

SAW Filter

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Submission date: 11-May-2018 11:24AM (UTC+0100)

Submission ID: 88960957

File name: filter-design_3.pdf (392.52K)

Word count: 2827

Character count: 13854



SAW Filter Design

May 11, 2018

Abstract

This report discusses the theory of how SAW (Surface Acoustic Wave) systems work and how they can be used to create a bandpass filter that works above frequencies that conventional passive filters can be used. Not only is theory discussed, but also the methods of manufacture for these devices using lithium niobate.

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1 Introduction

This report is designed around finding out the basic theory of operation of surface acoustic wave(SAW) systems and how to use the theory to design and manufacture devices for specific applications. For example, creating a attenuating bandpass filter with values seen in Table: 1. The objective is to produce a working SAW filter with the specified values and aim to understand how to use the theory to design these systems for any set of values.

2 Theory

A SAW filter makes use of SAWs to transmit electrical data to mechanical data and back again by using a piezoelectric material (a material that outputs electrical voltage when deformed and vice versa). It does this by applying a voltage through a interdigital transducer[4] so that the piezoelectric device deforms and transmits waves along the surface of the device known as Rayleigh waves (named after Lord Rayleigh the discoverer[1]). These Rayleigh waves can then be received in the same fashion as emitting, by converting the mechanical energy into electrical energy. This is possible due to the elastic like properties of the lithium niobate surface. This technology is generally inefficient due to the conversion between different energy systems, the main inefficiency is due to the contact method, as the wires are not impedance matched the majority of the signal is reflected therefore acting as a large resistor. Another negative is that the traveling wave moves along the surface of the device and disrupts atoms underneath the surface and gets lost within the lattice.

The mechanical wave that moves along the surface of the device travels much slower than that of electrons in a conductor and therefore can also create an accurate delay, which can be designed and used in systems such as oscillators. If our system has a required bandpass response we can turn this frequency based wave into a time domain wave (what our signal must look like). This is done by using a fast Fourier transform and means that we can design our transmitter and receiver around this wave. SAWs are more useful than a bulk wave, as a bulk wave propagates throughout the entire structure, meaning oscillations can only be detected at the ends of the device, whereas SAWs can be detected at any point on the surface of the device. Due to this, SAWs are also much easier to manufacture as they just need to be in-line with the crystalline structure and can be designed into the UHF range.[2] There are many different types of finger layouts, but in this report we will only discuss the use of conventional layout. This is shown in Figure 1, where no dummy fingers or double fingers are used with a separation of $\frac{\lambda_0}{2}$.

