Reducing Anchor Loss in AlN Contour Mode Resonators

NSF Summer Undergraduate Fellowship in Sensor Technologies
Noah Tovares (Physics) – Occidental College
Advisor: Gianluca Piazza

Abstract

Many researchers have devoted money and effort toward developing of MEMS resonators. Much of this effort has been devoted to increasing the quality factor, a measure of the energy lost by the resonator.

Fabricating new resonators for testing is costly and time consuming. Methods for accurately simulating the quality factor of MEMS resonators would increase development efficiency.

By design, the resonator body is attached to the substrate via tethers. Due to the immense size of the substrate with respect to the resonator, any energy traveling from the resonator to the substrate is lost. In order to accurately simulate the resonator it is necessary to have a semi-infinite domain that behaves like the substrate.

The perfectly matched layer (PML) feature of COMSOL FEM software serves as an artificial medium: surrounding the smaller simulation-substrate and absorbing any radiation escaping from the resonator. Before resonator designs can be simulated, though, it must be confirmed that the PML does not affect the quality factor or resonant frequency of the resonator.

In order to determine the conditions for accurate simulations a resonator is modeled in COMSOL and simulations are performed while varying the PML width, maximum mesh element size in the PML sub-domain, substrate size, maximum mesh element size in the substrate sub-domain, and tether location. The quality factor is determined by calculating the admittance and using 3dB bandwidth.

The predicted results are that the quality factor will decrease with mesh density and will converge around 5-micron mesh size.

These results will allow accurate simulation of tether designs meant to reduce anchor loss, the biggest problem facing the development of MEMS resonators.

1. Introduction

Microscale devices have become a major trend in the consumer electronics market. In order for devices to become smaller, though, their components must also become smaller and more integrated. This has propelled many researchers to focus their efforts on developing microelectromechanical systems (MEMS). MEMS can be used, for example, to make mechanical switches, resonators, accelerometers, and sensors. Their compact size leads to many advantages such as system-on-a-chip (SoC) and power efficiency. These advantages are especially important when dealing with MEMS resonators for RF filters applications.

MEMS resonators for RF filters applications are implemented as band pass filters, and allow signals of selected frequencies to be transmitted and received. Recently a novel type of RF MEMS filter has emerged with many advantages over competing technologies. This paper focuses on the aluminum nitride (AlN) piezoelectric contour-mode (CM) MEMS resonators [1] for RF filter applications introduced by Piazza in his paper, Piezoelectric Aluminum Nitride Vibrating Contour-Mode MEMS Resonators.

The AlN CM resonator consists of an AlN film sandwiched between metal fingers. This geometry utilizes the lateral piezoelectric coefficient (d_{31}) to generate a horizontal displacement when an electric field is applied in the vertical direction. The resonant frequency is determined by the width of each finger, allowing for an array of resonators each with a different resonant frequency on one chip. In a world where mobile phones require at least four modes of wireless communication, an all-inclusive on chip solutions is very appealing.

Before AlN CM MEMS Resonators can be implemented, though, a few hurdles must be overcome, the most pressing of which is the improvement of the quality factor: a measure of the energy lost by the resonator. There are several mechanisms that can be responsible for the energy loss. Amongst them, the most important are air damping, thermo-elastic dissipation, material loss, phonon-phonon interactions, and anchor loss. Anchor loss, the escape of energy via the tether, is likely to be the dominant energy loss mechanism [2] in AlN CM resonators.

This paper examines the reduction of anchor loss in AlN CM resonators by simulating novel designs in COMSOL® finite element method (FEM) software and analyzing the quality factor and frequency response of the resonator. A significant portion of this work will be devoted to the determining the how COMSOL's parameters affect the simulations of the resonators.

2. Background

2.1 Piezoelectric MEMS Resonators for RF filter applications

Piezoelectricity, discovered in the 1880's by the Curie brothers, describes the behavior of crystals belonging to certain classes. Piezoelectric materials have the unique property whereby mechanical strain in the crystals induces electric polarization. Conversely, piezoelectric materials exposed to an electric field will be subject to mechanical strain.

Piezoelectric MEMS resonators for RF filter applications are implemented as band pass filters to allow signals of selected frequencies to be transmitted and received. These devices work by exploiting the reverse piezoelectric effect. The MEMS resonator is designed to resonate at a certain resonant frequency and have a certain impedance by properly dimensioning its geometrical parameters. When the resonator is exposed to a signal at the resonant frequency it amplifies its vibrations [5]. These vibrations induce the reverse piezoelectric effect and an electric potential arises across the piezoelectric material. The electrodes placed on the resonators are subject to the induced electric potential, allowing the routing of the signal to the external circuitries.

2.2 AlN Contour-Mode MEMS Resonators

The AlN vibrating Contour-Mode MEMS resonators introduced by Piazza *et al.* have great potential to become a widely implemented technology [1]. The PMANS lab at the University of Pennsylvania, under the direction of Professor Gianluca Piazza, has done much work developing AlN vibrating Contour-Mode resonators [9]. This sections outlines the previous work done by Piazza.

