

# Band-Pass SAW Filters on 128° Rotated Y-Cut Black Lithium Niobate

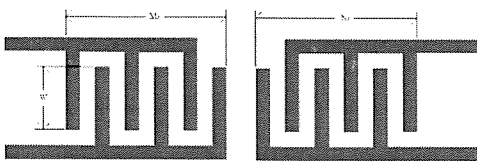
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**Abstract**—128° rotated Y-cut Black Lithium Niobate is used as a substrate material for the creation of simple one pass SAW bandpass filters. Center frequencies between 100 and 300 MHz were designed with varying aperture widths and designed bandwidths. The  $S_{21}$  measurements were made with Agilent Technologies E5071C, two port network analyzer, and were compared to theory. Without considering the effects of the asymmetric coplanar waveguides (ACPW) used to connect the ground-signal-ground probes to the device under test (DUT) the average distance between measured and theoretical data is 0.523dB, near the center frequency.

**Index Terms**—asymmetric coplanar waveguides (ACPW), inter-digital transducer (IDT), polyimide, surface acoustic wave (SAW).

## XVIII. INTRODUCTION

**B**ANDPASS filters can be created on a piezoelectric substrate in a multitude of ways. One such way is to rotate and cut the crystal such that the direction of wave propagation becomes that of the surface of the substrate. This allows for all the energy to travel in one direction with relatively low loss. The metallization of the surface in a periodic array of positive and ground electrodes allows for the distribution of a periodic charge distribution to form across the surface. This is transformed into a wave front and propagates along the surface of the crystal [1]. The periodic array of electrodes can be many different shapes and sizes however the design space uses a basic IDT. The devices tested comprise of two such devices and the basic structure can be seen in figure 1.



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Fig. 1. The 2 IDT structure whose geometrical variables control center frequency, bandwidth, and insertion lose.

This structure is the DUT; however a means to probe the device is still needed. ACPW [2] were used to connect ground signal ground probes to each of the devices, such that each pair of fingers was connected by one signal and one ground probe. The final ground probe on each port is tied together so both ports share an external common ground. This still leaves stray acoustic waves propagating passed the IDT structures and can possibly interfere with measurements. Common practice is to use acoustic absorbing material in order to dampen any stray signals. For this design the choice of material was a polyimide [3]. This process includes more intense thermal processing increasing the chance of wafer breakage since lithium niobate is a pyroelectric material. The end result shows a characteristic bandpass frequency response.

## XIX. THEORETICAL OPERATION

In order to evaluate the performance of the devices first the theoretical operation must be calculated. This is accomplished by modeling each part of the device and building up a circuit model to include all of the parameters such that the reflection coefficients can be calculated in a circuit equivalent of the network analyzer. Ultimately this leads to the characteristic  $S_{21}$  curves experienced in normal operation. In order to this the characteristic response of a single IDT must be evaluated.

The electrical response of the circuit depends on all of the geometric factors of the IDT,

as well as the material properties of the chosen substrate. A simple case of alternating positive and ground electrodes will be taken into consideration. This arrangement is shown below in figure 2.

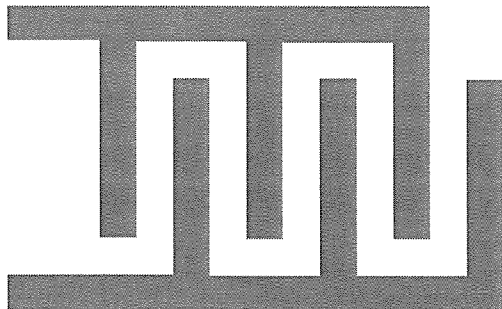


Fig. 2. IDT structure whose geometrical variables control center frequency, bandwidth, and insertion loss.

