_{gap} from desired f_{synch}.

e) From desired BW, determine $N_S = f_o/f$.

f) Check feasibility: angled lines too narrow?

(If yes, increase W_T and go to C)

g) Generate pattern

5) Future MSMC Options

The straight lines and gaps in the LAW track can probably be eliminated if the angled electrode region that connects the SAW and LAW track electrodes is made large. Such a structure would have the appearance of a fan. One anticipated advantage of this structure is that the ratio of line spacing between the LAW and SAW tracks can be changed at the time of device fabrication. If the angled electrodes are truncated by the edge, the effective LAW line to line spacing will be larger than if the full length connection lines are used. This can be done at the time of fabrication by aligning the mask so that a portion of the angled connection lines overhang the edge. Thus the SAW to LAW line spacing ratio can be varied at the time of fabrication without changing the mask. In addition the large connection electrode region would allow the large variations in velocity to be accounted for by larger bends in the angled connection electrode region and eliminate the need for the LAW track gaps. Such a device would have 100% bandwidth, however the coupling efficiency will be somewhat reduced by additional losses suffered in the larger electrode connection region.

B. MSMC Experimental Results

The experimental results for the MSMC are very encouraging and demonstrate that the efficiency and bandwidth goals of this program can be met with the present design. The experiment also demonstrates that the MSMCs are very tolerant of fabrication errors and work satisfactorily even under less than optimum conditions.

The MSMCs tested in the final phase of this program are shown in Figure 5 and described in Table II. Table II tabulates the dimensions of this MSMC and driving SAW transducer. Figure 5 is a photo of about one half of the MSMC pattern on the mask. The photo shows that :

a) The segments are designed to be functionally identical, but are not geometrically congruent.

b) Some of the lines are shorted together at the ends of the MSMC as a result of errors in the mask generation.

Several problems were encountered in the generation of the mask for the final devices. In addition to line shorting by over exposure in the mask as shown in the photo, the distance between lines is in error. An inconsistency between two of our design programs caused the LAW gaps in all of the segmented MSMCs to be too large. This made the synchronous frequencies of the MSMCs about 2/3 of those of the associated SAW transducers on the mask.

Since the MSMC was originally designed to operate at 163 MHz, it actually operates at 100 MHz. It has to be driven by a 98 MHz SAW transducer from another part of the mask. The resulting convolvers which were made by combining transducers from one device and MSMCs from another had the following difficulties:

1) A minor mismatch in SAW track apertures. The SAW transducer has an aperture of 250 microns, while the

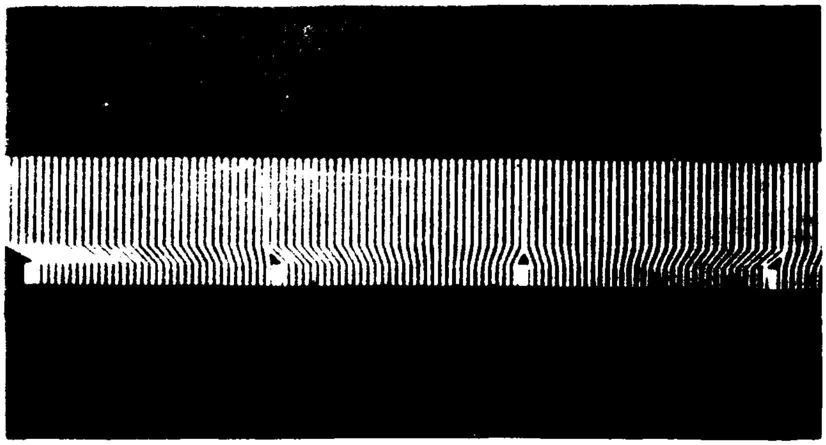


Figure 5. Photo of part of MSMC pattern on photomask.

TABLE II

DIMENSIONS AND PARAMETERS OF MSMCs AND DRIVING TRANSDUCERS

MSMC:	
SAW Track Width W_{SAW}	192 microns
Transistion Width W_T	40 microns
LAW Track Width W_{LAW}	48 microns
SAW Grating Pitch P_{SAW}	17.75 microns
LAW Grating Pitch P_{LAW}	15.75 microns
LAW Gap Spacing	37.25 microns
Number of Segments	4
Lines Per Segment	33
SAW Transducer:	
Aperture	290 microns
Number of Finger Pairs	3.5
Finger Type	50%; solid lines
Wavelength	40 microns

MSMC aperature is 192 microns. This should cause an additional loss of 1.6 dB per MSMC.

2) Because the MSMC was designed for operation at a different frequency range, the stopband frequency is at 111 MHz, which is now inside the passband. This is unfortunate, but not a serious problem for these experiments.

The MSMC was characterized by measurements on LAW delay lines, as depicted schematically in Figure 6. These delay lines were fabricated on cleaved 128-degree X-propagating $LiNbO_3$. The delay path between MSMCs was left metallized to facilitate laser probing and to provide a grounded electrode on the top surface for good RF feedthrough suppression. The length of the central delay path was made as long as possible, commensurate with allowing the device to fit on a 1" package header, to allow SAW and LAW pulses to be clearly resolved due to the velocity difference between the two modes.

Figure 7 shows a sequence of pulse pictures made on such a device, before any attenuating material was applied to the SAW track region in the central free area. The presence of two distinct pulses clearly demonstrates the presence of both SAW energy going directly through both MSMCs and energy converted to slower line acoustic waves and then back to SAW energy. This conclusion is further strengthened by the next photos: touching an absorber to the cleaved edge only causes the slower (LAW) pulse to decrease, without affecting the earlier (SAW) pulse.

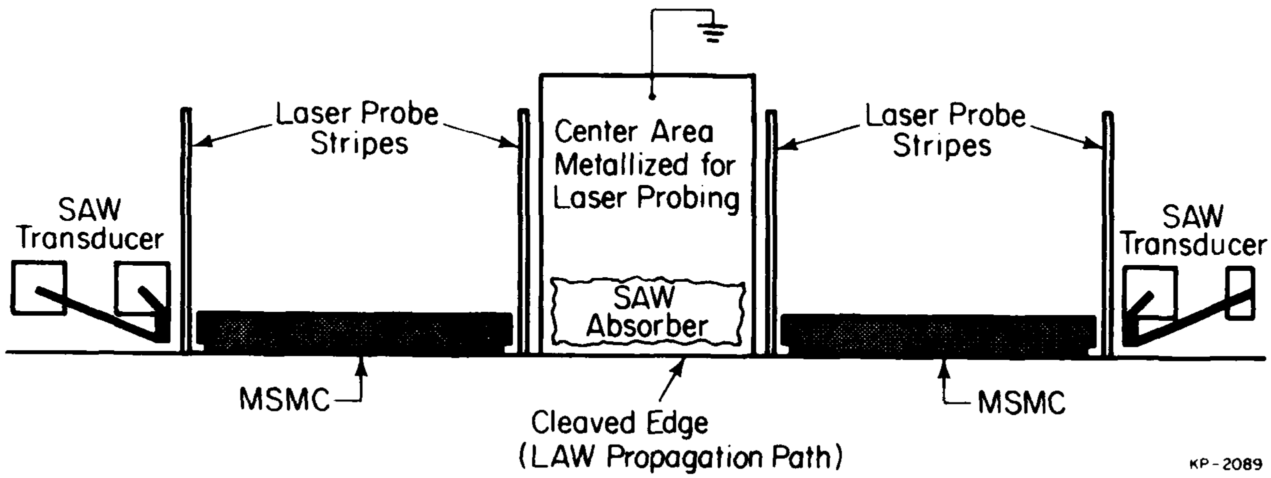
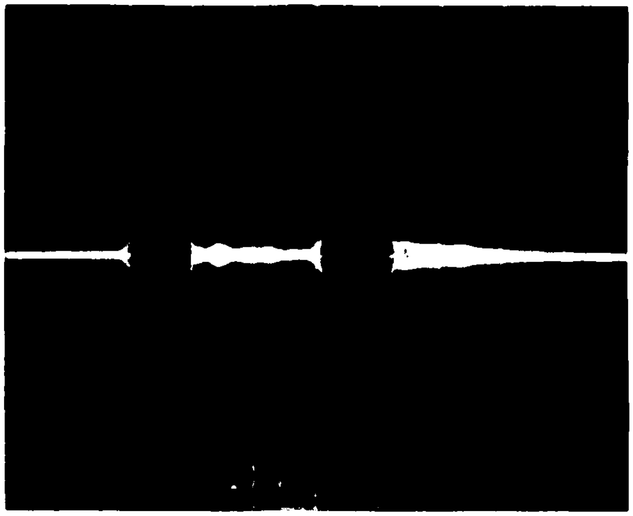
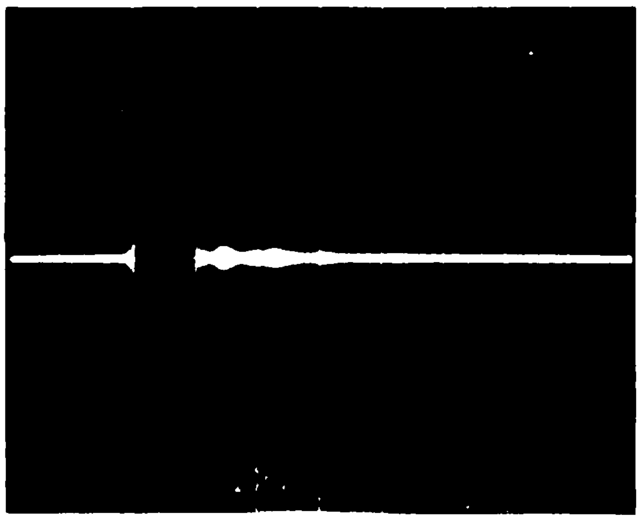


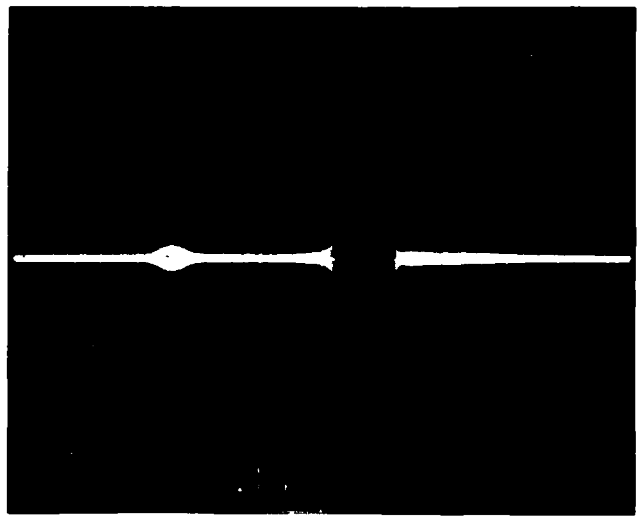
Figure 6. Schematic of typical LAW delay line.



