Influence of Diffraction on the SAW Tag Characteristics

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***Abstract*— A unique feature of the acoustoelectric scattering of the non-uniform SAW beams by the straight metal strips placed on the piezoelectric substrates is underlined. Closed-form solution is obtained to describe the diffraction influence on the reflective delay line properties. The found results allow fast simulation and optimization of SAW tags with high capacity taking into account the diffraction effect consistently.**

I. Introduction

Metal electrodes or their regular blocks, placed on piezoelectric substrate, are used worldwide as reflectors forming the coding sequence in the SAW tags and those based RFID systems.

As it is well known, there are several reasons to increase the tag length:

a) delay of the first reflected pulse should be enough long to separate the tag response from parasitic EM signals;

b) distance between reflectors must be sufficient to escape overlapping (at a transponder) of the neighboring reflected pulses each of which has a duration $\Delta t \sim 1/\Delta fs$, where '$\Delta fs$' is the permitted bandwidth of the RFID system operation;

c) the larger tag's capacity the greater number of reflectors we need.

One cannot simply increase an acoustic aperture 'W' to prevent the beam spreading effects because of the ohm losses in a transponder, rising in direct proportion to W^2-value. So, the diffraction effects, which perturb the amplitude and phase of the surface wave arriving at a particular reflector, may influence considerably the SAW tag features [1].

Usage of the curved reflectors, shaped in accordance with their distance from a transponder, is proposed in Ref. [1] to solve that dilemma. However, such a solution looks to be enough cumbersome one in the face of the mass production needs.

When considering the diffraction problem in SAW devices it is necessary to note a unique feature of the acoustoelectric interaction of SAW beams with metal strips placed on the piezoelectric substrates. The point is that SAW itself is formed by two coupled physical sub-systems, namely: elastic displacements and accompanying electric field. Respectively, the wave reflected by each electrode represents a superposition of two beams appeared because of, firstly, perturbation of the elastic boundary condition and, secondly, due to electric shorting beneath electrodes. In case of substrates with high piezoelectricity, such as widely used $LiNbO_3$(0,38,0), amplitudes of both beams may have comparable magnitudes. However, their transverse profiles are different to each other in the presence of unavoidable (due to diffraction) transverse non-uniformity of incident wave front along a reflector.

Naturally, one has to summarize properly the "elastic" and "electric" reflection terms in order to estimate correctly the diffraction influence on the tag characteristics. This is just an objective of the present paper.

II. Diffractionless Simulation

The developed previously modeling of multi-track SAW devices [2] opens a highly expedite way to simulate characteristics of SAW tags with practically arbitrary architectures.

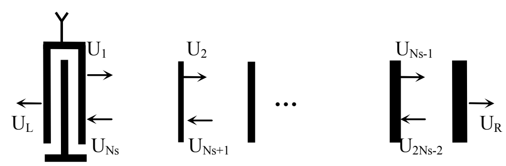

Figure 1. Schematic structure of the single-track "in-line" SAW tag

Let us illustrate the simulation principles by simple example of SAW tag (Figure 1). It contains 'N' structures (blocks) with the same aperture W: the 1st block is a transponder, while the others represent reflectors forming the desired system response to the interrogating radio-frequency pulse with duration $\Delta t \approx 1/\Delta f_s$.

According to the "single track" variant of SEA concept, simplified in application to the considered case, one can write a set of (2N-2) equations for (2N-2) acoustic amplitudes U_j appeared between all blocks when unit voltage is applied to the 1st block (transponder):

$$U_j = M_{jk} \cdot U_k + H_j \quad (1)$$

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Here j,k = 1…2N-2; M_{jk} –scattering matrix, depending on the reflection and transmission coefficients of the tag blocks, as well on the phasors between them; $H_j = P_{13}\cdot\delta(1,j)$; P_{13} is the relevant term of the transponder P-matrix, while 'δ' is the Kronecker delta function. At this point index of any "backward" wave comes to hand from "forward" index at the same cross-section simply by adding figure 'N-1'. Just due to this "end-to-end'' listing manner that technique is named as "Sequential Enumeration of Amplitudes" (SEA-method) [2].

The following evident equality solves the system (1) in the matrix form:

$$\vec{U} = (\hat{I} - \hat{M})^{-1} \cdot \vec{H} \quad , \qquad (2)$$

where $\hat{I}$ is the unit (2N-2)×(2N-2) matrix.

