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Leaky Wave Propagation in Layered Structures

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Abstract - The propagation characteristics of leaky waves in layered structures are analyzed as functions of overlay thickness. The behavior of different types of degenerate leaky waves with negligible attenuation, existing in quartz and lithium tetraborate, are studied when thin film of ZnO or Al is deposited on the substrate. In particular, the propagation characteristics of a leaky wave are analyzed when its velocity approaches to that of the limiting bulk wave. The general features in the behavior of leaky waves in layered structures are established as well as some peculiarities caused by the occurrence of a concavity on the slowness surface of a substrate material.

1. INTRODUCTION

The rapid development of modern communication systems results in the increasing requirements to SAW devices which are the key elements of such systems. The most important of these requirements are high frequency, low insertion loss and temperature stability. Therefore SAW materials with high propagation velocity, strong piezoelectric coupling and low temperature coefficient of frequency are preferable. Some of these requirements can be satisfied if leaky surface acoustic wave (LSAW) is used instead of common SAW. However, in general LSAW exhibits high attenuation, and only selected orientations which support propagation of low-attenuated leaky waves can be useful.

Additional possibility to improve device performance is provided if a layered structure is used with an optimal combination of overlay and substrate materials. Though SAW propagation in such structures has been extensively studied, only a few works have been published on the analysis of LSAWs. Moreover, it can be shown that some earlier made conclusions concerning the behavior of LSAWs in layered structures [1] are true only for particular case and cannot be generalized for all leaky waves, because this behavior depends considerably upon the structure of a leaky wave. The main purpose of the present work is to reveal some general features and peculiarities of the propagation of leaky waves in layered structures which result from the nature of leaky waves. Since in SAW devices only low-attenuated leaky waves are applicable, four main types of degenerate non-attenuated leaky waves existing in half-infinite medium will be further considered (see also [2,3]).

Type 1. “True” SAW with the structure similar to that of Rayleigh surface wave. It is composed of inhomogeneous partial waves while the contribution of bulk partial waves tends to zero.

Type 2. One-partial exceptional bulk wave (EW) with energy flux parallel to the surface, which satisfies the stress-free boundary condition.

Type 3. Two-partial or three-partial composite exceptional wave (CEW) satisfying stress-free condition while none of contributing bulk waves is exceptional.

Type 4. Brewster’s reflection of a bulk wave resulting in satisfying boundary conditions by a combination of incident (incoming) and reflected (outgoing) bulk waves. Though this type of degenerate LSAW with a structure of composite bulk wave may be considered as “non-physical”, we shall analyze its behavior in layered structures, first, because this type is the most frequently found in crystals, and second, because it can be easily transformed into the “physical” one if a thin overlay is deposited on the substrate.

While degenerate LSAWs of type 1 or type 4 exist in non-piezoelectric and in piezoelectric crystals, pure types 2 and 3 can be found only in non-piezoelectric crystals or certain symmetric orientations of piezoelectric crystals. Deposition of a thin layer, as well as the piezoelectric effect, perturbs the structure of degenerate leaky wave. However, the main features of LSAW behavior can be predicted if the type of unperturbed LSAW is properly identified.

The examples of different types of degenerate leaky waves have been found in crystals of quartz and LBO and analyzed as functions of overlay (ZnO, Al) thickness.

2. Leaky waves propagating in rotated Y-cuts of quartz with ZnO overlay

Deposition of ZnO overlay on quartz substrate enables to provide simultaneously high piezoelectric coupling and temperature stability. The propagation characteristics of SAWs and LSAWs have been analyzed in two rotated Y-cuts of quartz, ST,X-cut [Euler angles (0^0, 132.75^0, 0^0)] and LST-cut [Euler angles (0^0, 15^0, 0^0)], as functions of ZnO overlay thickness. Two types of degenerate leaky waves can be found in the analyzed orientations, type 1 and type 4, though the last one is modified into the low-attenuated quasibulk wave. As it was shown in [4], the pure solution of type 4 exists in ST,X+29° cut. In all calculations the material constants of "film ZnO" were used [5].

