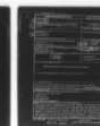


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SYSTEMS APPLICATIONS OF SAW FILTERS AND DELAY LINES

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SUMMARY

This paper reviews the applications that SAW (Surface Acoustic Wave) filters and delay lines have to communications and radar systems. The development of SAW resonators at frequencies up to 1 GHz is reported together with their promise for stabilizing precision oscillators. Such oscillators could be useful, for example, as clocks for CCDs. Operation directly at 1 GHz eliminates the multiplier chains required for conventional quartz oscillators. The use of miniature SAW transversal filters for banks of contiguous filters is shown to be important in reducing the size of fast frequency synthesizers and multiplexers for spread-spectrum communications applications. The design of a 9.1  $\mu$ sec delay line with all spurious echoes 70 dB down is described together with its radar signal processing application.

1. INTRODUCTION

The signal processing capabilities of SAW and CCD are generally complementary. SAW (Surface Acoustic Wave) devices are capable of bandwidths up to 1 GHz but are limited in time delay to 100  $\mu$ sec, while CCD (Charge Coupled Devices) can have time delays up to 0.1 sec but bandwidths are generally tens of megahertz. (See Fig. 1.) The two technologies are also complementary in that CCD devices require a clock which can be provided by SAW technology. This paper will focus on the very small time delay section of Fig. 1 and will be concerned with SAW bandpass filters and resonators. These components are much smaller than their electromagnetic counterparts and are lower cost, as they are fabricated by the same photolithographic techniques used for integrated circuits. We will describe applications of these filters towards stabilizing precision oscillators and reducing the size of fast frequency synthesizers and frequency multiplexers. Finally, the application of SAW delay lines to radar signal processing applications will be described including the techniques required to maintain all spurious responses 70 dB below the 9.1- $\mu$ sec delay time.

2. SAW RESONATORS

Recently Laker, et. al. (LAKER, K.H., 1977) have reported on the development of SAW resonators with Qs from 4000 to 5000 at 0.8 GHz. (Fig. 2) Such high-Q resonators are of importance in stabilizing the frequency of precision oscillators used in communication and radar systems. Figure 3 shows the two small transducers in the center which are used for the electromagnetic input and output. Acoustic standing waves are built up between the long reflectors consisting of 1- $\mu$ m-wide aluminum lines on 2- $\mu$ m centers. The high-Q of the acoustic resonance couples the input to the output transducer.

A simple estimate of the Q can be obtained by assuming a reflectivity parameter for each grating line and accounting for propagation and diffraction loss (BELL, D.T., JR., 1976). Because stripe reflection coefficient data are scarce at these high frequencies, the value of  $r = -0.006$  gave reasonable agreement with experiment. For this case, the unloaded Q-factor in air was calculated (LAKER, K.R., 1977) to be 5090, in air and 5540 in vacuum. Figure 2 shows that the increase in Q obtained by evacuating the resonator was in good agreement with that calculated by simple theory. The Q due to propagation loss in vacuum on quartz is 12,500 at 0.8 GHz. This when combined with diffraction loss results in a Q of 8000, which can be approached as other loss mechanisms are minimized.

Figure 4 shows a comparison of SAW and conventional electromagnetic resonators. The helical resonator is one-half wavelength long. The dielectric resonator uses strontium titanate to reduce its size. The SAW resonators have smaller size, substantially higher Q, and the advantage of being planar. The last factor makes them compatible with integrated circuits and microstrip and contributes to low-cost mass production.

Figure 5 shows a comparison between a SAW stabilized resonator at 1 GHz and a conventional 20 MHz crystal oscillator with the multipliers, amplifiers, and filters necessary to produce an output at 1 GHz. Quartz crystal oscillators cannot operate at frequencies substantially higher than 20 MHz, as the thickness of the crystal must be either one-half acoustic wavelength thick or an odd multiple thereof. For frequencies above 20 MHz the quartz crystal becomes too fragile. The planar SAW device operating directly at 1 GHz eliminates the multiplier chain with an approximate savings in size and weight of a factor of 20 together with increased reliability. The SAW filter requires the use of only one surface of the crystal. The remaining five sides may be chosen, for example, to reduce the vibration sensitivity.