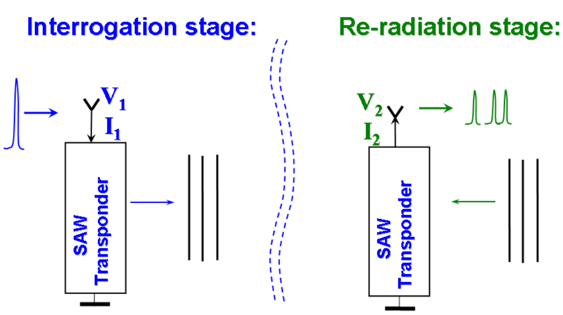
When knowing admittance Yt of the input transducer in the absence of other reflectors, one can find the system Y-parameters as follows:

$$Y11 = P_{31}\cdot U_N \;,\; Y21 = Y11 - Yt \qquad (3)$$

The obtained results should be ever verified by two fundamental principles:

1) in the absence of dissipation the normalized acoustic power $Pa = |U_R|^2 + |U_L|^2$, going outside a tag (Figure 1), coincides with the system input conductance: Pa=Re(Y11), while unavoidable losses always reduce the ratio Pa/Re(Y11) at every frequency point (conservation of energy);

2) in general, due to reciprocity of SAW systems, the determinant of the classic transmission matrix $\hat{A}$, coupled with Y-parameters by the well known relations, should be equal to unity: |A| =1 (Figure 2).



$$\begin{pmatrix} V_1 \\ I_1 \end{pmatrix} = \hat{A} \cdot \begin{pmatrix} V_2 \\ -I_2 \end{pmatrix}$$

Figure 2. Two stages of the tag operation

Satisfaction of both mentioned principles gives us an opportunity to be assured regarding the simulation validity.

The time-domain response of a tag to interrogating radio-frequency pulse with arbitrary duration is calculated by usual FFT technique.

It has to be noted that there is one important difference between consideration of diffraction phenomena here and in [2], where the reflective inhomogeneities assumed to be infinitely long along the transverse direction. That assumption was quite acceptable only for SAW devices based on rather weak piezoelectric substrates.

III. Peculiarity of the SAW Scattering by Metal Strips

We're expecting, following [3], that total reflection coefficient of plane wave from metal strip may be represented as superposition of "elastic" (depending on the normalized width and thickness of a strip) and "electrical" (depending only on w/λ) terms:

$$r_t(w/\lambda,t/\lambda) = r_u(w/\lambda,t/\lambda) + r_e(w/\lambda) \qquad (4)$$

However, reflection of SAW beam with non-uniform transverse profile Φ(y), incident normally on straight metal strip (with length W) being parallel to y-axis, demands a special consideration.

Any function Φ(y) may be expressed as superposition of uniform and non-uniform parts: $\Phi(y) = \overline{\Phi} + \tilde{\Phi}(y)$,

$$\overline{\Phi} = \frac{1}{W}\int_{-W/2}^{W/2} \Phi(y)dy \;,\; \tilde{\Phi}(y) = \Phi(y) - \overline{\Phi} \qquad (5)$$

Neglecting the metal resistance, each strip is considered as equipotential surface. Therefore, the non-uniform part of incident beam cannot induce the secondary charges which disturb the electrical boundary conditions beneath electrode, and may be reflected by metal strip only elastically.

On the other hand, following the Huyghens principle, one can assume that initially a profile of the backward beam reflected "elastically" has the same form as the incident beam in the frame of the reflector aperture.

So, neglecting the beam spreading within a reflector, the reflected SAW beam in total may be expressed as follows:

$$\Phi R(y) = (Rt\cdot\overline{\Phi} + Ru\cdot\tilde{\Phi})\cdot\Pi(y) = \{(Rt - Ru)\cdot\overline{\Phi} + Ru\cdot\Phi(y)\}\cdot\Pi(y), \qquad (6)$$

$$\Pi(y) = \begin{cases} 1, \text{ if } |y| \le W/2 \\ 0 \text{ otherwise} \end{cases}$$

Here Rt- and Ru- terms concern the total and elastic reflectivity, if the analyzed reflector is formed by a set of regular strips (i.e., they represent the corresponding P_{11}-parameters of periodic structures described by the well known COM formulae).

IV. Reflecivity Reduction Because of Diffraction

Let us consider now the diffraction influence on characteristics of SAW tag with acoustic aperture W in the "one-bounce" approximation. We'd like to answer the question: how diffraction changes a contribution of the first SAW reflection by each reflector to Y21-parameter of a tag?

