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Using COMSOL to model high frequency surface acoustic wave (SAW) device

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Finite element method (FEM) analysis of SAW devices is recently popular to be achieved using the basic information of stress and strain equations for linear elastic piezoelectric materials. A delay line is modeled using Gallium arsenide piezoelectric substrate and is modeled and simulated with center frequency of 1.5 GHz to be used in many electronic devices like oscillators at ultrahigh frequency range (RF-MEMES). A 5 periodic cycles of output voltage is simulated and monitored at output port of delay line while applying a sine wave to input port. Displacement of the SAW through the thickness of piezoelectric substrate is recorded and proofed that SAW does not penetrate more than the designed thickness. Displacement along wave direction is also monitored.

Key words: Finite element method surface acoustic wave (FEM SAW), delay line, radio frequency (RF)

INTRODUCTION

Acoustic wave devices shown in Figure 1 based upon wave generated on the surface of a piezoelectric substrate like Quartz, GaAs, LiNaBo3, LiTaO3, etc. Surface acoustic wave (SAW) delay line structure have three ports, two of them are acoustic; one Input and the other is for output and the third is for electric port.

Each port of two acoustics consists of IDT structure with many fingers spaced as a function of wavelength, one acts as a transmitter (input port) that converts electrical signal into electromechanical wave propagates on the surface of piezoelectric material.

The travel length between receiver and transmitter IDT is called as Delay Time. IDTs have a comb-like structure, where the distance between the fingers in the IDT determines the frequency of the waves propagating over the substrate. The study of these waves is useful in seismology and other areas. The piezoelectric effect is a deflection induced by a voltage across the substrate material or a voltage created by deflection across the material (MacDonald, 2010). Rayleigh waves SAW have two components, longitudinal and vertical shear components, they couple with a media in contact with the surface and affect the amplitude and velocity of the wave. This allows SAW device to sense mechanical properties. SAW devices found in many applications like filters, oscillators, and transformers based on transmission the acoustic wave between input and output ports. Each port employs one or more IDTs (inter-digital transducers) to convert between electrical signals and acoustic (electromechanical) wave and vice versa using piezoelectric effect. More deep applications are now found using SAW devices in Radio, TV, Geophysics,

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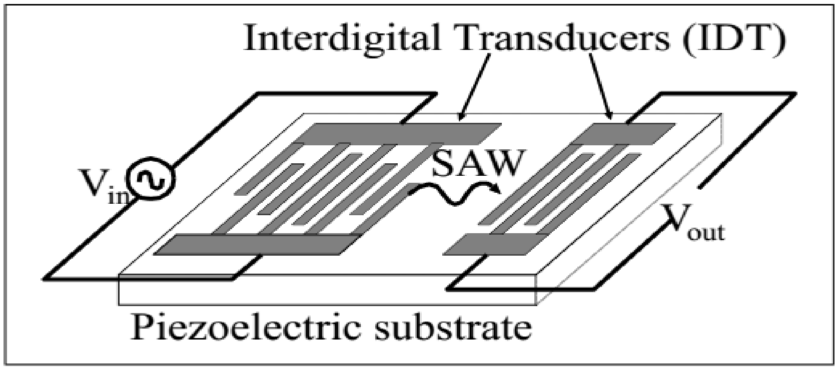

Figure 1. SAW delay line (Hashimoto).

Microfluidics, Flow measurement and Military uses (Wikipedia, 2015). Some previous simulation attempts for SAW devices like filters and correlators are illustrated in frequency domain (Elkordy et al., 2013).

Other study for frequency domain analysis for SAW delay line is introduced (Elsherbini et al., 2015). Model (FEM) is the most appropriate numerical representation of field theory where the piezoelectric characteristics of the SAW devices are easy to be analyzed (Hofer et al., 2006; 2002). FEM tools also provide 3D view for SAW device, such as COMSOL and ANSYS (COMSOL, 2015; ANSYS, 2015).