The results of calculation for ST-cut are presented in Fig.1. In addition to the first-order SAW1 and the second-order SAW2, low-velocity (LSAW1, LSAW2) and high-velocity (LSAW3) leaky waves can propagate within the analyzed range of ZnO thicknesses. Theoretical and experimental analysis of different propagation modes existing in this layered structure was performed in [6], and we shall focus on some peculiarities which have not been discussed earlier.

On the contrary to the low-velocity leaky wave branch LSAW1, which exhibits deep minimum of attenuation coefficient when $h/\lambda=0.06$, the high-velocity branch LSAW3 is strongly attenuated for any ZnO thickness, except for $h/\lambda=0$. It is explained by the nature of LSAW3. Without overlay it is a modified Brewster's reflection solution of boundary

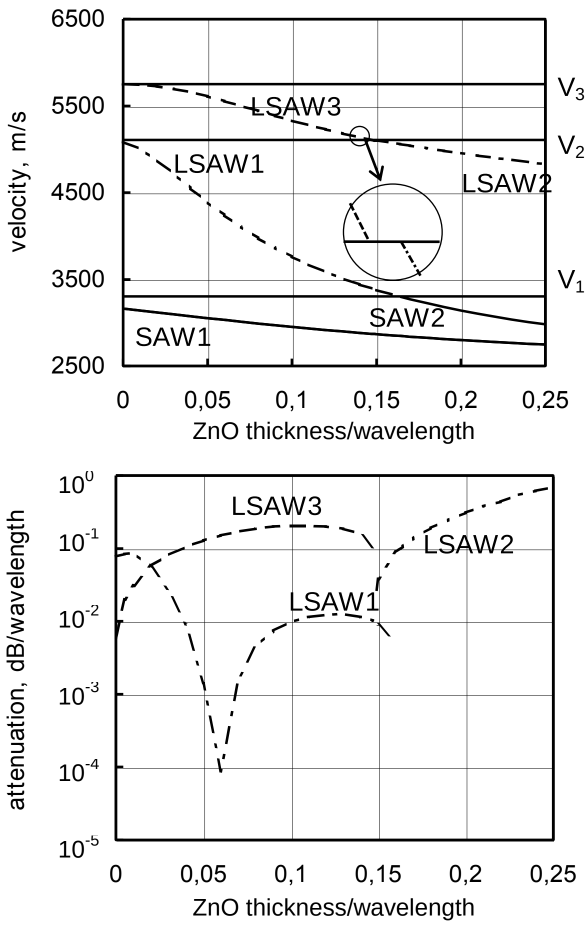

Fig. 1. Propagation characteristics of SAWs and LSAWs in ST,X cut of quartz as functions of normalized ZnO thickness. V_1, V_2 and V_3 are the limiting velocities of bulk waves

problem with velocity exceeding the limiting value V_3. Though deposition of ZnO film reduces LSAW velocity, moves it into the interval (V_2,V_3) and hence makes LSAW "physical", any perturbation disturbs the equality between the normal components of incident and reflected energy fluxes in the Brewster's solution and is followed by the drastic growth of attenuation . Moreover, it has been found that no shift of crystallographic orientation can ensure zero attenuation of this type of LSAW if an overlay thickness is nonzero. Therefore, though non-attenuated solutions of type 4 can be easily found in many crystals, their application in SAW devices is problematic.

Let us consider the behavior of LSAW characteristics when the velocity tends to the limiting value V_1 or V_2. The accurate numerical analysis shows that there is no "merging" of LSAW3 into LSAW2 in the point $V=V_2$ (see enlarged fragment in Fig.1), the discontinuity being proportional to the attenuation coefficient. All the other LSAW characteristics also exhibit non-monotone change in the vicinity of the limiting velocity V_2. Similar discontinuity takes place between the branches LSAW1 and SAW2 when $V=V_1$.