(a)



(b)



(c)

Figure 7. LAW delay line pulse response. a) Pulse response of LAW delay line, before SAW attenuator applied to center area. b) Attenuator touched to cleave face absorbs slower LAW pulse, leaving earlier pulse unchanged. c) Earlier pulse is identified as SAW by touching attenuator to top surface in SAW track.

Similarly, applying an absorber to the SAW track area of the top surface causes the first pulse to disappear, leaving the second pulse unaffected.

Figure 8 shows the frequency response of an untuned LAW delay line. The stopband at 111 MHz is clearly visible. The selectivity is the product of two SAW transducers of N = 3.5, and two MSMCs having 4 segments each. A rough estimate of MSMC bandwidth may be obtained from this photo: the 8 dB fractional bandwidth is 20%, as each MSMC has a 4 dB bandwidth of at least 20%.

To determine the frequency response of the MSMC alone, we used a knife-edge type laser probe [5,6] in combination with a network analyzer, shown schematically in Figure 9. Using the network analyzer's storage normalizer, we could quickly take ratios of frequency responses measured at different points on the sample.

Figure 10 shows an example of this technique. The response curve in Figure 10a shows the frequency response of the SAW into the MSMC, measured when the laser spot is situated on a metal stripe in front of the input transducer. This response is stored in the network analyzer's reference memory. Next, the laser spot is moved to the LAW track output of the MSMC, where the response measured is shown in Figure 10b. This represents the product of the response of the SAW transducer and that of the MSMC, in decibels. The storage normalizer INPUT MINUS MEMORY function shows the frequency response of the MSMC alone, as shown in Figure 10c. An expanded view of the MSMC response is shown in Figure 10d.

Figure 8. Frequency response of untuned LAW delay line. Insertion loss = -57 dB. Vertical scale: 2.5 dB/division. Horizontal scal: 5 MHz/division. Center line: 100 MHz.

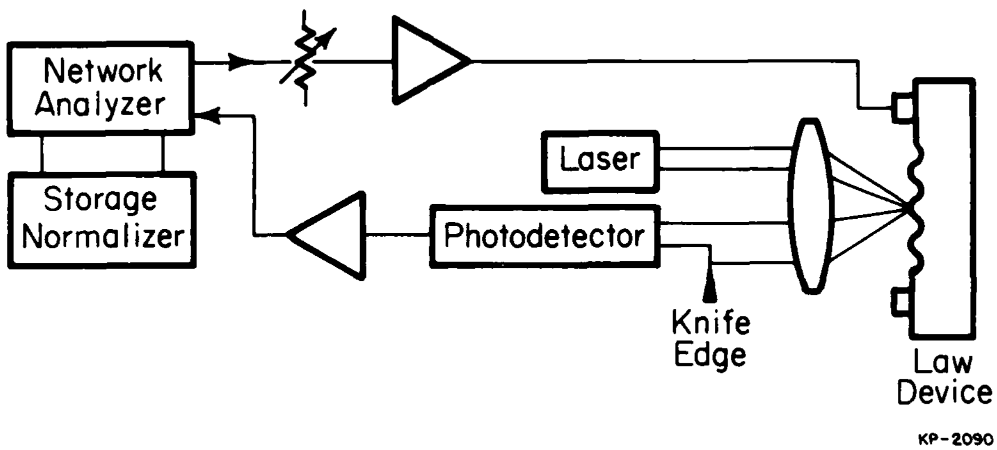
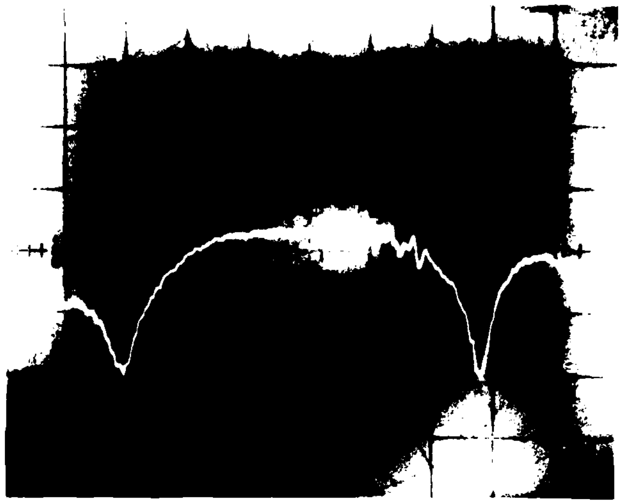
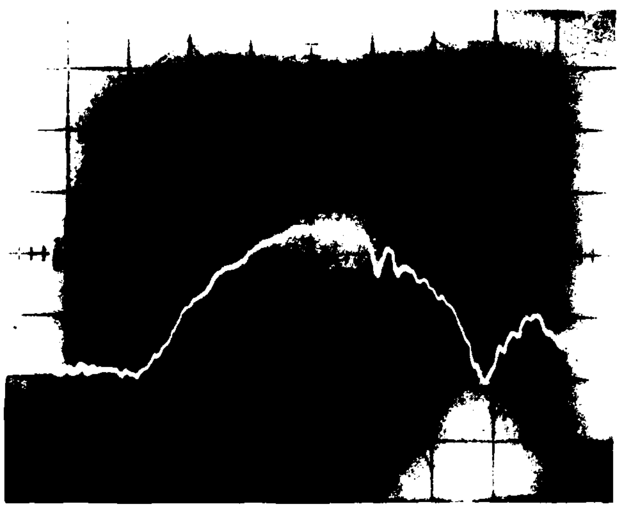


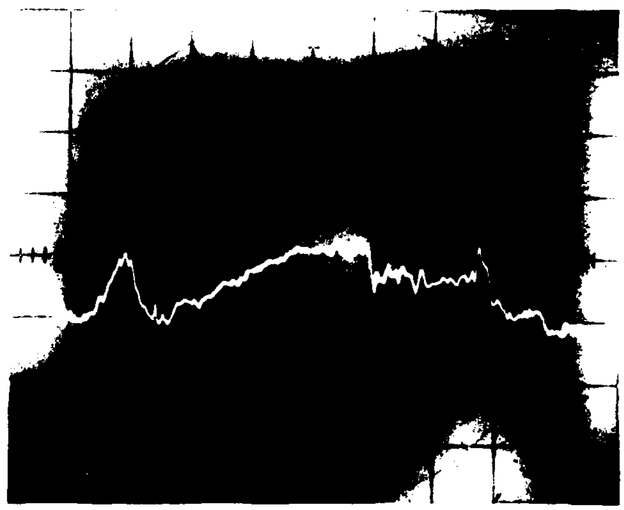
Figure 9. Use of knife-edge type laser probe with network analyzer.



(a)



(b)



(c)

Figure 10. MSMC frequency response. a) Frequency response of SAW into left MSMC. b) Frequency response of LAW out of left MSMC. c) INPUT - MEMORY function of storage-normalizer shows frequency response of MSMC alone. Vertical scales: 10 dB/division. Horizontal scales: 10 MHz/division. Center line: 100 MHz.

Although the upper half of the MSMC passband is somewhat obscured by the stopband and some extra ripples, the response is clearly broadband. The 4 dB fractional bandwidth appears to be 25%, as expected for 4 segments.

To determine the conversion loss of this MSMC, laser probe beam profiles were made across the input to the left MSMC, the output from the left MSMC, and the output from the right MSMC. Numerical integration of this data across the SAW track region of each plot allowed direct comparison of SAW power. Figure 11 shows SAW beam profiles at the input and output transducer, indicating the SAW -> LAW -> SAW conversion loss of two MSMCs in cascade. Vectorially integrating across the beam as a transducer would do indicates a SAW -> LAW -> SAW conversion loss of 9.4 dB.

A similar comparison was made of SAW power out of the left MSMC to SAW power in. A vector integration across the SAW track indicates the SAW beam out is reduced by 1.7 dB. This indicates SAW -> LAW conversion loss in a single MSMC to be about 5 dB, about half of the measured loss for two MSMCs.

Figure 12 shows measurements of SAW and LAW power levels at the segment boundaries within each MSMC, as measured with the laser probe. Although the curves are not the smooth sinusoidal curves one would expect, they do indicate that energy is converted from SAW to LAW and back again.

Table III summarizes the performance of this MSMC. Although we feel the conversion loss shows room for improvement, the contract goals have clearly been met.