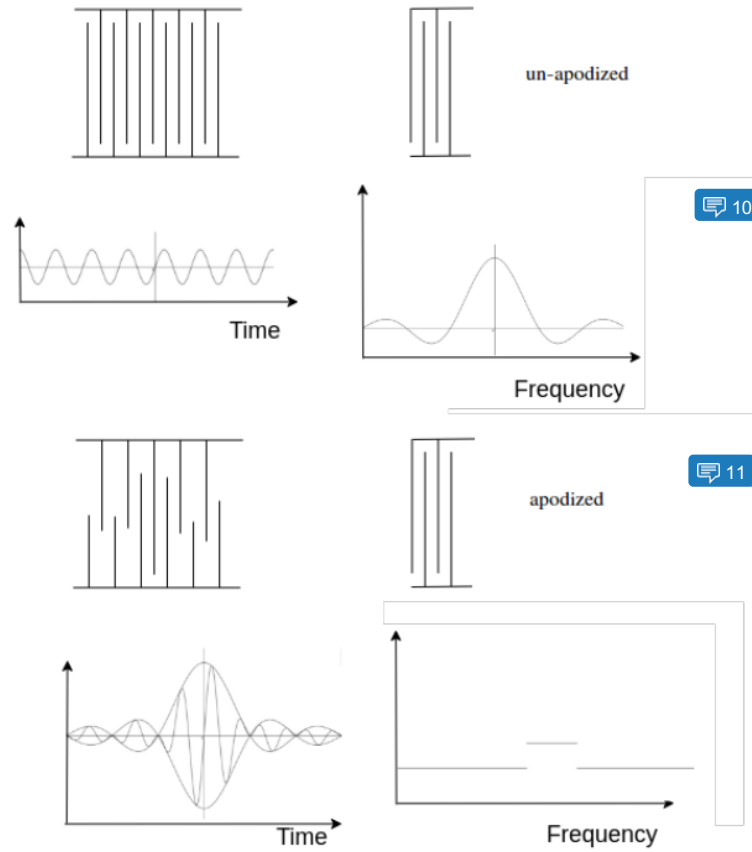


Figure 1: Frequency and time graphs dependent on fingers

3 Design

| Denoter | Value | Definition |
|----------|------------|--|
| L_{rm} | 20mm | Length of Lithium niobate rhombus |
| H_{rm} | 15mm | Height of Lithium niobate rhombus |
| θ | 77° | Angle of Lithium niobate rhombus |
| V_0 | 3495 | Speed of surface wave in Lithium niobate[2][3] |
| f_0 | 25MHz | Center frequency |
| B | 6MHz | Bandwidth |
| P_g | 8mm | Gap between pads for transmitter and reciever |
| P_h | 0.75mm | Pad height for transmitter and reciever |
| R_f | 4 | Number of fingers on the reciever |

Table 1: Saw filter pre-defined values

The lithium niobate sheet is first defined as a rhombic pad length 20mm and height 15mm with a 77° angle. This angle is used so that surface waves that reflect at the end reflect at a different angle, which reduces any noise caused by this reflection. The crystalline structure also breaks easily along that angle. With this our connection pads are 8mm apart and are 0.75mm tall, meaning a total 9.5mm height. Using this and Pythagoras theorem, there is a 15.6mm long rectangle to work in. A value of 2mm was used for error caused by measuring, aligning and most importantly the lip of photoresist from the surface tension in the spinning process. Surface waves travel at a velocity

of $3495mS^{-1}$ [3] and the time delay desired is $2\mu S$ and so using basic SUVAT the distance needed is $7mm$ leaving $6.6mm$ for the transmitter and receiver. The width of each finger can be given by $fingerwidth = \frac{\lambda_0}{4}$. The receiver has a pre-defined value of 4 fingers (2 on each pad) and so the pad must therefore be $P_{rl} = \frac{7*\lambda}{4}$ where $d = \frac{V_0}{f_0} = 139.8\mu m$ meaning our receiver pad $P_{rl} = 245\mu m$ leaving $6.355mm$ for the transmitter.

Now having the transmitter pad length and the periodic finger length the number of fingers on each pad is given by $N = \frac{P_{tl}}{d} = 45$ and with 2 pads means 90 data points needed for the finger length. As the distance is only for one side of the sinc function we can actually fit 180 fingers on the substrate.

Next the shape of the fingers needs to be designed. For a signal input we use we get a frequency response which is quantified by the Fourier transform of the signal. Instead we are given a design for our filters frequency response and so the inverse Fourier transform of this frequency response will give us the needed signal input. We cannot change the signal input but we can change the transmitter design to transmit as we want. If we do the inverse Fourier transform of our square wave we get a sinc function and so our fingers should be designed as the sinc function shown in figure 3. Our system obviously cannot have an infinite finger length and so we must reduce this down to the quantity we can fit onto the substrate, in our case 90, and look at the finger design to be produced onto our mask. As we don't have the exact fingers desired to create our square wave, we can use a Fourier transform of our actual fingers to see what the actual frequency response will look like shown in figure 5