The discontinuity can be explained if we consider the behavior of the pair of complex roots of the characteristic equation around any limiting velocity V_0. For simplicity, let us take the case of isotropic medium. Then the pair of complex roots is defined by

$$\alpha^2 = (V/V_0)^2 - 1 \qquad (1)$$

For leaky wave with mechanical displacement $U=U_0 \exp[jk(x-Vt)] \exp(jk\alpha z)$ and complex velocity $V(1-j\delta)$, where δ is attenuation coefficient along the propagation direction, (1) can be written as

$$\alpha^2 = (a^2+b^2)^{1/2} \exp[j \tan^{-1}(b/a)] \qquad (2)$$

where

$a = (V/V_0)^2 (1-\delta^2) - 1,$

$b = -2\delta (V/V_0)^2$

If attenuation tends to zero (b=0), then $V=V_0$ is a branch point with $\alpha_1=\alpha_2=0$. If the crystal occupies the half-space z>0, then the physically acceptable solution must satisfy $\mathrm{Im}(\alpha)>0$ when $V<V_0$ and $\mathrm{Re}(\alpha)>0$ when $V>V_0$. Consequently, there is a continuous transition from the "physical" branch α_1 to the "physical" branch α_2 in the point $V=V_0$ (see Fig.2a). In anisotropic medium $\alpha_1=\alpha_2=C$, where C is a real constant, which do not disturb the continuous change of roots in the point $V=V_0$.

If attenuation is nonzero, i.e. $b\neq 0$, then for small δ in the point $V=V_0$

$$\alpha_{1,2} \approx \pm\sqrt{2\delta} \exp[-j \tan^{-1}(2/\delta)/2] \qquad (3)$$

It follows from (3) that real and imaginary components of α_1 and α_2 have equal absolute values proportional to $\delta^{1/2}$ but opposite signs (see Fig.2b). If $V>V_0$, then the physically acceptable solution must satisfy $\mathrm{Im}(\alpha)<0$ which corresponds to the leak of energy into the bulk of crystal, and the transition from the branch α_1 at $V<V_0$ to the branch α_2 at $V>V_0$ results in the discontinuity of all LSAW characteristics in the point $V=V_0$. The conclusion about "merging" of high-velocity leaky wave branch into low-velocity one made in [1] is not valid in general and its validity is restricted to the cases of zero attenuation or uncoupled partial wave associated with limiting velocity V_0.

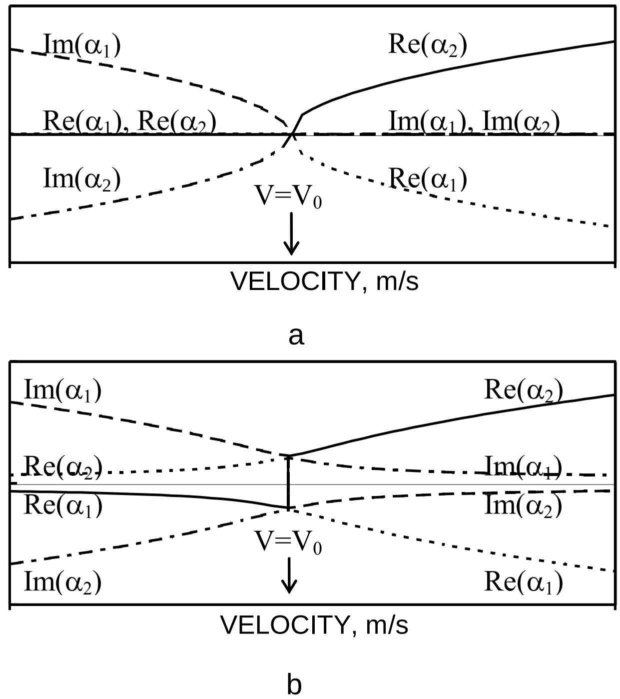

Fig.2. The behavior of a pair of complex roots α_1, α_2 of the characteristic equation around the limiting velocity V_0 when LSAW attenuation is neglected (a) or taken into account (b).