SUBSTRATE SELECTION

GaAs, gallium arsenide is selected in order to its electronic properties like higher speed switching in semiconductor devices. Also in SAW devices, it has large mobility of electrons. GaAs rarely affect with high temperature (overheating) because it has wide energy band. Devices made of GaAs can operate at frequencies more than 250 GHz. It also generates a very low noise in the circuit with high device frequency. For all above specifications, GaAs can be used in many applications like mobile phones, satellite, radar systems, and solar detectors (Yablonovitch et al., 2012). From the basics of SAW, it is known that SAW propagation in a piezoelectric substrate is controlled through both stress and strain equation (electromechanical) of motion (Auld, 1973).

$$T = CE*S- eT *E \quad (1)$$

$$D =e*S +\varepsilon s*E \quad (2)$$

T is the stress matrix, S is the strain tensors, E is the electric potential field and D is the displacement vector. Parameters CE, εs and e are for the elasticity matrix, permittivity matrix and coupling matrix of the piezoelectric substrate respectively.

Through SAW delay line design, the authors used GaAs as a substrate material with the following parameters and specifications (Table 1):

(a) Density (ρ): 5307 Kg/m^3.
(b) Relative permittivity:

$$\varepsilon = \begin{pmatrix} \varepsilon_{11} & 0 & 0 \\ 0 & \varepsilon_{11} & 0 \\ 0 & 0 & \varepsilon_{33} \end{pmatrix}$$

So the relative permitivity :

$$\varepsilon = \begin{pmatrix} 12.459 & 0 & 0 \\ 0 & 12.459 & 0 \\ 0 & 0 & 12.459 \end{pmatrix}$$

Coupling matrix: Represents strain charge form.

$$e = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & e_{24} & 0 & 0 \\ 0 & e_{32} & 0 & 0 & 0 & e36 \end{pmatrix}$$

$$e = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.139785 & 0 & 0 \\ 0 & 0.139785 & 0 & 0 & 0 & 0.139785 \end{pmatrix}$$

Elasticity matrix: Represents stress charge form.

SAW device model analysis

Analysis of SAW delay line performed with COMSOL multi-physics ver. 5.0. Finite Element Method used due to its wide math equations and calculations in the field of electronic devices (Kutiš et al., 2013; Gálik et al., 2014; Elsherbini, 2015).

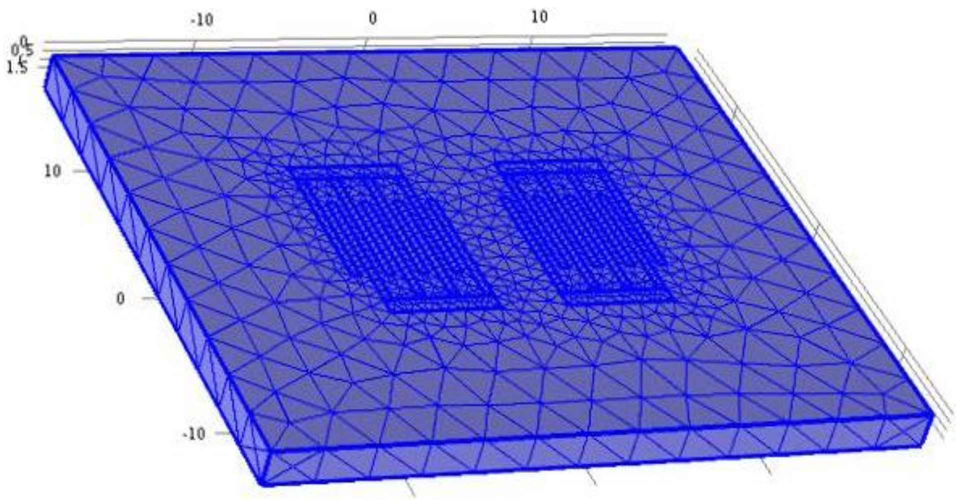

Figure 2. Physical Controlled Mesh.

SAW delay line is modeled as a substrate layer of GaAS, Electrode layers (Au) and air gap between input and output IDTs. A 10V peak of periodic sine wave is applied to the input IDT of 4 electrodes with 1.5 GHz frequency, 2840 m/s acoustic velocity and the wavelength is 1.89 µm. A 5 cycles of output waveform is recorded as a voltage difference on fingers of IDT electrodes. Output is formed by the relation between the mechanical and electrical properties of selected piezoelectric substrate material. It is expected that the amplitude of generated waveform is less than applied input due to energy loss, interference in surface waves and with the fact of SAW decay with the thickness of substrate.