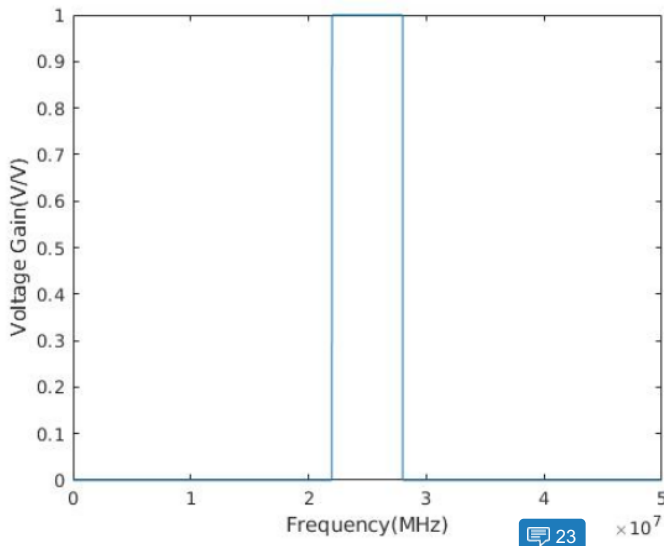


Figure 2: Desired output

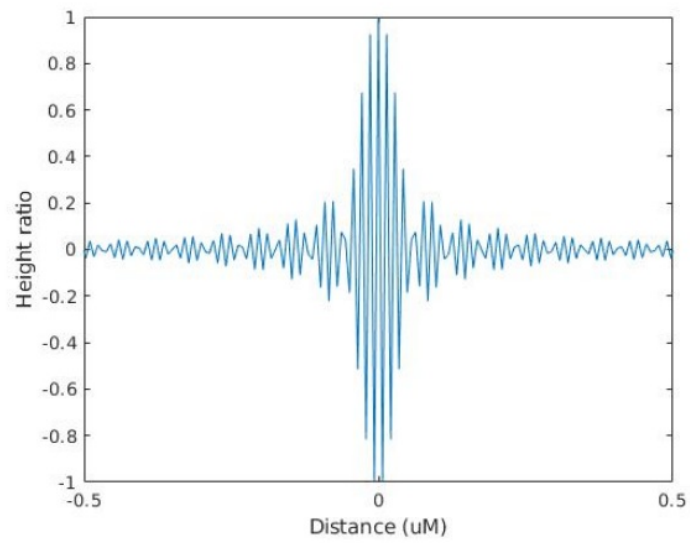


Figure 3: Desired fingers

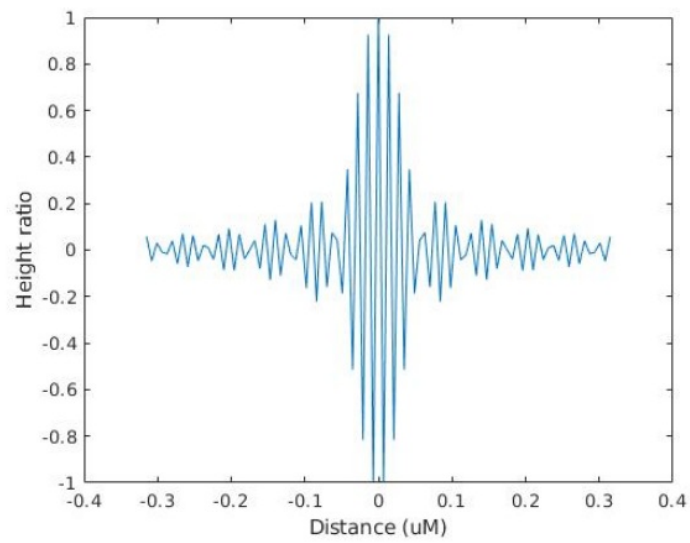


Figure 4: Actual fingers

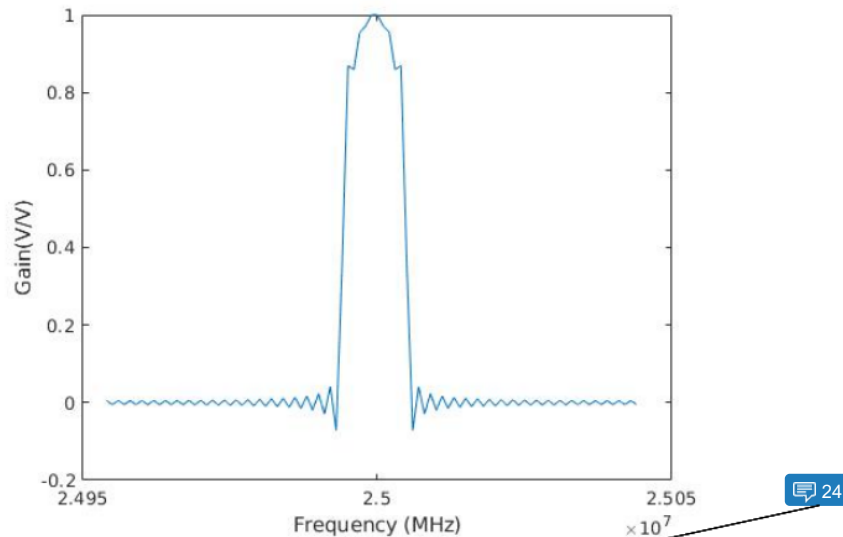


Figure 5: Expected output

Using the values from Figure: 6 we can work out a percentage for each finger height which can then be used to calculate the height of the fingers to be designed. These percentages are then multiplied by 7.5mm to leave a 5mm gap so the fingers don't short the pads.

4 Design

4.1 Mask

Once the design is made in KLayout it is ready to be used. The blank mask is bought from a supplier, but can be made easily by depositing a thin layer of chromium on a sheet of glass by boiling a rod of chromium in a vacuum. This is done at a height above the sheet of glass creating an chromium mist, which lines the whole system and sheet of glass to about a thickness of $1\mu\text{m}$ depending on distance and quantity of chromium evaporated. This is then spun at a high speed with a few drops of photoresist to create a thin layer preferably completely flat. Unfortunately an edge bead usually occurs from the surface tension of the photoresist, which can cause an issue when curing. This mask is then loaded into the mask writer dull side up (it is dull as the chromium oxidizes when in contact with the air before the photoresist is applied). The mask writer then uses a precise ultraviolet laser to cure the photoresist everywhere except where the design specifies. This mask is now ready to be etched using the specific developer that we used (in our case AZ), which removes any photoresist that has been weakened by the ultraviolet light. The mask now has chrome everywhere but is covered by photoresist in the area where our mask was printed (by not being exposed to ultraviolet). The mask is then placed in chromium etchant which will attack any chromium which is exposed. If under etched the chromium won't have been completely removed. However, if over etched the chromium underneath the photoresist may start to be removed as the sides are exposed when the connecting chromium is removed. The mask now has glass everywhere except for our design which is covered with