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Effective and rapid technique for temporal response modeling of surface acoustic wave interdigital transducers

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ABSTRACT

Surface Acoustic Wave Interdigital Transducers (SAW-IDT) has a considerable application potential for characterization of properties of thin layers, coatings and functional surfaces. For optimization of these SAW-IDTs, it is necessary to study various SAW-IDT configurations by varying the number of electrodes, dimensions of the electrodes, their shapes and spacings. The finite element method (FEM) is generally used to model such transducers but results are obtained in several hours (or days). Thus it is necessary to implement effective and rapid technique for SAW-IDT modeling. In this study, we develop simulation tool based on Spatial Impulse Response model. Therefore, we reduce considerably computing time and results are obtained in a few seconds. In order to validate this method, theoretical and experimental results are compared with finite element method. The results obtained show a good concordance and confirm effectiveness of suggested method. In additional, this method requires less computer memory.

1. Introduction

In recent years, the velocity of surface waves has been exploited to characterize different structures, in particular thin metal films, and residual stress gradients [1–3]. Among the methods used to characterize thin films, ultrasonic methods using Rayleigh waves are particularly interesting because the propagation of these waves is close to the surface of the material and the energy is concentrated within a layer under the surface of about one wavelength thick. In order to characterize very thin films (coatings for example), the Rayleigh wave wavelength should be of the same order as the film thickness. High frequencies (10–100 MHz) are, therefore, necessary to characterize very thin films and to achieve this we have developed a broadband SAW-IDT for surface wave generation [4]. A SAW-IDT consists of two overlapping metal comb-shaped electrodes with interdigitated fingers and coverage length Wa [Fig. 1].

The electrodes are deposited on a piezoelectric lithium niobate ($LiNbO_3$) substrate. When a voltage U is applied between the two electrodes there is an accumulation of charge of which the signs alternate from one finger to the other thus creating an electric field E_x between each pair of fingers. The combination of the piezoelectric effect of the substrate and the electric field generates expansions and compressions in the material thus creating displacement. This displacement gives rise to Rayleigh waves which radiate mainly perpendicular to the fingers [5,6].

2. Rayleigh wave excitation with SAW-IDT

The setup shown in Fig. 2 gives an example of the SAW-IDT used to measure velocity in the tested sample. The SAW-IDT surface is coupled with the sample using an acoustic coupling agent. The Rayleigh wave generated by the SAW-IDT then propagates along the sample surface perpendicularly to the fingers in *x* direction. The surface displacement induced by the propagating Rayleigh wave is measured by a focused laser interferometer. The signal corresponding to the normal component of Rayleigh wave displacement as a function of time (i.e. A-scan) is measured at position *x* and recorded via an oscilloscope.

In order to improve the performance of such transducers, it is necessary to optimize them by choosing the right electrode number, shape, and spacing. The finite element method (FEM) has shown its effectiveness and can be used to model such transducers. However, the considerable memory requirements [7] and long computation times [1] have led us to develop an effective and rapid simulation tool for modeling SAW-IDT. This new simulation tool is validated experimentally and by comparison with FEM results. The results obtained show good agreement and confirm the effectiveness of the proposed approach.

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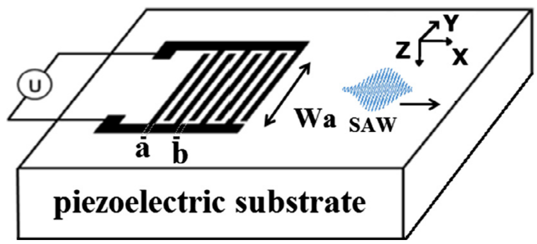

Fig. 1. Schematic diagram of an interdigital SAW-IDT with 8 fingers.

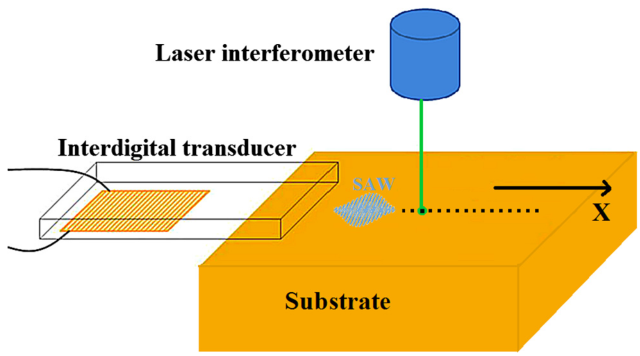

Fig. 2. Rayleigh wave generation by SAW-IDT in the test sample and its recording by the focused laser interferometer.