Figure 6 shows the insertion loss of the SAW resonators over a much broader range than in Figure 2. The insertion loss of the unmatched resonator is 33 dB (LAKER, K.R., 1977). By crude stub tuner matching the insertion loss was reduced to 22 dB and the Q-factor degraded to about 3900. The lowest insertion loss of 10 dB was obtained by inductive matching of the input and output transducers.

The off-resonance coupling between the input and output is due to electromagnetic leakage and acoustic cross talk. Fildes and Hunsinger (FILDES, R.D., 1976) have shown that unidirectional transducers can be used to substantially reduce the acoustic cross-talk between the transducers.

The long term stability or aging of SAW resonators is not as good as conventional resonators. Adams and Kusters (ADAMS, C.A., 1977) have observed long term stabilities of no better than 1 part in  $10^6$  per day as compared to bulk-wave resonators, whose long term aging is better than 1 part in  $10^{10}$  per day. As the relatively young SAW technology matures, the aging should also improve.

3. FAST FREQUENCY SYNTHESIZER

We shall now discuss important applications of SAW bandpass, transversal filters, which in analogy to resonators are much more compact than their electromagnetic counterparts. SAW transversal filters below 100 MHz are being mass produced at a cost of under \$2.00 for use in color TV and games. This paper will

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discuss SAW filters at higher frequencies, where they are even smaller. A 21 channel contiguous filter bank from 500 to 600 MHz occupies an area of only 9 by 25mm. (See line drawing in Figure 7 and photograph in Figure 8.) Frequencies can be switched by the PIN diodes in less than 5 nsec, a function useful for coherent frequency-hop coding in spread spectrum communications systems (LAKER, K.R.,....1976).

The desired frequency synthesis is achieved by feeding a uniform comb spectrum, which is harmonically related to a stable reference oscillator or clock, into the filterbank. Each SAW filter is tuned to one of the different frequencies of the comb spectrum. Hence, a given frequency is continuously available at the output of the filter. The spectral purity of this signal is as good as the out-of-band rejection of the filter. Out-of-band rejections in excess of 60 dB are achievable. The stability of the signal is the same as that of the reference clock. The switching speed is that of the diode switch, whose on-off-ratio can be held in excess of 60 dB.

Figure 9 shows a mixer technique of using two of the above basic building blocks to substantially increase the number of available frequencies (SLOBODNIK, A.J.,JR.,....1976). As illustrated, one tone from the 9 channel filter bank is mixed with one from the 7 channel bank to obtain 63 tones with only 16 filters. The frequencies of each of the banks is carefully chosen so that, for a given mixing stage, only the desired sum or difference frequency falls within the bandwidth of the broadband electromagnetic filter following the mixer (thereby eliminating mixer spurious). The second mixer stage can be used to produce the desired output frequencies. Figure 9 also illustrates the multipliers and snap-diode comb generators which can be used to implement the dual comb generator.

Frequencies in the low gigahertz range can be met with sub-micrometer linewidth interdigital transducers using either electron-beam fabrication or direct optical projection from 10X masters. (BUDREAU, A.J.,....1975). To reduce the demands on the device fabrication, these high operating frequencies may also be achieved by operating filters at third overtone modes or by using high velocity substrate materials such as aluminum nitride-on-sapphire thin films and beryllium oxide, whose velocities are of the order of 6000 m/sec. (roughly twice that of ordinary materials such as quartz). (BUDREAU, A.J.,....1975).

SAW filters with 0.7  $\mu$ m linewidths and spaces on lithium tantalate and with a frequency of 1.03 GHz were fabricated using direct optical projection (BUDREAU, A.J.,....1975). Advantages of this technique are (1) 10X photolithographic masters are less expensive than one-to-one masters, (2) the master need not be in physical contact with the substrate thereby increasing its lifetime, and (3) ease of varying the magnification slightly about 10X for fine frequency tuning. The final one-to-one image is obtained with a high resolution reducing lens directly in photoresist on the substrate. Figure 10 illustrates high quality 0.6 and 0.9  $\mu$ m wide metal transducer lines made by direct optical projection (KEARNS, W.J.,....1977).

