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Simulation on Effects of Electrical Loading due to Interdigital Transducers in Surface Acoustic Wave Resonator

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Abstract

This paper investigates the effects of electrical loading due to metallic interdigital transducer (IDT) on surface acoustic wave (SAW) velocity in SAW resonators by simulation using FEM in COMSOL Multiphysics. The IDT electrodes fabricated over the piezo-substrate short circuit the parallel electric field associated with SAW under the IDT during wave propagation and affect the SAW phase velocity. The simulation considers a SAW resonator with massless infinite number of IDT fingers on Y–Z cut lithium niobate substrate. The changes in resonance frequency and SAW phase velocity of SAW resonator due to electrical loading are studied for various metallization ratios. The electric field distribution at the surface of piezo-substrate is obtained and it is observed that the short circuit of the electric field due to metallic IDT reduces the SAW phase velocity; consequently, the resonance frequency of the SAW device decreases.

Keywords: FEM; IDT; MEMS; SAW Devices; SAW Resonator; SAW Velocity;

Nomenclature

λ	SAW wavelength	N	Number of reflectors' strips
v_0	Free surface SAW phase velocity	r_s	Reflection coefficient of one strip
ϕ_s	Surface potential associated with wave	P_s	Wave power per unit width in x_2 direction

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1. Introduction

The surface acoustic wave (SAW) devices such as resonators, delay lines, filters, convolvers, oscillators, correlators, actuators and sensors have been used in electronic equipments and industries [1-4]. The SAW devices have the following unique properties that have made the devices popular. With considerably small wavelength for a given frequency compared to electromagnetic waves the SAW devices can perform signal processing in a compact device. The surface waves are mostly confined to the surface and are easily influenced by the electrodes at the surface. The propagation losses are small as the device is made on a single crystal piezo-substrate [1]. Usually the device does not need tuning. The SAW device consists of interdigital transducer (IDT) fabricated over the surface of piezo-substrate [5]. The IDT is a metal comb-shaped structure fabricated over the piezo-substrate using lithography fabrication process. The RF signal applied to the IDT produces an electric field which generates SAW on the surface of the piezo-substrate and vice versa [2] [5]. The presence of metallic IDT over the substrate causes the following secondary effects: reemission from the receiver IDT, bulk wave generation, phase speed variation, and reflections from neighbor electrodes [2]. The mass load effects due to metallic IDT is well known and reported by many authors [6-10]. The simulations using finite element method (FEM) to study the bulk wave generation and mass loading effects due to IDT are presented in [11-12]. The metallic IDT fabricated over the piezo-substrate short circuit the parallel electric field associated with the SAW [1] [13]. This effect is known as electrical loading. The short circuiting of surface electric fields due to a conducting thin film over the piezo-substrate is reported by many researches. Schulz et al. (1972) presented the relative change in the SAW velocity caused by the thin conducting film on surface of several piezo-substrates and reported that the thin conducting film completely short circuited the surface electric field [14]. The relative change of SAW phase velocity due to thin conducting film on the surface of the substrate is demonstrated by measuring the phase shift in a delay line. Hemphil (1972) presented the measurement of attenuation of SAW as a function of the thickness of gold and aluminum metal thin film over the substrate [15]. Morgan (2007) gave a simplified account of the work of Bløtekjaer et al. (1973) related to electrical loading in an array of regular electrodes [16-17].

The velocity change due to loading effects of IDT can be expressed as a power series expansion on the relative electrode thickness h/λ as [4]

$$\frac{v-v_0}{v_0} \approx \left[\frac{\Delta v}{v}\right]_e + \left[\frac{\Delta v}{v}\right]_{m1}\left(\frac{h}{\lambda}\right) + \left[\frac{\Delta v}{v}\right]_{m1}\left(\frac{h}{\lambda}\right)^2 + ... \tag{1}$$

The expansion coefficients depend on the electrode geometry. The first term on the right side in equation (1) represents electrical loading as explained above. The conductive electrodes short circuit the electric fields and decrease the SAW velocity and energy flow in the wave. The term is roughly proportional to the piezoelectric coupling coefficient [4]. The perturbation theory estimates the change in velocity due to electrical loading as given below [1].

