Finite Element Method Simulation for SAW Resonator-Based Sensors

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Abstract— **In this paper, finite element method is used for modeling of 433MHz one port SAW resonator. The simulation process performed using COMSOL in 2D models. Impedance, admittance and scattering parameters for SAWR with 2 electrodes are predicted. The equivalent circuit parameters of one port SAW resonator extracted from FEM results which considered as a contribution.**

Index Terms— *FEM, Resonator, 2D and COMSOL*

I. INTRODUCTION

SAW resonator is a typical SAW device in sensor applications. It is found in high frequency circuits where other traditional resonators made of ceramic or crystals failed to be available. SAW resonators have the advantage of more stability with their fundamental frequency. The resonance occurs by using metal gratings in the propagation path of SAW. There are two main classifications for SAW resonators, one with one-port and the other with two-port. One port resonators uses only single IDT with metal gratings placed on any side of the device [1]. The reflective metal gratings are used with SAW resonators to produce high quality factor (Q). The largest quality factor enables SAW device to operate in high frequency range with low insertion loss, small size (in micron) and with high speed operation. SAW resonator is the best choice that used to stabilize and sustain oscillation in oscillator circuits. The development of SAW resonators researches can be summarized by the same way introduced for SAW delay lines and filters in the previous section. Development of SAW resonators starts from 1998 till now and our thesis continues in this way of research. In 1998, one - port SAW device configuration resonated at 90MHz is investigated [2]. In 2003, the resonant frequency for 1.2 GHz one-port SAW resonator is calculated while the propagating velocity was varied and after five years, the recorded measurement results for fabrication of 3GHz SAW resonators based gallium nitride with Q larger than 800 is recorded and it is increased with orientation change of gallium nitride [3].

Through the next year, a design for 5 GHz one and two port SAW resonators is presented [4]. Recently, SAW resonators using coupling of mode (COM) is discussed (2011) [5]. Within the same year, the design for RF SAW resonator is inspected [6].

In previous research work, the frequency response of SAW resonator is predicted using equivalent circuit model [7, 8],. In this research work, we model both one and two SAW resonators but in 2D structure using COMSOL multi-physics over FEM. The choice of piezoelectric material must exhibit thermal stability, high velocity for acoustic wave and coupling coefficient. So, YX LiNbO3 is a promising material used as a substrate for SAWR. Aluminum is the best choice material for IDTs. A very narrow spacing between electrodes in IDT is required to obtain high resonance frequencies. The next section we introduce a full design for 2D – one port SAWR operating at 433.9MHz. The introduced design has the facility of changing the geometry to reach the required resonant frequency.

II. Modeling of One Port SAWR

All FEM simulation are performed using COMSOL 5.0 through HP4520s with 4GB RAM and Core I5 M460 (2.53GHz / Cash 3MB) over windows 7 (64bit). Simulation process passes through the following steps:

1. Geometry Settings

Figure (1) indicates a small 2D section of SAW resonator [9, 10]. The width of the substrate material is selected as λ or periodic number of half wavelength, while the thickness (height) is selected as the same as the material length or greater. The IDT is selected with two electrodes of width λ/8 and very small thickness λ/150. The spacing between the two fingers (electrodes) is λ/4, so the pitch is (spacing + electrode width = 3λ/8). The final material in the design is air which represents the surface of IDT. Table (1) summarizes the whole geometry of one port SAW resonator. Figure (2) shows the geometry design performed in COMSOL.
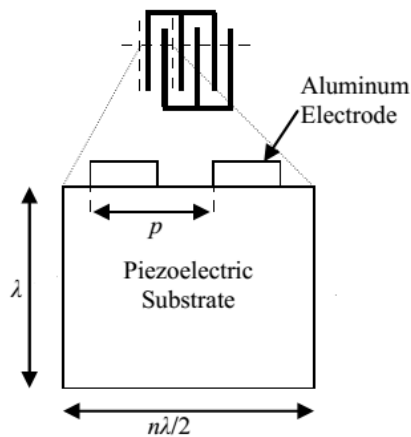
Figure (1): Geometry Settings for One port SAWR

Table (1): Proposed Geometry Settings for One port SAWR

Description	Expression	Value
Rayleigh wave velocity	3996 [m/s]	2840 m/s
center freq.	433.9[MHz]	4.33E9 Hz
wavelength	VR/f0	9.23E-06 m
electrode width	lambda/8	1.15375e-6 m
electrode thickness	lambda/150	6.153E-8 m
Number of Electrodes	2	2
pitch of Electrodes	3 * lambda /8	3.46125e-6 m
substrate thickness	lambda	9.23E-06 m
Angular Frequency	2*pi*f0	2.7206E9

Figure (2): Building SAWR geometry in COMSOL

2. Subdomain settings

LiNbO$_3$ piezoelectric material is used a substrate and Aluminum for IDT. The elastic, permittivity and stress constantans are presented in [11]. Y cut X propagating constants are given in equation (1) to (4). Aluminum is the electrode material with Poisson ratio, density, Young's modulus shown in equations (5) to (8).

