SAW Filter Design

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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 $\frac{\lambda_0}{2}$.

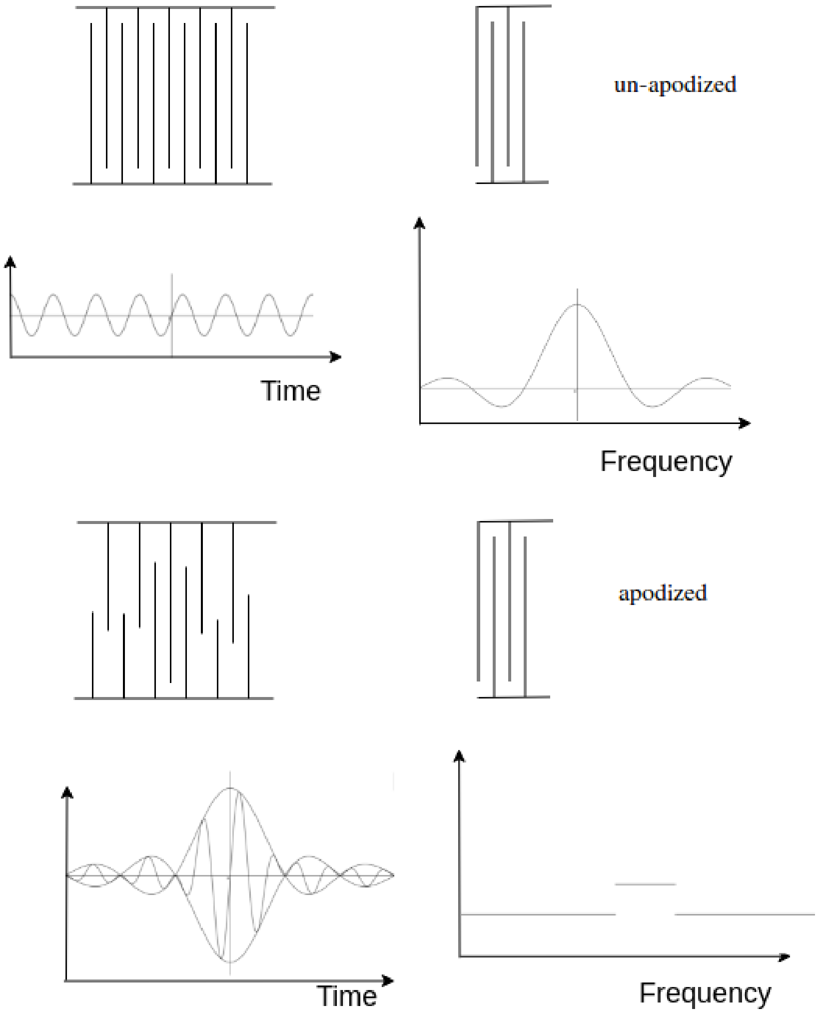

Figure 1: Frequency and time graphs dependent on fingers

3 Design

Denoter	Value	Definition
L_{rm}	20mm	Length of Lithium niobate rhombus
H_{rm}	15mm	Height of Lithium niobate rhombus
θ_{rm}	77^o	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^o 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 reciever 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 reciever 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