$$\frac{v-v_0}{v_0} \approx \frac{\left(\varepsilon_0 + \varepsilon_{\mathrm{P}}^T\right)\left|\phi_s\right|^2 \omega}{4P_s} \tag{2}$$

Here, $\varepsilon_{\mathrm{P}}^T = \left[\varepsilon_{33}^T\varepsilon_{11}^T - \left(\varepsilon_{13}^T\right)^2\right]^{1/2}$ is the permittivity tensor for constant strain, ϕ_s is the surface potential associated with the wave, and P_s is the wave power per unit width in x_2 direction (see figure 2).. The second and third terms show the linear shift of velocity due to mechanical loading. In practical case mass loading must be controlled to avoid undue dispersion [1].

In this paper, we present the study of short circuit of electric field associated with surface wave on piezo-substrate by simulation using FEM in COMSOL Multiphysics. The free surface wave velocity is calculated using Eigen frequency study of the device in COMSOL Multiphysics. The change in resonance frequency and phase velocity of the SAW due to electrical loading in SAW resonator with massless infinite number of IDT fingers is calculated. The massless electrodes are considered to avoid the effect of mechanical loading of metallic IDT electrodes on the piezo-substrate. The metallization ratio of IDT is changed to investigate the effect of electrical loading on the resonance frequency and phase velocity of SAW. The model description, constitutive equations for piezo-substrate, simulation methodology, results and discussions are given in the following sections.

2. Model descriptions

The effects of electrical loading on SAW phase velocity and resonance frequency of one port SAW resonator with infinite number of IDT electrodes are modeled in three steps: the calculation of electric fields associated with SAW on one port SAW resonator with infinite number of massless IDT fingers, the calculation of electric field associated with SAW on free surface of the piezo-substrate and then the calculation of electric fields with various metallization ratios of IDT.

2.1. SAW resonator structures

Normally, SAW resonator consists of IDT(s) and reflectors fabricated over the surface of the piezo-substrate. In case resonator the SAW propagates within the resonant cavity such that the wave is reflected back to the generating IDT. The resonator devices are mainly two types: one port resonator and two port resonator.

In a one port SAW resonator, two sets of reflectors are fabricated in the either side of the bidirectional IDT as shown in figure 1(a). The reflectors could be made of shorted metal strips or grooves to avoid the regeneration of the SAW. According to the Bragg's frequency, the periodicity of reflector electrodes should be equal to the half of the wavelength, and the reflections from individual strips in the same phase so that the deformations add

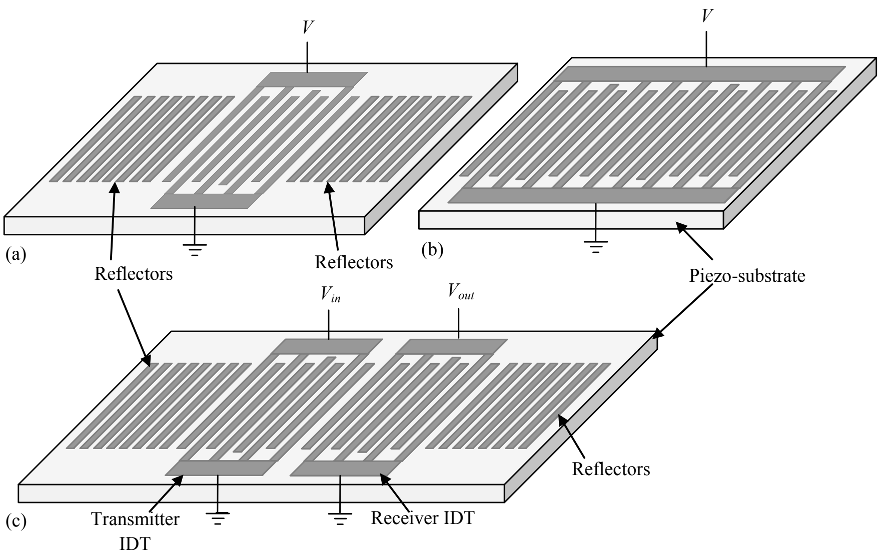

Fig. 1. Pictorial representation of SAW resonators; (a) one port saw resonator with reflectors; (b) one port SAW resonator with long IDT; (c) two port SAW resonator.

coherently. The strong reflections are obtained when $N |r_s| > 1$, N is the number of reflectors' strips and r_s is the reflection coefficient of one strip. Typically in practical case, $|r_s|$ is about 2% and N is 200 or more [2]. The propagation of SAW depends on the substrate material properties, crystal cuts and IDT electrode dimensions. A One port SAW resonator can also be made by using long IDT having large number of fingers without reflector strips as shown in figure 1(b). Multiple reflections occur within the IDT lead to standing wave and the device resonates at a particular frequency known as resonance frequency.