3. Rayleigh wave propagation

The plane surface wave includes both longitudinal and transverse components, u_1 and u_3, with a $\pi/2$ phase shift [Fig. 3]. The amplitude of in-plane Rayleigh wave decreases exponentially with sample depth z [8]:

where E_x is the electric field between each pair of fingers when a voltage U.

$$\begin{cases} u_1 = A_1(e^{-k\chi_1 z} - \sqrt{\chi_1\chi_2}e^{-k\chi_2 z})e^{i(\omega t-kx)} \\ u_3 = i\sqrt{\frac{\chi_1}{\chi_2}}A_1(e^{-k\chi_2 z} - \sqrt{\chi_1\chi_2}e^{-k\chi_1 z})e^{i(\omega t-kx)} \end{cases} \quad (1)$$

where

$\chi_1 = (1 - V_R^2/V_L^2)$; $\chi_2 = (1 - V_R^2/V_T^2)$; $V_R = \omega/k$.

V_R is the Rayleigh wave velocity, V_L and V_T are the longitudinal and transverse waves velocities, respectively, $k = 2\pi/\lambda$ is the wave number, and $\omega = 2\pi f$ is the angular frequency.

At the surface (z = 0), the two displacements become, respectively,

$$\begin{cases} u_1 = Be^{i(\omega t-kx)} \\ u_3 = i\sqrt{\frac{\chi_1}{\chi_2}}Be^{i(\omega t-kx)} \end{cases} \quad (2)$$

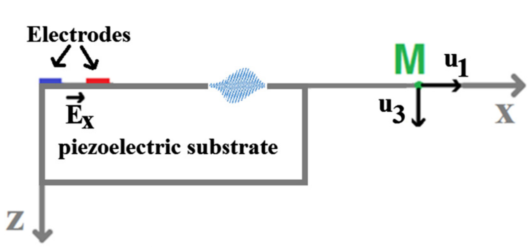

Fig. 3. Geometry for Rayleigh wave propagation.

where

$$B = A_1(1 - \sqrt{\chi_1\chi_2})$$

Finally the Green's function of the plane Rayleigh wave propagating at the surface (z = 0) in the x-direction, can be presented as:

$$G(\omega, R) = Ue^{-j(\omega t-kR)} \quad (3)$$

where R represents the distance travelled by Rayleigh wave [9].

For an emitting finite size transducer, the Rayleigh wave is not a plane wave and its Green's function for a non-absorbing medium can be presented as [10,11]:

$$G(\omega, R) = A\frac{e^{-j(\omega t-kR)}}{2\pi\sqrt{R}} \quad (4)$$

By taking the inverse Fourier transform this yields the time-domain Green's function for Rayleigh wave as:

$$g(t, R) = A\frac{\delta(t-\frac{R}{V_R})}{2\pi\sqrt{R}} \quad (5)$$

To measure displacements, we used an interferometer which evaluates the normal component u_3 (transverse component) and not the tangential component u_1. The latter can be determined directly using the Green's function defined previously. Therefore, to use DREAM (Discrete REpresentation Array Modeling), it is necessary to study the relation between normal and tangential displacement. This was achieved using FEM.

4. Acoustic field modeling using a spatial pulse response method

Spatial impulse response was introduced by Stepanishen [12]. The calculation is based on the velocity potential impulse response obtained from the Rayleigh Integral [13]:

$$h(M, t) = \int_S v_n(P)\frac{\delta(t-\frac{R}{c})}{2\pi R}dS(P) \quad (6)$$

where S is radiating planar surface, R represents the distance between the surface element dS(P) and the observation point (M) and δ is the Dirac delta function [Fig. 4].

Each point P of the surface S is excited by a Dirac pulse $v_n(P) \times \delta(t)$, $v_n(P)$ is the normal velocity associated with point P. This equation expresses in fact Huygens' principle: the potential at the observation point M is obtained by summing the elementary waveforms $(v_n \cdot (\delta(t)/2\pi R) \cdot dS)$ radiated by all elements dS with a propagation delay R/c (c is the propagation velocity). The integral of Eq. (6) represents the principle of superposition from elementary waves radiated by elements dS. It was typically used for modeling radiation of plane transducers in liquid media [14]. This principle has been also largely exploited for modeling an IDT for generating Lamb waves [15,16]. In recent years, some

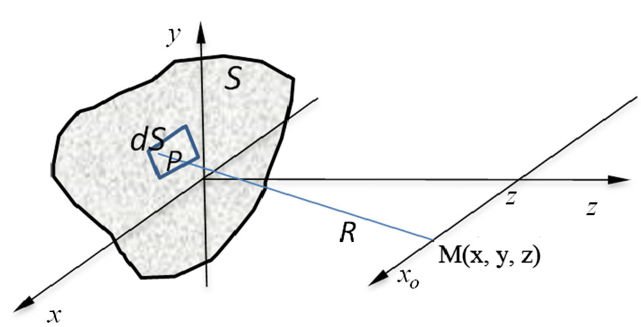

Fig. 4. Radiation from a disk source.