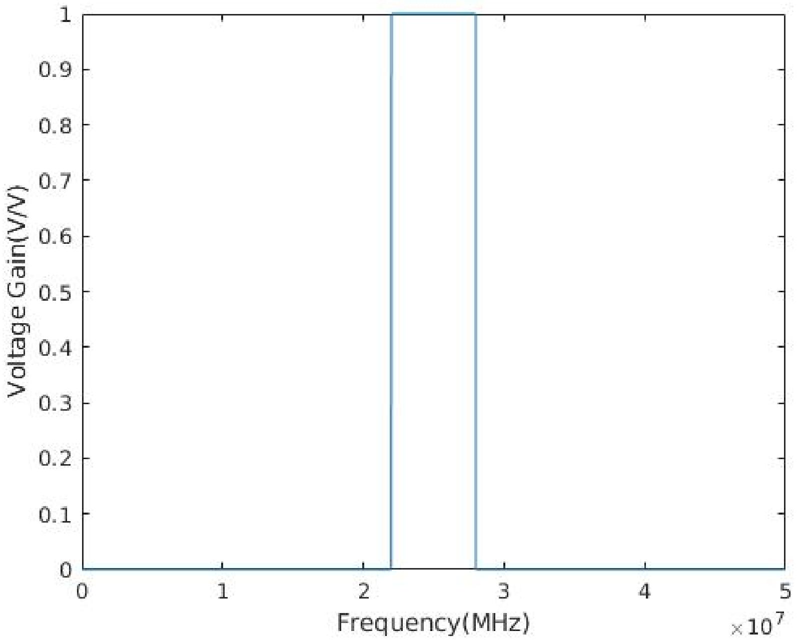

Figure 2: Desired output

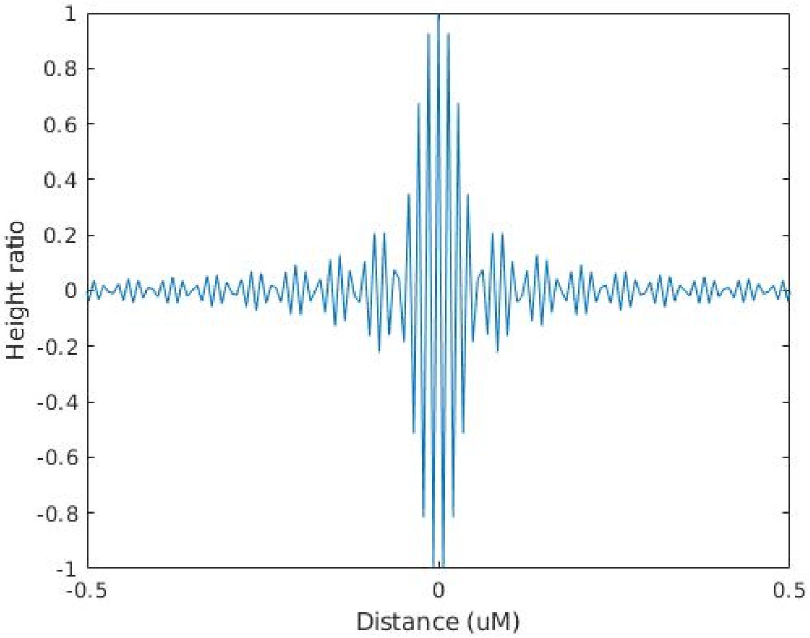

Figure 3: Desired fingers

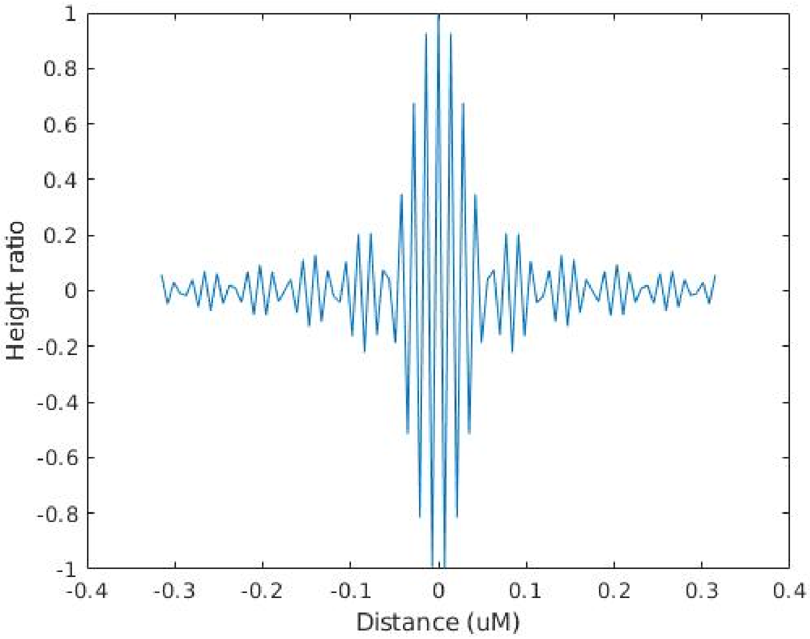

Figure 4: Actual fingers

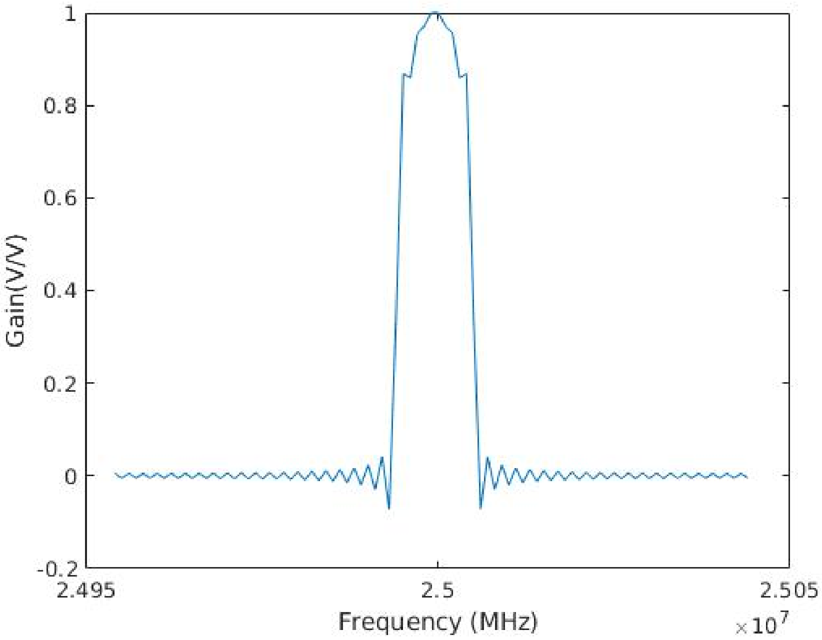

Figure 5: Expected output

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 $1\mu m$ 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 of 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.