#### 4. MULTIPLEXERS

Contiguous banks of SAW filters can be used, as shown in Figure 11, to make compact frequency multiplexers. The single electromagnetic input in Figure 11 comes through the 3 dB input attenuation (whose purpose is to keep the input voltage-standing-wave-ratio below 2) to the 8 input transducers. These are connected electrically in parallel to keep the triple-transit spurious below 45 dB (SLOBODNIK, A.J.,JR.,....1975). This novel technique eliminates the need for an electronic power-divider at the input, with its associated size and losses. The 8 output transducers, which are barely visible in the photograph, are connected to 8 matching output inductors. These, in turn, are connected to the 8 coaxial cables going to the output connectors on the front of the package. It is apparent that these are the largest size determining elements in this laboratory prototype package. These connectors would not, of course, be required in a systems application, where the filterbank would be directly connected to the output electronics. Note also that there are actually 16 SAW filters visible on the two lithium tantalate chips. The extra filters would not be necessary due to the very high yields recently achieved with direct optical projection (KEARNS, W.J.,...1977).

A photograph of the insertion loss (10 dB per division) versus the frequency (20 MHz per division) for the 8 output channels is shown in Figure 12. The insertion loss across the band was 33.5 dB plus or minus 1.5 dB. The insertion loss could have been at least 4 dB lower if there had not been a 45 dB triple-transit requirement. Van de Vaart and Solie (VAN DE VAART, H.,....1976) have obtained 10 dB insertion loss for an 8-channel multiplexer ranging from 190 to 232 MHz by the novel use of multistrip couplers for dividing the acoustic power on a lithium niobate substrate. The triple-transit was only 20 dB down, however.

The multiplexers under discussion are useful for (1) frequency division multiplexing to obtain optimum use of the bandwidth capacity of a communications channel, and (2) channelized receivers for the real-time spectral analysis of pulses. Filter responses useful for pulses are different from those for continuous waves (of the sort used for the frequency synthesizer). For pulses, filters are sought to be highly selective in the frequency domain and relatively distortionless in the time domain. One approach is to use contiguous Butterworth filters in a double-detection signal processing scheme (SLOBODNIK, A.J., JR.,....1975). In Figure 12, we have used a recently discovered (SLOBODNIK, A.J.,JR.,....1975) Flat Exponential Filter (FEF) function, which has a flat in-band response, and an exponential out-of-band response. In contrast to a Butterworth filter, which is straight-forward to implement with lumped constant elements, the Flat Exponential Filter, is straight-forward to implement with SAW transversal filters. When compared to a two-pole Butterworth filter, the FEF has better frequency selectivity, which is surprisingly not sacrificed in the time domain. This may well be the first of a series of new filter functions which are easier to implement with SAW rather than conventional filters.

#### 5. LOW SPURIOUS DELAY LINE

Finally, the application of a SAW delay line to a radar signal processing application will now be described. The most critical goal was to maintain the triple-transit and other spurious responses below 60 dB at the 30 MHz intermediate signal processing frequency (See Table I). At this frequency, bulk waves had in the past been difficult to suppress due to the fact that they have negligible attenuation. The solution to this problem was to use an orientation of lithium tantalate for which the piezoelectric coupling to volume and plate waves was very weak (CARR, P.H.,...1976). The MDC (Minimum Diffraction Cut) of lithium tantalate



discovered by Slobodnik (SLOBODNIK, A.J., JR., .... 1975) to have diffraction spreading retarded with respect to an isotropic medium by a factor of 20, has this desirable property. Figure 13 illustrates that the longitudinal volume wave spurious, which arrives in about 5  $\mu$ sec for YZ lithium niobate, is absent for the MDC lithium tantalate.

A line drawing of the delay line is shown in Figure 14. The transducers were separated by 3.10385 cm. The bottom of the substrate was rough ground and tapered to minimize any possible interference from bulk waves. The lithium tantalate slab was epoxied onto a stainless steel backing plate. This gave a strong, rigid structure, which made it an easy task to maintain flatness of the top surface to within three optical wavelengths. Randomly spaced holes were drilled into the stainless steel in order to scatter any possible volume waves. The electromagnetic leakage was maintained well below the 70 dB level by (1) grounding opposite sides of the transducer and, (2) by maintaining the surface of the crystal within 0.025mm of the bottom of the cover. This delay line illustrates that it is indeed possible to keep the spurious responses of SAW components below 70 dB.