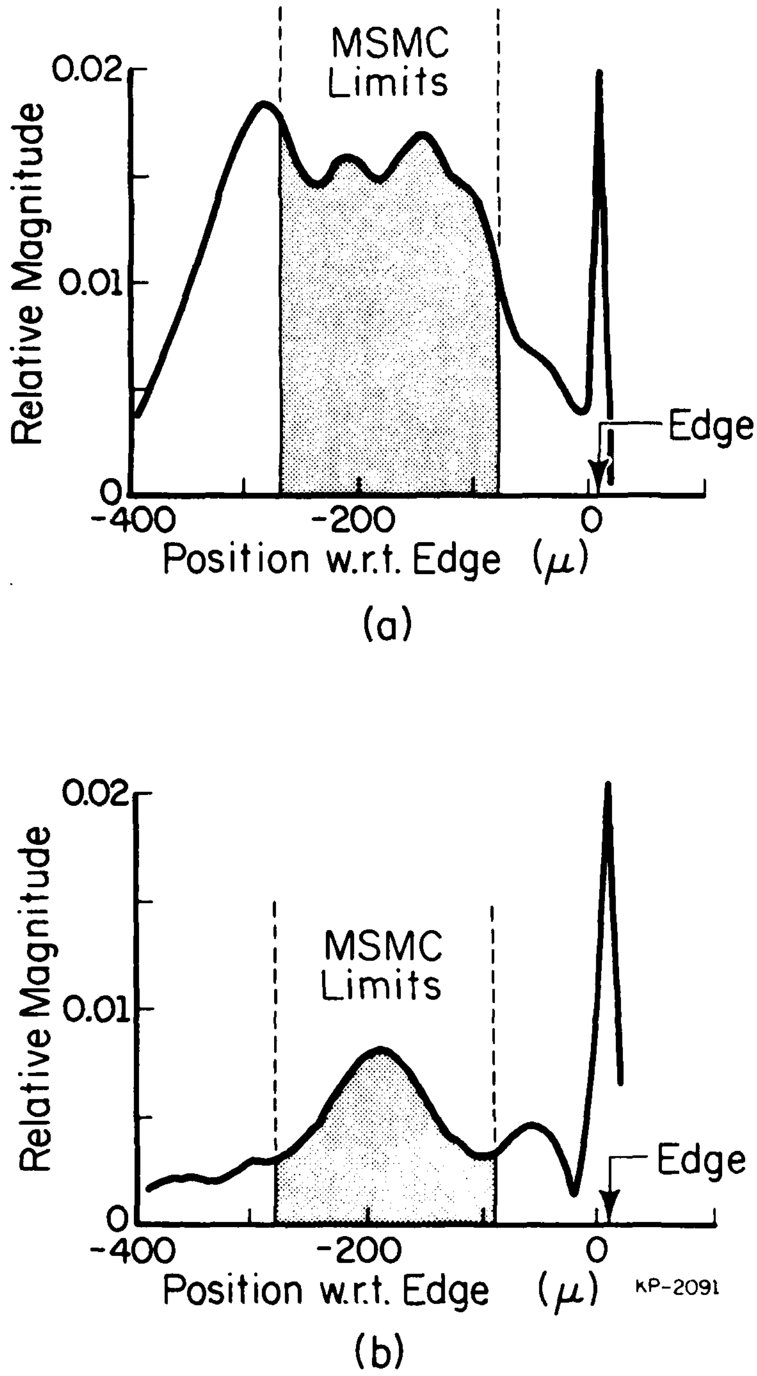


Figure 11. a) SAW beam profile into left MSMC. b) SAW beam profile out of right MSMC.

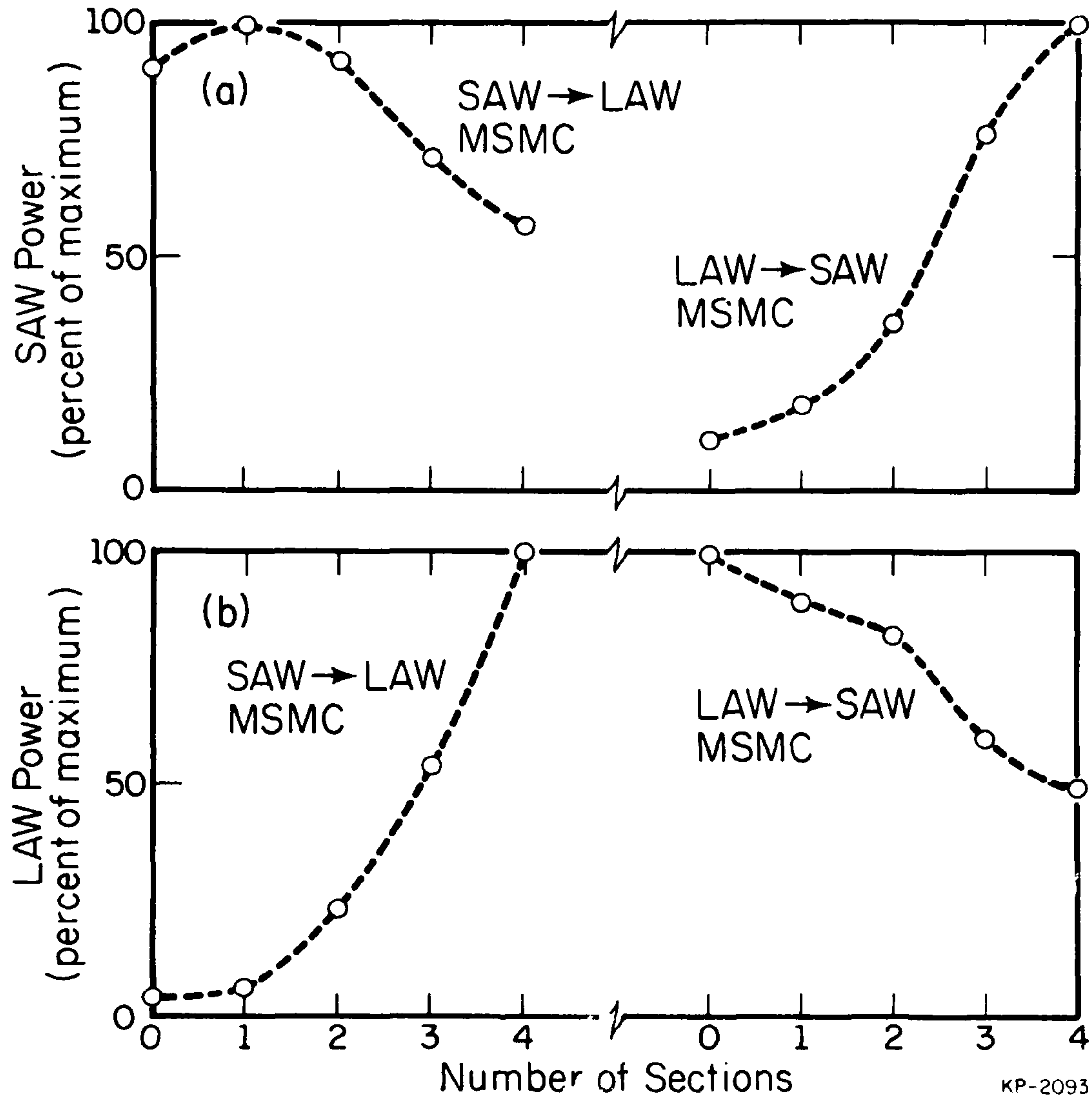


Figure 12. a) SAW track power variation in SAW -> LAW and LAW -> SAW MSMCs. b) LAW track power variation in SAW -> LAW and LAW -> SAW MSMCs.

TABLE III

MSMC Performance Summary

Center Frequency	100 MHz
Fractional Bandwidth	25 %
Conversion Loss	5 dB

III. LAW DEVICE FABRICATION CONSIDERATIONS

A. Fabrication of Sharp Corners

We have been able to fabricate edges suitable for line acoustic wave propagation by cleaving and by saw cutting. Both methods have advantages and disadvantages, and both methods need more development to improve yields.

1. Cleaving

Cleaving is capable of producing nearly perfect edges, at least with regard to edge sharpness. However, not all materials cleave alike, and $LiNbO_3$ is not an easy material to cleave even along a so-called "cleavage plane". It is prone to have two kinds of defects: striations and crack wandering (non-straightness of cleave).

Striations, as shown in Figure 13, are periodic ripples in the cleave face, which may or may not extend up to the LAW apex. Even though they are not very deep, their periodicity makes it likely that they would reflect LAW energy strongly at some frequency. The periodicity of the striations varies from one sample to the next, so we discard pieces that have striations extending up to the LAW apex; if it has a striation-free band a few wavelengths wide up at the apex, the piece is perfectly usable. If the force is applied correctly during the cleaving process, striations can be nearly eliminated on every cleave.

Crack wandering is more difficult to control. At first thought, it is hard to believe that a crack following a cleavage

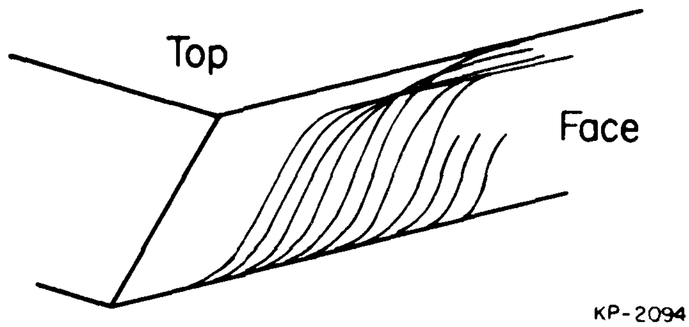


Figure 13. Striations on cleave face.

plane could possibly be anything but straight. However, experimental evidence as shown in Figure 14 for convolver device M24, shows that cleaves on 128-degree $LiNbO_3$ are indeed prone to slight curvature.

The reasons for this behavior can be illuminated by a quote from J. Gilman, "Cleavage, Ductility and Tenacity in Crystals", starting on p. 201 of reference [7]. In this section, he is comparing the stress distributions around the tip of a crack for two cases: a) a cleavage crack in a finite plate, evidently caused by a driven wedge, versus b) a crack in an infinite plate, evidently subjected to purely tensile stress:

"Comparison with the distribution for a cleavage crack allows that the chief qualitative difference between the two distributions is the position of the steepest gradient of the maximum tensile stress (closest spacing of the contour lines). For a crack in an infinite body, this gradient is coincident with the plane of the crack; but for a cleavage-type crack, it lies on a direction nearly perpendicular to the plane of the crack. The reason for the difference is, of course, the fact that a bending moment is present in the latter case but not in the former. Since cracks tend to run in the direction of the steepest gradient of the maximum tensile stress, a cleavage-type crack in an isotropic body will not run straight but will veer out of its own plane and run out the side of the specimen. The anisotropy of the cleavage strength of crystals makes it possible to obtain straight plane cleavages."[7]