By applying a voltage to one of the buses and tying the other bus to ground, the frequency of the signal can be swept in order to generate an acoustic response in terms of frequency. The natural response of the structure is shown to be closely related to a sinc function, electrically appearing as a band pass filter. The center frequency of this function is simply determined by

$$f = v_0 / \lambda \quad (1)$$

Where  $\lambda$  is equal to the distance between the centers of two positive electrodes [4]. This is true for the case where the distance between the metal lines and the thickness of the metal lines are equivalent. Another important quality of filters that is typically defined when designing for filter applications is the bandwidth. The bandwidth for these devices is a function of the number of positive electrodes in the IDT, denoted by  $N$ . The bandwidth for SAW devices is typically measured by the first order zero crossing in the sinc function which is given by,

$$\Delta f = 2f/N \quad (2)$$

This then allows for the design of a single function IDT to cause acoustic wave fronts to propagate as a function of frequency. Since the device is symmetrical these waves will propagate in both directions along the surface of the crystal. By

placing another IDT in line with the wave it is possible to receive the wave front and convert it back into electrical energy, leading to the device shown in figure 1.

The resulting electrical output is correlated to the multiplication of the two sinc functions determined by the geometries of each IDT. However in order to tailor this response, the exact transfer function of a single IDT must be evaluated. In order to get the response of an IDT the charge distribution across the fingers must be looked at.

Assuming that the electrodes overlap for an infinite distance, and the number of positive electrode to either side is large, one could say that the distribution represents a rectangular square wave. This approximation does not take into account the end effects of the fingers, however even with a small amount of electrodes the approximation holds quite well. By Fourier analysis of this charge distribution across one finger, convoluted with an array factor, or the function of repetition of positive electrodes, an acoustic response could be generated. This model would be quite tedious and difficult to solve for each pair of electrodes. For this analysis only the first harmonic of the IDT will be looked at, in which case there is a commonly accepted circuit model for a single IDT, formed from approximations of the product of the convolution.

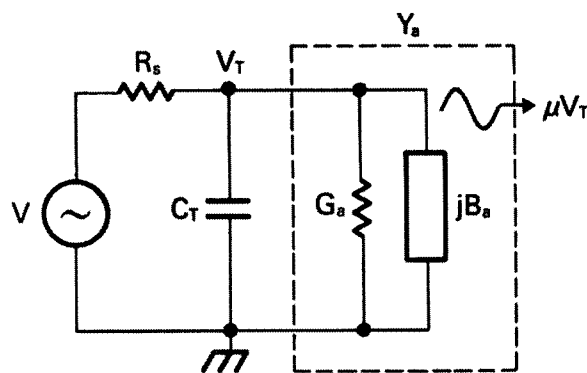


Fig. 3. Circuit Equivalent of a single IDT. [4]

Figure 4 shows the circuit equivalent of the single IDT where  $R_s$  is the source impedance of the signal generator, and the other terms will be developed. The first term that will be explored is the static capacitance represented by  $C_i$ . This capacitance represents the capacitance obtained by the summation of the capacitances between the fingers of the IDT. The analysis done assumes that

the length of the fingers is infinite, and  $N$ , the number of repeat positive electrodes, is large. The result used for the calculation then becomes

$$C_t = WN(\epsilon_0 + \epsilon_p^T)C_t^{\sim} \quad (3)$$

Where  $C_t^{\sim}$  is a numerical constant based on the physical arrangement of positive and ground electrodes, for which in this case, is equal to one. The value of  $(\epsilon_0 + \epsilon_p^T)$  is a material based parameter, and  $W$  denotes the aperture width, or the overlap distance of positive and ground electrodes [4].

The acoustic conductance can be calculate in two parts, similar to the capacitance there is a coefficient used to account for the physical arrangement, however this value is also dependent upon the order of harmonic resonance  $M$ . Overall the acoustic conductance, or the inverse of the ability for the crystal to propagate electrical signals as acoustic wave-fronts, can be written as,

$$G_a(\omega) = G_a(\omega_c)[\sin(X)/X]^2 \quad (4)$$

Where  $X$  is,

$$X = \pi N(\omega - \omega_c)/\omega_c \quad (5)$$

and  $G_a(\omega_c)$  is denoted as,

$$G_a(\omega_c) = M\omega_c(\epsilon_0 + \epsilon_p^T)^2 N^2 W \Gamma_s G_{aM}^{\sim} \quad (6)$$