Obviously, the discontinuity cannot occur in practice, and to provide a gradual change of LSAW characteristics in the point $V=V_0$ one should take into account some amount of "non-physical" solutions, α_2 at $V<V_0$ and α_1 at $V>V_0$. This is true not only in the case of layered structure but also when other kind of perturbation occurs which results in variation of LSAW velocity around V_0.

One more peculiarity of LSAW propagation in layered structures can be observed in LST-cut. The cross-section of the slowness surface by the sagittal plane is plotted for this orientation in Fig.3, and the propagation characteristics of SAWs and LSAWs are presented in Fig.4. Within the interval of slownesses (S_2,S_3) (Fig.3) there is a negative curvature (concavity) of the slowness section, and the solution of the characteristic equation in this

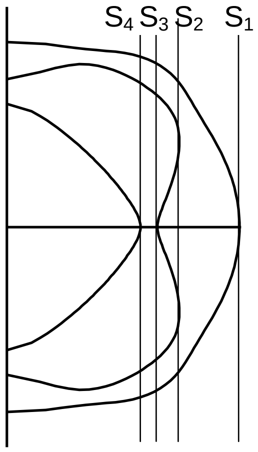

Fig. 3.Slowness section in the sagittal plane of LST cut of quartz.

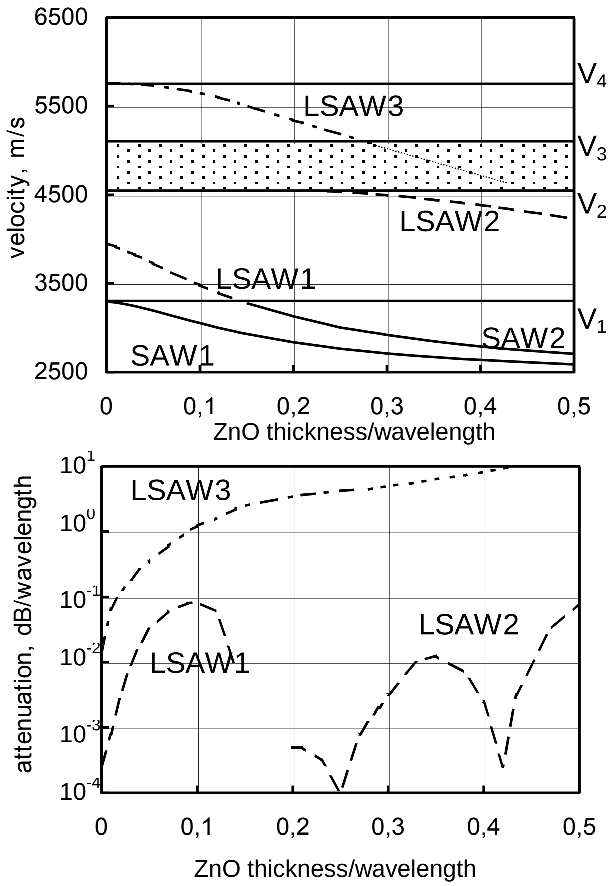

Fig. 4. Propagation characteristics of SAWs and LSAWs on metallized surface of LST cut of quartz with ZnO overlay as functions of ZnO thickness.

region gives an additional pair of real roots, corresponding to incoming and outgoing bulk modes. When the high-velocity leaky wave branch LSAW3 with two partial modes radiating the energy into the bulk approaches V_3 (see Fig.4), one more bulk wave is involved in LSAW structure. The only LSAW solution found in the interval (V_2,V_3) refers to the choice of incoming bulk mode with energy carried from the depth to the surface of crystal. The velocity interval (V_2,V_3) is shaded in Fig.4, and "non-physical" solutions are plotted as a dotted line. From the analysis of the slowness section it follows that this line cannot be continued into the velocity interval (V_1,V_2) because in this case two inhomogeneous partial waves belonging to the same complex conjugate pair of roots would be involved in LSAW structure. One of these partial waves has the amplitude which grows with depth. Thus if there is a concavity of the slowness section in the sagittal plane, LSAW branch can exist only within the certain interval of overlay thicknesses.