In a two port SAW resonator, two sets of reflectors are fabricated in the either side of the two bidirectional IDTs as shown in figure 1(c). Two port resonators are used as a controlling element for a high stability oscillator.

In this paper we present the simulations of one port SAW resonator with infinite number of IDT fingers using periodic boundary conditions to study the effects of electric loading on the SAW phase velocity and resonance frequency of the SAW resonators.

2.2. Modeling of SAW resonator

Rayleigh SAW propagates over the surface of the piezo-substrate and amplitude decays exponentially with the depth of the substrate. Most of the energy is concentrated near the surface of the substrate. The displacement has both surface normal and surface parallel components in the direction of the wave propagation. In case of Rayleigh SAW, there is no displacement in parallel transverse direction of the wave propagation. These features enable us to model the SAW resonator device in 2 dimensions (2D) and with only few wavelengths depth of the piezo-substrate. The infinite numbers of IDT fingers are modeled using periodic boundary conditions and it is explained below. The 2D geometry used for simulation is shown in figure 2.

Piezo plain strain application mode of COMSOL Multiphysics is used which requires the out-of-plane strain components to be zero. The linear constitutive equations for piezo-substrate are governed by the continuum equation of motion, Maxwell's equations under the quasi-static assumptions, strain-mechanical displacement relations and proper boundary conditions [1]. In a homogeneous piezo-substrate the stress component T_{ij} at each point of substrate depends on the applied electric field **E** or electric displacement **D**. If the stiffness tensor for constant electric field is defined as c_{ijkl}^{E} , strain tensor as S_{kl}, and piezoelectric tensor as e_{kij}, then the stress tensor component T_{ij} can be expressed as

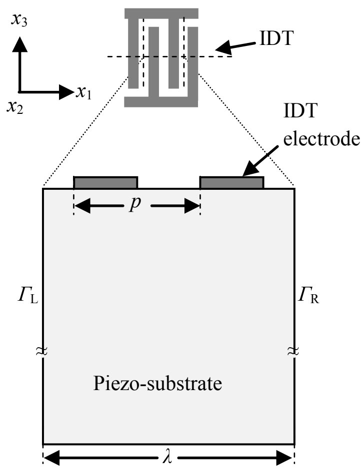

Fig. 2. 2D geometry used for simulation of a one port SAW resonator with infinite number of IDT fingers.

$$T_{ij} = \sum_k \sum_l c^E_{ijkl} S_{kl} - \sum_k e_{kij} E_k \tag{3}$$

The electric displacement **D** is determined by electric field **E** and ε^S_{ij} permittivity of the material. The electric displacement D_i in piezo-substrate is also related to strain and it can be expressed as

$$D_i = \sum_j \varepsilon^S_{ij} E_j + \sum_j \sum_k e_{ijk} S_{jk} \tag{4}$$

A quasi-static approximation is used to express the electric field since the elastic vibration travels much slower than the electromagnetic waves. The equation of motion for piezoelectric material as given in [1] can be expressed as

$$\rho \frac{\partial^2 u_i}{\partial t^2} = \sum_j \sum_k \left\{ e_{kij} \frac{\partial^2 V}{\partial x_j \partial x_k} + \sum_l c^E_{ijkl} \frac{\partial^2 u_k}{\partial x_j \partial x_l} \right\} \tag{5}$$

where, ρ is the density, u is the particle displacement, and ϕ represents the electric potential. In addition, the material is taken to be an insulator there are no free charges. Thus div **D** = 0.

$$\sum_i \sum_j \left\{ \varepsilon^S_{ij} \frac{\partial^2 V}{\partial x_i \partial x_j} - \sum_k e_{ijk} \frac{\partial^2 u_j}{\partial x_i \partial x_k} \right\} = 0 \tag{6}$$

The degrees of freedom (dependent variables) are the global displacements u_1, u_2, and u_3 in the global directions x_1, x_2, and x_3, respectively, and the electric potential V can be obtained by solving the equations (5) and (6) using appropriate boundary conditions.

