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FEM Study on the Effect of Metallic Interdigital Transducers on Surface Acoustic Wave (SAW) Velocity in SAW Devices

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Abstract: In this paper, we present study on the mass loading effect of the interdigital transducer (IDT) on surface acoustic wave (SAW) velocity in SAW devices, using COMSOL Multiphysics™. An IDT consists of metallic comb-shaped electrodes normally fabricated over the surface of the piezoelectric substrate. Owing to the mass load of metallic IDTs over substrate the surface wave's velocity reduces. We have simulated a one port SAW resonator represents the mass loaded device made on *YZ*-cut lithium niobate substrate and investigated the reduction of SAW velocity caused by the mass loading of metal IDT. An Eigen frequency analysis provided by COMSOL Multiphysics™ is useful for finding the true surface and bulk wave velocities in the absence of IDT. The surface wave velocity and the bulk wave velocity are observed. The surface plots of surface and bulk standing waves in the device with IDT and without IDT are shown.

Keywords: Surface acoustic wave, SAW resonator, Interdigital transducer (IDT), Mass loading, Eigen frequency, COMSOL Multiphysics™, FEM.

1. Introduction

SAW devices play a very important role in the field of modern electronics [1]. Various types of SAW devices such as actuators, filters, oscillators, resonators, and sensors have been reported by researchers and are used in many industries and electronic equipment [2] [3] [4].The SAW devices basically consist of electro-acoustic transducers such as interdigital transducer (IDT) fabricated on a piezoelectric substrate [5]. The IDTs are comb shaped electrodes normally made of aluminium metal with the thickness of around 200 nm over the piezoelectric substrate to avoid the electrodes side capacitances [7]. IDTs made of metal fabricated over the substrate introduce secondary effects such as reemission from receiver, BAW interior to substrate, and reflections from neighbor electrodes and consequently affect the performance of the SAW device [6]. The IDT over the substrate reduces the phase velocity of the surface waves propagating along the piezoelectric substrate, since the metal fabricated over the piezoelectric substrate exerts the mass load. In this paper we present the mass load effect of metallic IDT electrodes on the SAW phase velocity in a SAW resonator. The SAWs are very sensitive to mass from external sources. Because of high sensitivity to mass load, the SAW devices have been used for developing many sensors. However, the mass load due to IDT introduces unwanted effects in SAW device response.

Due to the mass load of IDT the phase velocity of the SAW device reduces from the ideal phase velocity. The mass load of IDT on substrate also is one of the reasons for generation of bulk waves interior to substrate [8]. Gamble *et. al*. [9] performed finite element method (FEM) simulation of bulk acoustic wave (BAW) generation caused by mass loading of transducers fabricated on *YZ*-cut lithium niobate substrate. The IDT fabricated over the substrate affects mostly the surface wave velocity and the bulk wave velocity is not much affected since the bulk waves propagate interior to the device substrate.

In this paper, the Eigen frequency analysis available in COMSOL Multiphysics™ [10] is used to find the ideal phase velocity of SAW and BAW in the device. The velocity of BAW is normally higher than the SAW velocity [6]. The decrease in SAW phase velocity caused by mass load of IDT is studied in a one port SAW resonator. The effect on bulk wave velocity is also studied for comparison. The constitutive equations for SAW in piezoelectric substrate, simulation methodology, results and discussion are discussed in the following sections.

2. Constitutive equations for piezoelectric substrate

The linear constitutive equations are governed by the continuum equation of motion, Maxwell's equations under the quasi-static assumption, the strain-mechanical displacement relations and proper boundary conditions. This is well explained in Morgan *et. al*. [1]. In a homogeneous piezoelectric substrate the stress component at each point depends on the applied electric field. The stress tensor component T_{ij} can be expressed as

$$T_{ij} = \sum_{k}\sum_{l} c^{E}_{ijkl} S_{kl} - \sum_{k} e_{kij} E_{k}$$

where, c^{E}_{ijkl} represents the stiffness tensor for constant electric field, S_{kl} represents strain tensor, e_{kij} is the elastic constant or piezoelectric tensor, and E_k is the electric field.

