On the Polynomial Approximation of the Dispersive COM-Parameters

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Abstract—**The polynomial approximation of the COM parameters as functions of multiple variables (including the frequency) is developed to accelerate dramatically the fast simulation tools. These tools, based on the widely used COM analysis or matrix (P & T) modeling approaches, are needed to synthesize different kinds of the Leaky SAW-devices with good accuracy and in a shortest time.**

Keywords – leaky waves; COM parameters; approximation

I. INTRODUCTION

Inevitable excitation of the bulk acoustic wave (BAW) modes complicates an evaluation (extraction) of the so called Coupling of Mode (COM) parameters, needed to describe the LSAW devices in terms of the coupled slowly varying amplitudes of only two counter-propagating LSAWs. Among a great number of publications, devoted to the extraction problem, there are two major milestones. In 1993 Victor Plessky introduced a two parameter form for the STW dispersion relation [1]. Then, Ben Abbot and Ken-Ya Hashimoto have improved the ability of the Plessky's fitting procedure, taking into account the "LSAW⇔BAW" interaction more rigorously [2]. The quality of the COM parameter evaluation was checked by comparing the numerically found[1] complex wavenumber, characterizing the LSAW propagation beneath an infinitely long short-circuited periodic grating (SCG), with the relevant eigen-value of COM equations, where the proper COM parameters must be substituted.

However, by using the abovementioned approaches nobody can provide the desired agreement of the corresponding dispersion figures at frequencies outside the Bragg stopband (look, e.g., at Fig.1 from Ref.[4]). The reason for this shortcoming is that, in order to use the convenient dispersion equation, an interaction of LSAWs only with one type of BAW modes (fast shear, to be precise) was taken into account. Nevertheless, many investigators have been trying to extend the capability of the Plessky-Abbot approach till now due to its rather simple analytical form (e.g., [5,6]). However, it demands a cumbersome multi-parameter fitting procedure: all the unknowns must be fitted there simultaneously, even in the absence of the directionality effect.

II. EXCOM ALGORITHM

In reality, the excitation of all BAW modes influence notably each of the COM parameters. By using the denotations, brought in [7], they may be expressed by the following real-valued positive quantities: LSAW coupling (κ_{12}) and dissipation (γ) coefficients beneath an SCG, as well the total transduction (α) and dissipation coefficients (γt), characterizing the collective excitation of both LSAW and BAW modes beneath interdigital transducer [7]. In general $\gamma t \neq \gamma$ because of the quite clear physical reason that under an IDT there are two mechanisms of bulk generation: 1) backscattering of LSAWs on a grating, and 2) direct radiation of BAWs under external voltage applied to an IDT.

As the BAW excitation processes have, evidently, the frequency dependent character, all the mentioned parameters acquire a dispersive nature too. Their dispersion portraits may be found by using the novel extraction algorithm, proposed last year [7] (we name this "ExCOM"). It allows evaluation of the desired parameters in the normalized form directly from the numerical data provided by two of Hashimoto's software tools, FEMSDA and SYNC. From the first program we use a part, calculating the wavenumber of LSAW beneath a short-circuited grating. The SYNC software evaluates numerically the normalized admittance $y_S = \frac{Y_1}{\omega\varepsilon(\infty)}$ per period of infinitely long regular IDT [3], where ω = angular frequency, and $\varepsilon(k)$ = effective dielectric permittivity of a substrate.

The ExCOM algorithm has several important advantages:

[1] With help, e.g., of the FEMSDA software [3].

- Only by means of this tool one can evaluate: a) the dispersion in all COM parameters simultaneously, and b) the physically evident difference in the figures concerning the LSAW dissipation and velocity beneath SCG, on the one hand, and IDT, on another hand;
- All COM parameters are expressed in analytical form directly through the FEMSDA- SYNC results;
- The extraction route is divided into two clear steps, when comparing the analytical and numerical analysis of SCG and IDT;
- Only three fitting parameters are used **in general**, and only one of them is fitted at the first extraction step.

The unknowns, to be fitted, are as follows: (1) systematic error (dv) in the numerical calculations of the LSAW velocity beneath the short-circuited grating; (2) difference (δV) between the LSAW velocities within a short-circuited grating and an IDTphase ; (3) phase parameter of directionality (φ).

