SPICE Macromodel for SAW

Alberto M. Barbosa, Edval J. P. Santos
{abarbosa, edval}@ee.ufpe.br

Laboratory for Devices and Nanostructures/DES
Universidade Federal de Pernambuco - UFPE
Caixa Postal 7800 CEP: 50711-970 Recife-PE

Abstract

Simulation of sensors based on Surface Acoustic Waves (SAW) requires models that can be used in circuit simulators. SPICE is a general purpose simulator for integrated circuits and its engine is used by several commercial simulators. This article shows the development of a simple SAW macromodel derived from coupled-mode equations that can be implemented directly in SPICE.

1 Introduction

SAW devices have a large application range, such as: TV, cellular phones, signal processing devices, industry and biomedical sensors. In sensor applications, SAWs are used as delay lines or resonators. Acoustic device models have been proposed since Mason's equivalent circuit [MAS 48] for bulk waves. Based on Mason's work, a model for surface waves was also developed [SMI 69]. To our knowledge, the first SAW SPICE model was proposed in 1995 [BHA 95]. However, this model represents each pair of electrodes as a separated circuit, which makes it difficult to represent long IDTs. In this present paper, the coupled-mode theory for waves in periodic structures is applied, this theory has been used in optical wave guides, non linear optical and more recently in SAW transducers [NAK 93]. We will use this model approach to develop a macromodel for SPICE. This article is divided in four parts, this introduction is the first part, next the macromodel is presented, third, an example of a SAW resonator is shown, and finally the conclusions.

2 A SPICE Macromodel Derived from Coupled-Mode Equations

Considering surface wave propagating in +x e -x directions, we can represent its amplitudes $v^+(x)$ and $v^-(x)$, respectively, with the time dependence ($e^{j\omega t}$).

$$v^+(x) = A^+(x)\, e^{-jkx}, \quad v^-(x) = A^-(x)\, e^{jkx}$$

where k is expressed as: $k = \omega / vf$

Neglecting losses and in the presence of the grating with N pairs of fingers and period L, wave changes the propagation constant and introduces coupling between the forward and backward waves, and the effect of the voltage have to be considered.

The amplitudes $A^+(x)$ and $A^-(x)$ obey the following coupled-mode equations [SUZ 76]:

$$dA^+(x) / dx = -jk_{11}A^+(x) - jk_{12}e^{j2\delta x}A^-(x) + j\zeta e^{j\delta x}V$$

$$dA^{-}(x) / dx = jk_{12}e^{-j2\delta x}A^{+}(x) + jk_{11}A^{-}(x) - j\zeta e^{-j\delta x}V \quad (1)$$

where V is the voltage applied to the interdigital transducer (IDT), ζ is the constant associated with the conversion from electrical to SAW quantities, and δ is defined as

$$\delta = k - k_{0,} \qquad k_0 = 2\pi / L \quad (2)$$

Considering two acoustical ports, 1 and 2, at the centers of both end finger-electrodes of the IDT, x=0 and x=NL, neglecting losses and the forces thought as voltages, and the velocities as currents, one obtains the following admittance matrix [NAK 93]:

$$\begin{pmatrix} I \\ v_1 \\ v_2 \end{pmatrix} = \begin{pmatrix} J\omega C_T + \phi^2 / j2\theta Z_0 & \phi / j2\theta Z_0 & -\phi / j2\theta Z_0 \\ \phi / j2\theta Z_0 & 1 / jZ_0 \tan 2\theta & -1 / jZ_0 \mathrm{sen} 2\theta \\ -\phi / j2\theta Z_0 & -1 / jZ_0 \mathrm{sen} 2\theta & 1 / jZ_0 \tan 2\theta \end{pmatrix} \begin{pmatrix} V \\ F_1 \\ F_2 \end{pmatrix} \quad (3)$$

where

$$Z_0 = (1 - p) / (1 + p) = 1 / q\beta = [(\omega - \omega_{S1}) / (\omega - \omega_{S2})]^{1/2}$$
$$\phi = \eta NL = 2j\zeta NL$$
$$C_T = NC_S \quad (4)$$

C_S is the capacitance per electrode pair, $\omega S1$ and $\omega S2$ are the stopband-edge frequencies.

Our intention is to represent the admittance matrix by a circuit that can be implemented in SPICE and to relate the physical parameters with its components.