2.3. Simulation methodology

Multiphysics finite element package COMSOL Multiphysics, 2D piezo plain strain mode is used to simulate a one port SAW resonator with infinite number of IDT fingers. The application mode assumes that the out-of-plane strain, i.e. in x_2 direction, is zero. The effect of short circuit of the electric fields associated with the surface during wave propagation in the resonator is investigated. A 2D geometry used for FEM simulation is given in figure 2. The IDT of one period of electrode fingers is considered to simulate the one port SAW resonator owing to the periodic nature of the IDT structure. The dimensions used for simulation are as follows: finger width (d) 4 µm, finger pitch (p) 8 µm, and depth of the substrate 160 µm (10λ). We consider massless IDT electrodes to avoid the mass loading effect on the substrate, hence the thickness (h) of IDT fingers is taken zero. The piezo-substrate of Y-Z cut lithium niobate (YZ $LiNbO_3$) material is used. The material properties of piezo-substrate such as elasticity matrix, coupling matrix, relative permittivity and density are referred from Ahmadi *et al*. (2004) [18] and are given in appendix A. The Eigen frequency calculation provided by COMSOL Multiphysics is used. The effect on SAW phase velocity and resonance frequency as a result of short circuit of the electric fields due to metallic IDT electrodes is presented.

Appropriate boundary conditions are applied to the model in the simulation as follows. In Rayleigh waves, the particle is displaced perpendicular to the direction of IDT electrodes and there is no displacement along the x_2 direction. Thus the top surface of the substrate is kept stress free and bottom of the substrate is assumed fixed. The periodic boundary condition is applied to left (Γ_L) and right (Γ_R) sides of the device [8]. The expressions for periodic condition are given below.

$$u_i\left(x+np\right)=u_i\left(x\right)e^{(-j2\pi\gamma n)} \tag{7}$$

$$V_i\left(x+np\right)=V_i\left(x\right)e^{(-j2\pi\gamma n)} \tag{8}$$

$$\Gamma_L\,(u,V)=\rho\Gamma_R\,(u,V), \qquad \rho=(-1)^m,\ m=2a/\lambda \tag{9}$$

where, a identifies width of the substrate in multiple of λ, u identifies the displacement components, n identifies the integer numbers, and V is the piezoelectric potential. The mesh element size used is 0.125 µm which gives velocity accuracy of 0.00014%. The Eigen modes of the device are calculated with zero driven voltages at the IDT electrodes. The free surface SAW phase velocity of the substrate is calculated without metallic IDTs over the piezo-substrate. The SAW phase velocity v in the presence of metallic IDT over the piezo-substrate is calculated using symmetry and anti-symmetry modes of the device. The expression for the calculation of the SAW phase velocity is shown below [4].

$$v = p\left(f_{\mathrm{sc}+} + f_{\mathrm{sc}-}\right) \tag{10}$$

where, $f_{\mathrm{sc}+}$ and $f_{\mathrm{sc}-}$ is the frequency obtained from the anti-symmetry and symmetry resonance modes of vibration of the device, respectively. These frequencies are the edges of stop band of the device.

3. Results and discussions

The Eigen frequencies of one port SAW resonator with massless infinite number of IDT fingers are calculated by FEM using COMSOL Multiphysics. The resonance frequency of the resonator with massless IDT electrode fingers obtained from simulation is 213.37 MHz and SAW phase velocity is 3429.00 m/s. The electric field at the surface of the device at its resonance frequency is extracted and shown in figure 3(a). Figure 3(a) with broken line shows the plot of electric field at the surface of one port SAW resonator versus distance along the direction of wave propagation. As its theory implies, the IDT generates sinusoidal deformation on the substrate thus the electric field distribution to the surface of the substrate should be in shape of sinusoidal. From simulation results, it is observed that the electric field under the IDT fingers is short circuited due to conductive IDT fingers as shown in figure 3(a).