Model is built with λ/4 electrode width, four times of λ for electrode length and electrode pitch. The substrate thickness is selected λ and number of elements required for analysis (Mesh) is one tenth of λ. A time dependent analysis used with equations embedded in COMSOL.

$$\rho \frac{\partial^2 u}{\partial t^2} = \nabla . s + Fv \quad (1)$$

$$\nabla . D = \rho v \quad (2)$$

$$D = D_r + e(\varepsilon - \varepsilon_o) + \varepsilon_o v_{ac} \varepsilon_{rs} E \quad (3)$$

$$\varepsilon = \frac{1}{2}(\nabla u + (\nabla u)^T) \quad (4)$$

Where: ρ is the density, u is the displacement field, ∇u is the structural velocity field, ε_{rs} is the relative permittivity, S is strain, E is electric field, and D_r is remanent electric displacement.

SIMULATION RESULTS

Number of degrees of freedom solved for 56273 shown in Figure 2. Complete mesh consists of 8280 domain elements, 2930 boundary elements, and 544 edge elements. Time Dependent Solver in Solution of SAW model took Solution time of 391 s (6 min, 31 s) to perform the output. Simulation is done with 4GB RAM only and exhausted a physical memory of 773 MB and virtual memory of 840 MB. Maximum mesh size is selected as substrate thickness divided by 10. The maximum solve time step is selected as 1.3333e-11 s as a function of acoustic wave velocity and maximum mesh size. The Rayleigh wave needs approximately 3.32 ns to propagate from input to output IDT (Displacement time). The frequency determined by modal (1.5 GHz) analysis is used as input in transient piezoelectric analysis as frequency of excitation, where 3D model was used.

Input and Output Voltages of SAW delay line IDTs have been monitored in Figure 3. The Rayleigh wave propagates towards output IDT through piezoelectric substate. The output is amplified by a factor of 20 to compensate the energy loss. Comparing it with SAW delay line made LiNaBo3 substrate (Figure 4), the output generated in a time shorter than the LiNaBo3.

Displacement of SAW along wave propagation (X) direction is presented and two values selected for the time, 1.68e-9 s and 6.8e-10 s with offset between them and shown in Figure 5. Rayleigh wave propagated on the surface of GaAs has been recorded in Figure 6. Elastic wave propagation along thickness of substrate (Figures 7 and 8) achieves that SAW does not propagate more than the thickness of λ. Fast Fourrier Transform done for the generated output signal and visualized in Figure 9.