## 6. CONCLUSION

We have reviewed the promise that SAW devices have for stabilizing precision oscillators directly at frequencies up to 1 GHz. Such oscillators are useful, for example, as clocks for CCDs. Operation directly at 1 GHz eliminates the bulky multiplier chains required with conventional quartz oscillators. We have shown how the small size of SAW transversal contiguous banks can play an important role in reducing the size of fast frequency synthesizers and multiplexers for important communications applications. Finally, we have shown how it is possible to design SAW delay lines for radar signal processing applications with all spurious echoes below 70 dB.

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FIGURE CAPTIONS

1. Plot of the signal processing bandwidth versus processing time for Surface Acoustic Wave and Charge Coupled Devices.
2. Plot of the amplitude response versus frequency for 780 MHz SAW resonator in air and in vacuum.
3. Photograph of a SAW resonator.
4. Comparison of different resonators at 1 GHz. On the left, is a helical resonator ( $Q = 1000$ ), in the center is a high dielectric constant resonator ( $Q = 1000$ ), and on the right is a quartz chip with 5 SAW resonators with  $Q$  for 4000 to 5000.
5. SAW oscillators operate directly at 1 GHz and thereby eliminate the bulky multiplier chains required with conventional quartz crystal oscillators.
6. Insertion loss versus frequency plot for the resonator shown in Figures 2 and 3 for unmatched (top) and matching with stub tuners (bottom).
7. Drawing of UHF Frequency Synthesizer using a compact contiguous SAW filter bank.
8. Photograph of the Frequency Synthesizer of Figure 7.
9. Schematic of how the outputs from two "building-block" frequency synthesizers of Figures 8 and 9 can be mixed to increase the number of available frequencies.
10. Photograph of submicrometer aluminum transducer lines made by direct optical projection.
11. Photographs of a  $1 \times 8$  UHF SAW multiplexer. The photograph on the left shows the empty can while on the right we see the SAW filters.
12. Plot of the insertion loss (10 dB/div) versus frequency (20 MHz/div) for the eight different outputs of the SAW multiplexer of Figure 11.
13. Comparison of the 9.1  $\mu\text{sec}$  delay line output for Y-cut, Z-propagating lithium niobate (left), and Minimum Diffraction Cut lithium tantalate, illustrating the lower volume waves of the latter.
14. Line drawing of the 9.1  $\mu\text{sec}$  delay line showing the canted sides for suppression of bulk waves.

TABLE I  
9.1  $\mu$ sec DELAY LINE PERFORMANCE

	GOAL	THEORETICAL	EXPERIMENTAL
INSERTION LOSS (dB)	35	37.6	34.1 - 37.7
TRIPLE TRANSIT AND OTHER SPIRIOUS (dB)	60 min	73.6	73.6
INPUT VSWR FOR 50 OHMS	2.0	2.0	2.1
DELAY V. S. FREQUENCY 29 - 31 MHz DEVIATION FROM LINEAR	$\pm 1.5^\circ$	$\pm .2$	$\pm 1.5^\circ$
TEMP. COEF. OF TIME DELAY (PPM)	100	64	MDC LT103
1 dB BANDWIDTH (MHZ)	3.0	2.4	2.3
CENTER FREQUENCY (MHZ)	30.0	30.0	29.6
MAX. INPUT POWER (dBm)	20	20	20