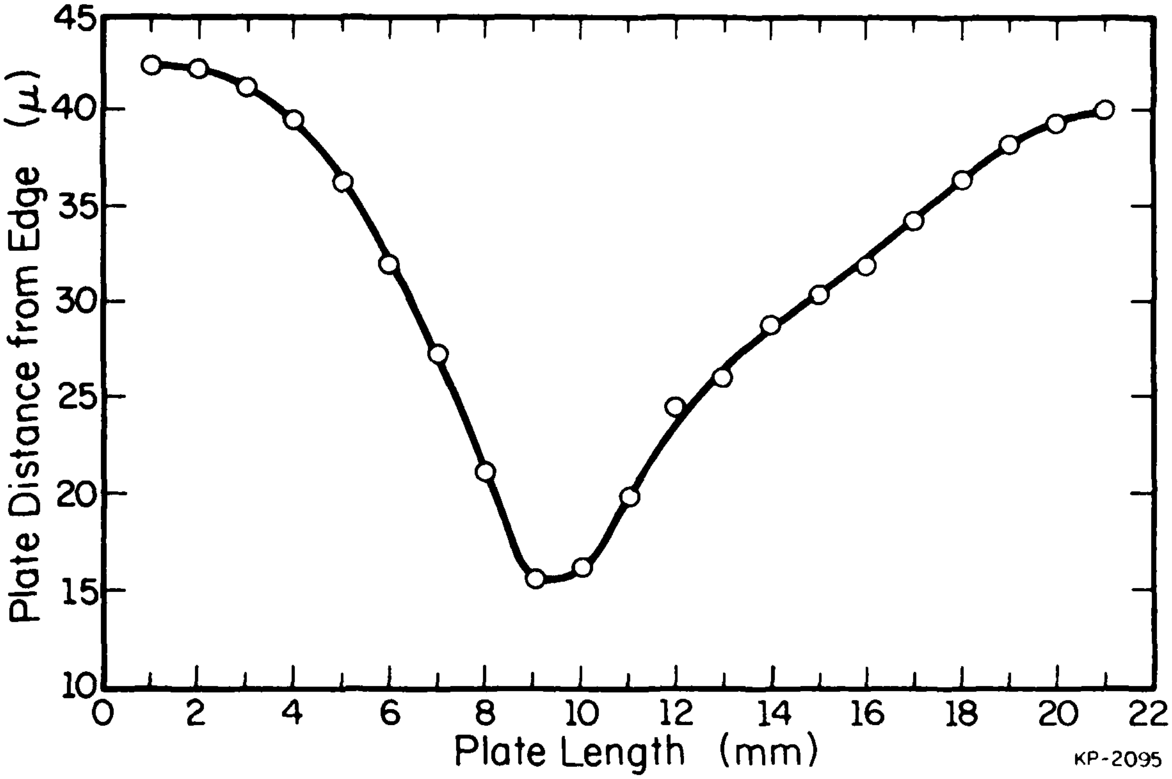


Figure 14. Cleave curvature on delivered convolver. Distance from cleaved edge to convolver plate vs. plate length.

If the same method is used to make cleaves in GaAs and $LiNbO_3$, the GaAs cleaves are much straighter and less prone to striations. Thus, in light of Gilman's comments, one must conclude that for $LiNbO_3$, the cleavage strength is not strongly anisotropic, so that a cleavage crack may not be strongly guided along a single plane. In order to obtain high-quality cleaves, then, one must take special care in the way forces are applied during the cleaving operation.

Perhaps the ideal way to cleave wafers would be to build a mechanical apparatus which would only apply tensile stresses, and to adjust this equipment carefully. In our laboratory, we have been able to get good quality cleaves on 128-degree $LiNbO_3$ in a much simpler manner, without special mechanical equipment.

Until recently, we started by lapping our wafers to about 10 mil thickness, in order to minimize striations along the cleave face. We no longer feel this is necessary, since our new cleaving method appears to be reliable, and thinning does make long devices more fragile. However, thinning is an option that can be kept in mind. Regardless of whether or not the wafer is thinned, it must be metallized and coated with photoresist before cleaving. Appendix B gives a detailed description of our most reliable cleaving method to date.

2) Saw Cutting

We have been able to demonstrate LAW propagation at 132 MHz along an edge made by saw cutting [8]. Figure 15 shows the technique in a schematic way.

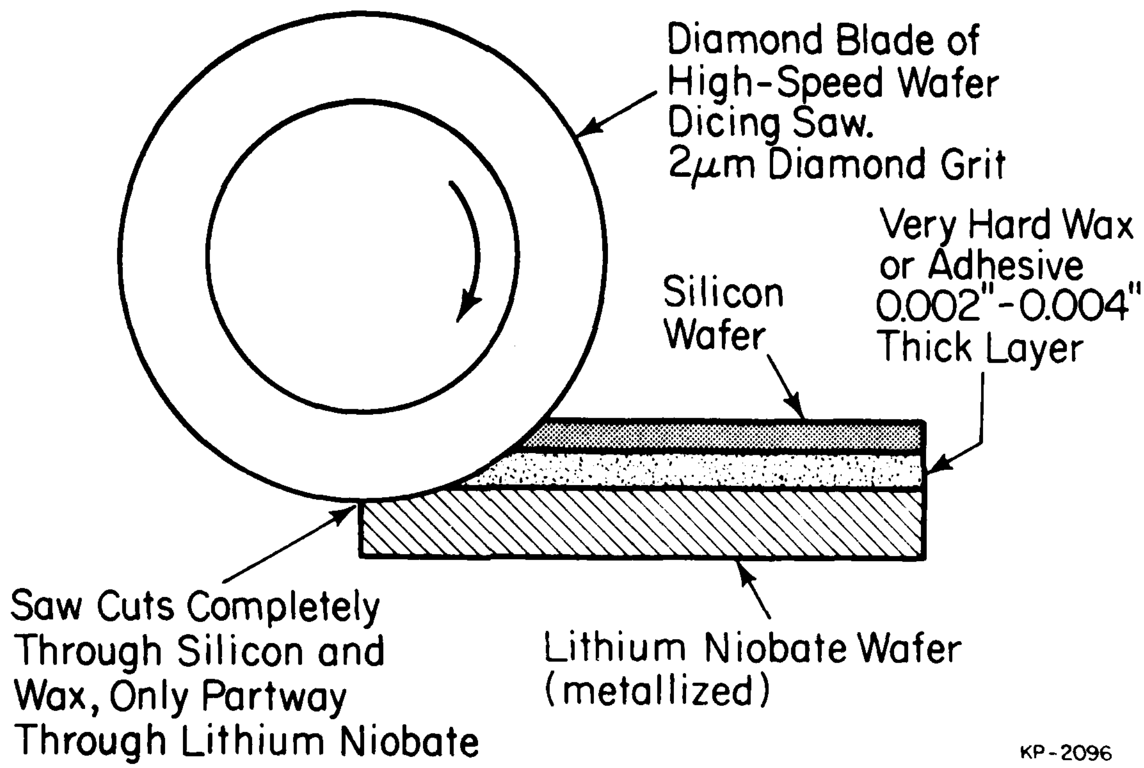


Figure 15. Schematic of LAW edge fabrication by SAW cutting.

The saw used, at Zenith Radio Corp. in Elk Grove, IL, was a Tempress Model 602 wafer dicing saw, which uses very thin diamond blades and has a spindle speed of about 20000 RPM. The diamond saw blade has been found to be one of the critical factors: it must have the smallest grit size possible, around 2 microns or less. Moreover, a new blade works best for this demanding application, since the amount of exposed diamond points is the greatest then. Even on a new blade, there are more diamonds exposed on one side of the blade than the other, so the corresponding side of the kerf is of higher quality.

To minimize chipping at the LAW apex, a .010" silicon wafer is first "waxed" down to the top surface of the $LiNbO_3$. The adhesive used is critical. The only material with which we have had any success is a plastic material called "Crystabound 509" from Arenco Products, Ossing, New York. This material is very hard, melts at about 120^{o}C, and dissolves in acetone. The latter two properties require us to apply photoresist after saw cutting (see next section). It is important to get a very thin layer of this wax, only a few mils thick.

Figure 16 shows an electron micrograph of a saw kerf made in this manner. We fabricated a LAW delay line on such an edge using an earlier mask, and determined that the LAW velocity on a 90^{o} wedge on 128-degree cut, X propagating $LiNbO_3$ is 3650 meters/second.

The potential advantages of saw cutting include the ability to make LAW edges in any direction on any material, not limited by the existence of cleavage planes, and the fact that saw cut edges on $LiNbO_3$ can be very straight.

Figure 16. Scanning electron microscope photo of saw cut edge.

The disadvantages include the requirement, at least with present methods and materials, of applying photoresist after saw cutting.

The main problem with saw cutting at this time is that there are still a number of unknowns. We have had only a few chances to try experiments, since the saw did not belong to us. Unless conditions are exactly right, the edge produced has subsurface damage and some chips, making LAW propagation impossible.

The present state of saw cutting can be summarized by the following statement: it is a promising technique, but it needs a good deal more experimentation before it can be made reliable. The cutting methods we have indicated above can at least provide a good starting point for such work.

B) Application of Photoresist by Drain Coating

It is well known that during photoresist spinning, a thick bead of PR tends to accumulate at substrate edges, precisely where the most critical features of a LAW device must be formed. Experiments on saw cut $LiNbO_3$, which could not be coated with PR until after sawing, made it essential that we find an alternative method of PR application. Even though cleaved devices usually avoid the buildup problem by cleaving through an existing PR layer, the method described below allows us to apply a new PR layer to a cleaved piece for re-work purposes, in case the original image was damaged. Our method also avoids the serious fume hazards associated with spray coating.

The technique is a variant of dip coating, in which a sample is immersed in PR and slowly pulled out at constant speed. Instead, as shown in Figure 17, it is much simpler to immerse the sample and then slowly drain the PR out the bottom of the container. (This method was originally suggested to us by Dr. Oscar Gaddy.) The velocity of the meniscus varies only slightly with depth, the average value being 0.7 cm per minute for the thinned resist mixture (2 parts Shipley AZ1350J to 1 part AZ thinner, by volume) and 1 mm hole size we use.

On saw cut pieces, we find it necessary to separate the wafer into individual pieces before drain coating. Otherwise, each saw kerf (only a few mils wide) exerts such strong capillary action that it pulls resist away from the kerf edges, often leaving a band on either side of the kerf which is totally devoid of photoresist.

Coating individual pieces avoids that problem, but may be subject to some slight edge buildup. To control that, we usually tilt the sample a few degrees from the vertical, as depicted in Figure 17, to cause PR to drain away from the edge just a bit.