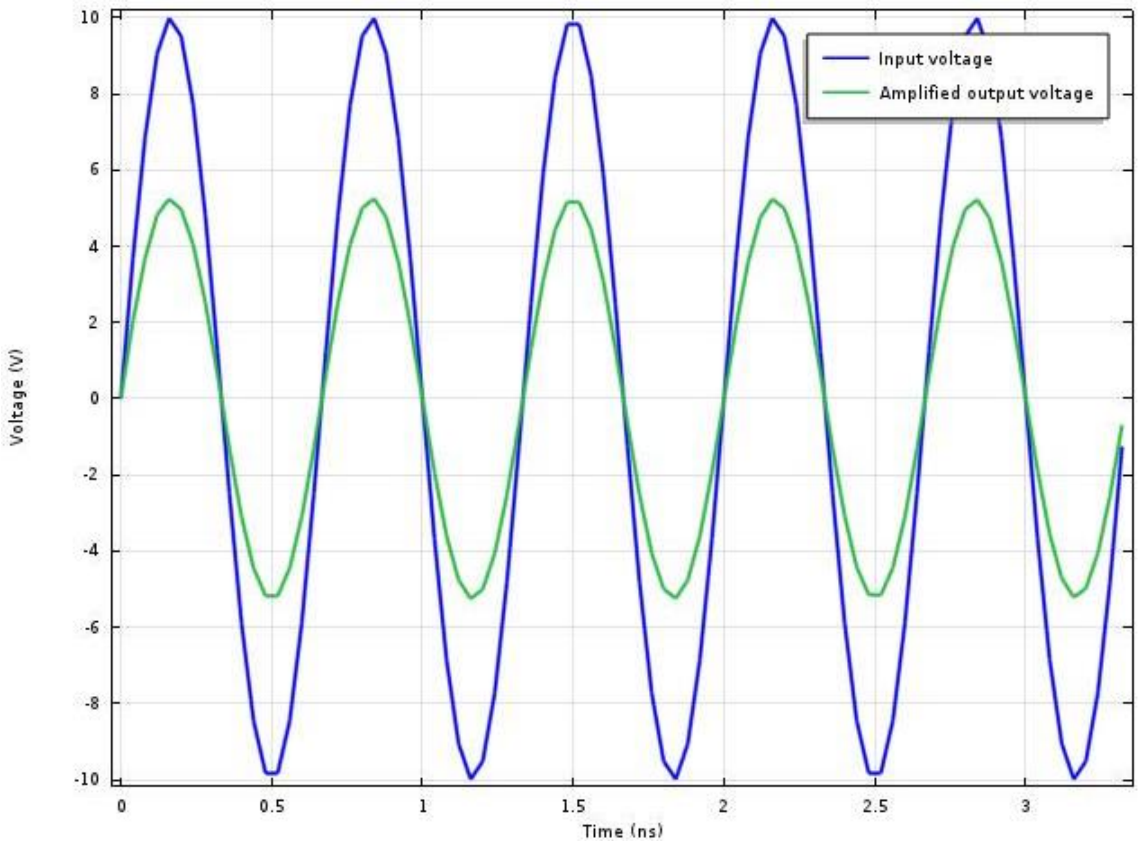

Figure 3. Applied input voltage and generated output voltage of IDTs.

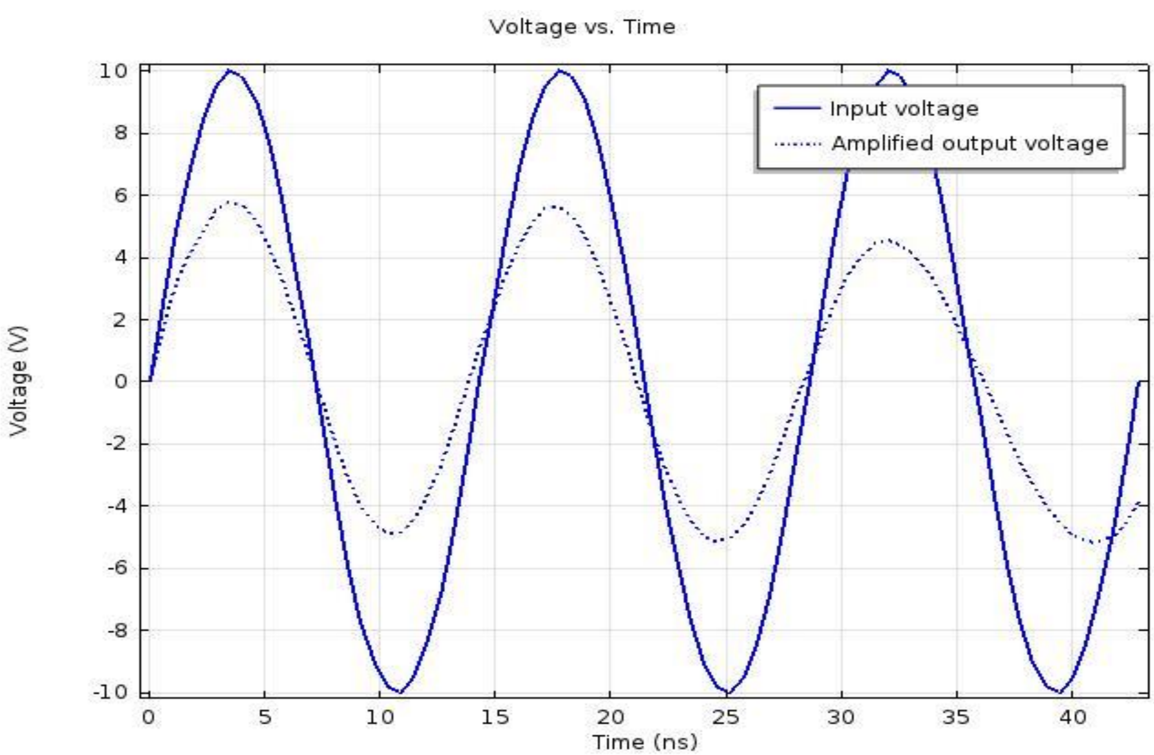

Figure 4. Input and Output Voltage recorded in SAW delay line of LiNaBo3 substrate.