A software developed previously to provide the complex global search for the LSAW-, PSAW- and HVPSAW- solutions in piezoelectric crystals [8], can be used now for the two parameter optimization problem (over δV- and φ- values), arising at the 2nd extraction step. This problem is reduced to the rather simple task of global search over a single parameter in many widely used applications, when the natural directionality effect is negligible (as on 42^0-YX $LiTaO_3$ substrate).

The dispersive COM-parameters are surely influenced by the grating input parameters (GIPs) - metallization ratio (w/p) and normalized thickness of electrodes (h/p), where "p" is the grating pitch. The form factor of the non-rectangular electrodes (trapezoidal, for example) may become a GIP too.

Figures 1-2 show some "shots" related to the normalized coefficients: coupling ($\Gamma=\kappa_{12}\cdot 2p$), dissipation beneath SCG ($\zeta=\gamma\cdot 2p$) and IDT ($\zeta t=\gamma t\cdot 2p$), as well the transduction parameter $\chi=(2p\alpha)^2/(\omega C_1)$, where $C_1=C_1(w/p,h/p)$ is the static capacitance per IDT's period. Al grating on the 42^0-YX $LiTaO_3$ substrate is assumed here under w/p=0.6 & h/p=0.16.

The following denotations are utilized: the points f-SS, f-FS, and f-L relate to the onsets of the LSAW backscattering into the slow shear, fast shear and longitudinal BAW modes, while fr-FS & fr-L mean the onsets of the radiation of FS-BAW and L-BAW modes, respectively; the designations SB-*l* and SB-*h* denote the low- and high-frequency edges of the Bragg stopband.

Figures 3 illustrates an evolution of the normalized coupling and dissipation coefficients beneath a short-circuited grating as functions of the normalized frequency and metal thickness for two different metallization ratios.

Rigorously speaking, the ExCOM results relate to the infinitely long structures. However, being substituted into the relevant simulator describing the real devices, they provide a good agreement between the simulation and measurements even for the quite short systems [7].

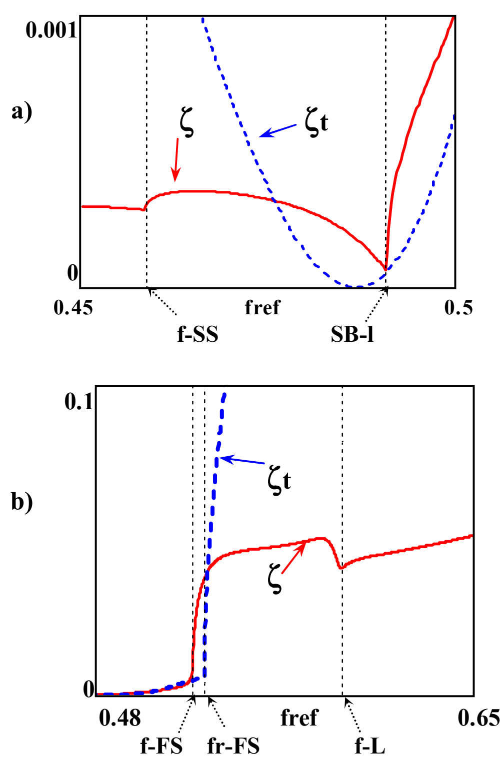

Figure 1. Two spectral segments for the dissipation coefficients beneath infinite SCG (ζ) and IDT (ζt); fref=f·p/Vn. (Vn = 4000 m/s conventially).