It has been demonstrated that LAW convolvers can be fabricated using the cleaving method (Appendix B) and standard photolithographic techniques. In addition, the saw cutting and drain coating techniques provide future options.

IV. GUIDED ELASTIC CONVOLVER EFFICIENCY

The LAW convolver is similar to and modelled by a guided SAW convolver with a guide width of one-half of an acoustic wavelength. Electrical access to the vertical edge in the LAW

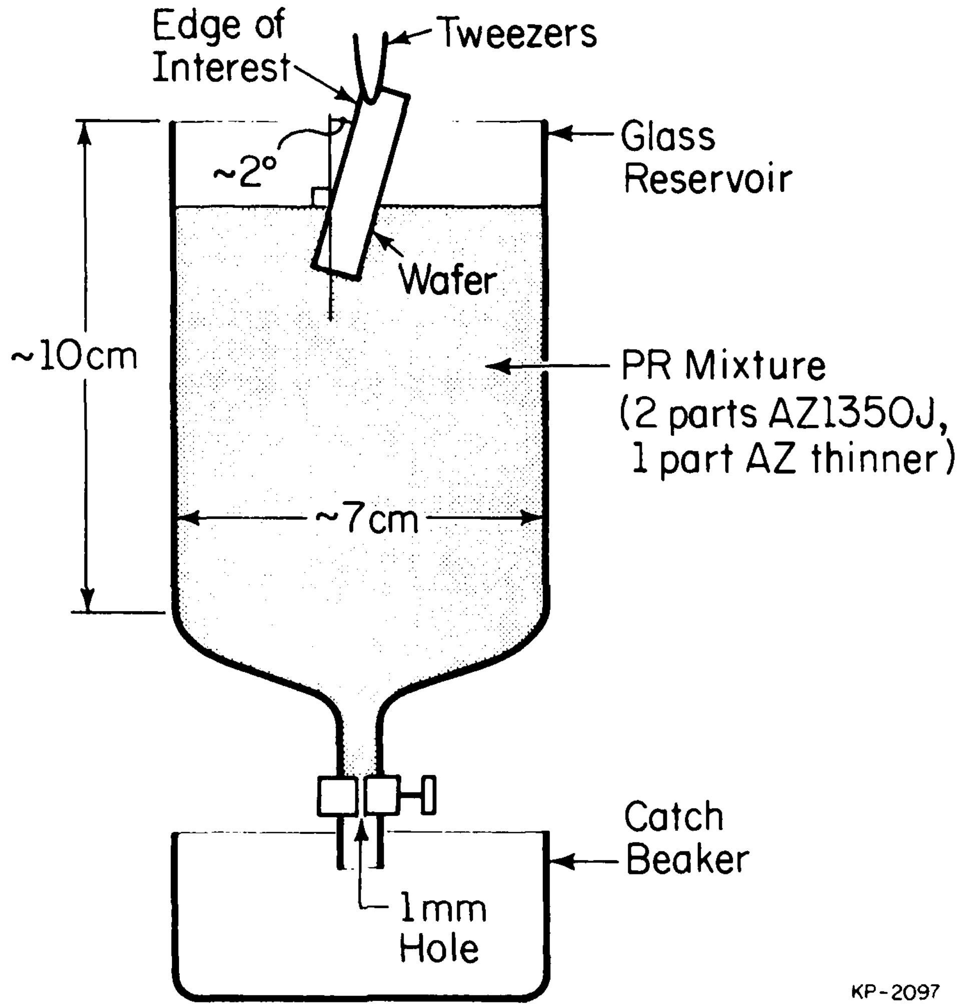


Figure 17. Apparatus for drain coating of photoresist.

convolver eliminates the coupling capacitance inherent to the SAW convolver. This section is written to provide a better understanding of convolver output coupling, by comparing it to the well known guided SAW convolver case.

A transverse cross-section of a typical SAW convolver is shown in Figure 18a. The SAW fields are confined primarily to the interaction region which is a 1/2 wavelength thick layer under the center electrode. An imaginary electrode is shown immediately under the interaction region. This is an effective conductor plane placed there for conceptual purposes.

The equivalent circuit for the convolver output port is shown in Figure 18b. The center electrode is connected to the load, and the ground planes are placed on each side with a gap equal to the guide width. The capacitor formed across the interaction region is called C_I and the capacitors formed between the ground electrodes and the imaginary electrode are called the coupling capacitors C_C. The fields carried by the counter-propagating acoustic beams interact due to the nonlinearities of the material and produce a polarization charge distribution in the interaction region. If no load is attached, the polarization charge induces a voltage (V_o) across the interaction region capacitance and that voltage represents the convolution signal. The internal resistance that is associated with the conversion process is modeled as a resistor R_o. The output voltage induces electric fields in the material and generates bulk waves that carry power away from the contact; this gives rise to the radiation resistance (R_a). The current flowing through the leads

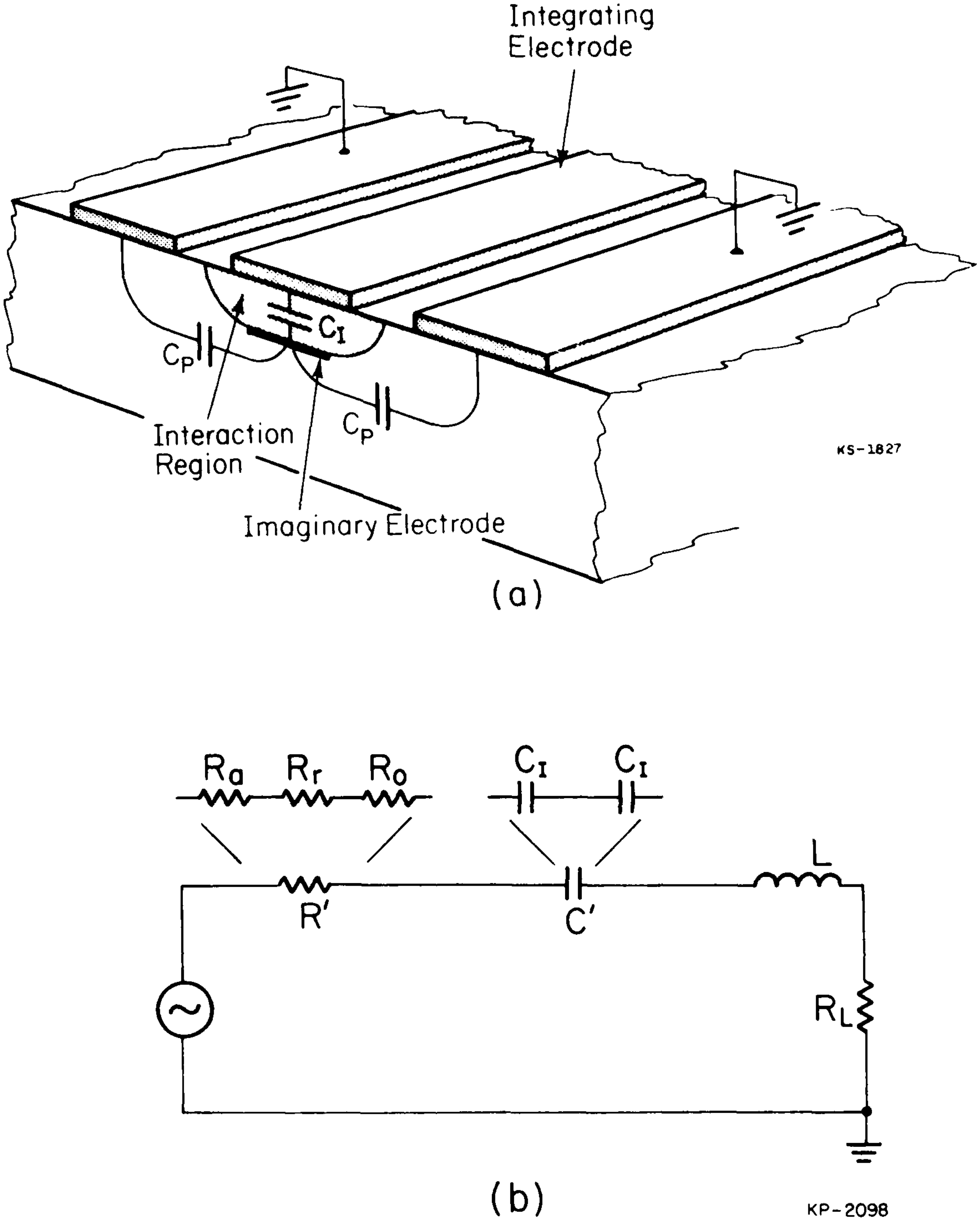


Figure 18. Elastic convolver
a) Model
b) Equivalent Cirucit

and resistive surface metallizations also dissipate power and this is modelled as resistance R_r. The sum of these resistances is called R' in Figure 18b.

If the signal and reference are continuous and correlate perfectly the open circuit voltage is a function of the material, input powers, and guide width [7,8,9]

$$V_o = \frac{M_s (P_1 P_2)^{\frac{1}{2}}}{W}$$

Where: W is the guide width in acoustic wavelengths

P_1 is the signal power in watts

P_2 is the reference power in watts

M_s is the material constant (volt-meter/watt)

The interaction region capacitance is approximated by the parallel plate model:

$$C_I = 2\epsilon_s WL$$

Where: ϵ_s is the dielectric constant of the material
L is the electrode length in centimeters
W is the guide width measured in acoustic wavelengths

The guide can be analyzed as a one electrode IDT with a capacity C'. This capacity is a series combination of C_I and C_C: [9]

$$C' = \eta c_s L$$

Where: η is the ratio of capacity of an IDT with a duty factor of .25 to that of an IDT with a duty factor of 0.5
c_s is the capacity per centimeter of IDT electrode length

The internal, bulk radiation, and electrical loss resistances are related to the output capacity by the convolver quality factor Q_c.

$$R' = 1/(C'Q_c)$$

The losses are typically found to be proportional to the inverse of the electrode width. Since the resistance decreases with electrode width and the capacitance remains the same, the Q_c increases with guide width.

$$Q_c = q_c W$$

Where: q_c is a constant that depends on the material and the design

W is the guide width in acoustic wavelengths

As a practical matter, typical values of quality factor q_c are found to range from 1 to 6 depending on the design.