For LiNbO$_3$ material of Substrate

Density (LiNbO$_3$) = 4647 kg/m^3 (1)

Elasticity Matrix =

$$\begin{pmatrix} 2.0290\text{e}11 & 0.5252\text{e}11 & 0.7531\text{e}11 & -0.0849\text{e}11 & 0 & 0 \\ 0.5252\text{e}11 & 2.1566\text{e}11 & 0.8610\text{e}11 & -0.0354\text{e}11 & 0 & 0 \\ 0.7531\text{e}11 & 0.8610\text{e}11 & 2.0792\text{e}11 & -0.1813\text{e}11 & 0 & 0 \\ -0.0849\text{e}11 & -0.0354\text{e}11 & -0.1813\text{e}11 & 0.7110\text{e}11 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.7430\text{e}11 & 0.0944\text{e}11 \\ 0 & 0 & 0 & 0 & 0.0944\text{e}11 & 0.6048\text{e}11 \end{pmatrix} \quad (2)$$

Coupling Matrix=

$$\begin{pmatrix} 0 & 0 & 0 & 0 & 1.3525 & -4.2721 \\ -2.1189 & -1.9633 & 3.0381 & 2.0077 & 0 & 0 \\ -1.4097 & -0.7518 & 3.4979 & 0.8821 & 0 & 0 \end{pmatrix} \quad (3)$$

Relative Permittivity =

$$\begin{pmatrix} 43.6 & 0 & 0 \\ 0 & 38.1267 & 7.0055 \\ 0 & 0 & 34.6333 \end{pmatrix} \quad (4)$$

For Aluminum material of IDT

Density (Aluminum) = 2700 kg/m^3 (5)
Young's modulus= 70E9Pa (6)
Poisson ratio= 0.33 (7)
Electrical Conductivity = 3.538x10^7 (8)

3. Mesh Settings

The mesh geometry is calibrated to "user controlled" or Extra-fine from "physics controlled" and mesh optimized with 44 elements per λ is used in the simulation. Table (2) identifies the mesh settings used in the simulation. Figure (3) describes the mesh done by COMSOL. The number of degree of freedom (DOF) is solved for 38063 domain elements and more than 519 boundary elements.

Table (2): Proposed Mesh settings for one port SAWR

Description	Value
Maximum element Size	2.08E-7
Minimum element Size	7.79E-10
Maximum element growth rate	1.2
Curvature factor	0.25
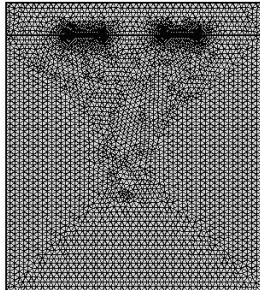
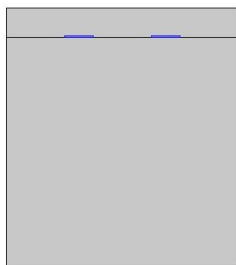**Figure (3):** Mesh used in Simulation

4. Boundary Settings

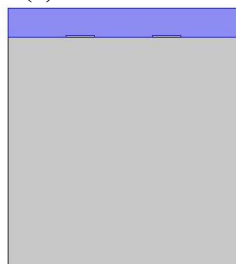The linear elastic material model is assigned to the two electrodes, figure (4) and using equation (9).

$$-\rho\omega^2 u - \nabla.\sigma = FVe^{i\phi}, \sigma = S \tag{9}$$

The electrical material model is assigned to the air, figure (5) and using equation (10).
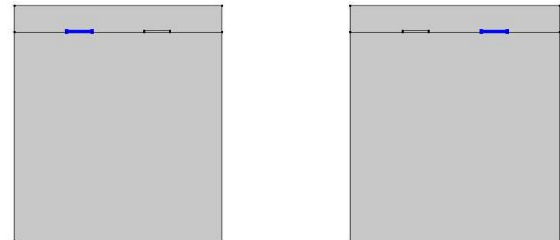
$$E = -\nabla V \tag{10}$$
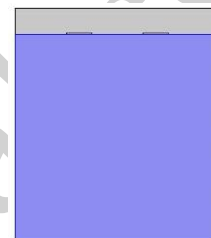

Figure (4): Linear Elastic Model.

Figure (5): Electrical Material Model.

One of two electrodes is defines as the terminal which 1V electrical potential is applied; the other terminal is considered as a ground with zero potential (Figure 6).

Figure (6): Input terminal and Ground

The piezoelectric material model is assigned to the substrate domain as shown in figure (6-7).