2.2.1 Introduction

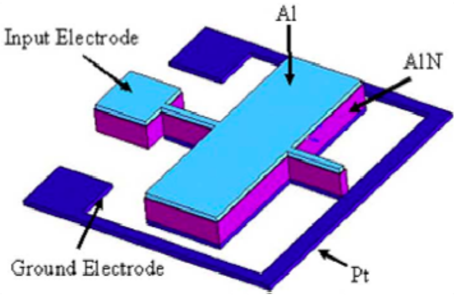

Figure 1 – Rectangular AlN Resonator with Al and Pt Electrodes

The current designs being tested are rectangular plate and ring (circular and square) resonators. A Pt electrode on bottom and an Al electrode on top surround the resonator's AlN body [1]. The physical dimensions (lateral features) of the resonator determine the resonant frequency. For further analysis Piazza *et al.* derived the equivalent electromechanical parameters.

2.2.2 Frequency Settings

While the in-plane dimensions have the greatest effect on the resonant frequency electrode thickness, sidewall angle, and anchor size also have an effect. When high-density materials are being used the electrode thickness becomes an issue, lowering the resonant frequency significantly. The effect of sidewall angle becomes significant when the difference between the size of the top and bottom portions of the resonators are on the order of one wavelength of the resonant frequency. The effect of temperature is considered negligible in AlN resonators.

2.2.3 Experimental Results

The quality factors of the rectangular and ring resonators were calculated by dividing the center frequency by the 3dB bandwidth. For rectangular plate resonators [1] it was found that an aspect ratio of 4:1 resulted in higher quality factors. This previous work also obtained Q's between 2000 and 3000 for the rectangular resonators at standard temperature and pressure (STP). For ring resonators notched supports were introduced in several structures in an attempt to reduce anchor interference, but were found to have little effect on the quality factor. The highest Q of 2900 was recorded for a circular ring resonator at 472.7 MHz.

2.2.4 Quality Factor

The quality factor is defined by the equation

$$Q = \frac{2\pi \cdot \mathrm{EnergyStoredPerCycle}}{\mathrm{EnergyLostPerCycle}} \quad (3)$$

In order to maximize the quality factor energy loss must be minimized. Air damping, thermo-elastic dissipation, phonon-phonon interactions, material loss, and anchor loss have all been identified as energy loss mechanisms [2]. Piazza examined these mechanisms and determined that anchor size, material losses in the electrodes, and trapping energy in the resonators were worth investigating.

2.3 Anchor Loss

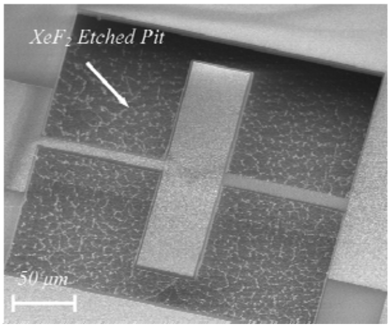

Figure 2 – SEM of AlN Rectangular Resonator [1]

Anchor loss describes the escape of energy from the resonator to the substrate through the anchor. Because there is no acoustic mismatch between the resonator body and the substrate, acoustic waves that travel to the substrate via the tether are considered lost energy. In order to improve the quality factor of the resonators this energy must not be allowed to go into the substrate. This paper describes some of the current methods being tested in the PMANS lab as an effort to reduce anchor loss.

2.4 COMSOL Finite Element Method and Perfectly Matched Layers

COMSOL (Finite Element Method) software was utilized to perform the simulations in the following sections. The AlN CM resonator was modeled and studied using the piezo-solid model. In order to more accurately simulate the energy lost via the tether a perfectly matched layer (PML) is employed. The PML, in the solid stress-strain module, serves as an artificial medium designed to absorb all incoming radiation. The main goal of these simulations is to explore PML parameters and determine how each of them affects the quality factor of the resonator under test.

3. Novel Designs for Reducing Anchor Loss in AlN Contour-Mode Resonators

The tether has been identified as the conduit through which the majority of energy escapes from the resonator. Knowing this, several parameters were investigated in order to explore whether the design of the tether can be manipulated in order to minimize energy loss. First, the width of the tether is fixed and the length is varied. Next, the length is fixed and the width is varied. Lastly, both the length and width are fixed and “branching” is explored. Tethers with one and two branches are explored. Figures 3 through 5 show the different branch models.

Figure 3 – Single tether design

Figure 4 – Single branch design

Figure 5 – Double branch design

These designs, being investigated by Songbin Gong [8], utilize transmission line modeling and impedance matching to maximize the wave reflection and minimize energy loss.

When the tethers are thin enough their behavior can be compared to that of a transmission line. A transmission line is a medium that directs the flow of energy. The transmission line model allows for the use of impedance matching.