For the cases used  $M$  will be equal to one, this correlates to a value of 2.871 for  $G_{aM}^{\sim}$ .  $\Gamma_s$  denotes a material constant given by,

$$\Gamma_s = K^2/(\epsilon_0 + \epsilon_p^T) \quad (7)$$

Where  $K^2$  is the piezoelectric coupling coefficient. The final part of the circuit model is the acoustic susceptance. This can be found by taking the Hilbert transform of the acoustic conductance. The result of this analysis is approximately,

$$B_a(\omega) = G_a(\omega_c) (\sin(2X) - 2X) / 2X^2 \quad (8)$$

These values complete the circuit model for a single IDT.

In order to complete the circuit model in a testing situation the ACPW needs to be accounted for in the circuit model. This can be added to the circuit model of a single IDT through the calculation of the characteristic impedance, length, and basic transmission line theory. However, the characteristic impedance of these lines becomes quite complex with the addition of the width of the ground lines. Therefore a simpler analysis with the ground lines being considered infinite is implemented. For the design the ground strips are approximately an order of magnitude wider than the signal line in order to assure this approximation. The input impedance could then be shown to be,

$$Z_o = [30\pi((1+\epsilon_r)/2)^{-1/2}] * K'(k_1)/K(k_1) \quad (15)$$

Where the function  $K$  is the complete elliptical integral of the first kind, and  $k_1$  is comprised of the signal line width and line to ground spacing [2].

With this in place it is possible to design the ACPW to match a 50 ohm resistance, which when tested would not be seen by the network analyzer. When comparing the impedance mismatch of the transmission line it becomes apparent that any change in imaginary impedance is based on the length of the transmission line. In the design space being used the length of these lines is on the order of 100 $\mu$ m. When comparing the relative error introduced it becomes apparent the transmission line is insignificant in the circuit model if the impedance is matched and the length kept relatively short.

Ignoring the ACPW it is possible to calculate  $\rho$ , the inherent mismatch, of the DUT. This can be done using the circuit model of a single IDT. This is justified because the devices are electrically isolated and when modeling the second IDT, an ideal current source can be used which is based on the propagating acoustic wave that is established. Once this is established only the transfer function of the 2 IDT pair needs to be evaluated. In this case the

transfer function is the square root of each acoustic impedance multiplied together. However a phase shift needs to be incorporated based on the distance between the two devices. Then the  $S_{21}$  can be found in the usual manner by finding the function of the power delivered to the load which will be denoted as  $H$ , and is a function of frequency.

$$S_{21} = -20 \log[|H| * |1 + \rho|] \quad (16)$$

This yields the entire response of the fabricated devices to compare to measured data.

## XX. FABRICATION

Fabrication of these devices were done in a limited number of steps in order to minimize any handling of the wafer and

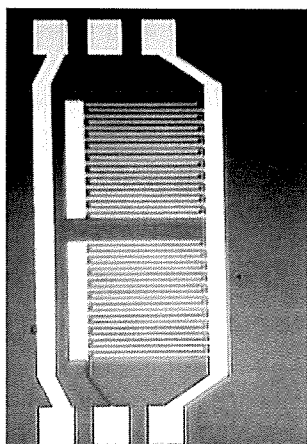


Fig. 4. Fabricated bandpass device with ACPW.

thermal processes. The substrates undergo an aluminum evaporation process yielding approximately  $7000\text{\AA}$ . The wafer then undergoes conventional contact lithography in order to define the IDT and ACPW structures. The metal lines were define by a wet etch process and the resist stripped by an  $O_2$  plasma. The next step is to define the polyimide acoustic absorbers using similar lithography techniques, followed by a slow curing process. However, for this run wafer breakage had accord before the final cure. This completes the entire process for creating the bandpass devices. An example device fully fabricated is shown in figure 4.