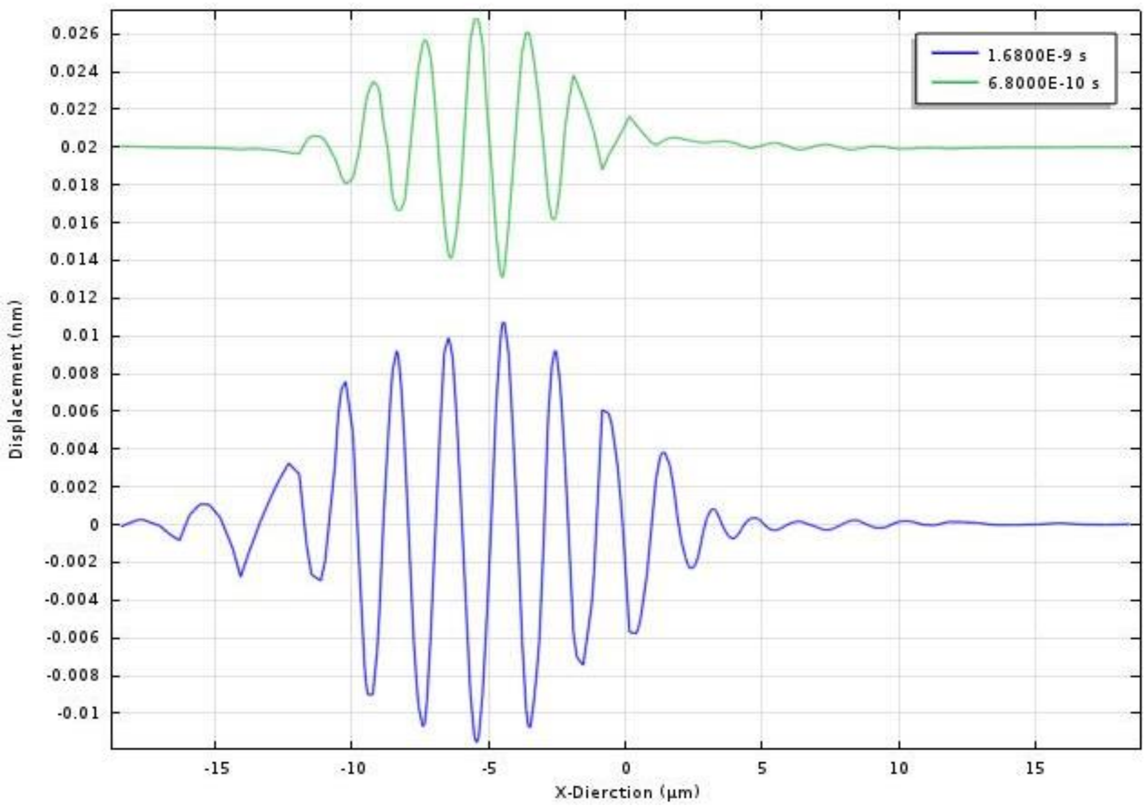

Figure 5. Displacement along X- direction.