Impedance, a term most commonly used when discussing electronics, is often thought of as the AC equivalent of resistance. When designing electronics it is essential to match impedances in order to maximize the transfer of power between components and minimize the reflections from the source. In the case of our MEMS resonators, though, it is ideal to minimize the transfer of power between the tether and the substrate and maximize the reflection from the source. This is accomplished by creating a mismatch between the impedances of the body, tether, and substrate. For our purposes, the parameter that affects the impedance is the cross-section area of the tether.

$$Z = A\sqrt{E\rho} \quad (4)$$

Equation 4 says that Z, the impedance, is equal to the cross-sectional area of the wire multiplied by the square root of the product of the wire’s young’s modulus and density.

Figure 6 shows a stepped transmission line. In this model there are three segments that each have an impedance mismatch with the segment(s) next to it.

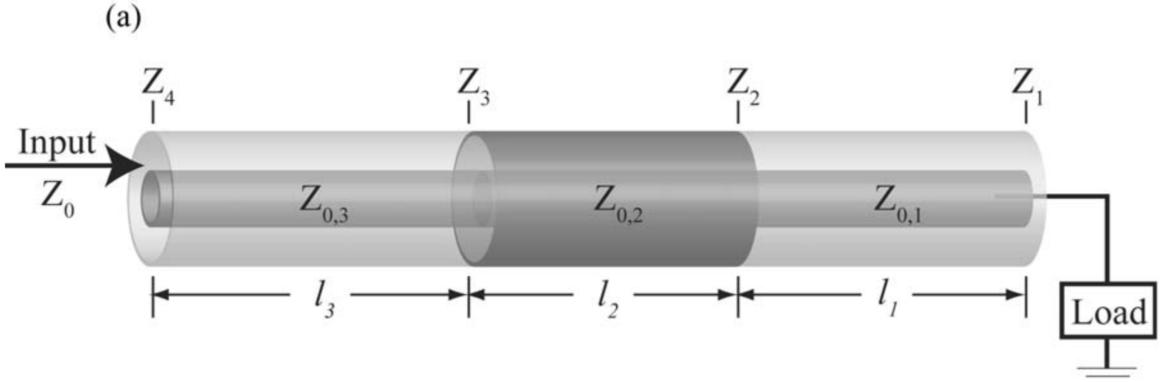

Figure 6 – Stepped transmission line

4. Methods

The use of COMSOL’s PML feature is essential to the accurate simulation of resonators. When testing actual resonators, any energy that escapes through the tether into the silicon substrate is considered lost. The silicon substrate is so large in comparison to the resonators that it is essentially an infinite domain. When simulating resonator results, though, it is impossible to have an infinite domain. When used with the correct parameters, the PML acts as an infinite domain: fully absorbing radiation from any angle.

In order to determine the ideal situation for the simulations several parameters will be investigated. The effect of the PML mesh-density, substrate mesh-density, PML size, substrate size, and tether location on the quality factor is yet unknown.

The base model used for these simulations is a three finger inter-digitated resonator with finger widths of 20 microns. The width of the fingers determines the wavelength to be 40 microns. The tether width and height are 2 microns and the length is 10 microns. The silicon substrate is a 40 micronx40micronx40micron cube, surrounded on 4 sides by the PML of 20 micron width. The PML used in these simulations utilizes a Cartesian coordinate system. The model uses planar symmetry in order to reduce the number of mesh elements. Once the simulation is completed, the admittance is calculated using equation 5 and the quality factor is determined by utilizing the 3dB bandwidth.

$$20 * \log 10(abs(I / V)) \quad (5)$$

The following sections outline the various parameters being investigated.

5. Methods and Results

After each simulation was performed the data was exported in a text file and imported into Origin. The resonant frequency was determined and the quality factor calculated by using the 3db bandwidth. Graphs were made of the frequency response and quality factor.

5.1 PML Width Simulations

PML width is varied between 5 and 40 microns, while all other parameters kept constant. Maximum mesh element size is kept constant at 10 microns. This set of simulations was performed once for a tether width of 2 micron and once for a tether width of 5 micron.