chromium and photoresist on-top. This would work but the chromium isn't as reflective as we would like and the photoresist may diverge any light when we use our mask, therefore we use acetone to remove the remaining photoresist on the mask. The acetone dries quickly when exposed to air and will leave drying stains on the surface of our mask which will create undesired effects. To remove these, a quick exposure to IPA (Isopropyl Alcohol) should re-hydrate these stains and then give us time to remove the IPA using filtered pressurized nitrogen to blow the liquid off. Now the mask should be completely glass except for the area where the pattern is written where a very thin layer of chromium should exist to reflect the light when writing using the mask. The mask is now ready to be used in the production of substrate.

4.2 Substrate

Like the mask, our substrate is first off created by depositing a thin layer onto the surface of the device using evaporation, in this case we use aluminum instead of chromium. The substrate then has the photoresist added using the same method as before - it is important to add the photoresist as soon as possible after depositing the aluminium to reduce the effects of aluminum oxide being formed. The substrate is then aligned with the pre-made mask in the mask aligner making sure that the design and substrate are perfectly perpendicular, ignoring the edge bead formed on the substrate. After being aligned the mask and substrate should then be brought together to touch and cured using a general area UV light and developed using the corresponding developer. The aluminium is removed using an aluminium etchant, meaning the photoresist protects the aluminium underneath leaving that untouched. The photoresist and drying stains are then removed using the same process as that of the mask, leaving the lithium niobate with aluminium fingers, pads and nothing else. With the substrate, wire bonds are added using a silver paste to create a connection which later dries. These wires are then joined to BNC connectors inside of a metal box to protect the substrate from interference. Unfortunately there wire bonds are not impedance matched to the system meaning huge proportions of the signal is reflected.