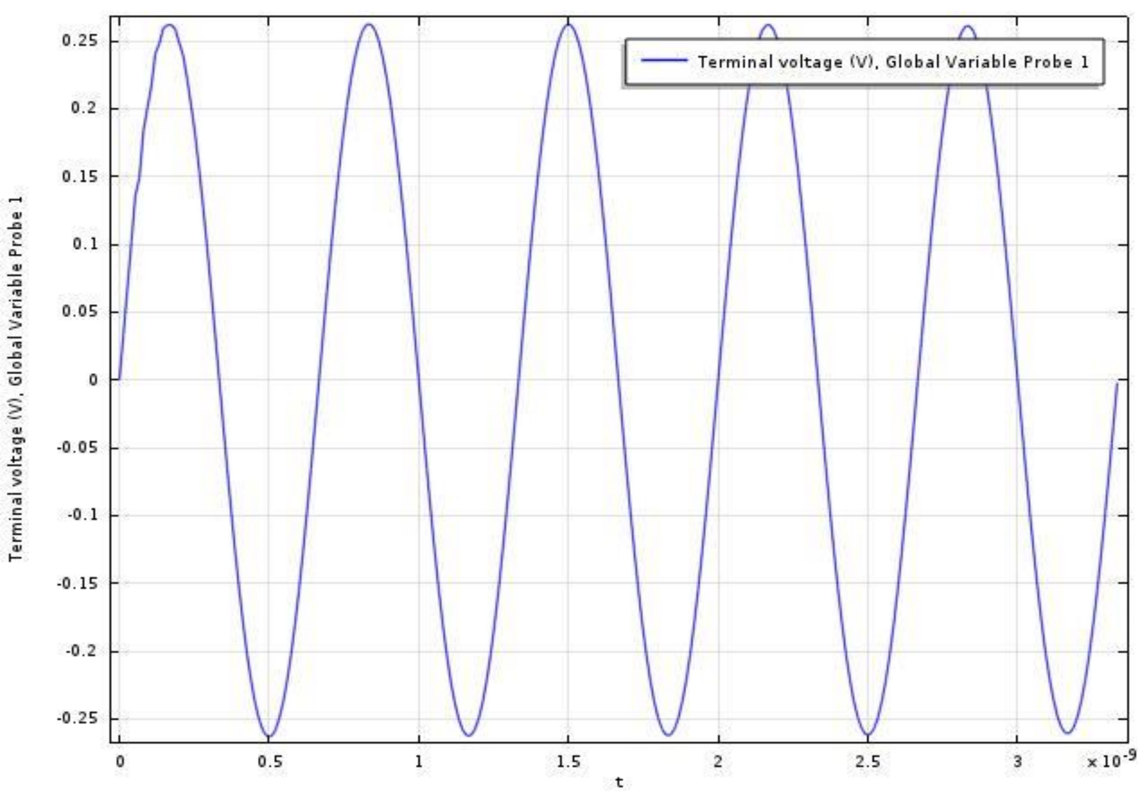

Figure 6. Rayleigh wave propagation on the surface of GaAS.