The electric displacement in piezoelectric substrate is also related to strain. It can be expressed as

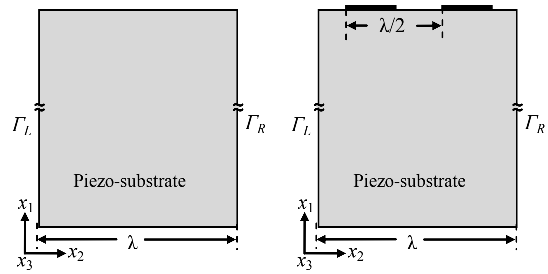
$$D_{i} = \sum_{j} \varepsilon^{S}_{ij} E_{j} + \sum_{j}\sum_{k} e_{ijk} S_{jk}$$

where, D_i is the electric displacement and ε^{T}_{ij} is permittivity tensor for constant strain.

3. Simulation setup

The effect of mass load on SAW phase velocity due to metallic IDT fabricated in piezoelectric substrate is demonstrated using plane strain and piezo plane strain physics. The geometry, material used for subdomains, boundary conditions, and result extractions are described below. The ideal phase velocity of SAW substrate used for this paper is calculated using Eigen frequency analysis.

A SAW substrate of one wavelength of 4 μm (1 λ) along x_2 direction and depth of 40 μm (10 λ) along – x_1 direction is chosen for simulation. A one port SAW resonator, resonance frequency of 869.8 MHz is modeled to demonstrate the effect of the mass of metal IDT on phase velocity of SAW. The IDT of 200 nm thickness along x_1 axis direction over the substrate is used for the device. The 2D geometries used for simulation are shown in Figure 1 (a) and (b), where Figure 1 (a) shows the 2D geometry model of SAW substrate without IDT and Figure 1 (b) shows the 2D geometry model of SAW substrate with IDT. The *YZ*-cut lithium niobate material is used as device substrate. The material properties such as elasticity matrix, coupling matrix, relative permittivity and density are referred from [12]. One pair of IDT electrode is used for one port SAW resonator since the structure of IDT is periodic [6].

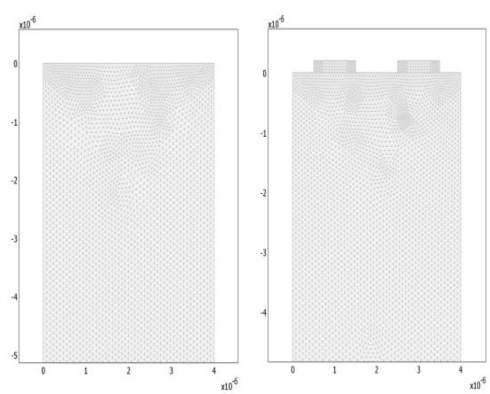


(a) (b)

Figure 1. The 2D geometry model of SAW substrate, (a) without IDT, and (b) with IDT.

Different application modes are used to perform the mass load effect caused by metal IDT in SAW substrate. The SAW substrate is simulated as 2D piezo plain strain using Eigen frequency analysis. The SAW resonator substrate is modeled using piezo plain strain and the IDT is used in plain strain.

The proper boundary conditions are applied. In case of Rayleigh SAW, there are no displacement components in x_3 direction. The top surface of substrate is assumed stress free and the bottom boundary of the substrate is fixed for both models. In case of SAW resonator the IDT



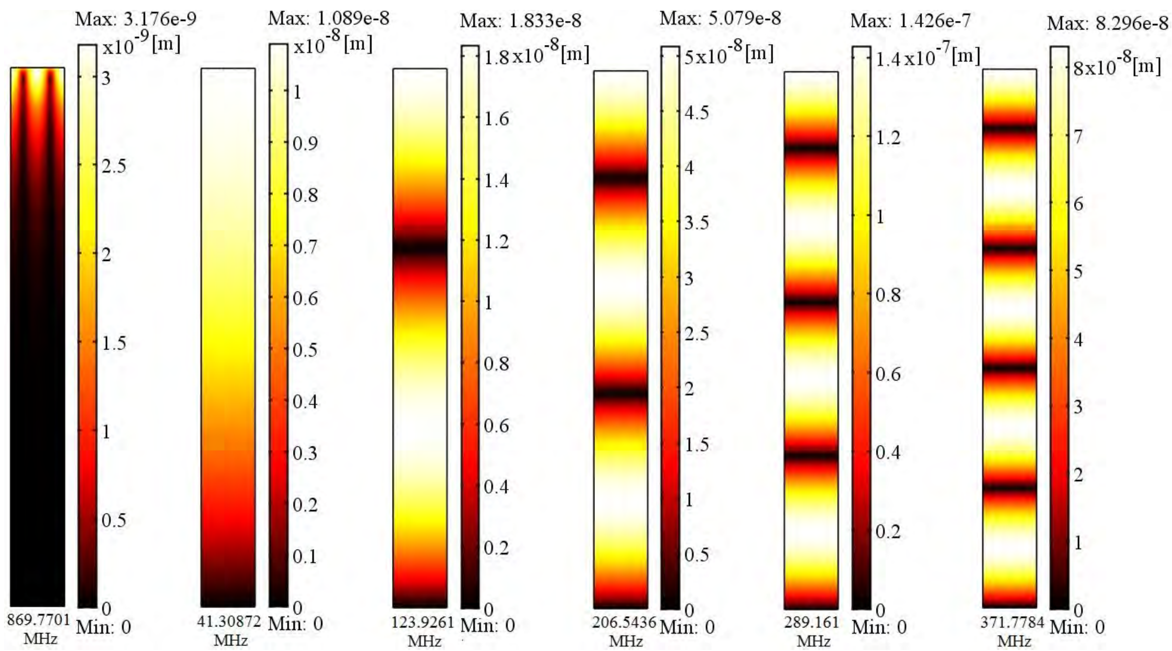
(a) (b)