Figure (7): The piezoelectric Material Model

The periodic condition is assigned to both sides of the structure, while fixed constraint assigned to the bottom of substrate.

5. Simulation Study (Frequency Domain Study)

By applying ground to one of the two electrodes and a constant voltage to the other, then impedance, admittance and S-parameters can be determined. Frequency domain study selected with range between 430 and 436 MHz with step 0.01MHz. The stationary solver performed the simulation in 28 minutes exhausting 684MB physical memory. The surface deformation profile of displacement of one port SAWR at resonance frequency is recorded in figure (8) and (9) showing the resonant (symmetric mode) and anti-resonant frequency (anti-symmetric mode). The excitation occurs towards the terminals. Figure (10) shows the surface electrical potential profile at resonant frequency.
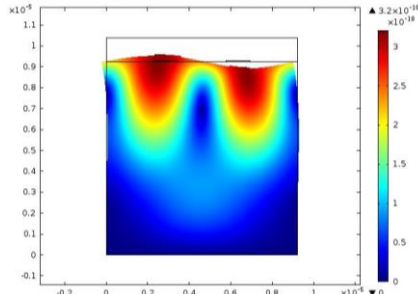
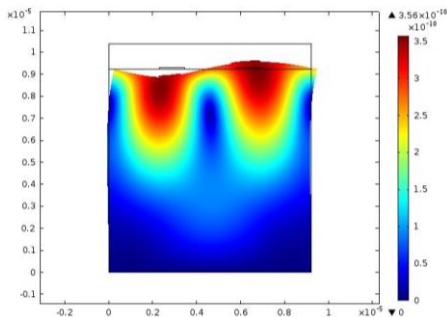**Figure (8):** Surface Displacement at symmetric mode

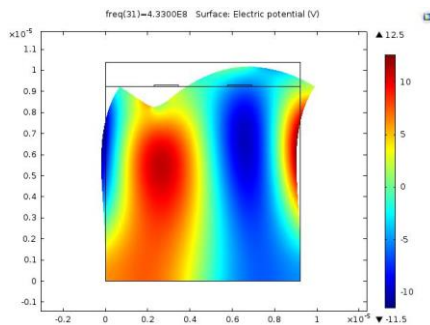**Figure (9):** Surface Displacement at anti symmetric

Figure (10): Surface Electrical potential Profile at resonant frequency

The real (conductance) and imaginary (susceptance) of admittance (Y_{11}) is predicted in figure (11). S_{11} parameter is calculated from equation (11) and plotted at figure (12). The insertion loss is predicted as -8.6dB, it performs an adequate value compared with obtained in [12].

$$S_{11} = 20 * \text{LOG}_{10}\left((-\text{PZD.Y11} + (1/50)) / (\text{PZD.Y11} + (1/50))\right) \quad (11)$$
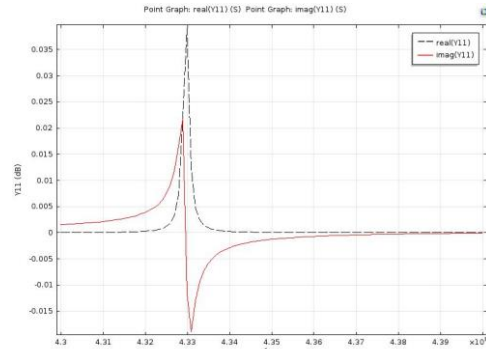

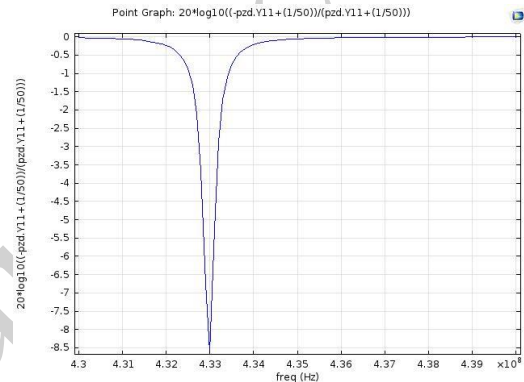**Figure (11):** Y_{11} real and imaginary parts resonated at 433MHz.

Figure (12): S_{11} parameter with -8.6dB insertion loss.

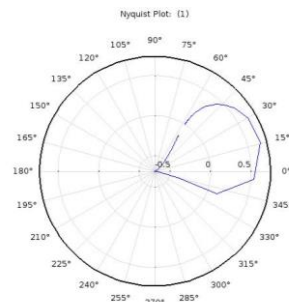The nyquist plot for S parameter is recorded in polar plot shown in figure (13).

Figure (13): Polar plot for S_{11} parameter.

We may replace the second electrode with charge rather than terminated power. Z_{22} obtained in this case rather than S-parameters directly, it is easy to transform the impedance into S-parameter using (13).