The internal efficiency (F_I) is defined as:

$$F_I = 10 \text{ Log } P_o/(P_1 P_2 1000)\text{dBm}$$

Where: P_o is the power out in watts
P_1 is the signal SAW beam power in watts
P_2 is the reference SAW beam power in watts

A. Resistive Loading

When the convolver plate is attached directly to a small resistive load without an inductor, the internal efficiency factor is:

$$F_I = 10 \text{ Log}\left[\frac{M_s}{W\Lambda}\right]^2 \frac{(\omega C')^2 R_L}{1000} \quad @ \; R_L << \frac{1}{\omega C'}$$

This is difficult to precisely implement as a practical matter because lead inductance is usually not negligible.

B. Tuned Broadband Matching

If the application calls for a wide bandwidth and maximum efficiency, then the inductor shown in the equivalent circuit is used to tune out the capacitive reactance, and the load resistor is chosen so that the overall electrical circuit Q is low enough to handle the bandwidth. The load quality factor Q_L and the convolver quality factor Q_c are defined as:

$$Q_L = 1/(C'R_L)$$
$$Q_c = 1/(C'R')$$

The internal efficiency of the tuned SAW convolver output electrode is:

$$F_I = 10 \text{ Log}\left[\frac{M_s}{W\Lambda}\right]^2 \frac{\omega C' \, Q_L}{[1 + Q_L/Q_c]^2 \; 1000}$$

C. Wideband Matching

The convolver efficiency is increased by decreasing the load resistance and thereby increasing the load circuit quality factor (Q_L) as long as $Q_L \leq Q_c$. If the fractional bandwidth (BWF) requirement is sufficiently wide so that a small load resistor will result in an excessive output circuit Q, the efficiency must be reduced to get bandwidth. In this case the Internal Efficiency Bandwidth Product (EBP_I) is the important measure of performance.

$$EBP_I = F_I + 10 \text{ Log } (BWF)$$

$$EBP_I = 10 \text{ Log} \left[\frac{M_s}{W\Lambda} \right]^2 \frac{\omega C'}{1000}$$

D. Conjugate Matching

If the specified convolver fractional bandwidth is relatively small

$$BWF < 2/Q_C$$

then the optimum efficiency can be achieved and the load resistance is adjusted for maximum power transfer ($Q_C=Q_L$).

$$F_I = 10 \text{ Log} \left[\frac{M_s}{W\Lambda} \right]^2 \frac{1}{4000\ R'}$$

$$F_I = 10 \text{ Log} \left[\frac{M_s}{\Lambda} \right]^2 \frac{1}{W} \frac{q_c \omega C'}{4000}$$

This is the conjugate matched case and the convolver internal efficiency agrees with previous results that showed that it varies with the reciprocal of the guide width.

E. Magnitude Matching

In many cases it is desirable to couple the output electrode to the load resistor without the use of an inductor. In this case the maximum output power is achieved when the load resistor is adjusted to have a resistance equal to the capacitive reactance of the output electrode (Q_L=1). The internal efficiency is:

$$F_I = 10 \text{ Log} \left[\frac{M_s}{W\Lambda} \right]^2 \frac{\omega C'}{[1 + 1/Q_c]^2} \frac{1}{1000}$$

This type of matching results in a circuit which acts like a low pass filter with the corner at the device center frequency.

F. Summary

This analysis provides a simple means to compare the performance of convolvers with different matching, guide width, M factor, and Q_c factor. It is accurate for wide guide widths where the majority of the acoustic energy is confined underneath the center electrode. Optical probe measurements have shown that a significant portion of the acoustic energy in an actual convolver propagates in the gap between the center and the ground electrodes when the guide width is made smaller than five wavelengths. The waves propagating past the center of the gap or under the ground electrodes are counter-productive and a good part of the gains expected from reduced guide widths are not realized. This model typically predicts efficiencies higher than those measured in actual devices with narrow guides, because of the imperfect SAW guiding.

The efficiency improvements realized by reducing the guide width result from two sources. The convolution efficiency increases as the guide width becomes smaller because the SAW energy density increases. Secondly, the bandwidth increases as the guide width becomes smaller because the coupling capacitor increases in size relative to the interaction region capacity.

Reducing the width by a factor of 10 can produce a two order of magnitude improvement in the gain bandwidth product.

V. LAW CONVOLVERS

A. Efficiency Relations

The LAW degenerate convolver output electrode has a configuration similar to that shown in Figure 19a. The output electrode is W_e wavelengths wide and is placed over the interaction region parallel to the edge. The distance from the edge is set at W_g acoustic wavelengths. The typical values of W_e and W_g are both 1/2 wavelength. The vertical face is metallized and grounded to form the opposite plate of the interaction capacitance.

A LAW beam with a power P_1 generated by the signal transducer propagates from left to right and one with a power P_2 generated by the reference transducer propagates in the opposite direction. Both waves are confined to within 1/2 wavelength of the edge by the elastic boundary conditions and form the interaction region. The fields produced by the waves interact in the nonlinear material to produce a polarization charge distribution in the interaction region capacitor. The voltage resulting from this charge is proportional to the convolution of the signal and the reference.

If the signal and reference are continuous and correlate perfectly the open circuit voltage is a function of the material and the input LAW powers.

$$V_o = 2M_L \, (P_1 P_2)^{\frac{1}{2}} / (P_o \Lambda)$$

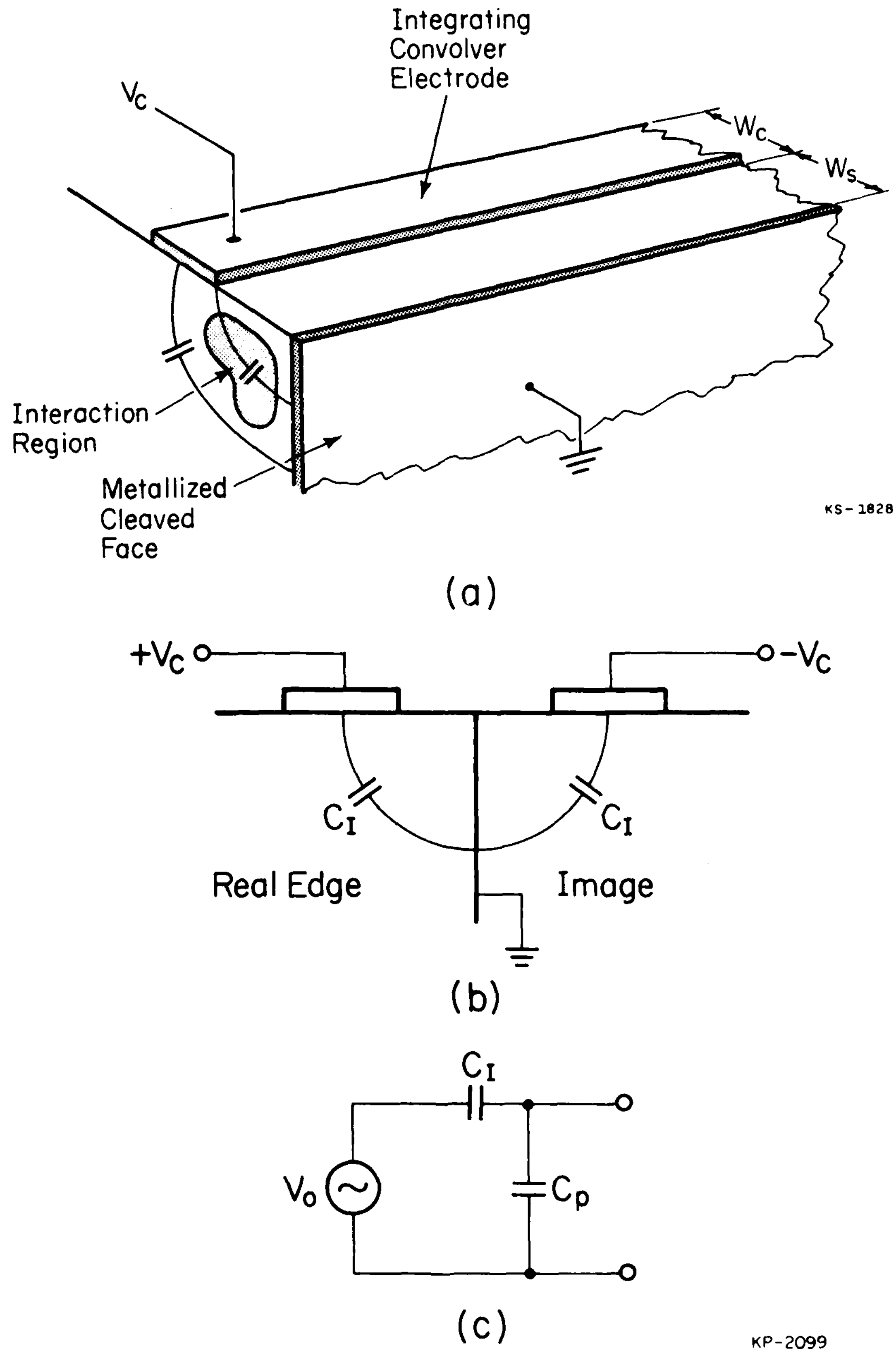


Figure 19. LAW convolver
a) Drawing of actual convolver
b) Model
c) Equivalent Circuit

This is identical to the open circuit voltage equation for the SAW convolver if W is set to 1/2. This value is chosen for W because the interaction region is 1/2 an acoustic wavelength wide. The next section justifies this choice because the material constant M_L for the LAW convolver is approximately the same as that for the SAW device (M_S) when W is set to 1/2.

The size of the interaction capacitor formed by the output electrodes and the ground face on a 90 degree wedge can be calculated by using a well known SAW IDT capacitance relationship and the model in Figure 19b. This is modelled as a SAW IDT electrode with a duty factor of 1/3. It is connected between plus and minus V_C with a conductor sheet placed on the zero potential plane. (This is really a negative image LAW convolver plate placed against the edge.) The conductor plane is identified with the grounded vertical edge of the LAW convolver.

$$C_I = .75 C_S L$$

Where: C_S is the capacity of a SAW IDT electrode with a duty factor of .5.

