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A NEW APPROACH TO CHARACTERIZING ACOUSTIC WAVES PROPAGATING UNDER A PERIODICALLY ELECTRODED ARRAY ON PIEZOELECTRIC SUBSTRATE

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Abstract:

The coupling problem between electrodes owing to acoustic wave propagation and electrostatic effect in a periodic metal grating on a piezoelectric substrate is theoretically studied. Harmonic admittance approach is used to obtain the complete acoustic wave spectrum, and mutual admittance is taken to describe wave propagation properties under the grating. Analytical expression for the contribution of surface wave (SAW) is proposed, and its characteristic parameters are numerically determined. A particular feature of the present study consists of using a particular curve-fitting technique to deal with a leaky SAW as well as a conventional Rayleigh SAW. The accurately determined SAW's parameters allow to correctly remove the participation of SAW from the global coupling, so makes it easier to analyze the spurious bulk waves (BAW), especially the surface skimming bulk waves (SSBW) in such devices. The plot as a function of propagation distance, n , of the BAW mutual admittance shows that the BAW's amplitude in the far-field varies according to a power law, i.e., n^{-p} , the value of p strongly depends on the substrate configuration.

1. Introduction and Formulation of the problem

Surface acoustic wave (SAW) propagation in a system of metal strips deposited on a piezoelectric substrate is a very important but difficult problem. In spite of the efforts contributed by a number of workers [1-6] with some idealization, a complete description and characterization of all acoustic waves is not available. In this work we present a method for analyzing coupling phenomena between electrodes, taking into account all acoustic waves and electrostatic contributions. Using the concept of "harmonic admittance" and adopting the formulation given by Bløtekjær *et al* [2] for obtaining harmonic admittance, we put the emphasis of our study on the analytical description and numerical determination of the characteristic parameters of the SAW that can propagate under a grating. In our study, a piezoelectric substrate is assumed to occupy the half-space $x_2 \geq 0$; an infinitely thin, perfectly conductive grating is deposited from $x_1 = -\infty$ to $x_1 = +\infty$ on its plane surface. The width of a strip is a and the period of the grating is p . The length W of the strips is assumed to be large enough for edge effects to be neglected.

1.1 : Harmonic and Mutual admittance

In the case where the voltages applied on all the strips have the same amplitude V_0 but the phase progresses uniformly along the electrodes of the grating at the rate of kp per period, the voltage and current of the n^{th} electrode can be written as

$$V_n = V_0 \exp(-jnkp) = V_0 \exp(-j2\pi n\gamma) \quad I_n = I_0 \exp(-j2\pi n\gamma) \quad (1)$$

where γ is defined by the fractional part of $(kp/2\pi)$, and represents the normalized propagation constant. Then, the harmonic admittance, Y is defined as the ratio of the current in the strip, I_n to its voltage, V_n , i.e., $Y(\omega, \gamma) = I_n/V_n = I_0/V_0$, so that Y is independent of the strip number, n . In these equations both I_0 and V_0 are functions of γ and of the frequency, ω , and they also depend on the substrate configuration (material and orientation). In what follows, the argument ω will be omitted. The detailed deduction of the expressions of I_0 , V_0 and Y are given in Ref. [2], according to which the harmonic admittance can be written as

$$Y(\gamma) = [2 \omega \varepsilon(\omega) W] Y_0(\gamma) \quad (2)$$

where $Y_0(\gamma)$ can be known only in the numerical form via the wavenumber-dependent effective surface permittivity. A more general problem is the case where the electrical potential V_n on the

strips is arbitrary. One of the possible approaches to solving this problem is to use the charge superposition principle. A key step of this approach is to determine the charge distribution in the grating when only one of the strips is excited, all the others being grounded. Without loss of generality, we consider I_n , the current circulating in electrode number n due to a potential applied onto electrode number zero, V_0 . The mutual admittance, Y_n is defined by the relation: $Y_n(\omega) = I_n/V_0$. Then it can be shown that the harmonic admittance and mutual admittance is related by the following integral:

$$Y_n = \int_0^1 Y(\gamma) \exp(-j2n\pi\gamma) d\gamma \quad (3)$$

1.2: Identification of diverse participations to $Y(\gamma)$ and Y_n

The mutual admittance, Y_n expressed by eq.(3), upon substitution of $Y(\gamma)$ from eq.(2), represents the global coupling between any two electrodes separated by n periods. The coupling occurs from diverse origins: propagation of acoustic waves (namely, SAW and SSBW) and the electrostatic effect (dielectric). To search for analytical development of Y_n and give an appropriate analytical expression for each physical origin we write:

$$Y_n = Y_{nd} + Y_{ns} + Y_{nr}; \quad Y(\gamma) = Y_d(\gamma) + Y_s(\gamma) + Y_r(\gamma) \quad (4)$$