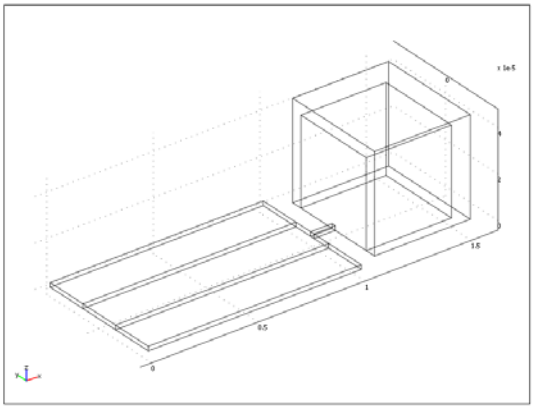

Figure 7 – PML Width of 5 Micron

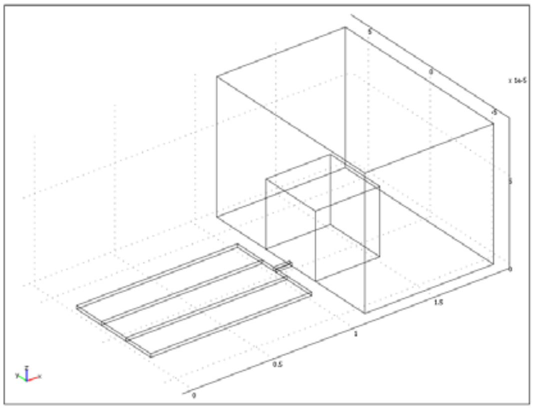

Figure 8 – PML Width of 40 Micron

5.1.1 PML Width Simulation Results (5 Micron Tether width)

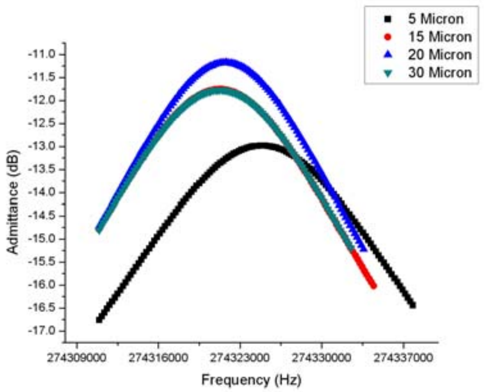

Figure 9 – Frequency Response for various PML widths

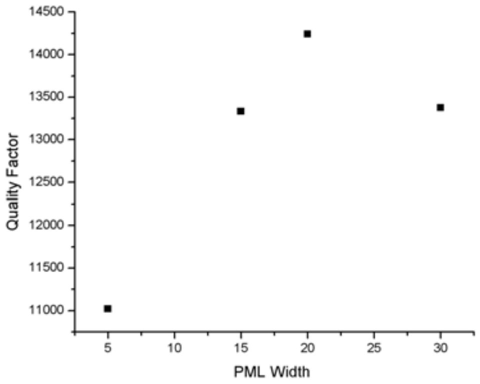

Figure 10 – Quality Factor vs. PML width

Figure 9 shows the frequency response of the resonators as the PML width is varied. The quality factor does not seem to depend on the PML width. The average quality factor is 12991.1 with a standard deviation of 1379.9.

5.1.2 PML Width Simulation Results (2 Micron Tether Width)

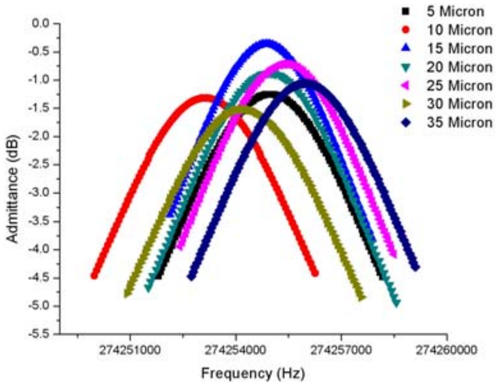

Figure 11 – Frequency Response for various PML Mesh Densities

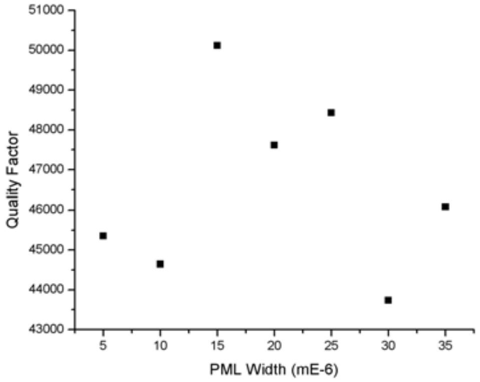

Figure 12 – Quality Factor vs. PML width

The previous simulations were repeated with a tether width of 2 microns. The average quality factor was 46563.2 with a standard deviation of 2260.9. The quality factor is affected little by the PML width.

5.2 PML Sub-domain Mesh Density Simulations

The only parameter being changed is the maximum mesh element size in the PML sub-domain. The smaller the maximum mesh element size the denser the mesh will be. This maximum mesh element size is varied from 6 microns to 15 microns.