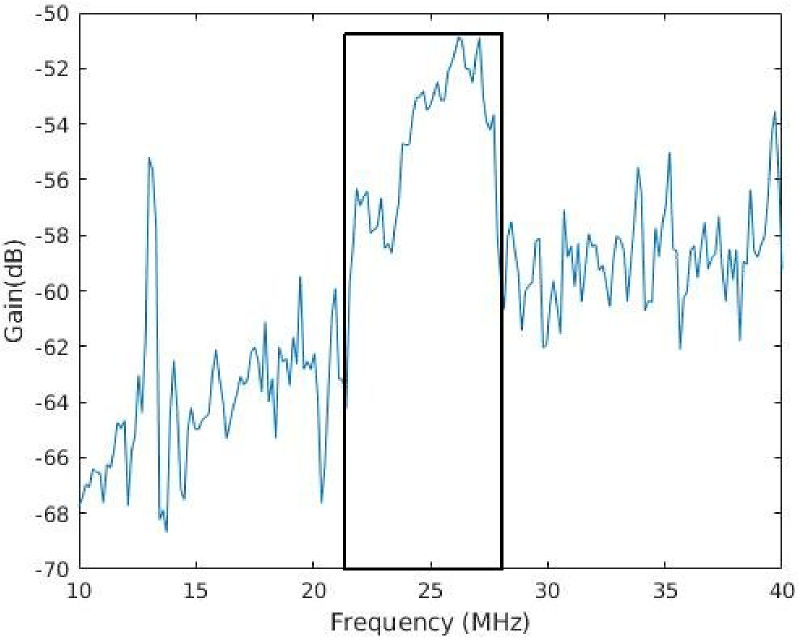

Figure 6: Frequency response of S12

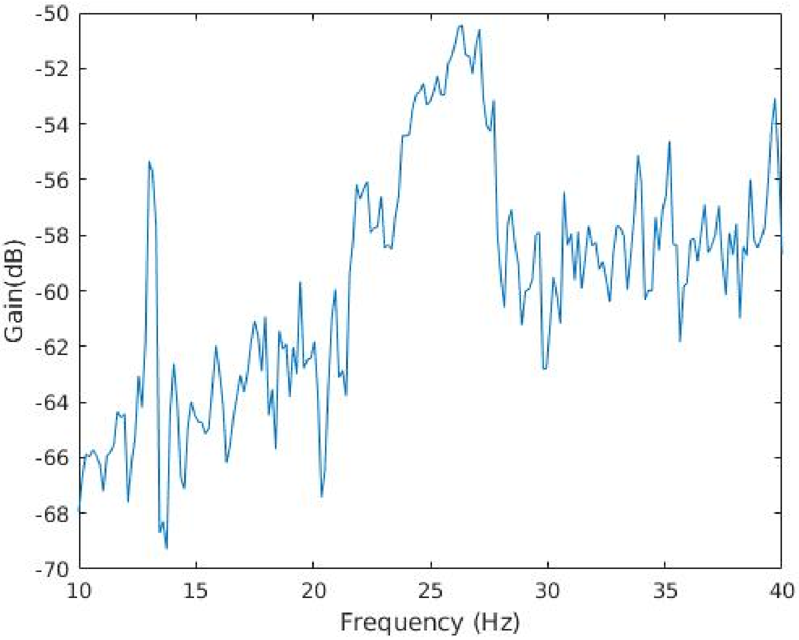

Figure 7: Frequency response of S21

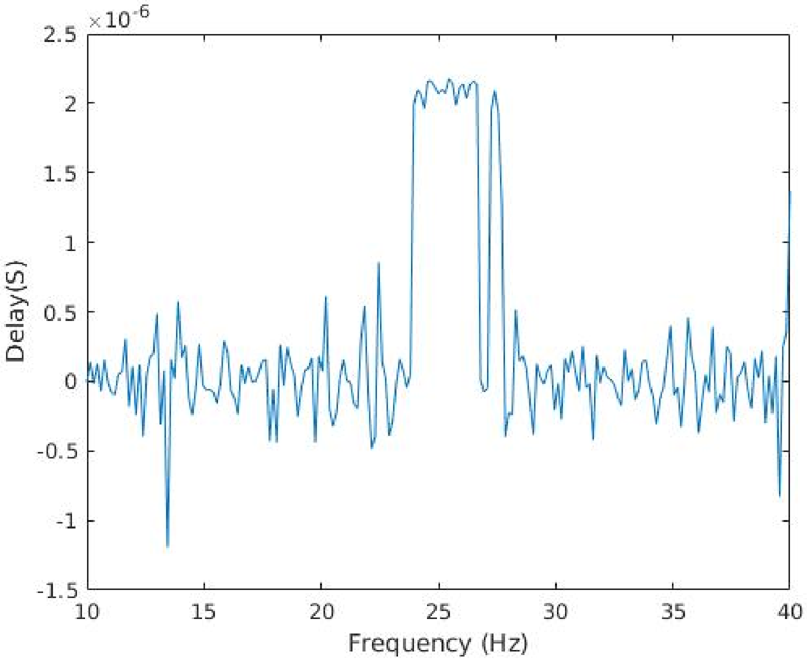

Figure 8: Delay of signal across different frequencies

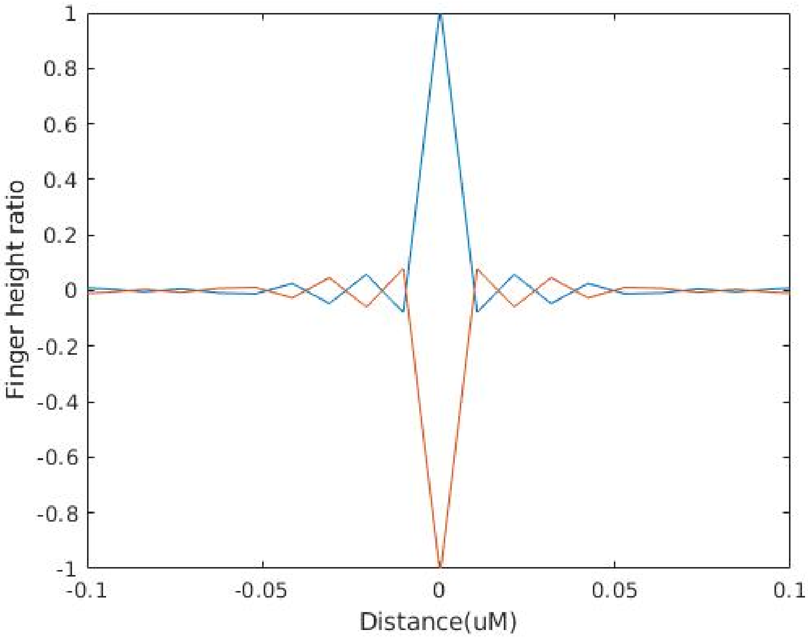

Figure 9: Inverse Fourier of actual filter response (effective finger design)

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 be 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 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

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