Let us consider the low-velocity leaky wave branch LSAW1. This branch degenerates into the non-attenuated "true" SAW (type 1) at $h/\lambda=0$. Theoretical analysis [7] has revealed that such solutions form a continuous line in the space of SAW orientations defined by three Euler angles. Unlike Brewster's solution, the "true" SAW does not disappear with increasing overlay thickness, but moves to another orientation. Therefore, the optimal cut angles can be adjusted to the normalized overlay thickness to provide low insertion loss.

Similar adjustment can be made for EW (type 2). For example, in [8] it was found that LSAW propagating with negligible attenuation in 36°-YX-cut of lithium tantalate, which was proved to be EW [9], moves continuously to 41°-YX-cut if the thickness of Al electrodes grows from 0 to 10%.

The second-order low-velocity leaky wave LSAW2 appears in LST-cut when $h/\lambda>0.2$ and exhibits sufficiently low attenuation within the analyzed range of ZnO thicknesses with two deep minima, $\delta=0.0001$ and $\delta=0.0002$ dB/λ at $h/\lambda=0.25$ and $h/\lambda=0.42$ respectively. In the interval of ZnO thicknesses $h/\lambda=0.3–0.4$ the piezoelectric coupling of LSAW2 is rather high (k^2=1-2%[10]), and it is possible to implement the analyzed leaky waves in SAW devices.

3. LEAKY WAVES PROPAGATING IN LBO, EULER ANGLES (45°,90°,70°), WITH ALUMINUM OVERLAY

The behavior of CEW (degenerate type 3) in layered structures is illustrated by the example of such a wave propagating in the orientation of lithium tetraborate (LBO) defined by the Euler angles (45°,90°,70°), with aluminum overlay. Theoretical analysis of leaky waves in LBO orientations (45°,90°,ψ) was performed, for example, in [11]. The propagation characteristics of SAWs and LSAWs in these orientations are plotted in Fig. 5. The case of metallized surface is considered. The low-velocity LSAW exists within the interval ψ=20-68° and exhibits zero attenuation in orientation ψ≈37°, in which degenerate LSAW type 1 propagates. When ψ=68-76°, in addition to SAW1 there is one more surface wave branch, SAW2. It arises from CEW which exists in the point ψ≈70° if the electrical boundary condition is disregarded. CEW is composed of two limiting bulk waves due to concavity of the slowness sheet corresponding to the slow shear bulk mode. The electrical boundary condition, while taken into account, reduces the velocity of the analyzed degenerate bulk wave, and the second subsonic surface wave branch SAW2 occurs within the certain interval of propagation angles ψ.

Let us consider how this wave behaves, for example, in orientation (45°, 90°, 70°) when thin aluminum overlay is deposited on the surface. The velocities of SAWs and LSAWs are plotted in Fig.6 as functions of normalized Al thickness. The shaded interval corresponds to the concavity of the slowness surface, and the dotted line inside this interval refers to "non-physical" solutions. LSAW velocity grows with increasing Al thickness and "physical" LSAW branch occurs when h/λ>0.12. Attenuation coefficient is very high in the analyzed interval, about 1 dB/λ.

While the velocity of SAW1 reduces with Al thickness, SAW2 velocity grows and in the point h/λ ≈0.03 reaches the limiting value V_1. The range of aluminum thicknesses, within which the additional branch SAW2 exists, depends on the propagation angle ψ . If ψ>76°, there is no second surface wave.

One can expect similar behavior of CEW in layered structures when degenerate solution of type 3 occurs on leaky wave branch, i.e. when it is composed of two fast shear bulk waves due to