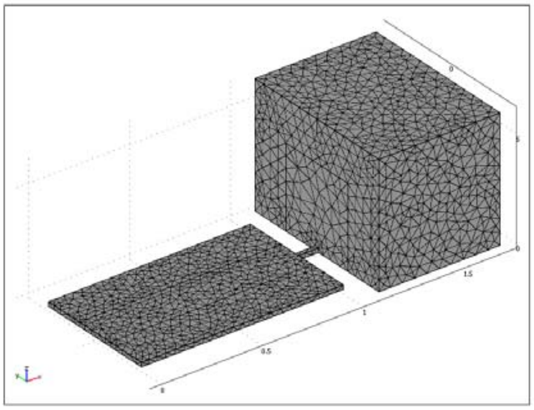

Figure 13 – PML Mesh Size of 6 Micron

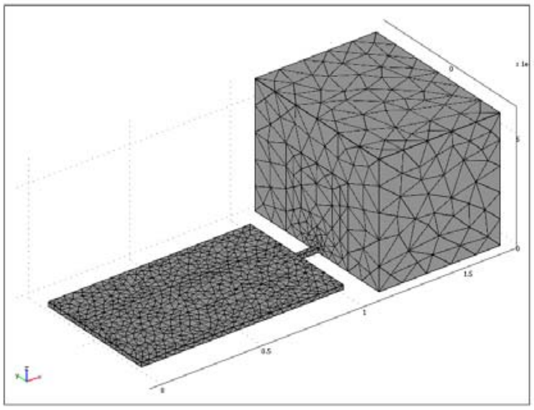

Figure 14 – PML Mesh Size of 15 Micron

5.2.1 PML Sub-domain Mesh Density Simulation Results

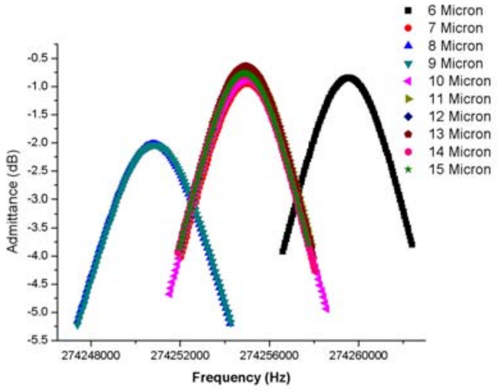

Figure 15– Frequency Response for various Max Mesh Element Sizes

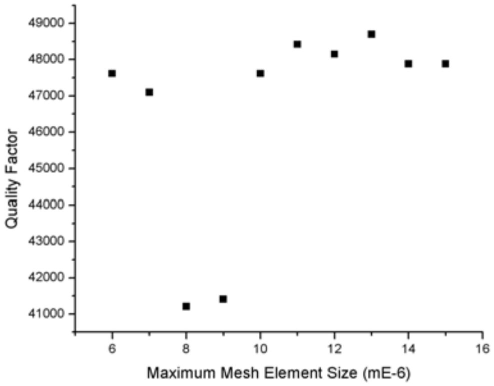

Figure 16 – Quality Factor vs. Max Mesh Element Size

The average quality factor was 46594.9 with a standard deviation of 2824.7. This deviation leads to the conclusion that the quality factor is not greatly affected by the mesh density in the PML sub-domain.

5.3 Substrate Size Simulations

The substrate size is varied from 10 micron^3 to 40 micron^3 while the PML width is kept constant at 20 microns.

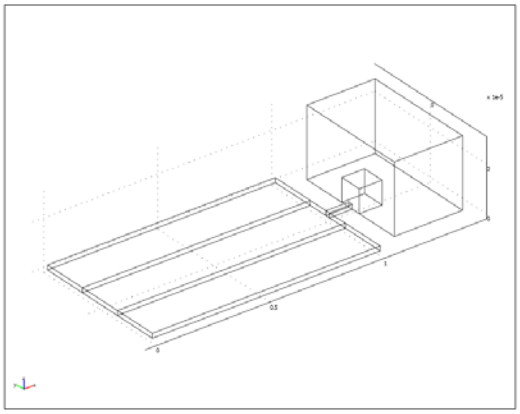

Figure 17 – Substrate Size of 10^3 microns

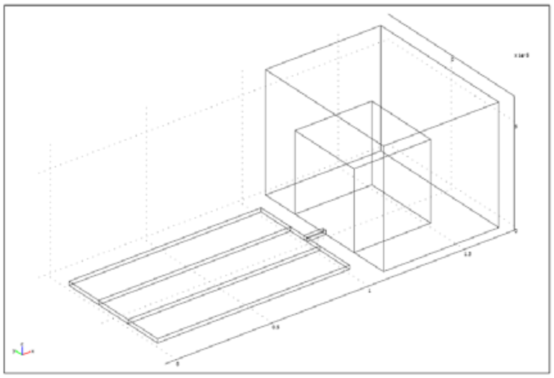

Figure 18 – Substrate Size of 40^3 microns

5.3.1 Substrate Size Simulation Results

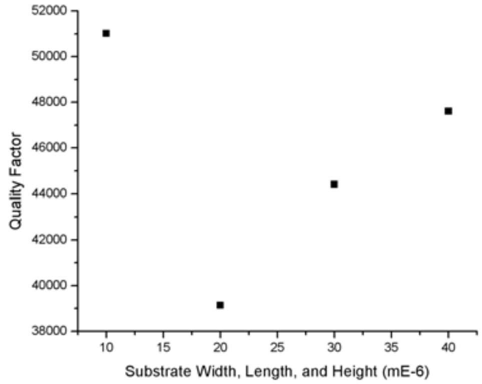

Figure 19– Quality Factor vs. Substrate Size (Max Mesh element Size of 10 in PML and Substrate)