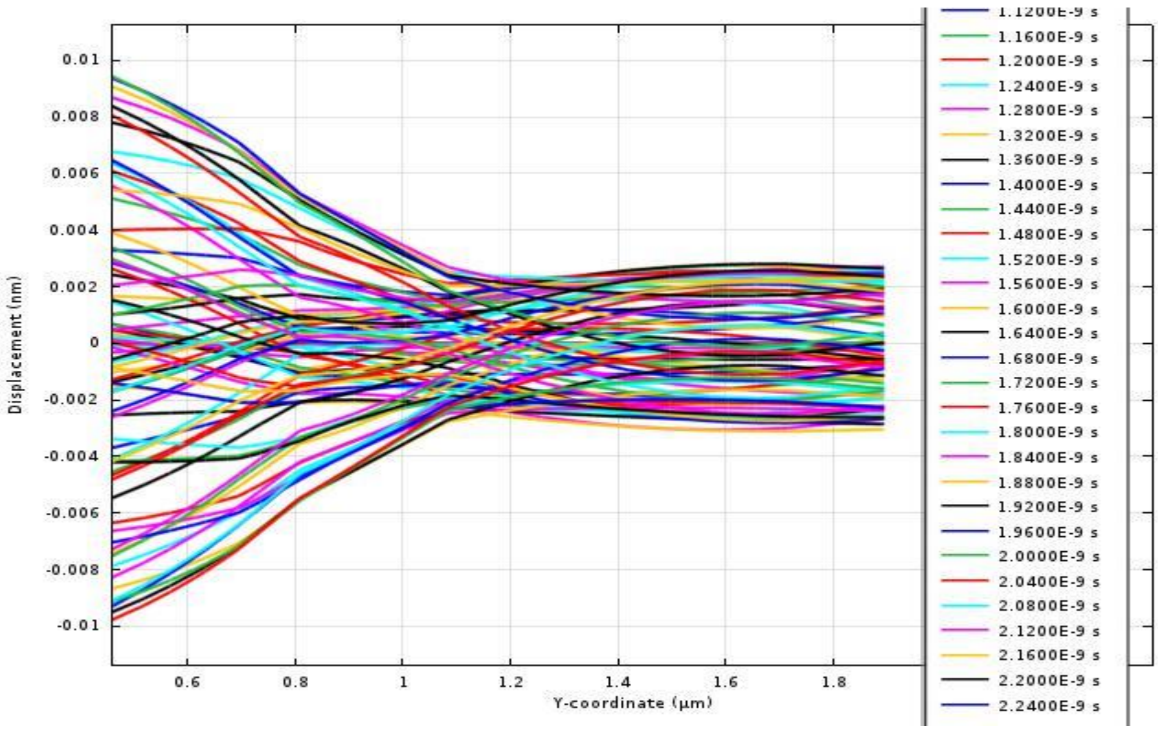

Figure 7. Elastic wave propagation along thickness of substrate via different time periods.

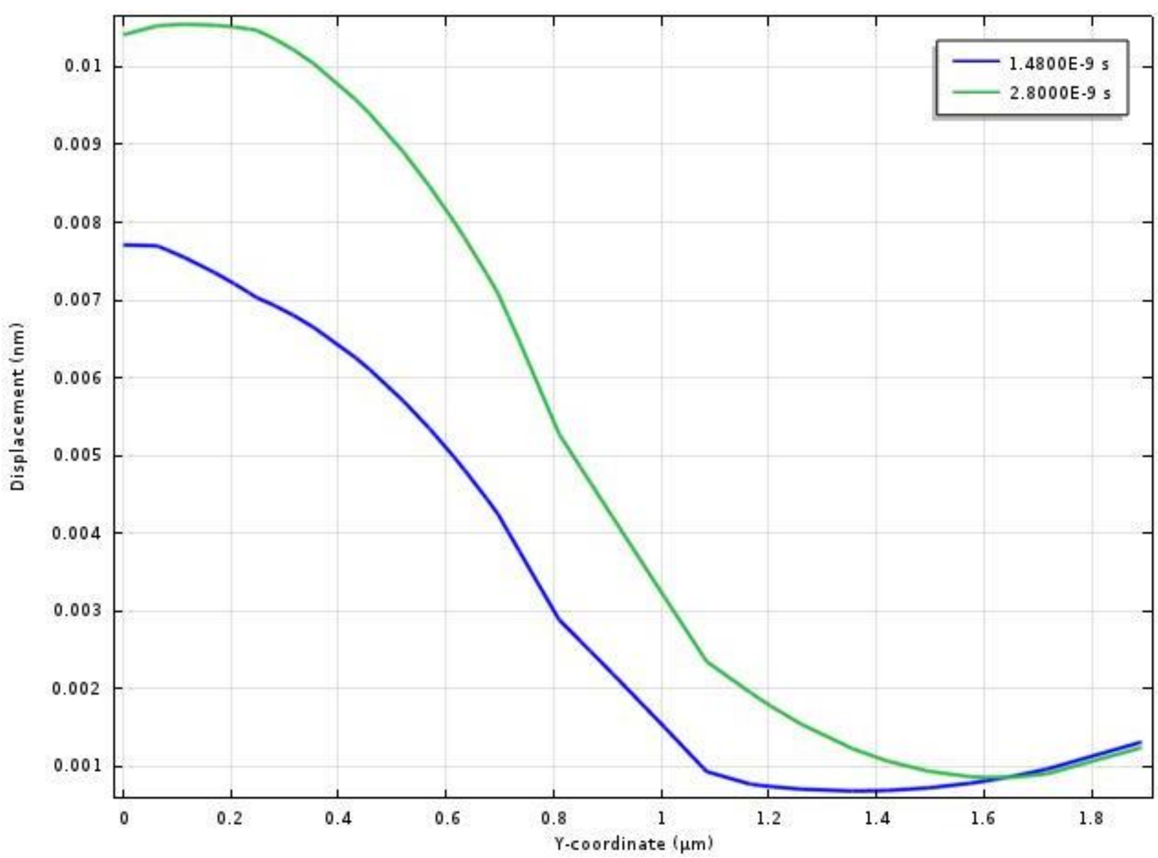

Figure 8. Displacement along thickness.