The coupling capacitor C_c which significantly reduces the bandwidth of the SAW convolver output, has been eliminated in the LAW configuration. This provides an approximate improvement in bandwidth of 2W when compared to a SAW convolver with a guide width of W wavelengths.

The capacitance (C_p) to ground that does not involve the interaction region is called the parallel capacity. This should be limited to a small fraction of C_I in a well designed device and is modelled as a parallel capacitor loading the output. The addition of parallel capacitance C_p attenuates the open circuit voltage by the factor alpha$_p$.

$$\text{alpha}_p = \alpha_p = C_I/(C_I + C_p)$$

It also increases the capacity of the output electrode.

$$C' = C_I + C_p$$

In a well designed LAW convolver the value of alpha$_p$ ~~should~~ should be one and the electrode capacity should be C_I.

The LAW convolver, like the SAW counterpart, has an internal resistance R_o, a bulk wave radiation resistance R_a, and a metallization resistance R_r.

The SAW relationships are modified with the above conditions to provide the LAW relationships for efficiency (F_I) and efficiency-bandwidth product (EBP).

1. <u>Low Resistive Termination</u>

$$F_I = 10 \text{ Log}\left[\frac{2M_L}{\Lambda}\right]^2 \frac{\alpha_p^2 (\omega C')^2 R_L}{1000}$$

2. <u>Tuned Convolver Plate</u>

$$F_I = 10 \text{ Log}\left[\frac{2M_L}{\Lambda}\right]^2 \frac{\alpha_p^2 \; Q_L \; \omega C'}{[1 + Q_L/Q_c]^2 \; 1000}$$

3. <u>Tuned Convolver Plate Efficiency Bandwidth Product</u>

$$EBP_I = 10 \text{ Log}\left[\frac{2M_L}{\Lambda}\right]^2 \frac{\omega C' \; \alpha_p^2}{1000}$$

4. Conjugate Matching

$$F_I = 10 \text{ Log} \left[\frac{2M_L}{\Lambda} \right]^2 \frac{q_c \ \omega C' \ \alpha_p^2}{8000}$$

5. Inductorless Magnitude Matching

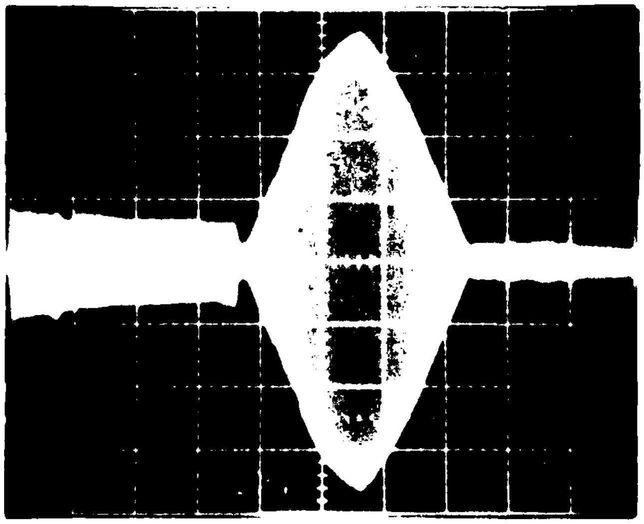
$$F_I = 10 \text{ Log} \left[\frac{2M_L}{\Lambda} \right]^2 \frac{\omega C' \ \alpha_p^2}{[1 + 1/Q_c]^2 \ 1000}$$

B. LAW Convolver Measurements

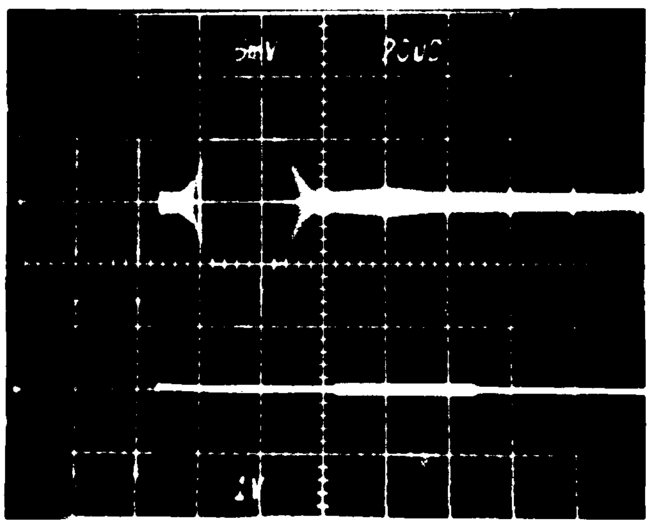
A LAW convolver is a line acoustic wave delay line like that pictured in Figure 6 with a third electrode placed near the edge in the propagation path to detect the convolution signal. Both of the delay line transducers are used to generate LAWs, and the output ele trode is similar to that shown in Figure 19. It provides an output that is proportional to the convolution of two counter-propagating LAWs.

Three LAW convolvers (two with MSMC LAW transducers) have been constructed to verify the concept feasibility, determine the equivalent material factor (M_L), and to evaluate the impedance characteristics of the LAW convolver output electrode.

The burst responses of the two MSMC convolvers are shown in Figure 20. Figure 20a shows the output voltage which results from two counter-propagating, two microsecond, rectangular bursts applied to the delay line transducers of convolver #2. Figure 20b is the convolution response taken when 3.5 microsecond duration rectangular bursts are applied to convolver #3.



(a)



(b)

Figure 20. LAW convolver burst response
a) Convolver #2
b) Convolver #3

Convolver #1 is constructed with the old type of narrowband direct transduction LAW transducers as described in Appendix C and the results are tabulated here for completeness. The convolvers #2 and #3 are constructed in a similar manner but using MSMCs to generate the signal and reference LAWs. The results are presented in Table IV. The internal efficiency factor of these convolvers varies widely because of the difference in convolver plate length, center frequency, and parallel capacity. However note that the material constants M_L for the three cases all agree within our margin of measurement error. This data supports the model postulated in this report.

The greatest ambiguity in this model is the determination of the interaction region capacity which cannot be measured directly and thus must be calculated.

The material factors for the LAW convolvers are of the same order as the material factors for SAW convolvers when the LAW is treated as a SAW with a beamwidth equal to one half a wavelength. This comparison is presented in Table V.

C. Potential LAW Convolver Efficiency

This work has demonstrated that wideband LAW beams can be generated and that the model used to calculate the LAW convolver internal efficiency is consistent over a range of LAW convolver configurations. The actual LAW internal efficiencies achieved in this work have not been startlingly high because fabrication and mask difficulties prevented us from realizing the optimum design. However, the efficiencies projected by the model for improved

TABLE IV

LAW CONVOLVER MEASURED PARAMETERS

Convolver	#1	#2	#3
Measured F_I	-46 dBm	-72 dBm	-68 dBm
Output Tuned	no	yes	no
Load Resistance	50 ohms	50 ohms	50 ohms
Center Freq.	146 MHz	98 MHz	98 MHz
Wavelength	24×10^{-6}m	36.7×10^{-6}m	36.7×10^{-6}m
Effective Length	2.6 cm	1 cm	2.45 cm
Electrode gap (Wavelengths)	1/2	1/2-1	1/2
C_I	9 pF	3.4 pF	8.5 pF
C_I+C_p	34 pF	14 pF	19 pF
alpha_p	.26	.25	.45
Reactance	32.3 ohms	114 ohms	84 ohms
R'	4.6 ohms	.5 ohms	___
Q_L	.646	2.28	.912
Q_C	10.8	228	---
M_L (volt-meter/watt)	$.439 \times 10^{-6}$	$.45 \times 10^{-6}$	$.57 \times 10^{-6}$

TABLE V

ELASTIC CONVOLVER MATERIAL CONSTANTS

MATERIAL	TYPE	M ($\times 10^{-6}$) (volt-meter/watt)	REFERENCE
128° $LiNbO_3$	SAW theoretical	1.02	9
YZ $LiNbO_3$	SAW theoretical	2.63	9
YZ $LiNbO_3$	SAW experimental	0.78	10
YZ $LiNbO_3$	SAW experimental	1.2	11
128° $LiNbO_3$	LAW experimental	.44-.57	current

configurations, higher frequencies, and longer delays are very encouraging. A well designed 100 Mhz bandwidth, 20 microsecond processing time LAW convolver, centered at 500 MHz should have an internal efficiency factor of -35 dBm.

APPENDIX A MSMC Pattern Generation

The generation of the MSMC mask can cause considerable difficulty. In order to be able to try a number of options (including saw cut YZ and 128-degree $LiNbO_3$ in addition to cleaved edges), we needed to have the pattern generator make our mask at actual size. We only had software to drive a MANN 3000 pattern generator, which has position resolution of 1 micron. Since the required pitch ratios could not be realized as ratios of small whole numbers of microns, we tried a trick which would increase the effective position resolution by a factor of 4. The trick involved forming each grating line by means of two partially overlapping rectangles. Unfortunately, it appears that stray light around each exposure caused fogging between the lines, which ruined most of the mask. We were very fortunate to be able to get any results at all from this mask.

APPENDIX B Cleaving Techniques

Regardless of whether or not the wafer is thinned it must be metallized and coated with Shipley 1300-series photoresist (PR) before cleaving. After the PR is soft baked, the wafer is attached, PR-side down, to a simple fixture made from glass microscope slides, using ordinary paraffin wax, as shown in Figure B-1. The fixture, wafer, and wax may be heated during assembly or disassembly in the same oven used for PR soft bake. This assures that the photoresist is never overheated. Of course, extreme care must be taken to avoid scratching the PR layer.

The purpose of the fixture is to insure that the cleavage plane (parallel to the crystal X-axis on 128° cut $LiNbO_3$ and therefore perpendicular to the wafer flat) is parallel to the edges of the glass slides. The fixture is made by first putting two microscope slides together along their long edges. Next, a 10-mil thick glass cover slip is placed across the two, with bottom edge parallel to the bottom edges of the slides, and is epoxied in place. After the epoxy has cured, the cover slip will break along the line between the slides.

Once the wafer is in place and the paraffin has cooled, the wafer is ready to be cleaved. The wafer and fixture should be placed on a resilient surface. We have found that a stack of papers works best: a 3-mm stack of papers, with a few pieces of filter paper on top of that.