Interrogation pulse, applied to transponder, excites the rectangle SAW beam with the unit amplitude $A_1(0,y)=\Pi(y)$. This beam undergoes the diffraction distortion propagating toward reflector placed beyond a transponder on distance ‘L’ (Figure 3a). We assume the transverse power flow drift of SAW beams (beam steering effect) to be negligible, as this assumption is the well grounded one for the considered here 128-LNO substrate.

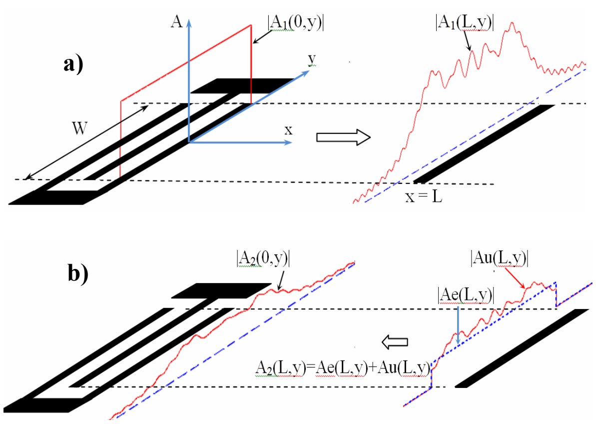


Figure 3. Forward (a) and backward (b) stages of the “one-bounce” SAW beam propagation within a tag.

Being valid under $L/\lambda << 4(W/\lambda)^4$, the quasi-optical approach in the Angular Spectrum of Waves method [4] is applied below to evaluate approximately the diffraction distortions. Assuming the parabolic dependence of SAW velocity on the angular ‘ϑ’ between propagation direction and the system longitudinal axis $v(\vartheta) \approx v_o(1+\gamma\cdot\vartheta^2/2)$, one can write:

$$A_1(L,y) \approx \frac{e^{-i\cdot k\cdot L}}{2\pi}\cdot\int_{-\infty}^{\infty}\frac{\sin(qW/2)}{q/2}\cdot e^{i\cdot\frac{q^2|1+\gamma|}{2k}L + i\cdot q\cdot y}dq \qquad (7)$$

An interference of fields, reflected elastically and electrically

$$A_2(L,y)=A_u(L,y)+A_e(L,y),$$

propagates backward to be integrated along the transponder electrodes at the final stage of the tag operation (Figure 3b):

$$A_2(0,y) \approx \frac{e^{-i\cdot 2k\cdot L}}{(2\pi)^2}\cdot\int_{-\infty}^{\infty}dq\int_{-W/2}^{W/2}A_2(L,z)\cdot e^{i\cdot\frac{q^2|1+\gamma|}{2k}L + i\cdot q(y-z)}dz \qquad (8)$$

Bearing in mind that $Y21 \propto \int_{-W/2}^{W/2}A_2(0,y)dy$, one can see how to describe correctly the effective reduction of reflection coefficients of all structures forming the coding pulses in the tag response to interrogation pulse:

$$RC_k \approx (Rt_k - Ru_k)\cdot De_k + Ru_k\cdot Du_k\,, \qquad (9)$$

$$De_k = \frac{1}{\pi^2}\cdot\left(\int_{-\infty}^{\infty}\left(\frac{\sin(z)}{z}\right)^2\cdot e^{i\alpha_k\cdot z^2}\cdot dz\right)^2, \qquad (10)$$

$$Du = \frac{1}{\pi^2}\cdot\left(\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\left(\frac{\sin(z)\sin(z')\sin(z-z')}{z\cdot(z-z')\cdot z'}\right)^2\cdot e^{i\alpha_k\cdot(z^2+z'^2)}\cdot dz\cdot dz'\right) \qquad (11)$$

Here $\alpha_k = \frac{|1+\gamma|\cdot\lambda\cdot L_k}{\pi\cdot W^2}$ is the diffraction parameter of k-th reflector placed on distance L_k beyond a transponder, while ‘λ’ is the free space wavelength.

NB: In the near-field zone ($\alpha<<1$) equality (9) may be evaluated analytically: $De \approx De0 = \left(1-\sqrt{\frac{\alpha}{2\pi}}-i\cdot\sqrt{\frac{\alpha}{2\pi}}\right)^2$.

Figures 4 illustrate dependence of magnitude (a) and normalized phase (b) of De(α)- and Du(α)- functions.