## XXI. RESULTS

In order to obtain results the Agilent Technologies E5071C, two port network analyzer is connected to a Cascade Microtech M150 probe station equipped with ground signal ground probe heads. Full two port calibration must occur including, short, open, through, and broadband loads. The measurement technique uses a 10 kHz bandwidth and measurements were taken from 100 to 300 MHz over 1001 points in 4 seconds. It is critical to use a narrow bandwidth and slow transition times in order to obtain accurate results. The  $S_{11}$  of the devices were measured first in order to obtain information about the designed ACPW a sample measurement could be seen in figure 5.

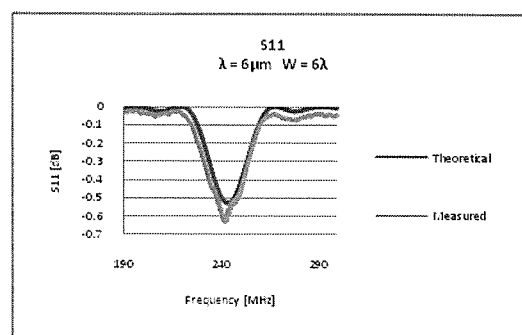


Fig. 5. Measured  $S_{11}$  compared to theoretical calculation.

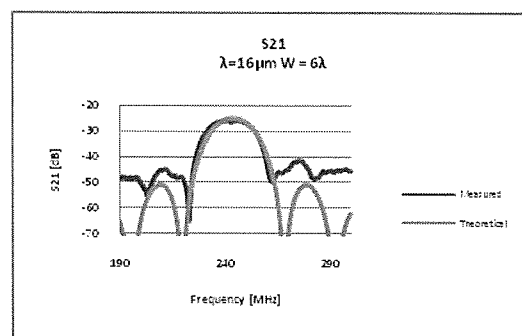


Fig. 6. Measured  $S_{21}$  compared to theoretical calculation.

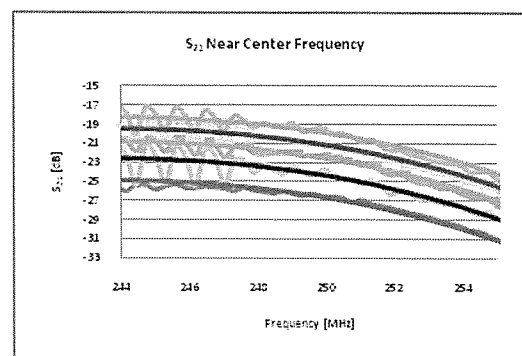


Fig. 7. Measured  $S_{21}$  around center frequency with varying aperture widths.

The  $S_{21}$  can then be measured for each of the devices across a reasonable frequency range. Figure 6 shows the  $S_{21}$  data for the same device in figure 5. Due to the sheer volume of data points and the symmetric nature of the device around the center frequency it becomes useful to plot data near the center frequency to compare different devices. Figure 7 compares the data from similar to devices, with the same metalized pitched, and bandwidth, at different aperture widths.

## XXII. CONCLUSION

The fabricated devices had undergone multiple measurements. The matching of the  $S_{11}$  curves between measured and theoretical shows very close behavior over all devices. The theoretical analysis used did not account for the ACPW used to connect from the network analyzer to the DUT. Any mismatch between the network analyzer's internal resistance and transmission line impedance would result in drastic differences in  $S_{11}$  curves. The modeling and design of the ACPW is accurate and can be safely ignored in the analysis.

The  $S_{21}$  measurements made showed that an intrinsic noise floor is reached at approximately -50dB. Since measurements were made in reference to 0dBm this correlates to approximately 10nW. The noise in the test environment was measured separately and similar results were obtained confirming the noise floor. Therefore evaluation of device performance is done around the center frequencies at data points above noise. The calculated absolute average distance between the theoretical and measured data is 0.523dB. The model used is accurately able to predict device behavior over a large range of frequencies within the first harmonic of the devices operation and can be used for future design.

## ACKNOWLEDGMENT

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Sean M. Dunphy is currently studying at the Rochester Institute of Technology in order to receive an undergraduate degree in microelectronic engineering and a master's degree in electrical engineering.