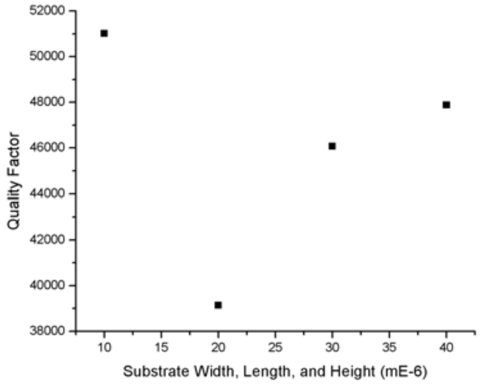

Figure 20– Quality Factor vs. Substrate Size (Max Mesh element Size of 15 in PML and Substrate)

For the simulation with the maximum mesh element size of 10 micron the average quality factor was 45542.1 with a standard deviation of 5052.0. For the simulation with the maximum mesh element size of 15 micron the average quality factor was 46026.4 with a standard deviation of 5026.5. Although the standard deviations were slightly higher in this case they do not indicate a significant dependence of the quality factor on substrate size.

5.4 Substrate Sub-domain Mesh Density

This maximum mesh element size in the substrate sub-domain is varied from 5 microns to 10 microns while all other parameters are held constant.

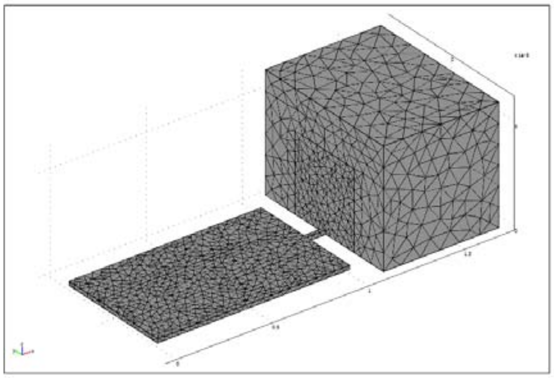

Figure 21 – Substrate Mesh Size of 5 Micron

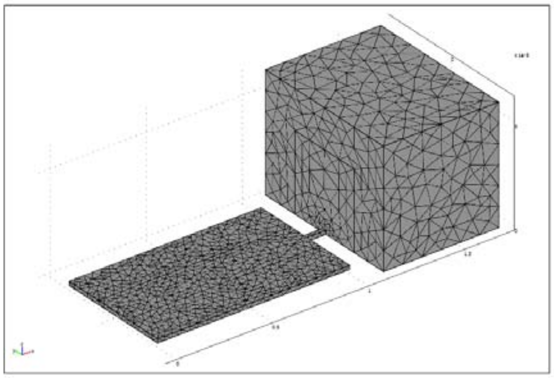

Figure 22 – Substrate Mesh Size of 10 Micron

5.4.1 Substrate Sub-domain Mesh Density Simulation Results

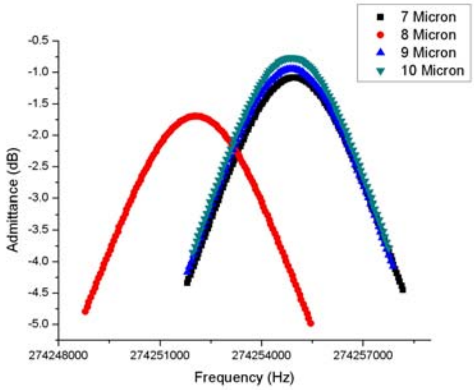

Figure 23– Frequency Response for various Max Mesh Element Sizes

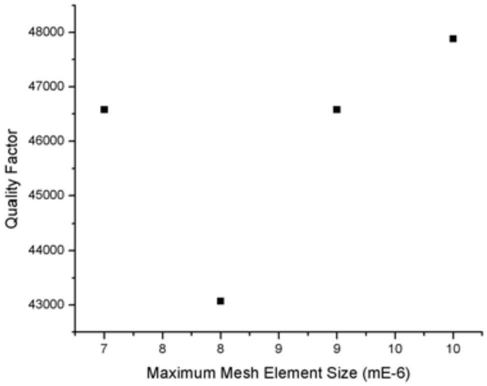

Figure 24 – Quality Factor vs. Max Mesh Element Size

The average quality factor was 46026.0 with a standard deviation of 2065.7. This low deviation leads to the conclusion that the mesh density in the substrate sub-domain does not greatly affect the quality factor.

5.5 Tether location

First the PML is removed, but the tether is not moved. A second simulation is done with the tether moved to the center of the PML. Although the second simulation represents a physically impossible situation it is nonetheless interesting.