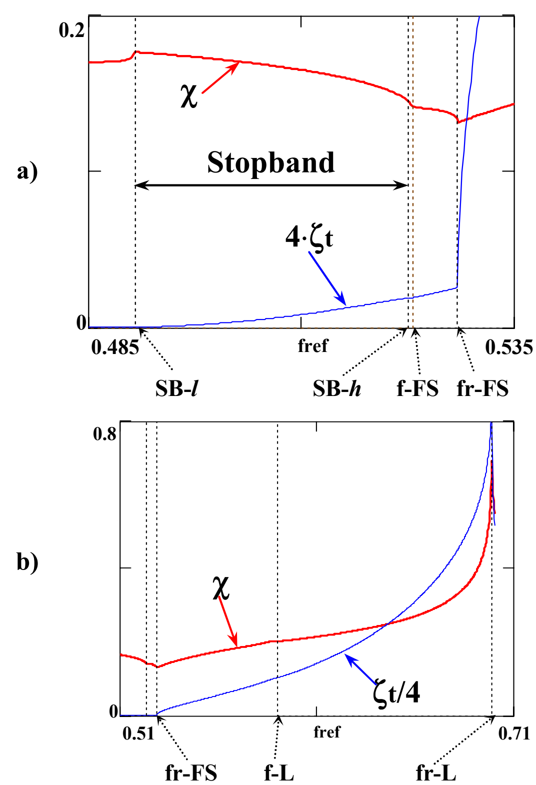

Figure 2. Spectral segments for the normalized transduction and dissipation coefficients within an infinite IDT.

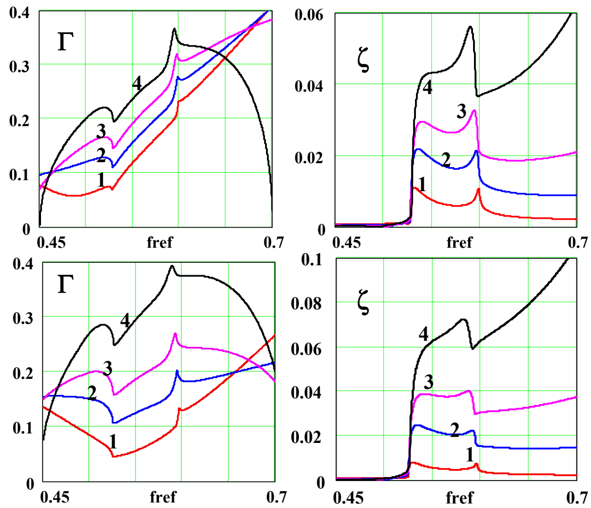

Figure 3. Evolution of the Γ- and ζ- dispersion portraits for variable thickness values under w/p=0.4 (upper) and w/p=0.5 (lower plots) if h/p = 0.02 (1), 0.1 (2), 0.14 (3), & 0.18 (4)

Evidently, it is too cumbersome to calculate the dispersion portraits every time when playing with GIPs during the real design of LSAW devices. Our goal was just to obtain a functional tool (applicable not only to the widely used one-port resonators), allowing us to involve into calculations instantaneously the relevant COM parameters, depending on multiple variables.

As one can see, the dispersion portraits of COM parameters have rather complex shapes. However, one favorable circumstance facilitates their approximation.

III. Checking Frequency Points and Evolution of the Dispersive COM-Portraits

The approximation technique, described in the present paper, assumes a sub-division of the frequency domain onto a set of intervals defined by the "checking frequency points". These points possess a clear physical sense and depend on GIPs as a whole. Within each of these intervals the frequency dependence of every COM parameter has a quite smooth form, simplifying a polynomial approximation of the required characteristics as functions of both GIPs and normalized frequency.

When looking into the coupling and dissipation coefficients per period of SCG, the corresponding "checking frequency points" relate to the onsets of LSAW backscattering in a grating into (i) Rayleigh mode, as well to (ii) slow shear (SS), (iii) fast shear (FS), and (iv) longitudinal (L) bulk wave modes.

On the other hand, the checking points, being related to the dispersion properties of both the transduction and the "total" dissipation coefficients, which characterize the collective acoustic generation of the leaky and bulk waves by an interdigital transducer under external voltage, correlate with the the onsets of radiation into SS-, FS-, and L-BAW modes: fn(j)=V(j)/(2Vn), where V(j) is the velocity of j-th BAW mode along, usually, a direction parallel to the substrate surface. The Bragg stopband edges serve as the checking points also.