2170

$$S_{22} = \frac{pzd.Z22 - 50}{pzd.Z22 + 50} \qquad (13)$$

Also, we may replace the second electrode with voltage terminal rather than terminated power or charge. Y22 obtained in this case rather than S-parameters directly, it is still easy to transform the impedance into S-parameter using (14).

$$S_{22} = \frac{\dfrac{1}{pzdY22} - 50}{\dfrac{1}{pzdY22} + 50} \qquad (14)$$

III. EXTRACTION OF ECM PARAMETERS

In this section, we introduce a novel method to extract the equivalent parameters for SAWR using FEM [13]. Figure (14) indicates the equivalent circuit model (ECM) for SAW resonator; it is required to calculate the parameters R, L and C from FEM simulation using COMSOL in order to achieve the resonant frequency.
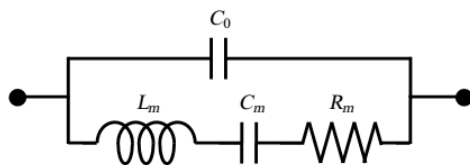

Figure (14): ECM for SAWR

Referring to our designed model of one port SAW resonator shown in figure (11). We can extract the four parameters from real and imaginary parts of admittance response (figure (15)) and according to the following equations.
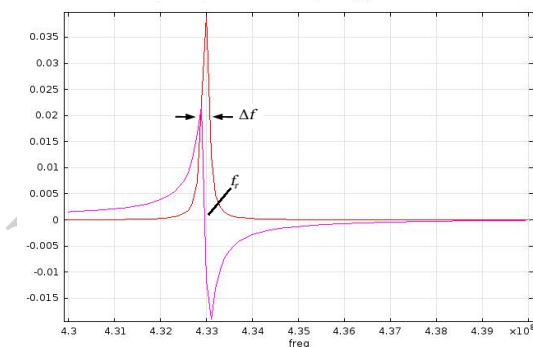

Figure (15): parameters extracted from admittance response

The Quality factor: $Q_r = \dfrac{f_r}{\Delta f} = \dfrac{433MHz}{0.02MHz} = 21650 \qquad (13)$

Where, Δf denote to the **3dB** bandwidth of the susceptance. From **figure (11)** it is found **0.02**MHz.

$$f_r = 433MHz \text{ (Center frequency)} \qquad (14)$$

$$f_p = 433.02MHz \qquad (15)$$

$$f_s = 432.98MHz \qquad (16)$$

$$\omega_r = 2*\pi*f_r = 2720.6MHz \qquad (17)$$

$$G_r = 0.039 \qquad (18)$$

$$R_m = \frac{1}{G_r} = \frac{1}{0.039} = 25.6\Omega \qquad (19)$$

$$L_m = \frac{G_r * Q_r}{\omega_r} = \frac{0.039 * 21650}{2720.6 * 10^6} = 310.35nH \qquad (20)$$

$$C_m = \frac{1}{G_r * Q_r * \omega_r} = 0.43532Pf \qquad (21)$$

$$C_o = \frac{C_m * f_r}{2*(f_p - f_s)} = 4.712nf \qquad (22)$$

fr is the resonant frequency (center) , fp is parallel the resonance frequency, fs is the series resonance frequency, Gr maximum (peak) of conductance, Rm is the equivalent motional resistance, Qr is the Quality factor, Lm is the equivalent motional inductance, Cm is the equivalent motional capacitance. The equivalent circuit of our designed model of one port SAW resonator can be re-drawn in figure (16).
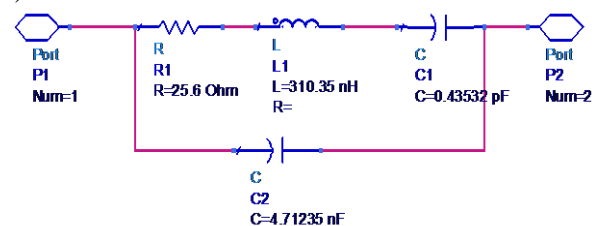

Figure (16): Extracted Parameters for one port SAWR.

IV. CONCLUSION

In this paper, advanced design for one and two port SAW resonator is investigated. All necessary device parameters predicted from the simulation process using COMSOL. Detailed discussion for modeling process with its various steps from geometry setting up to response plotting is clearly mentioned. The research work performed for one port SAWR with two electrodes represent IDT and with increasing the

2171

number of fingers. In the final section of the paper, a novel method for reverse design process of one port SAW resonator is introduced by extracting the equivalent circuit parameters of SAWR. This paper supports the designers who concerned with the fabrication of SAW resonators and their sensor - based applications. We can use the proposed simulation model to be agreed with previously work done in semiconductor devices like inverters [14].

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