5 Results and Discussion

With the substrate made deviations from the ideal can be spotted, such as the height of aluminum which isn't as small as possible but more avoidable things like dirt between fingers and in the delay zone can cause disruptions and error. More noticeably, fingers can be over-etched and broken off which appeared commonly on one side of the substrate and not so much on the other including one leg on the receiver side, this over etching also leads to line edge roughness which is where fingers borders are not straight and can allow noise to pass through the system and have a non ideal response. It can be noticed that a large particulate of dirt can be seen in the delay region

the substrate, which may effect the response. The frequency response of the substrate can be seen in Figure: 6 and Figure: 7. The center frequency is almost exactly where we designed it to be at 25Meg, with the edges at 28Meg and 22Meg . One edge of the bandpass is much more regimented than the other which is most likely due to more fingers being broken on one side of the substrate than the other. One thing that sticks out is the spike at around 14Meg which isn't a part of the design. Either sections of the device (the SAW filter or the bonding/wiring methods) have a resonant point around there causing the spike, or more likely some of the broken fingers caused a sub response, therefore acting like two separate saw filters

Using this actual frequency response, we can get the effective fingers by inverse Fourier transforming the gain(V/V) ($Gain(dB) = 20Log(\frac{V_o}{V_i})$), plotting this gives Figure: 9. This graph shows the general sinc shape that we designed with the maxima at the center. This shows the central peak fingers by far have the biggest effect and shortly after this the fingers get negligibly small in comparison to the noise ratio. This is good news for creating small packages, but bad news if we need very accurate filters as after a few cycles of the sinc function these fingers have next to no effect on the frequency response. In figure 8 we can see the delay of the signal given a frequency. Our system was designed to reflect all frequencies except that of our bandpass randomly around the substrate

by bouncing off the edges at non logical angles, this means for all other frequencies except that of our bandpass should have a random delay response, which we can see is random but around the 0 point. Instantly it is possible to see the area where our delay is accurate and is designed to be $2\mu S$ which is almost dead on our design criteria. Strangely we see this anomaly again around the 14Meg point, except this time it is peaking negatively showing a negative delay which may be a dependency of output to input instead of vice versa. The other noticeable feature of Figure: 8 is the drop off response at the right hand side of the bandpass response, this is most likely an issue with some fingers being broken off, causing issues or a singular frequency being blocked due to the large dirt spot in the middle of the delay region.