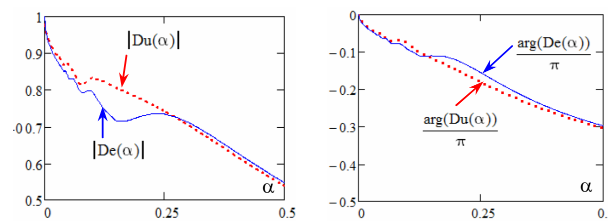


Figure 4. Correction factors De & Du as functions of the diffraction parameter.

V. Simulation Examples

Let us consider the in-line SAW tag designed for 2.45 GHz frequency range, containing SPUDT-transponder and 14 weighted reflectors on 128-LNO substrate (similar to [5]). Figures 5 show the calculated tag time-domain response to interrogating radio-frequency pulse with duration Δt = 25 ns (Δfs = 40MHz) and rectangular envelope.

As analysis shows, in the absence of diffraction the optimal aperture of transponder, equals 50 microns, providing the minimal insertion loss (IL) about $IL_{min} \approx 31.8$ dB (Figure 5.a).

When taking diffraction into account one can see the considerable deterioration of the tag response: IL_{min}-value is increased from 31.8 to 35.1 dB in the matched mode. Besides, ~ 5 dB non-uniformity appears in the amplitudes of the coding pulses (Figure 5b).

By rising acoustic aperture doubly we can improve the tag features: diffraction causes a rather moderate increasing of IL level (from 32.2 to 34 dB) keeping, at the same time, practically uniform level of the coding pulses (Figures 5c,d).

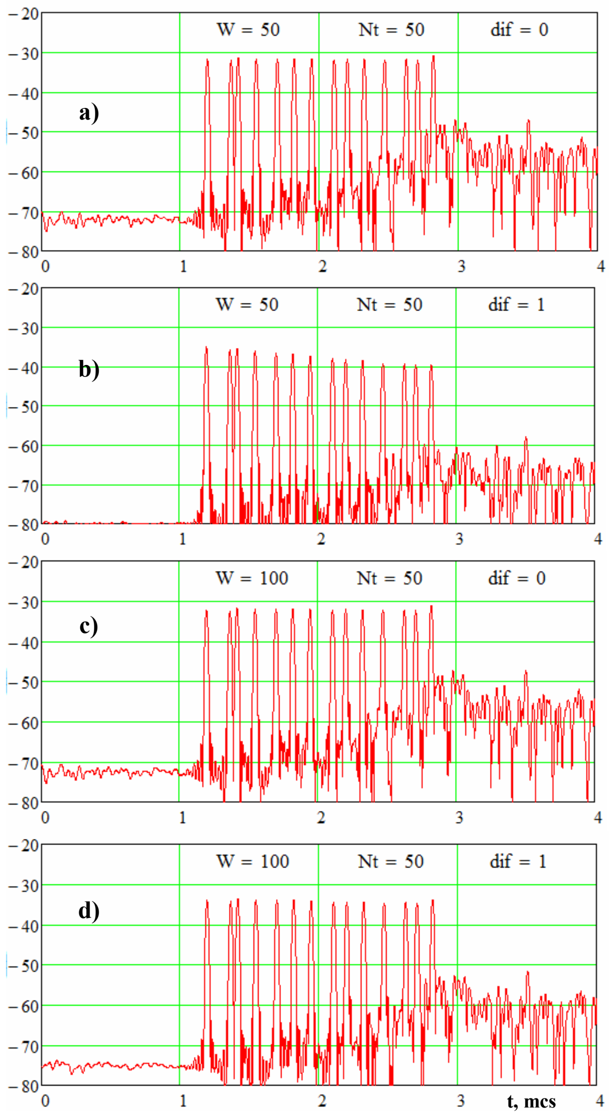


Figure 5. Time-domin response of SAW tag (2.45 GHz) as function of the time (microseconds) spent after the interrogation pulse start.

VI. CONCLUSIONS

Effective modeling is developed to simulate the SAW tags of practically arbitrary types, including the multi-track ones. Original and reliable criterion, based on two fundamental principles (The Energy Conservation Law and Reciprocity), is proposed to verify the simulation validity. Specific feature of the SAW beam scattering by metal strips is underlined. Closed form solution is found to estimate and compensate consistently the diffraction influence on the reflective SAW tags. It is shown that diffraction may impair notably the system quality even in case of tag with rather moderate capacity on 128-LNO substrate. Fine-tuning of the developed approach will allow us to create the powerful and flexible software tools facilitating considerably the synthesis and optimization of the RFID SAW systems.

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