Figure 2. (a) Meshing of SAW substrate without IDT and (b) Meshing of SAW resonator.

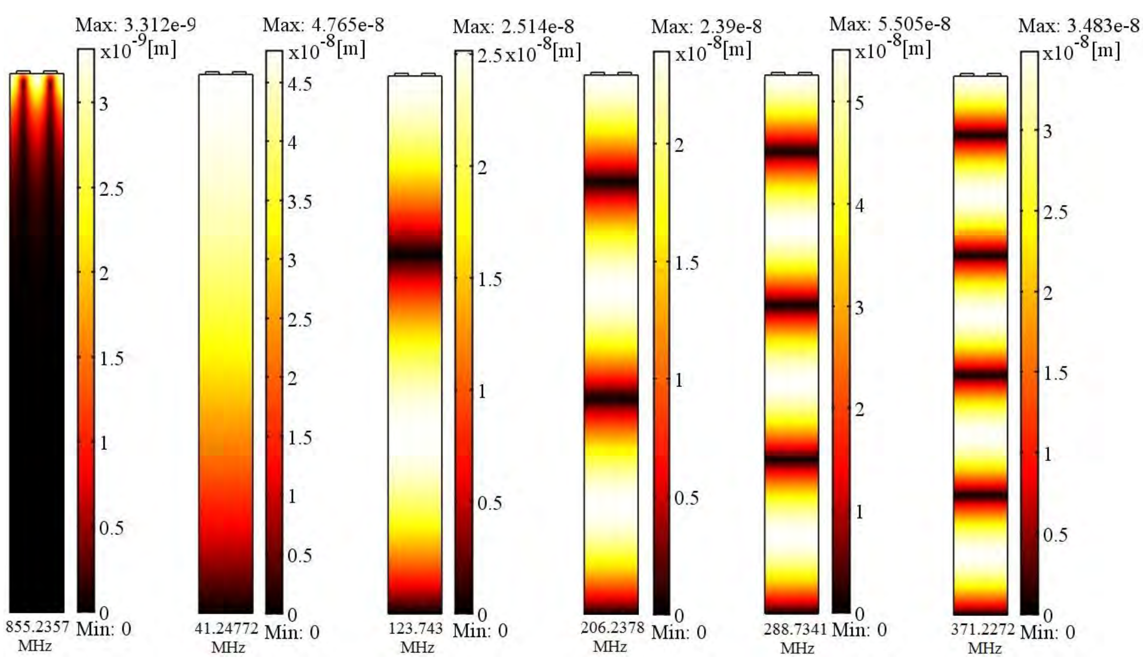
is coupled to the substrate using plain strain boundary conditions. Periodic boundary conditions are applied both ends of substrate as [11]

$$\Gamma_L(u,v,\mathrm{V}) = \rho \Gamma_R(u,v,\mathrm{V})$$
$$\rho = (-1)^n, \ \ n = 2a/\lambda$$

where, a is width of substrate multiple of λ, u is



(a)



(b)

Figure 3. (a) Surface plot of total displacement of *YZ*-cut lithium niobate substrate without IDT and (b) Surface plot of total displacement of *YZ*-cut lithium niobate substrate without IDT.

the displacement component in x_2 direction, v is the displacement component in x_1 direction, and V in the piezoelectric potential. Fine meshing is applied to both models with order of 2.5×10^5 degree of freedom. The meshed pictures of both 2D models are shown in Figure 2 (a) and (b).