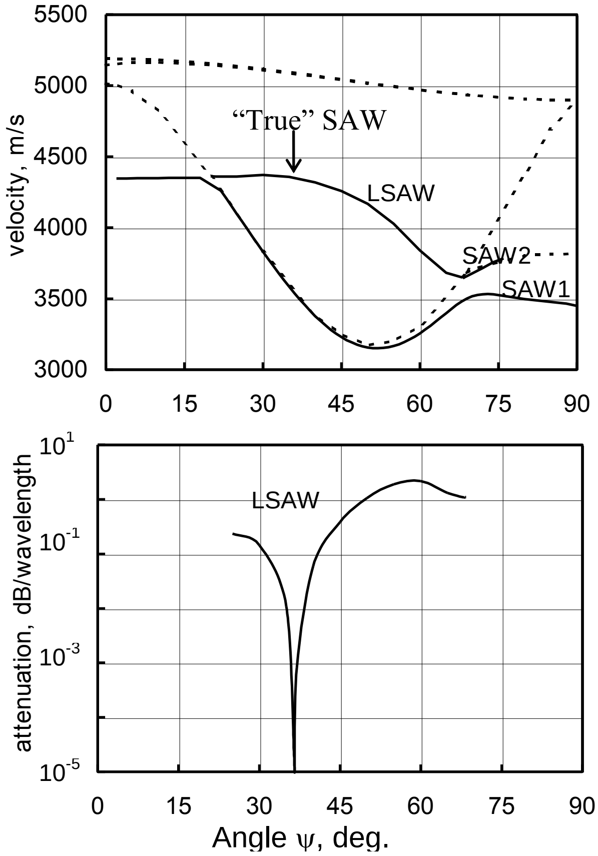

Fig. 5. Propagation characteristics of SAWs and LSAWs on metallized surface of LBO, Euler angles (45°, 90°, ψ). Dotted lines show the limiting velocities.

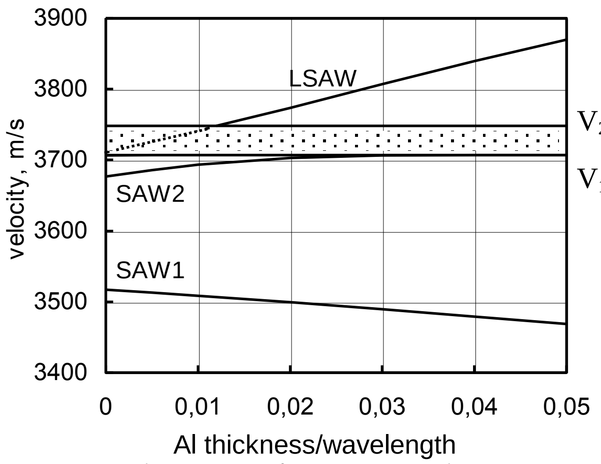

Fig. 6. Velocities of SAWs and LSAW on metallized surface of LBO, Euler angles (45°, 90°, 70°) with aluminum overlay, as functions of overlay thickness

concavity of the corresponding slowness sheet. However, this case needs more accurate treatment. In particular, the behavior of attenuation coefficient with increasing overlay thickness is of major practical importance.

Theoretically it was found that with increasing overlay thickness the growth of attenuation $\delta \sim (h/\lambda)^3$ for EW [12] and $\delta \sim (h/\lambda)^2$ for "true" SAW [13] while no theoretical analysis of CEW has been performed yet. The slow growth of attenuation in conjunction with sufficiently high piezoelectric coupling typical for type 1 and type 2 degenerate LSAWs makes these leaky waves the most attractive for implementing in SAW devices.

IV. CONCLUSIONS

The analysis of leaky wave propagation in layered structures has shown that the behavior of LSAW characteristics with increasing overlay thickness depends on the structure of a leaky wave. Different types of non-attenuated degenerate leaky waves propagating in quartz and LBO substrates have been studied when ZnO or Al overlay is deposited on the substrate. It was found that deposition of overlay moves leaky wave with negligible attenuation to another orientation if this wave has a structure of "true" SAW or exceptional bulk wave. If it is Brewster's reflection, no shift of orientation can ensure low attenuation. In general, the characteristics of a leaky wave do not change monotonically while its velocity tends to that of the limiting bulk wave, the discontinuity being proportional to the attenuation coefficient. If a concavity occurs on the slowness surface of the substrate material, then the existence of leaky wave is restricted to the certain interval of overlay thicknesses.

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