IV. Approximation of COM Parameters as Functions of Multiple Variables.

Different approximation methods - the least squares fitting and piece-wise parabolic or piece-wise linear interpolation by the Lagrange polynomials - have been tried and implemented in the software (ApCOM) written in "Borland C++ Builder". This tool allows us to evaluate all COM-portraits immediately after any changes of GIPs (w/p and h/p for a time being). It requires, as input files, the initial ("basic") set of related plots obtained preliminarily as discrete sets over all variables. Similar portraits have been created, presently, for Al gratings on the 42-YX $LiTaO_3$ substrate, using the normalized frequency step Δf_{ref}=0.0002 within an interval 0.465≤ fref ≤ 0.675, for the following values of GIPs: w/p = 0.2, 0.3…0.7 & h/p = 0.02, 0.04…0.2.

In order to check the quality of approximation, we have compared the analytical results, found with help of ApCOM at various intermediate points of the GIP-values not incorporated initially into the set of the basic COM-portraits, with the FEMSDA and SYNC results, established for the same "intermediate" points separately. Figures 4-5 illustrate an example of similar comparison, showing a good restoration of the FEMSDA-SYNC figures by means of approximation.

Note, the quality of restoration after the approximation looks, naturally, poorer than the restoration provided by ExCOM itself, if the chosen combination of GIPs don't coincide exactly with that one which form the "basic" mesh of the initial dispersion curves. For example, the root-mean-square deviation (RMS) of the approximated dispersion figures - velocity (V), attenuation (At), normalized conductance Re(Ys) and susceptance Im(Ys) - from the ones, found directly by the FEMSDA and SYNC programs, under w/p=0.572 & h/p=0.163 are as follows:

RMS_V_{ApCOM}=0.7149 & RMS_At_{ApCOM}= 0.01154
RMS_ReY_{ApCOM}=0.3063 & RMS_ImY_{ApCOM}= 2.9.

At the same time, the corresponding direct ExCOM results give us, naturally, the much better restoration quality:

RMS_V_{ExCOM} = 0.000325 & RMS_At_{ExCOM}= 0.0068
RMS_ReY_{ExCOM}= $3.7\cdot10^{-15}$ & RMS_ImY_{ExCOM}= $4\cdot10^{-14}$

This small shortcoming is the price to pay for the very convenient ability to utilize the COM parameters into the calculations instantaneously. Anyway, one can check and specify the results, found with help of ApCOM during the searching for a best combination of the system GIPs , at the last stage of the device synthesis by using the ExCOM program directly under the input parameters supposed to be the optimal ones. So, the combined ApExCOM software tools appear to be a quite flexible instrument for the real design of the different LSAW devices.

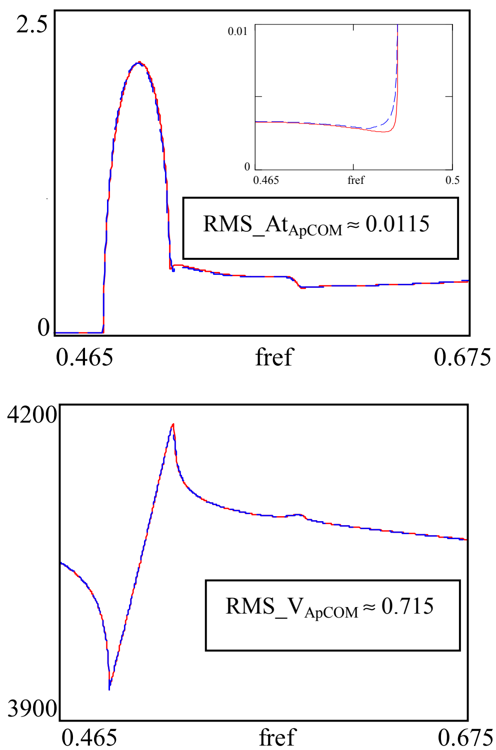

Figure 4. Comparison of the ApCOM results (dashed) with the ones, provided directly by FEMSDA (solid line) for a) attenuation (dB/λ) and b) velocity (m/s) beneath Al grating on 42-LT: w/p=0.572 & h/p=0.163.