The result is compared with free surface of piezo-substrate with identical dimensions and boundary conditions. The calculated resonance frequency and SAW phase velocity of free surface piezo-substrate are 217.44 MHz and 3479.09 m/s, respectively. In the absence of metallic IDT electrodes at the surface of the piezo-substrate, the electric field at the surface of the piezo-substrate is sinusoidal as shown in figure 3(a). Figure 3(a) with solid line shows the plot of electric field at the surface of piezo-substrate without metallic IDT versus distance along the direction of wave propagation. We observe from the simulation that the electric field under IDT electrodes is short circuited thus the shape of the electric field distribution is not sinusoidal. SAW phase velocity is reduced by 50.90 m/s from free surface velocity of 3479.09 m/s, and resonance frequency is reduced by 4.07 MHz from free surface resonance frequency of 217.44 MHz.

Further, the series of simulations of one port SAW resonator with massless infinite number of IDT fingers having different metallization ratio (d/p) are performed. The electric field associated with the surface wave is calculated at the surface of the device substrate at its resonance frequency. The electric field distribution calculated at the surface of the device substrate having various metallization ratios is shown in figure 3(b). As the metallization ratio of IDT reduces, the effect of electrical loading reduces, and resonance frequency and SAW phase velocity get closer to the free surface values. The plots of resonance frequency and SAW phase velocity for various metallization ratios are shown in figures 4 (a) and (b). SAW phase velocity of the resonator is calculated

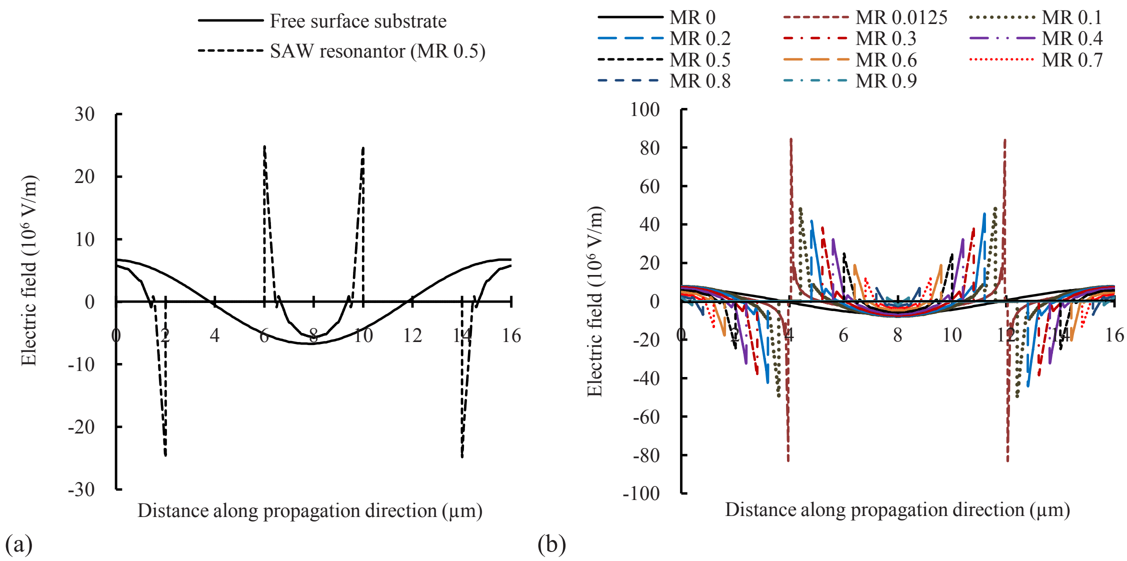

Fig. 3. Plot of electric field associated with the SAW versus distance along propagation direction in a SAW resonator; (a) for free surface and metallization ratio of 0.5; (b) for various values of metallization ratios. Note that electric field is zero under the IDT.