To initiate a crack, a sharp tungsten carbide or diamond type scribe is used to nick off part of the edge of the wafer,

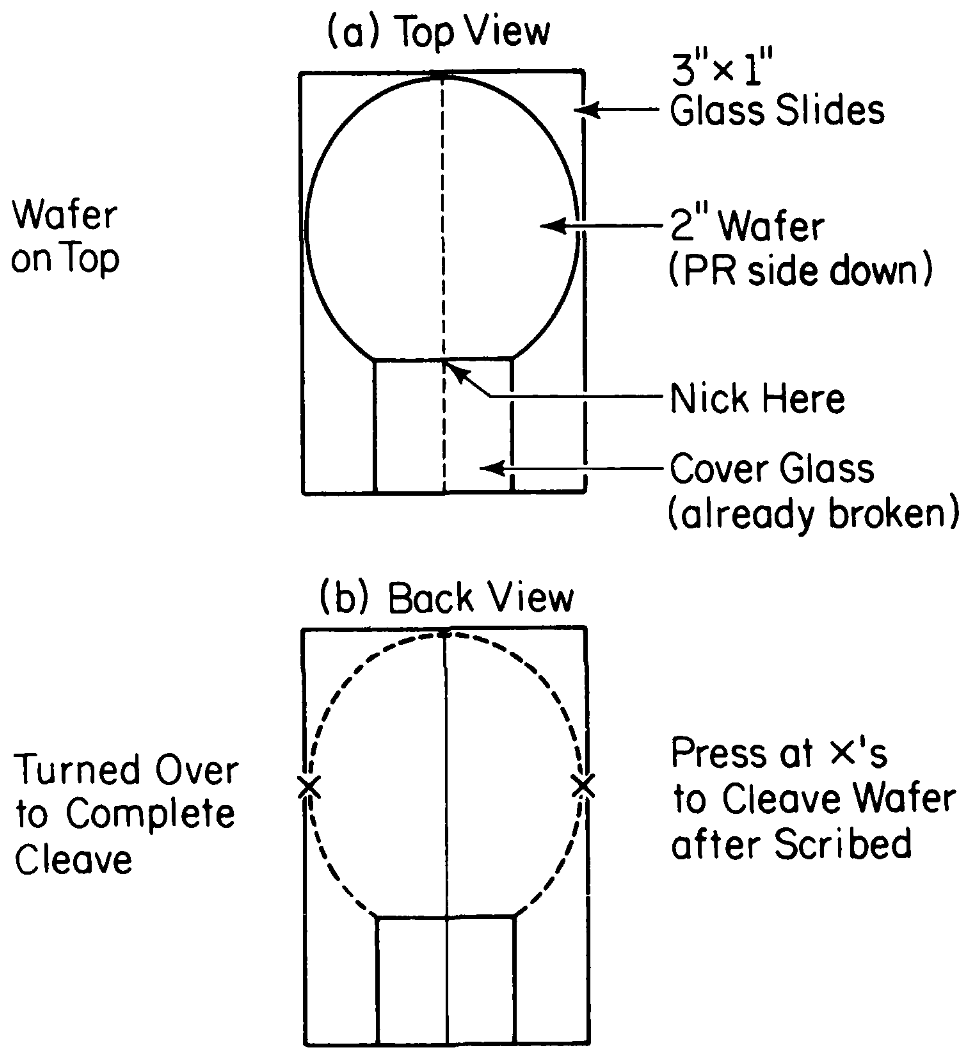


Figure B-1. Wafer cleaving diagrams

above and parallel to the line between the glass slides. A number of small nicks may be needed before a cleave starts. It is hard to describe on paper how much force should be applied: one should apply enough force to each time nibble away a piece from the edge about the size of a salt crystal by putting the scribe just on the $LiNbO_3$ surface, pressing down lightly and dragging it off the edge with a snapping motion.

When a cleave does start, it will often crack all the way to the end of the piece. If it only travels part way, it is best to carefully pick up the wafer and fixture and turn it over. Then, light downward pressure on the glass slide at the positions shown in Figure B-1 will cause the crack to propagate the rest of the way. Failure to invert the fixture will usually cause striations along the apex at the polished surface. To avoid striations at this apex, the crack must open up at this side.

Once the piece has been cleaved in two, special care should be taken to avoid chipping the edges. The two halves should be separated in a way which does not allow them to accidently bump together. Both halves should be carefully blown off with clean nitrogen, to remove any chips or flakes. At this point, the edge quality may be inspected, and the side containing the acute wedge may be identified, with the glass slide acting as a convenient handle.

Each piece may be removed from its slide by heating a few minutes in the soft-bake oven to melt the wax. Gilman [7] recommends that a crystal be cleaved into small pieces by a process of successive bisections, so each half from the previous cleave will need to be re-mounted to a fixture for more cleaving.

When pieces of the desired size have been obtained and removed from the glass slides, the remaining paraffin wax may be removed without harming the PR by a light spray with trichlorethylene (TCE). DO NOT USE 1,1,1, Trichlorethane (TCA): it will seriously damage Shipley 1300-series photoresist very quickly.

After the paraffin wax has been removed, the piece is immediately ready for pattern exposure and development. Of course, the piece should be handled carefully, in such a manner as to protect the side with the acute wedge from contact with anything.

This method is the best method we have found to date. It reliably produces cleaves which are nearly free of striations, and straighter than those made by other methods.

APPENDIX C LAW Convolver With Direct LAW Transducers

The first LAW convolver was constructed using triangular electrode transducers. The signal and reference transducers are identical and each has 100 electrode pairs spaced at 24 micron centers. The transducers were placed on an 84.5 degree edge formed by cleaving 128-degree cut Lithium Niobate. The LAW velocity on this edge (both faces shorted) is 3408 meters per second and the transducer center frequency is 142 MHz. The signal and reference transducers are spaced by 2.9 cm to form a delay line with an 8.5 microsecond delay. The device can be used as a delay line with the signal transducer used as the input and the reference transducer used as an output. This delay line is conjugate matched and has an insertion loss of 16 dB. The 10 dB of loss over and above bidirectional loss is resistive losses in the transducer structure. The propagation loss is negligible as verified with an optical probe.

The output electrode is placed 12 microns (1/2 wavelength) from the edge and is 2.6 centimeters long. This creates an interaction region that is 7.63 microseconds long. The vertical edge is metallized with aluminum and grounded. The output electrode has an average width of 96 microns; this is significantly wider than the one-half wavelength wide electrode and the extra width adds a significant capacitance in parallel with the interaction region capacitance. It was made wider for practical reasons unique to this test and capacitance between the electrode and the grounded vertical plane is measured to be 34 pF and the series equivalent resistance at 284 MHz is experimentally determined to be 4.6 ohms. The interaction region capacitance is calculated to be 9 pF. The parallel capacitance is 25 pF. The actual value of alpha_p can not be measured directly but these measurements and calculations indicate that it is equal to 0.38. The output electrode quality factor including the affects of all capacitance is 77. A 7.63 microsecond duration, 142 MHz burst is applied to both the signal and reference transducers. The output electrode is connected to an amplifier with a 50 ohm input impedance. When 8 dBm is applied to both transducers, then the signal and reference beam each carry one milliwatt (0 dBm) and the output power at 284 MHz is -46 dBm.

REFERENCES

[1] C. Maerfeld, P. Defrauould, G. Farnell, "Some Applications of a Non-Symmetrical Multistrip Coupler", 1973 IEEE Ultrasonics Symposium Proceedings, IEEE Catalog #73CH0807-8 SU, p. 155.

[2] C. Maerfeld, "Multistrip Couplers", Wave Electronics, vol. 2, 1976, pp. 82-110.

[3] K. Anderson, "An Improved Multistrip Mode Converter", M.S. Thesis, Electrical Engineering Dept., University of Illinois at Urbana-Champaign, 1981.

[4] M. Hoskins, S. Datta, C. Panasik, B. Hunsinger, "Line Acoustic Waves on Cleaved Edges in $LiNbO_3$ and GaAs", 1978 IEEE Ultrasonics Symposium Proceedings, IEEE Cat. # 78CH1344-1SU, p. 647.

[5] R. Adler, A. Korpel, P. Desmares, "An Instrument for Making Surface Waves Visible", IEEE Trans. Sonics and Ultrasonics, vol. 38 (13), 1968, p. 5138.

[6] M. Hoskins, B. Hunsinger, "Optical Probing of HF Guided Wave Surface Displacements with Arbitrary Profiles", IEEE Trans. Sonics and Ultrasonics, vol. SU-27, no. 3, May 1980, p. 103.

[7] J. Gilman, "Cleavage, Ductility, and Tenacity in Crystals", in Fracture, ed. B.L. Averback et. al, MIT Press and John Wiley and Sons, New York 1959, pp. 193-224.

[8] R. Miller, K. Anderson, E. Bogus, J. Bodett and B. Hunsinger, "Recent Progress in Line Acoustic Wave Devices", 1982 IEEE Ultrasonics Symposium Proc., IEEE Cat. # 82CH1823-4, p. 385.

[9] A.K. Ganguly and K.L. Davis, "Theory of Degenerate SAW Elastic Convolver," 1979 Ultrasonics Symposium Proceedings, pp. 715-720.

[10] P. Defranould and C. Maerfeld, "A SAW Planar Piezoelectric Convolver," Proc. IEEE, vol. 64, no. 5, May 1976, p. 748.

[11] T.C. Lim, E.A. Kraut and R.B. Thompson, "Nonlinear Materials for Acoustic Surface Wave Convolvers", Applied Physics Letters, vol. 3, February 1972, p. 127.

MISSION
of
Rome Air Development Center

RADC plans and executes research, development, test and selected acquisition programs in support of Command, Control Communications and Intelligence (C^3I) activities. Technical and engineering support within areas of technical competence is provided to ESD Program Offices (POs) and other ESD elements. The principal technical mission areas are communications, electromagnetic guidance and control, surveillance of ground and aerospace objects, intelligence data collection and handling, information system technology, ionospheric propagation, solid state sciences, microwave physics and electronic reliability, maintainability and compatibility.

Printed by
United States Air Force
Hanscom AFB, Mass. 01731