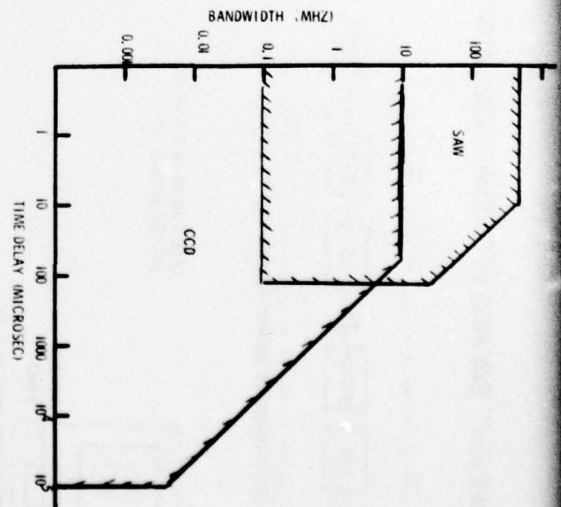


FIGURE 1

## ST-QUARTZ TWO-PORT RESONATOR

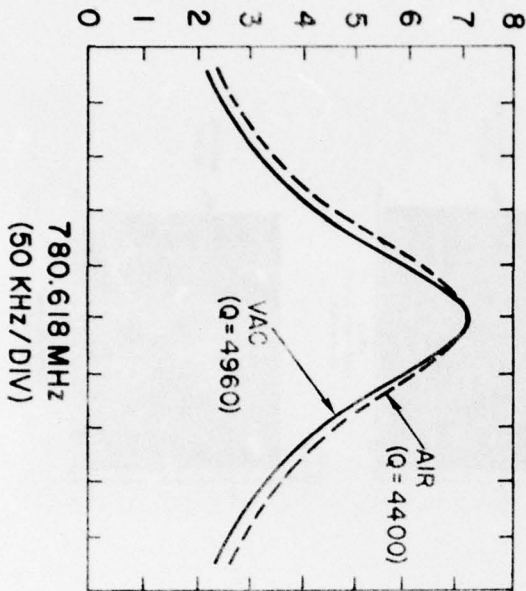


FIGURE 2

## TWO-PORT SAW RESONATOR

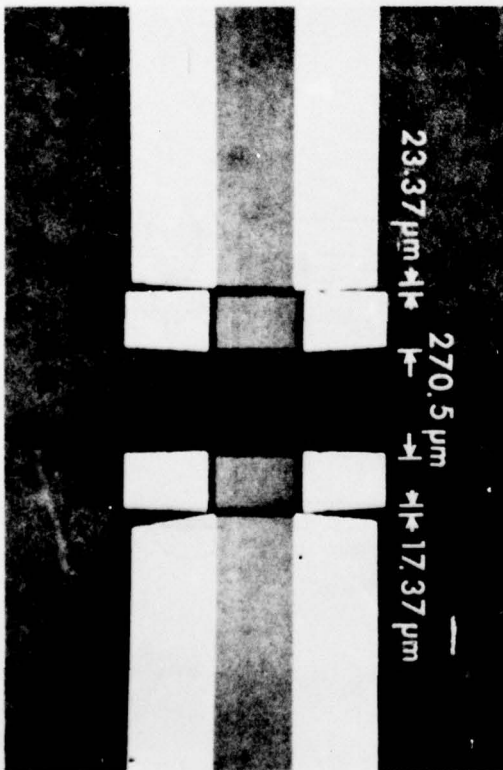
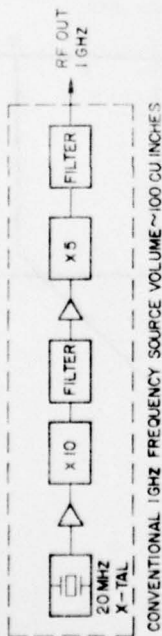