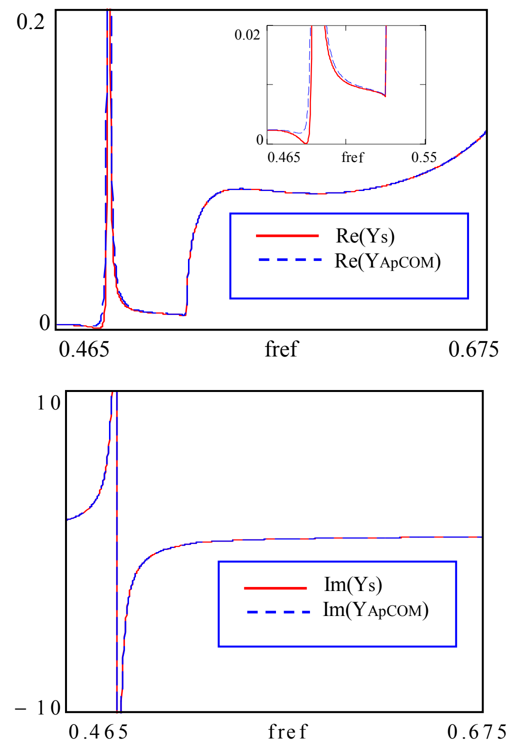

Figure 5. Comparison of the ApCOM results (dashed) with the ones, provided directly by SYNC (solid lines) for the normalized conductance (a) and susceptance (b) per period of infinitely long IDT; w/p=0.572, h/p=0.163. NB: max (|ImYs|) ≈ max (ReYs)/2 ≈ 1300.

V. Conclusion

An extraction algorithm is improved allowing, firstly, the reliable evaluation of the COM parameters for LSAW devices and, secondly, the polynomial approximation of these parameters as functions of three (presently) variables, namely: normalized frequency, metal thickness and metallization ratio. A discrepancy, arising between the LSAW characteristics (dissipation and velocity) beneath a transducer and short-circuited grating, is underlined.

The software tools have been implemented to provide both extraction (ExCOM) and approximation of COM parameters by polynomials (ApCOM). The latter tool can be used as a sub-routine in general programs, providing the instantaneous attraction of the desired COM parameters into calculations involved in actual design of the Leaky SAW devices.

The ApExCOM precision should be improved further by using, as a reference at the 2nd extraction step (instead of SYNC), the results of the FEM-BEM calculations, evaluating numerically an admittance of the finite-length IDT.

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References

[1] V.P. Plessky, "A Two Parameter Coupling-Of-Modes Model For Shear Horizontal Type SAW Propagation in Periodic Gratings", Ultrasonics Symposium Proceed., 1993, pp.195-200

[2] B.P.Abbott and K.Y.Hashimoto, "A Coupling-Of-Modes Formalism For Surface Transverse Wave Devices", IEEE Ultrasonics Symposium Proceedings, 1995, pp.239-245

[3] K.Y.Hashimoto, Surface Acoustic Wave Devices in Telecommunications, Springer, 2000

[4] K.Y. Hashimoto, T. Omori and M. Yamaguchi, "Modelling of Shear-Horizontal-Type Surface Acoustic Waves and Its Application to COM-Based Device Simulation", in Proc. 2001 IEEE Ultrason. Symp., pp. 127-132.

[5] K.Hasegawa and M.Koshiba, "Coupled-Mode Equation for Interdigital Transducers for Leaky Surface Acoustic Waves", Japanese Journal of Applied Physics, v.42, Part 1, no.5B, May 2003, pp.3157-3160

[6] K. Hirota and Y. Yamamoto, "Considerations on Coupling-of-Modes equations for Shear Horizontal type SAW", Preprint on the 2004 IEEE UFFC 50th Anniversary Joint Conference.

[7] B.V. Sveshnikov, A.P. Shitvov, and K.K. Bhattacharjee, "Evaluation of dispersion in COM parameters," in Proc. 2003 IEEE Ultrason. Symp., pp. 715-719.

[8] M.Yu. Dvoesherstov, V.I. Cherednick, A.P. Chirimanov, S.G. Petrov, "A method of search for SAW and leaky waves based on numerical global multi-variable procedures", SPIE, Vol. 3900, 0277-786X/1999, pp. 290-296.