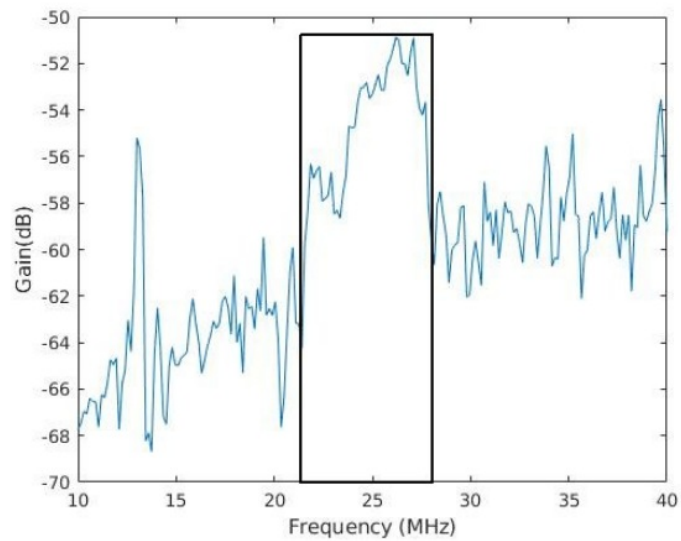


Figure 6: Frequency response of S12

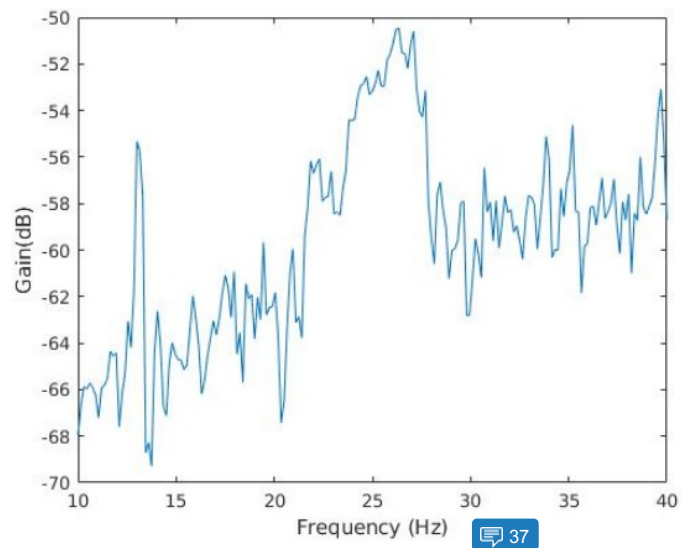


Figure 7: Frequency response of S21

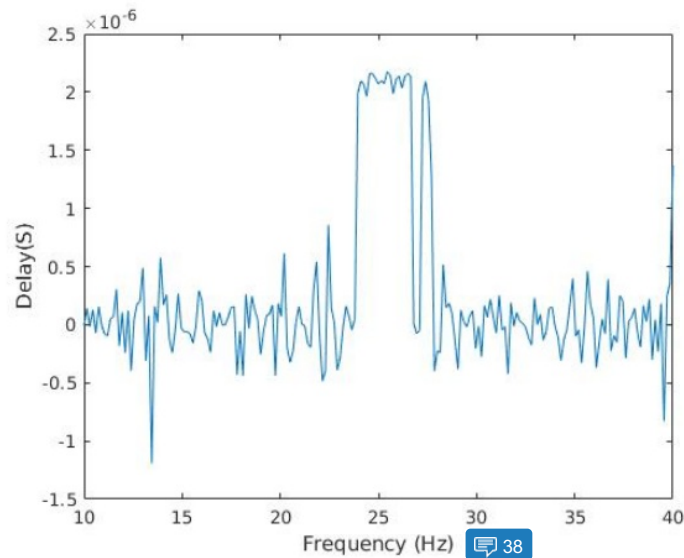


Figure 8: Delay of signal across different frequencies

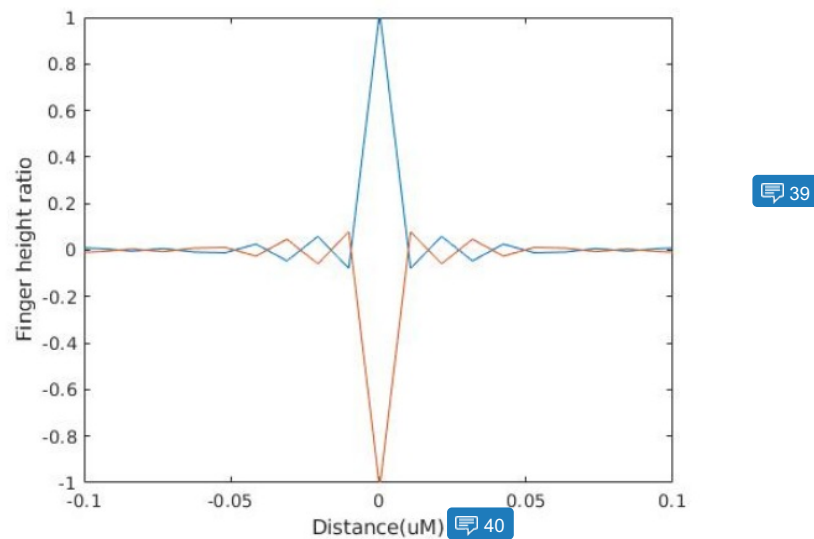


Figure 9: Inverse Fourier of actual filter response (effective finger design)