with "d, s, r" designating respectively "dielectric, surface wave, and residual" part. We propose for the dielectric part $Y_d(\gamma)$ and the SAW the following analytical expressions:

$$Y_d(\gamma) = j\omega W \epsilon_d \sin(n\pi\gamma); \quad Y_s(\gamma) = Y_{s0} \frac{1 - \cos(2n\pi\gamma)}{\cos(2n\pi\gamma_s) - \cos(2n\pi\gamma)} \quad (5)$$

where ϵ_d is an equivalent dielectric coefficient, the use of which is aimed at ensuring the continuity of the slope of the curve $Y_r(\gamma)$ at $\gamma = 0$ and 1 ; and γ_s and Y_{s0} are two characteristic parameters of the considered SAW mode, their values will be determined by numerical curve-fitting technique.

The above expression chosen for the SAW contribution, eq.(6) is justified by the facts: firstly, if $Y_s(\gamma)$ is subtracted from $Y(\gamma)$, the pole or pseudo-pole of $Y(\gamma)$ at $\gamma = \gamma_s$ will be removed; secondly, its inverse transform has the physically correct properties of the electrical potential associated with a SAW. In fact we can demonstrate that $Y_s(\gamma)$ defined in eq.(5) corresponds in spatial domain to a mutual admittance:

$$Y_{ns}(\omega) = \begin{cases} -j Y_{s0} \operatorname{tg}(\pi\gamma_s) \exp(-j2n|\alpha|\gamma_s) & \text{for } n \neq 0 \\ -j Y_{s0} \operatorname{tg}(\pi\gamma_s) (1 + j/\operatorname{tg}(\pi\gamma_s)) & \text{for } n = 0 \end{cases} \quad (6)$$

We see from eq.(6) that γ_s represents the propagation constant of the SAW in a shorted grating, the modulus of Y_{s0} is directly related to the SAW's amplitude. For an RSAW, γ_s is purely real, Y_{s0} purely imaginary; but, both γ_s and Y_{s0} have to be complex in the case of an LSAW. The accurate determination of γ_s and Y_{s0} is necessary for the behaviour of this kind of SAW to be correctly characterized.

2. Numerical results of harmonic admittances and SAW's parameters

The method has been applied to the study of a number of substrate configurations. The harmonic admittance was numerically computed from eq.(2). The integral in eq.(3) was evaluated using a fast fourier transform algorithm. In our numerical computations, 8192 samples were taken for γ in the interval $(0, 1)$. Y_n obtained in this manner corresponds to a periodic excitation, i.e., every 8192 electrode, instead of "unitary excitation".

On Fig.1(a) and 2(a) is plotted the harmonic admittance, $Y(\gamma)$ normalized by $(2\omega W \epsilon(\infty))$. Because of the symmetry, the plot is given only for $\gamma = 0$ to 0.5 . The RSAW and LSAW modes in a short-circuited grating can be identified on the plots, by respectively a true pole and a pseudo-pole of the function $Y(\gamma)$; while a true zero and a pseudo-zero of the function $Y(\gamma)$ are associated with these modes in an open circuited grating, except for $\gamma = 0$ and 1 . A discontinuity in the slope of the $Y(\gamma)$ curves indicates the existence of a SSBW mode, whose number varies with crystal orientations, but whose propagation constant (exact position of the discontinuity) does not depend on whether the grating is open or shorted, neither on the ratio a/p . Around a "pole" estimated by observation of the $Y(\gamma)$ curves, using second equation in (5) for the analytical expression of the SAW harmonic admittance, and the numerical data computed beforehand for the global harmonic admittance $Y(\gamma)$, we searched for the appropriate values of γ_s and Y_{s0} that can best fit the $Y_s(\gamma)$ defined in eq.(5) into the global $Y(\gamma)$. In this way we have been able to accurately deduce the two parameters γ_s and Y_{s0} . Then, the propagation velocity of the SAW, V_s , can be deduced by identification of $\exp(-j2n\pi\gamma_s)$ with $\exp(-j2n\pi \operatorname{Re}(\gamma_s)x_1/p)$; and for the LSAW, the attenuation coefficient, α (in dB/ λ_s), is given by (-20) times $\log_{10}(2\pi \operatorname{Im}(\gamma_s)x_1/p)$. These results are given in Table I. The amplitude factor, Y_{s0} was obtained for an array width equal to one wavelength ($W = \lambda_s$).

3. Analysis of the BAW's contribution

Subtracting from the global $Y(\gamma)$ the SAW's contribution and the electrostatic contribution defined in eq.(5), the residue of the harmonic admittance, $Y_r(\gamma)$ results and is plotted on Fig.1(b) and 2(b). This remainder is mainly composed of the SSBW's contributions and they are the main parasitic signals occurring in a SAW device. To improve device performances it will be necessary to take into account these parasitic effects in SAW device design.