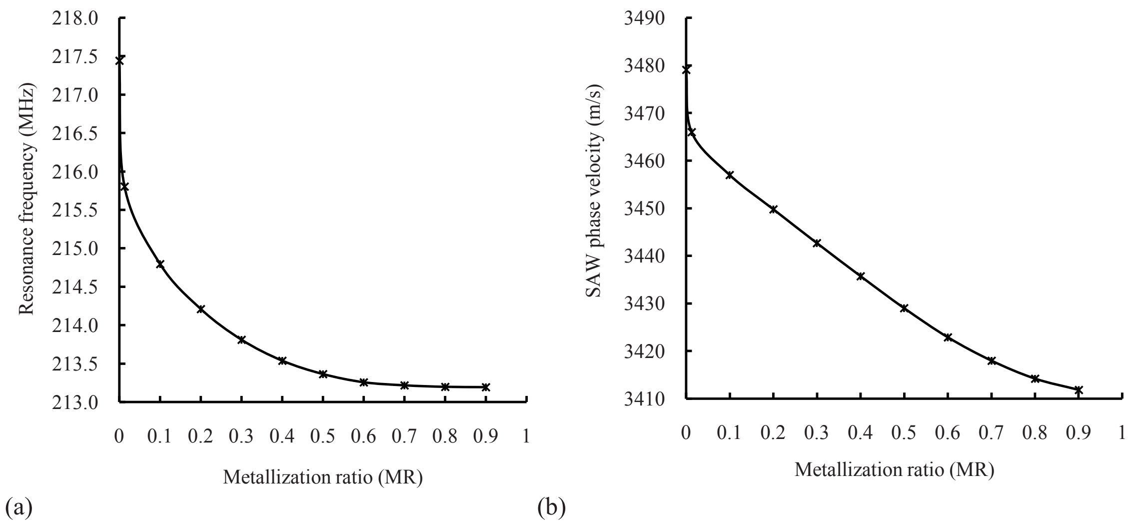

Fig. 4. (a) plot of resonance frequency versus metallization ratio; (b) plot of SAW phase velocity versus metallization ratio.

from the frequencies of symmetry and anti-symmetry resonance modes of vibration. The expression for SAW velocity calculation is given in equation (10).

4. Conclusions

The simulation of electrical loading due to patterned IDT electrodes over the piezo-substrate in a SAW resonator is presented using FEM in COMSOL Multiphysics. The Eigen frequency study provided by COMSOL Multiphysics is used to calculate the free surface SAW phase velocity and resonance frequency of the SAW resonator. The IDT of massless electrode patterned over the *YZ* $LiNbO_3$ substrate is considered to avoid the mass loading effects.

The electric field distribution with and without metal electrodes over the piezo-substrate is extracted for the top surface. The change in the shape of the electric potential is observed due to short circuit of the surface electric field under the IDT electrodes. The results are compared with 50% metallization ratio of the IDT fingers. It is observed that due to electric loading of metallic IDT electrodes, the SAW phase velocity is reduced by 50.90 m/s from free surface velocity of 3479.09 m/s and resonance frequency is reduced by 4.07 MHz from free surface resonance frequency of 217.44 MHz. Further, the resonance frequency of the resonator for various values of metallization ratios is observed. The reduction of metallization ratio reduces the effects of electrical loading of IDT, hence the SAW phase velocity and resonance frequency reach closer to the free surface values. In conclusion, the IDT in SAW devices cause electrical loading that affects the device parameters considerably and it is necessary to include effect of electrical loading while designing a SAW device.

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Appendix A.

Material constants of YZ $LiNbO_3$

Density (ρ) = 4675 kg/m^3

$$\text{Stiffness } \left(c^E\right) = \begin{pmatrix} 24.24 & 7.52 & 7.52 & 0 & 0 & 0 \\ 7.52 & 20.3 & 5.73 & 0 & 8.5 & 0 \\ 7.52 & 5.73 & 20.3 & 0 & -8.5 & 0 \\ 0 & 0 & 0 & 7.52 & 0 & 8.5 \\ 0 & 8.5 & -8.5 & 0 & 5.95 & 0 \\ 0 & 0 & 0 & 8.5 & 0 & 5.95 \end{pmatrix} \times 10^{10}\ \text{N/m}^2$$

$$\text{Piezoelectric constant } \left(e\right) = \begin{pmatrix} 1.3 & 0.23 & 0.23 & 0 & 0 & 0 \\ 0 & 0 & 0.0 & -2.5 & 0 & 3.7 \\ 0 & -2.5 & 2.5 & 0 & 3.7 & 0 \end{pmatrix} \text{C/m}^2$$