6 Conclusion

Generally the SAW filter designed worked as expected, despite issues during manufacture. The main point is that devices that are to be made have been made remarkably sterile by using a cleanroom. Even with a cleanroom, this doesn't mean the substrate will work, as micron perfect design is also required to keep the fingers in the perfect location to get the correct response and actually connect the fingers. If the system is designed as expected, these can be produced on a mass scale cheaply and using a small amount of materials where the filter can be re-designed easily to meet

42

different specs and just requires a new mask writing. These filters can have very steep edges when designed correctly, meaning they can be very accurate. All of these advantages make the system good for small high frequency devices, such as mobile phones. Unfortunately, SAWs can change response based on the temperature of the device and can be very lossy, even during the pass region especially if non impedance matched. These systems can be used in all kinds of filters other than transversal filters that are described here, such as unidirectional IDT, resonant and nyquist filters [5]. These systems could also be implemented in voltage controlled oscillators and signal mixers. These systems are widely used throughout the world and will continue to be used given their advantages.

7 References

- [1]L. Rayleigh, "On Waves Propagated along the Plane Surface of an Elastic Solid", Proceedings of the London Mathematical Society, vol. 1-17, no. 1, pp. 4-11, 1885.
- [2]C. Hartmann, D. Bell and R. Rosenfeld, "Impulse Model Design of Acoustic Surface-Wave Filters", IEEE Transactions on Microwave Theory and Techniques, vol. 21, no. 4, pp. 162-175, 1973.
- [3]J. Maines and E. Paige, "Surface-acoustic-wave components, devices and applications", Proceedings of the Institution of Electrical Engineers, vol. 120, no. 10, p. 1078, 1973.
- [4]J. MENDES, M. FERNANDES, D. MUKHERJEE and D. SANTOS, "Simulation of acoustic wave devices using Matlab", Przegląd Elektrotechniczny, pp. 155-158, 2012.
- [5]T. Trzcinski, "Surface Acoustic Wave (SAW) filter technology", Telecommunication Electronics Mini-project, Torino, Oct. 29, 2008, pp. 1-8.

FINAL GRADE

60/100

GENERAL COMMENTS

Instructor

In-lab (0-20% of design exercise mark) = 20

Presentation (0-20%) = 15

Report (marked out of 100%)

1 Introduction (/5) = 2

2 Theory (/10) = 7

3 Design (/10) = 6

4 Fabrication (/10) = 8

5 Test (/10) = 0

6 Results (/10) = 9

7 Discussion (/30) = 25

8 Conclusions (/5) = 2

9 Presentation style (/10) = 8

Report total (/100) = 67

Report total (scaled to /60) = 40

Total* (/80) = 60

* remaining 20% from Presentation, recorded elsewhere.

Lots of lazy errors cost you marks.

Could have been better structured

PAGE 1



Comment 1

and Fab and Test!

PAGE 2



Comment 2

I know you reference a later Table, but you should have specified f_0 and df here.

You should have also included a suitable general reference and mentioned some of the other applications of SAW devices.



Comment 3

references should appear be in numerical order



Comment 4

all surfaces are elastic but not all materials exhibit piezo.



Comment 5

dissipated



Comment 6

quantify!



Comment 7

inverse



Comment 8

Nice point!



Comment 9

You need to define λ_0



Comment 10

Diagrams show very thin fingers!



Comment 11

Units of y-axis not given :(



Comment 12

Nicely drawn but if you make it this complicated then you needs more comprehensive description in text.