Since the residual part of the harmonic admittance is known only in the form of numerical data, its properties in the spatial domain cannot be deduced directly through mathematical analysis as for the SAW or the dielectric contribution. To know the SSBW's behaviour in the physical space, especially the diminution with propagation distance, we have numerically evaluated the integral in eq.(3) with $Y(\gamma)$ replaced by $Y_r(\gamma)$. On Fig.3 is presented, as an example of Y_{nr} , the result for 36° YX-LiTaO₃. This figure represents Log-Log plots of the module of Y_{nr} as a function of n , the number of periods separating the excitation and detection electrodes. This presentation makes it evident that the mutual admittance decreases with n according to a law of the form :

$$Y_{nr} \sim n^{-p} \quad (7)$$

the slope of the curve's envelope gives directly the value of p to be determined.

Fig.3 shows a very regular envelope up to $n=10^3$, for $n > 10^3$, the presence of other signals become visible, they give rise to the appearance of small modulation on the envelope, and their influence goes up with n increasing. This phenomenon may be explained by the following: in this substrate, only longitudinal (L) and fast shear (FS) modes of SSBW are strongly coupled, slow shear mode of SSBW being negligibly small, the residual part of the mutual admittance is essentially contributed by these two waves. Since they propagate with different speed, their modulation takes place and forms the envelope of the resultant Y_{nr} . The small singularities occurring for large values of n may be attributed, on the one hand, to the residue of pole that was not a hundred per cent extracted by using eq.(5), an error coming from the limited precision implied in numerical iteration process but not from the formule itself; and on the other hand, to the returning signals of L mode and FS mode of SSBW, we recall that the response of Y_n obtained by FFT method corresponds to a periodic excitation, i.e., every 8192 electrodes. The overall envelope of the curve has approximately a slope value of $p = 1.2$. Computations made for other substrates give the value of p is 1.3 for 41° LiNbO₃, 0.56 for 42.5° quartz, and p varies with n in YZ LiNbO₃.

4. Summary and concluding remarks

We have analyzed the acoustic waves propagating under a periodic metal grating. The use of the harmonic admittance approach allows us to take into account the true and leaky SAW, SSBW, as well as electrostatic effects. Analytical expressions have been proposed for describing the individual participation to electrode coupling due to SAW and electrostatic effect. The two characteristic parameters of SAW have been determined using a curve-fitting technique. Even though all calculations are carried out in the real wavenumber domain, the method is still able to obtain the complex propagation constant of a leaky SAW. The behaviours of SSBW are analyzed after the numerical data resulting from the exact removal of SAW's and dielectric participations. The analysis has been made in both wavenumber domain and space domain. Studies of the mutual admittance associated with SSBW's show that their amplitude diminishes with propagation distance as a power law like n^{-p} , with the value of p , always positive, varying from one substrate configuration to another. Behaviours of Y_{nr} together with $Y_r(\gamma)$ also show that when only two SSBW are significant, the resultant Y_{nr} has a regular envelope form, but when three or more SSBW are present, the resultant Y_{nr} has a complicated figure, which may appear in the form of local modulation or on the level of overall envelope, this makes it very difficult to deduce the exact properties of SSBW modes in space domain directly from the numerical data that include several SSBW's. An accurate knowledge of the BAW's characteristics requires the identification of the individual contribution due to each SSBW's mode, so that finding an analytical expression appropriate to a SSBW mode will be our next objectif of studies.

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Table I : Substrate configurations, grating and frequency parameters used in the present study and the SAW(Rayleigh and leaky) parameters (propagation velocity, attenuation coefficient and amplitude factor) determined by curve-fitting method using equation (5).

substrates	a / p	f×p(m/s)	V _s (m/s)	α (dB/λ _s)	-j×tg(nγ _s)×Y _{s0}
42.5° YX-quartz	0.5	1082.4	5083.3436 3158.1105	4.65524e-1 0.	2.4066e-6, -1.4263e-7 9.7691e-6, 0.
36° YX-LiTaO ₃	0.486	1050	4134.5526 3132.2162	4.32185e-3 0.	4.9049e-4, -1.3595e-7 3.8277e-5, 0.
41° YX-LiNbO ₃	0.5	1200	4444.0654 3638.3225	2.71265e-2 0.	1.5084e-3, -1.1686e-5 2.2554e-5, 0.
YZ-LiNbO ₃	0.486	1400	3429.5085	0.	3.6909e-4, 0.

Fig. 1 : Harmonic admittance Y(γ) of 36° YX-LiTaO₃ substrate : (a) before and (b) after removal of SAW's contributions. broken line : negative real part, solid line : imaginary part
Fig. 2 : as figure 1, for YZ-LiNbO₃ substrate

Fig. 3 : Log-log plot of the module of BAW's mutual admittance obtained from figure 1(b), as a function of propagation distance, n. The amplitude of BAW decays as a low of n^{-1.2}