FIGURE 3



# SIZE AND WEIGHT SAVINGS WITH SAW OSCILLATORS



SIZE AND WEIGHT SAVINGS  
APPROXIMATELY 20:1

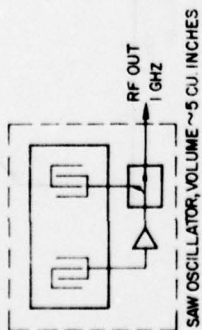


FIGURE 5

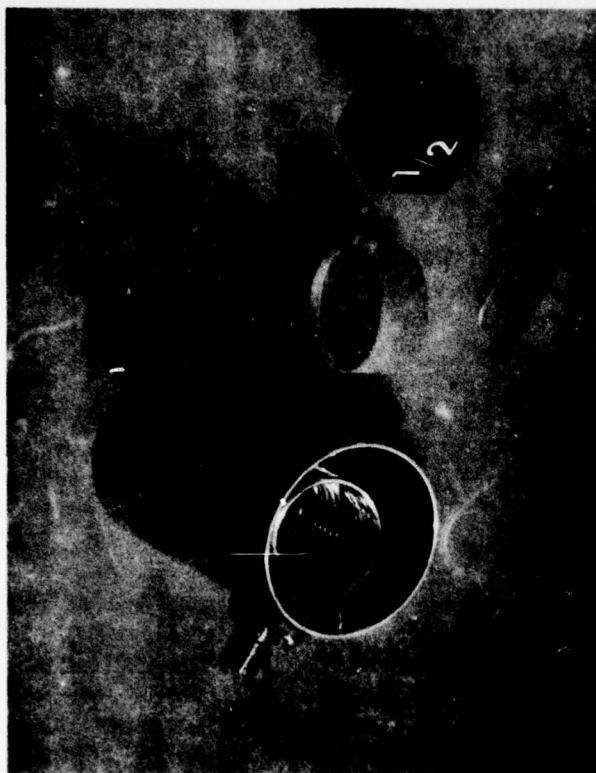


FIGURE 4

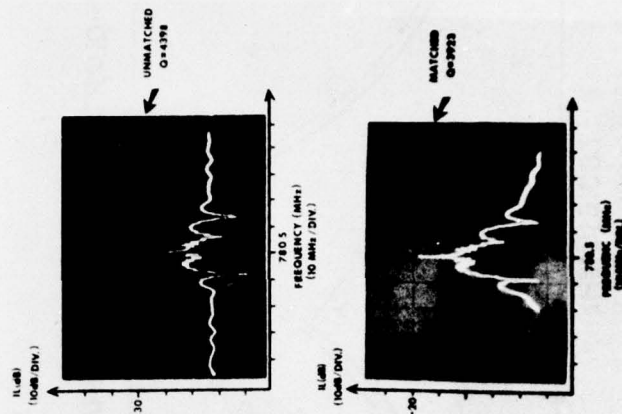


FIGURE 6

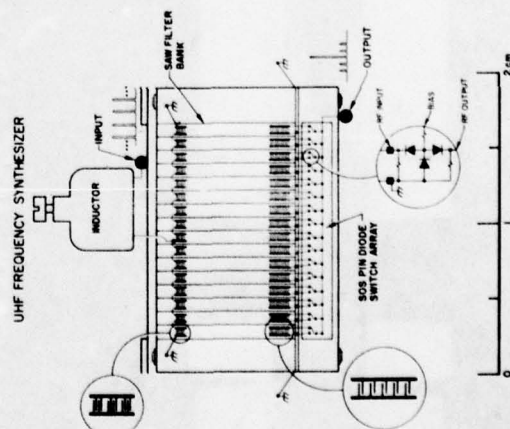


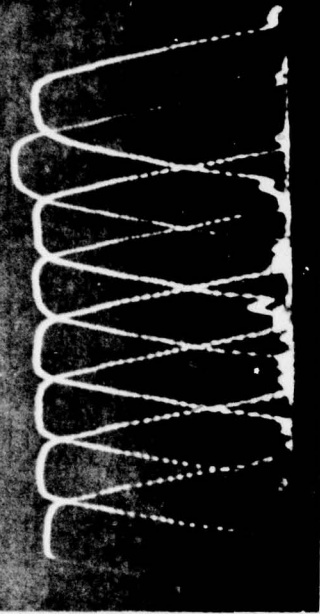
FIGURE 7





# RADC/EI SAW MULTIPLIER

30 dB



FREQ 245 MHz 405 MHz

FIGURE 12

## 30 MHz DELAY LINE OUTPUT



HORIZONTAL SCALE: 5 μsec/cm

FIGURE 13

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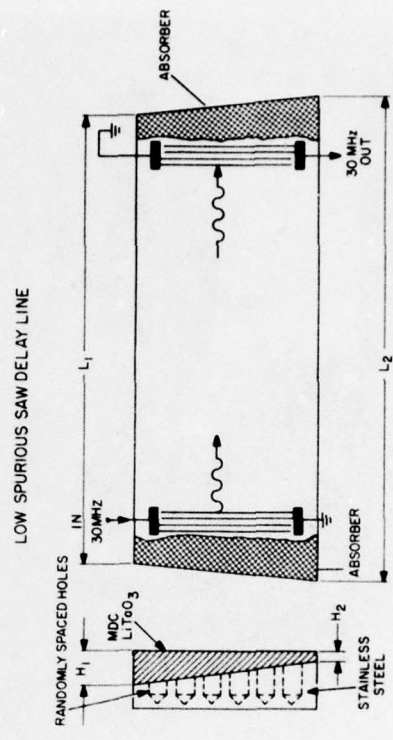


FIGURE 14

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