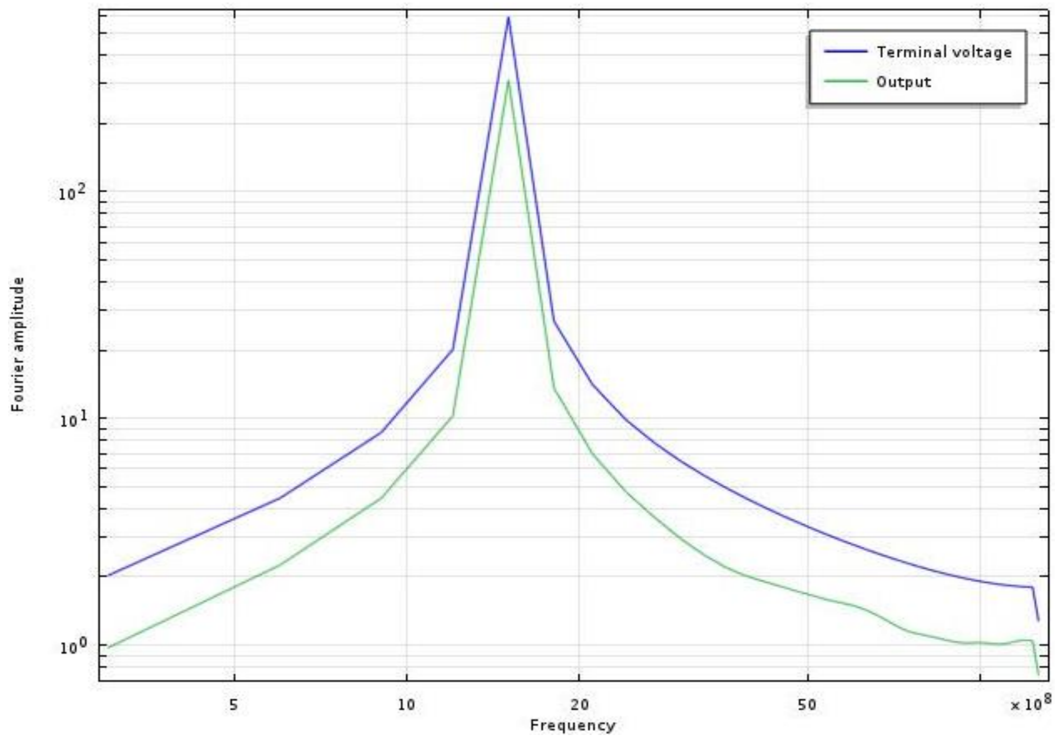

Figure 9. FFT of input voltage and output.

Table 1. Specifications of GaAs substate material.

Parameter	
ε_{11}	12.459
ε_{22}	12.459
ε_{33}	12.459
e_{24}	0.139785
e_{32}	0.139785
e_{36}	0.139785
C11	1.19263E+11
C12	5.99859E+10
C44	5.37634E+10

DISCUSSION

FEM is used to get a 3D view for SAW delay line and explain some results that cannot be explained by equivalent circuit (Impulse response model, matrix model, coupling of modes and modified matrix model). FEM of two port SAW delay line may require 20 mesh elements / wavelength. According to the working frequency, 3-D FEM representation of SAW delay line with hundreds of IDT fingers would require several thousand up to million elements and nodes.

Due to large degrees of freedom, FEM usually takes more time due to lot of electrodes in the real design and require a trial and error to find the results. In order to reduce this consumed time, the matrix method proposed to be used to extract the parameters of SAW devices.

Conclusion

This paper introduces a simple novel method for modeling and design SAW delay line fabricated in GaAs substrate (Table 1). The transient analysis of two port SAW delay line using FEM analysis in COMSOL software is presented. A time dependent study of SAW propagation on surface of piezoelectric material has been introduced using Gallium arsenide as a substrate of two port SAW delay line due to its wide applications. 3D Model for SAW device is designed as a function of the synchronous frequency and Rayleigh wavelength. The output voltage of SAW device is compared with the applied input for a 5 periodic cycles. Rayleigh wave propagation on the surface of GaAS has been visualized. Elastic wave propagation along Thickness of substrate has been monitored. Less time required to generate SAW in GaAs substrate than LiNaBo3.

Conflict of Interests

The authors have not declared any conflict of interests.

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