Direct SPOOLES solver is used for Eigen frequency analysis using COMSOL Multiphysics™ 3.5a. The Eigen frequency is observed for both models. The SAW phase velocity is calculated using

$$v_P = \lambda \times f$$

where, v_P is the SAW phase velocity, λ is the wavelength of the device and f is the Eigen frequency.

4. Results and discussions

The SAW resonance frequency and BAW resonance frequency with different resonance modes in SAW *YZ*-cut lithium niobate substrate without IDT and with IDT in the SAW resonator are calculated from Eigen frequency analysis using COMSOL Multiphysics™.

The Eigen frequency analysis of SAW substrate without IDT gives the ideal SAW phase velocity. The corresponding ideal phase velocity is 3479.08 m/s. It is observed that the SAW resonator with IDT over the substrate, the phase velocity of SAW is considerably reduced since the metal IDT implies the mass load on the substrate; however, the bulk wave velocity is comparatively unaffected. The results of phase velocity for several resonance modes calculated from the Eigen frequency analysis are tabulated below.

The BAW travels interior to the substrate with phase velocity normally greater than the SAW phase velocity as explained in Royer *et. al.* [6]. The ideal BAW phase velocity obtained from Eigen frequency analysis is 6609.4 m/s which is about 1.9 times of surface wave velocity. In the presence of IDT over the substrate, the phase velocity of SAW is reduced by 58.14 m/s. Comparatively, the change in bulk wave velocity is small, about 9.8 m/s.

The surface plots of total displacement in *YZ*-cut lithium niobate substrate without mass load and with mass load due to IDT are shown in Figure 3 (a) and (b), respectively. In Figure 3 (a) and (b), the first surface plot shows the surface wave on the substrate and rest of the plots show the bulk waves interior to the substrate. The mass load increases as the number of IDT electrodes increases. The bar chart in Figure 4 compares change in phase velocity in the presence of IDT for SAW and BAW.

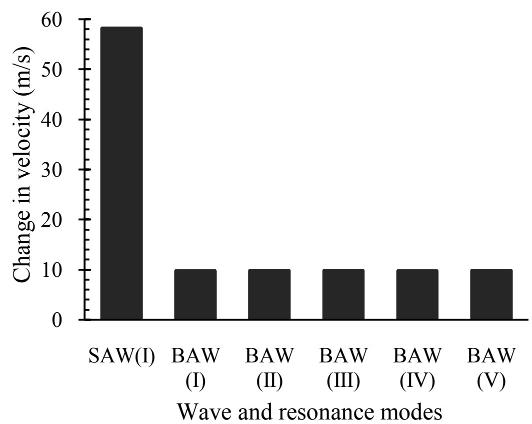


Figure 4. Bar chart of change in phase velocity due to mass load for SAW and BAW with first five resonance modes.

Table 1: Result of wave phase velocity

Wave and resonance mode	**Phase velocity [m/s]**		
	Ideal	**With massload**	**Change in velocity**
SAW (I resonance mode)	3479.08	3420.94	58.14
BAW (I resonance mode)	6609.39	6599.63	9.76
BAW (II resonance mode)	6609.39	6599.62	9.77
BAW (III resonance mode)	6609.40	6599.60	9.80
BAW (IV resonance mode)	6609.39	6599.63	9.76
BAW (V resonance mode)	6609.39	6599.59	9.80

5. Conclusions

The FEM study of mass load effect caused by metal IDT is demonstrated using COMSOL Multiphysics™. The Eigen frequency analysis of unloaded substrate is useful in obtaining the ideal phase velocity of the surface wave and bulk wave. The surface wave travels on the surface of the substrate and bulk waves interior to the substrate. The change in phase velocity due to the mass load of IDT is investigated. For a SAW resonator fabricated on *YZ*-cut lithium niobate substrate with aluminium IDT of 200 nm thickness and 50% metallization ratio, the velocity of surface wave is reduced by 58.14 m/s due to the mass load of metal IDT. However the bulk wave velocity is reduced by 9.8 m/s. This simulation can be further extended to study various other aspects of mass loading in different specifications of devices.

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