The impedance $j2\theta Z_0$ can be written as

$$j2\theta Z_0=jNL/q=j(NL/V_f)(\omega - \omega_{S1})=j(N/f_0)(\omega - \omega_{S1}) \quad (5)$$

In a series LC circuit, next to the center frequency, one can apply the following approximation

$$Z(\omega) \sim j2L(\omega - 1 / (LC)^{1/2})$$

From direct comparison to equation (5)

$$L = N/2f_{0,} \quad C = 1/L\omega^2_{s1} \sim 1/L\omega_0^2 \quad (6)$$

The constant η for an IDT with a metallization ratio of 0.5 can be given by [NAK 93]

$$\eta^2 = (2.268\omega_0 C_s K^2)^{1/2}/L \quad (7)$$

where K^2 is the effective electromechanical coupling factor for the SAW, and ω_0 is given by

$$\omega_0 = k_0 V_f = 2\pi V_f / L, \qquad C_S = (\varepsilon_p + \varepsilon_0)W/2$$

We saw that $\phi = \eta NL$, so one has:

$$\phi = N(2.268\omega_0 C_s K^2)^{1/2}$$

The 2 X 2 matrix at the lower right corner on equation (3) represents the acoustical part of the IDT. This two-port network can be represented as a π-network. As we may also represent a transmission line as a π-network, we may use a lossy transmission line to represent the acoustical part of the IDT with the following parameters

$$(L / C)^{1/2} = Z_0 \sim 1$$
$$R = G = 0$$
$$LEN = (N / f_0)^{1/2} \text{ x } (c / v_{saw}) = (N / f_0)^{1/2} \text{ x } 10^4$$

where c is the speed of light and v_{saw} is the speed of the surface acoustic wave.

The separation between IDTs is also modeled as transmission lines. The parameters are:

$$TD = d / v_{saw}\,, \quad Z_0 = 1$$

where d is the distance between IDT and v_{saw} the speed of wave propagation.

The negative impedance $-j2\theta Z_0$ can be modeled in SPICE using this approach:

$$Z_{neg} = V / (1- \alpha)I_z = Z / (1- \alpha)$$

For $\alpha = 2$, one gets Zneg = - Z. This can be implemented using a current source controlled by current with gain α in parallel with the impedance in reference. With this approach we develop a SPICE macromodel presented in Fig. 1.

3 Resonator application

To test the macromodel, a linux installation with SPICE 3f4 is used. As na example, an SH-SAW resonator having two stress-free edges is presented. The equivalent circuit of this resonator can be obtained by short-circuiting the two acoustical ports of the circuit shown in Fig. 1, as the force must be zero at the two edges.

To get a resonance at 50MHz, the design parameters are C_T=3.267pF, L=200nH, C=50pF and ϕ^2=47μ. The Figure 2 is a plot of the impedance as function of frequency.

4 Conclusions

The remarkable characteristic of our model is the simplicity. For example, the size of the IDT is modeled by the length of the transmission line, which makes simple to represent long IDTs. It opens the possibility for wide usage in the design of SAW applications. The model can be improved by modifying the lossy transmission line model to construct an acoustical transmission line model.

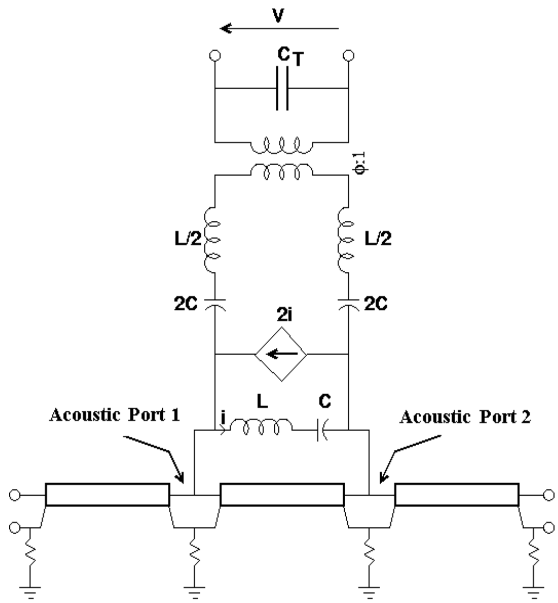

Figure 1 – SAW SPICE macromodel.

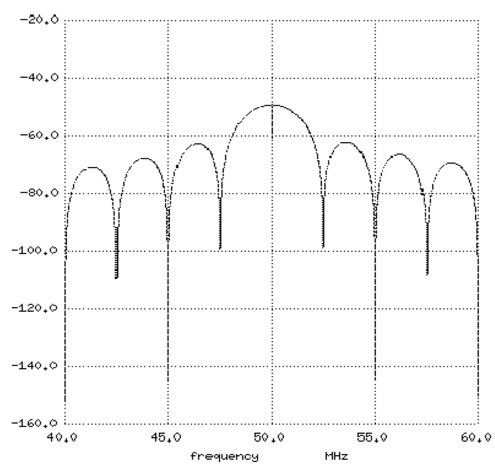

Figure 2 – Resonator frequency response.

6 References

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