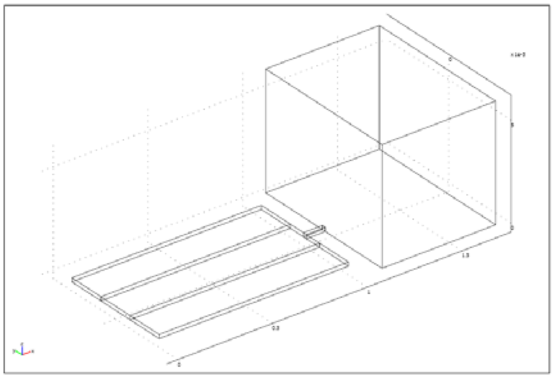

Figure 25 – Tether Attached Directly to PML

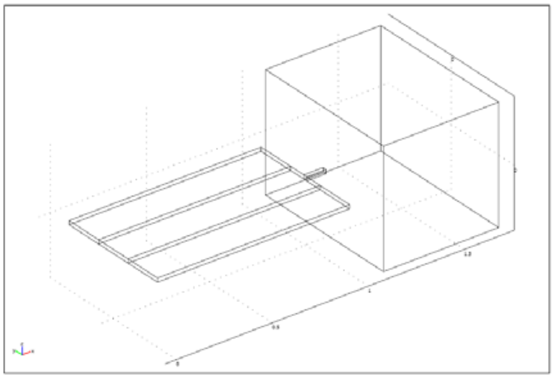

Figure 26 – Tether Attached Directly to PML at Midpoint

5.5.1 Tether Locations Simulation Results

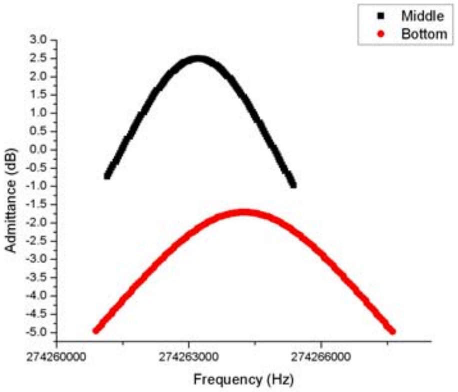

Figure 27 – Frequency Response for Alternate Tether Locations

When removing the substrate, but keeping the tether in the usual position the quality factor was found to be 42853. With the substrate of size 40^3 microns the quality factor was found to be 47613. When removing the substrate and moving the tether to the middle of the PML sub-domain the quality factor was found to be 70251. The difference between the two quality factors is 27,398. The resonant frequency also shifted, but the difference was negligible.

5.6 Tether Lengths and Widths

The base model was modified to examine the effect of the tether on the quality factor. Tether lengths of 1/8 λ, 1/4 λ, and 3/8 λ were explored along with tether widths of 2 and 5 microns.

5.6.1 Tether Lengths and Widths Simulation Results

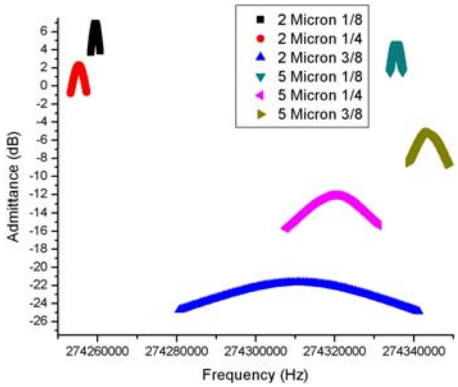

Figure 28 – Frequency Response for Various Tether Widths and Lengths

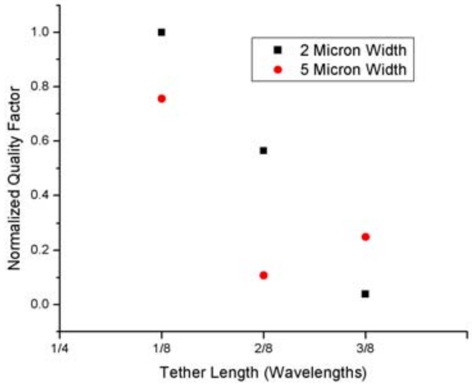

Figure 29 – Quality Factors for Various Tether Widths and Lengths

For the 1/8 and 1/4 wavelength tethers, there was a significant drop in the quality factor when moving from the 2 micron wide tether to the 5 micron wide tether. This was expected as more energy is able to escape from the resonator when the tether is wider.

For the 3/8 wavelength tether there was in increase in the quality factor when moving from the 2 micron wide tether to the 5 micron wide tether. The reason behind this is unknown and should be explored in future research.

5.7 Novel tether designs

The branch designs outlined in section 3 were tested using tether widths of 2 and five microns. The branches were all designed to be quarter λ and in order to ensure that the branches were of the current length their length was measured from the middle of the main tether. For the 2 micron tether width simulations the branches were 9 microns long, and for the 5 micron tether width simulations the branches were 7.5 microns long.