Comment 13

y cut



Comment 14

units?!



Comment 15

for what?



Comment 16

?



Comment 17

S = Siemens

s = seconds



Comment 18

why a sinc?

not explained :(



Comment 19

all the fingers are the same shape (rectangle), but they have different *length*



Comment 20

Ah ha, at last!

this should have been earlier



Comment 21

Leave it the the reader to decide if it's obvious!



Comment 22

did you fft the actual fingers of the sinc profile? not the same thing!



Comment 23

10^7 MHz?!

PAGE 5

PAGE 6



Comment 24

title needs to be more descriptive



Comment 25

wrong figure



Comment 26

Fabration

Strikethrough.



Comment 28

first mention!

how did data get in/out of the program?



Comment 29

nicely done, but much more detail than necessary



Comment 30

You have failed to describe the test method :(



Comment 31

do you mean thickness?

quantify!



Comment 32

MHz



Comment 33

nicely argued



Comment 34

this should be fig 8



Comment 35

not very scientific :(

instead you should have attempted to quantify the errors



Comment 36

did you consider combining fig 6&7?



Comment 37

MHz



Comment 38

MHz!



Comment 39

why 2 colours?

why 2 circles.



Comment 40

m not M!



Comment 41

quantify!

PAGE 10



Comment 42

this should have been in Intro!

SCOPE HW (8%)

0 / 5

EXCELLENT

(5)

GOOD

(4)

REASONABLE

(3)

ACCEPTABLE

(2)

POOR

(1)

NO SUBMISSION

(0)

QUALITY HW (12%)

0 / 5

EXCELLENT

(5)

GOOD

(4)

REASONABLE

(3)

ACCEPTABLE

(2)

POOR

(1)

NO SUBMISSION

(0)

CALCS HW (10%)

0 / 5

EXCELLENT

(5)

GOOD

(4)

REASONABLE

(3)

ACCEPTABLE
(2)

POOR
(1)

NO SUBMISSION
(0)

NOTATION SW (10%)

0 / 5

EXCELLENT
(5)

GOOD
(4)

REASONABLE
(3)

ACCEPTABLE
(2)

POOR
(1)

NO SUBMISSION
(0)

SCOPE SW (10%)

0 / 5

EXCELLENT
(5)

GOOD
(4)

REASONABLE
(3)

ACCEPTABLE
(2)

POOR
(1)

NO SUBMISSION
(0)

ACCURACY SW (15%)

0 / 5

EXCELLENT

(5)

GOOD

(4)

REASONABLE

(3)

ACCEPTABLE

(2)

POOR

(1)

NO SUBMISSION

(0)

RESULTS (5%)

0 / 5

EXCELLENT

(5)

GOOD

(4)

REASONABLE

(3)

ACCEPTABLE

(2)

POOR

(1)

NO SUBMISSION

(0)

APPEARANCE (6%)

0 / 5

EXCELLENT

(5)

GOOD

(4)

REASONABLE

(3)

ACCEPTABLE

(2)

POOR

(1)

NO SUBMISSION
(0)

ERRORS (6%)

0 / 5

EXCELLENT
(5)

GOOD
(4)

REASONABLE
(3)

ACCEPTABLE
(2)

POOR
(1)

NO SUBMISSION
(0)

DIAGRAMS (3%)

0 / 5

EXCELLENT
(5)

GOOD
(4)

REASONABLE
(3)

ACCEPTABLE
(2)

POOR
(1)

NO SUBMISSION
(0)

INTERPRET (10%)

0 / 5

EXCELLENT
(5)

GOOD
(4)

REASONABLE

(3)

ACCEPTABLE

(2)

POOR

(1)

NO SUBMISSION

(0)

RECOMM. (5%)

0 / 5

EXCELLENT

(5)

GOOD

(4)

REASONABLE

(3)

ACCEPTABLE

(2)

POOR

(1)

NO SUBMISSION

(0)