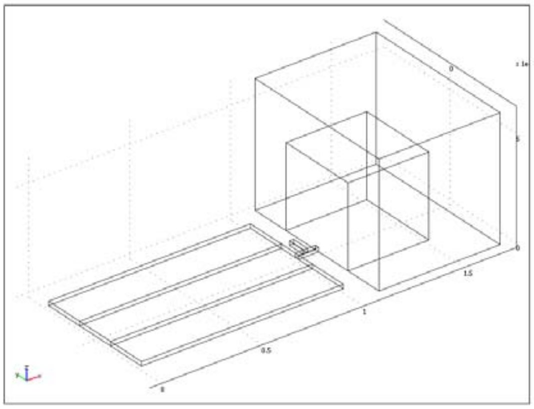

Figure 30 – One-branch Design for 2 Micron Tether Width

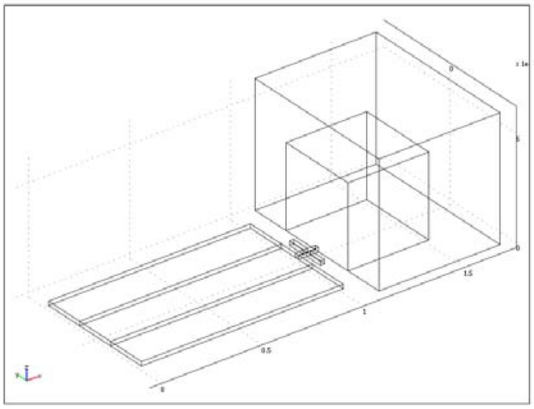

Figure 31 – Two-branch Design for 2 Micron Tether Width

5.7.1 Novel Tether Design Simulation Results

Due to time constraints simulations of the novel tether designs were not completed.

6. Discussions and Conclusion

The goal of the simulations was to determine the COMSOL parameters required to accurately simulate MEMS resonators. The effects of the PML mesh-density, substrate mesh-density, PML size, substrate size, and tether location on the quality factor were unknown at the beginning of this work. After examining the quality factors for the simulations it was determined that none of these parameters have a great effect on the quality factor. If the quality factor had exhibited a strong dependence on the any of the examined parameters the base model would be unusable. As a result of the independence from these parameters, simulations of novel resonator designs can now be performed in order to analyze quality factor trends.

The tether length and width simulations led to the conclusion that shorter and thinner tethers would lead to the best quality factors. This is intuitive given that a wider tether would allow more energy to escape. The reason why there was an increase in the quality factor for the 3/8-wavelength tether when going from 2 to 5 microns is unknown. More data is necessary before these trends can be fully understood.

7. Further Work

This research has led to the creation of a base model that can be modified to accurately simulate novel tethers designs. The following parameters have been identified as adequate.

PML width: 20 microns
PML max mesh element size: 10 microns
Substrate size: 40 microns x 40 microns x 40 microns
Substrate max mesh element size: 10 microns

Models for Gong’s novel tether branching designs can be created using this base model. The data from the simulations will allow for accurate analysis of trends.

8. Acknowledgements

I would like to thank Dr. Gianluca Piazza for choosing me to do research this past summer in his lab. This opportunity has been invaluable in helping me determine my future career path. I was also able to see the thought process behind engineering research. I was able to see how an initial questions leads to a set of experiments that then lead to a conclusion. I would also like to thank Dr. Songbin Gong and Nick Kuo who helped me on a daily basis understand my results and determine the next step in my research. Lastly I would like to thank Dr. Jan Van der Spiegel for organizing the SUNFEST program. This is truly a unique experience that I would not have been able to have without the generous help from the SUNFEST program and the National Science Foundation.

References

[1] G. Piazza; P.J. Stephanou; A.P. Pisano, "Piezoelectric Aluminum Nitride Vibrating Contour-Mode MEMS Resonators," *Microelectromechanical Systems, Journal of* , vol.15, no.6, pp.1406-1418, Dec. 2006

[2] S.A. Chandorkar; M. Agarwal; R. Melamud; R.N. Candler; K.E. Goodson; T.W. Kenny, "Limits of quality factor in bulk-mode micromechanical resonators," *Micro Electro Mechanical Systems, 2008. MEMS 2008. IEEE 21st International Conference on* , vol., no., pp.74-77, 13-17 Jan. 2008

[3] D. S. Bindel and S. Govindjee, "Elastic PMLs for Resonator Anchor Loss Simulation," Department Paper, University of California, Berkeley, 2005.

[4] V. Bottom, Introduction to Quartz Crystal Unit Design. New York: Van Nostrand Reinhold, 1982,

[5] J. Taylor, Classical Mechanics. Sausalito, Calif. Palgrave, 2003,

[6] G. Piazza, “Piezoelectric Aluminum Nitride Vibrating RF MEMS for Radio Front-End Technology,” Ph.D. dissertation, Electrical Engineering and Computer Sciences, Univ. of Cal. Berkeley, Berkeley, CA, 2005

[7] B. Sjodin, private communication, June 2010.

[8] S. Gong, “UPenn Lo-Bar CSSA,” unpublished

[9] C. Zuo, N. Sinha, J. Van der Spiegel, and G. Piazza, "Multi-Frequency Pierce Oscillators Based On Piezoelectric AlN Contour-Mode MEMS Resonators," Departmental Papers, 2008.